

SOUTHERN PINE BEETLE IN LOBLOLLY PINE: SIMULATING WITHIN STAND INTERACTIONS USING THE PROCESS MODEL SPBLOBTHIN

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Abstract—Pine stand density is a key determinant of damage resulting from attacks by the southern pine beetle (SPB, *Dendroctonus frontalis* Zimm.). High-density stands of maturing loblolly pine (*Pinus taeda* L.) are at high risk for losses to SPB, and reducing stand density is the primary tool available to forest managers for preventing and mitigating damage. Field studies are expensive and inflexible for evaluating various stand treatments over large areas and long time periods, especially with unpredictable SPB population levels. To address these shortcomings, and to provide guidance on silvicultural treatment selection for future field studies, we have developed a process model (SPBLOBTHIN) to simulate the joint population dynamics of loblolly pine and SPB in single stands. Our model grows and tracks individual trees and beetles, both temporally and spatially, and includes stochasticity where desired. The model allows great flexibility in assigning values to input parameters, including those that designate temperature, site index, tree resistance, stand density, and thinning regime. We have also linked model output values to the U.S. Department of Agriculture, Forest Service's Stand Visualization System (SVS), an existing tool for producing realistic and useful views of stand and tree characteristics over time. The objectives of this report are to highlight the flexibility and utility of SPBLOBTHIN, present output created by its linkage with SVS, and compare model simulation results with those obtained in an earlier field study from which pest management thinning recommendations were developed for loblolly pine.

INTRODUCTION

Loblolly pine, *Pinus taeda* L., is the most important commercial forest tree species in the southern U.S. and is a preferred host of the southern pine beetle (SPB, *Dendroctonus frontalis* Zimm.), the most damaging insect pest within its range. Current estimates are that about 32 million ha of SPB-susceptible forests exist nation-wide, of which about 56 percent is dominated by loblolly (Krist and others 2014). Host stand density has long been recognized as a key determinant of damage by SPB in relation to both infestation occurrence and expansion. In turn, thinning is recognized as an important tool for reducing susceptibility of stands to SPB invasion. Specific target basal areas (BAs) are available for residual densities of loblolly pine stands in order to mitigate SPB impacts (Nebeker and others 1985). Current recommendations arose primarily from a 3-year controlled field study conducted by Nebeker, Hodges, Brown and colleagues at Mississippi State University from 1978–80 (herein the NHB study, Brown and others 1987, Nebeker 1981, Nebeker and Hodges 1985). Since the NHB study, thinning recommendations have remained relatively unchanged for southern pines, but information has increased about underlying mechanisms that may be responsible for determining

stand resistance levels (e.g., stand meteorology; Thistle and others 2011). Recent results are complementary to older ones, but they have added complexity by increasing the number of relevant variables.

While the risk of SPB damage has continued to grow with increasing stand densities and tree ages in the South, our resources to establish long-term, large-scale field studies to address these concerns and to identify potential solutions have declined. As a result, predicting the outcomes from interactions between existing and future forests and their pests has become more dependent than ever on predictive simulation models. In this paper, we describe SPBLOBTHIN, one of the suite of “SPBLOB” process models (i.e., based on simulating biological processes and interactions), which tracks day-to-day changes in SPB populations and annual changes in loblolly pine growth and mortality in a plantation setting (Bishir and others 2009). The growth-and-yield portion of SPBLOBTHIN is derived from PTAEDA2 (Burkhart and others 1987, Daniels and Burkhart 1975), thus providing spatially explicit individual tree simulations for growth characteristics and mortality. The full model accounts for tree and beetle locations within the stand, with the latter being spatially referenced by tree locations. Beetle

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population updates are provided up to four times per day depending on temperature, while tree growth and mortality from intraspecific competition are updated annually.

Field studies have been essential for documenting the relationship of SPB attacks to stand characteristics (see Coster and Searcy 1981) and for developing thinning guidelines. Those of the NHB study are the basis for current pest management thinning recommendations in the southern pines. However, field studies are expensive and burdensome to maintain, and complex and unpredictable processes such as climate, host resistance, temperature, canopy structure, stand structure, host availability, and feral insect populations interact to produce variable outcomes. Each site and SPB spot is unique, so prediction of tree mortality and stand damage must address shifting probabilities and chance occurrences. Along with accumulation of this knowledge has come recognition that a modeling approach can be an effective or even necessary method for mechanistically addressing important management factors. The results can be used to revise and improve current thinning recommendations under variable meteorological and climatic conditions as well as to account for the dynamic constraints imposed by forest harvesting and business operations. That is, market and business forces—along with technological advances in equipment design, etc.—can foster changes in forest management practices over time that may not be predictable. Models offer maximum flexibility to address such issues in a timely manner. Accordingly, our objectives in this paper are:

1. To demonstrate the function, flexibility, and utility of SPBLOBTHIN as a means to evaluate thinning regimes for SPB prevention;
2. To compare results obtained from model simulations to those obtained from the NHB field study, a cornerstone study from which current southern pine pest management thinning guidelines are based.

MATERIALS AND METHODS

General Introduction to SPBLOBTHIN

SPBLOBTHIN uses a modified version of PTAEDA2 (Daniels and Burkhart 1975, Burkhart and others 1987) to produce spatially explicit individual tree simulations for growth and the mortality resulting from intraspecific competition within a stand. Each stand simulation consists of five stages: 1) choosing tree variables, site index, temperature regime, and planting density/spacing; 2) tree growth and survival through an 8-year juvenile period during which no SPBs are present; 3) daily updates of the number of SPBs at each tree and the tree mortality they cause (some beetle activities are updated four times daily); 4) yearly updates of tree

growth and mortality related to tree competition; and 5) timber harvest at designated periods determined by user-selected triggers and targets. The combination of thinning triggers along with the pattern and severity of tree removal can be set by the user, but 100 of the most useful combinations are “preprogrammed” into SPBLOBTHIN and may be chosen by their regime number (Bishir 2014). Regimes may be updated in future versions of SPBLOBTHIN based upon user input. In general, tree activities are simulated using PTAEDA2 subroutines (Burkhart and others 1987, Daniels and Burkhart 1975) generously provided by H. E. Burkhart for our use, while SPB activities are unique to SPBLOBTHIN. Output data vary by user preference and may include such things as the number of trees killed by competition or SPB, trees surviving, residual volume, and removed volume by product class (i.e., biomass, chip-and-saw, pulpwood, sawtimber). Additional information about these and many other model details—including parameter estimates, output options and references—are available in Bishir and others (2009) and Bishir (2014).

SPBLOBTHIN tracks day-to-day changes in tree survival and beetle populations, including the location within the stand of individual female beetles (males are assumed to join females; Bishir and others 2009). Beetle locations are spatially referenced by tree, and following Bunt and others (1980) are categorized as landed, parent, dispersing, or juvenile. Beetle population updates are provided up to four times per day, whenever thresholds of developmental and flight temperatures are achieved during the period (Bishir and others 2009).

Tree data output from SPBLOBTHIN may be visualized by inputting it to the U.S. Department of Agriculture, Forest Service’s Stand Visualization System (SVS, v. 3.30; McGaughey 1997; fig. 1). This can be done on a per treatment simulation basis by copying output and pasting into SVS one output file (simulation result) at a time or as a batch process via the SVS Image Generator (SIG), which is software code written for this project by Tony Austin (Austin and Bishir 2014) and updated by Dan Leduc (Information Technology Specialist, USDA Forest Service, Pineville, LA). The SIG links output from SPBLOBTHIN to SVS, producing pictures of events (before and after stand entries for thinning, initiation of SPB spots and their development over time, etc.) in the simulated stand through the time period specified by the user. The SIG output resembles a movie that can be played at speeds chosen by the user.

Objective 1—To demonstrate the function, flexibility, and utility of SPBLOBTHIN, we selected examples to show how simulated stands change following thinning or SPB infestation (spot occurrence and growth). Both examples are the result of SPBLOBTHIN simulations run with a 17 °C average annual temperature (as in Pineville,

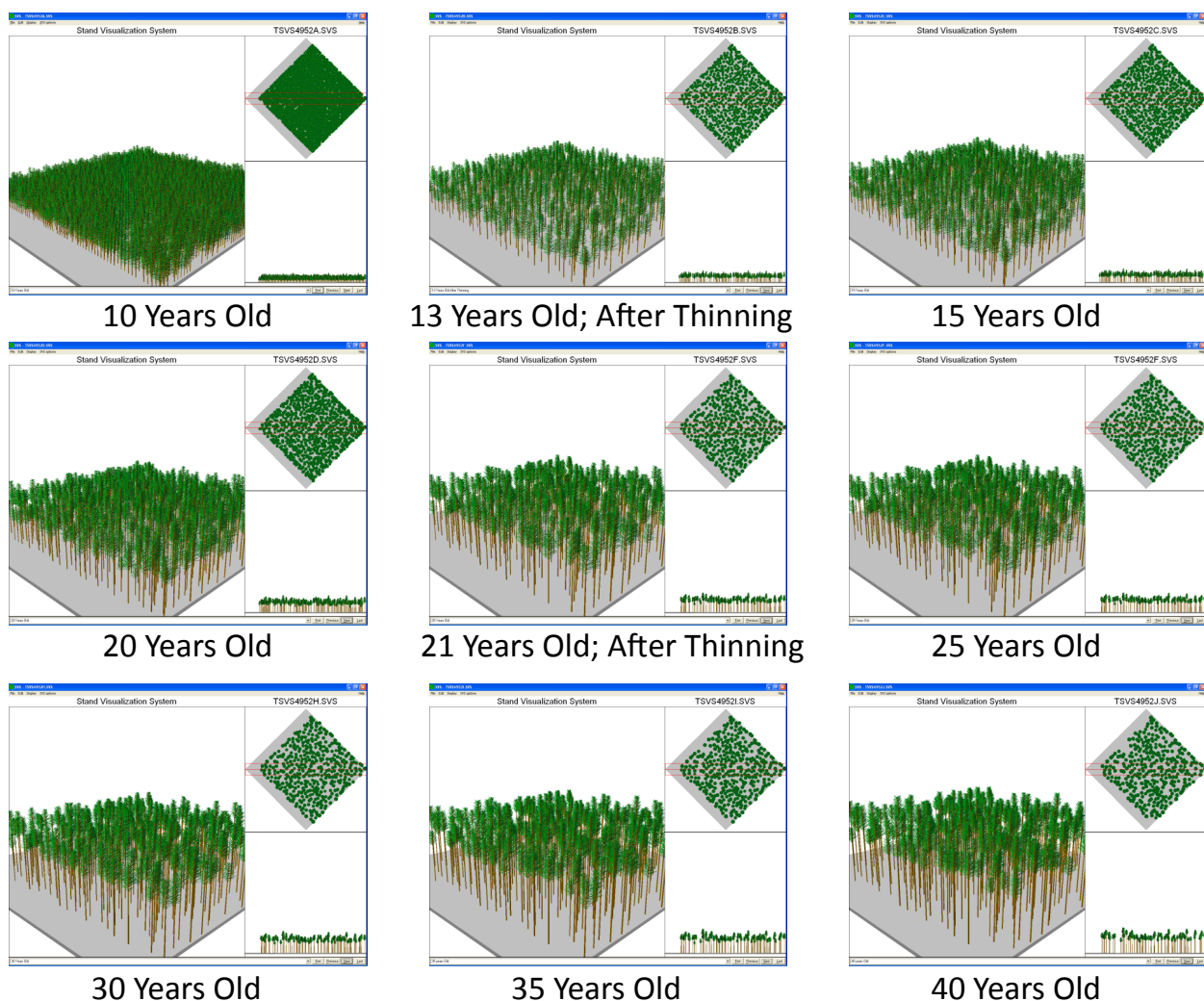


Figure 1—Example of SVS output at various stand ages between 10 and 40 years old.

LA) and a site index of 60 (base age 25). We also note that in our experience, PTAEDA2 (the base growth-and-yield model) does not provide reliable results for stands older than 40 years, so we end all of our stand simulations by that age.

The first example begins with an illustration of an unthinned stand (the no-management alternative, regime 1 of the preprogrammed regimes; Bishir 2014) and a pattern of tree mortality from SPB that is commonly observed in SPBLOBTHIN under this regime (fig. 2). In this simulation, the stand was planted at 2,000 trees per acre (TPA), a surrogate for high planting density with natural infill, and received no precommercial or commercial thinning.

In the second example (fig. 3), the stand was again established at 2,000 TPA, but in this simulation, we selected one of the preprogrammed management

regimes that included thinning (number 39; Bishir 2014). In this regime, there is a precommercial swath thinning triggered when there are >750 live TPA with average annual diameter growth of <5 percent for two consecutive years and average diameter at breast height (dbh) <5 inches. Target residual TPA was 450. This was followed by a commercial fifth-row thinning, perpendicular to the swath thinning, triggered in this regime when stand basal area (BA) exceeds 120 square feet per acre and average dbh is at least 5.5 inches. Target residual BA following the commercial thinning is 70 square feet per acre in this regime. We are not aware of field data documenting the pattern of tree mortality caused by SPB in row-thinned stands, but we believe the pattern resulting from this simulation is reasonable (fig. 3).

Objective 2—To compare field results to those produced by SPBLOBTHIN, we chose data and

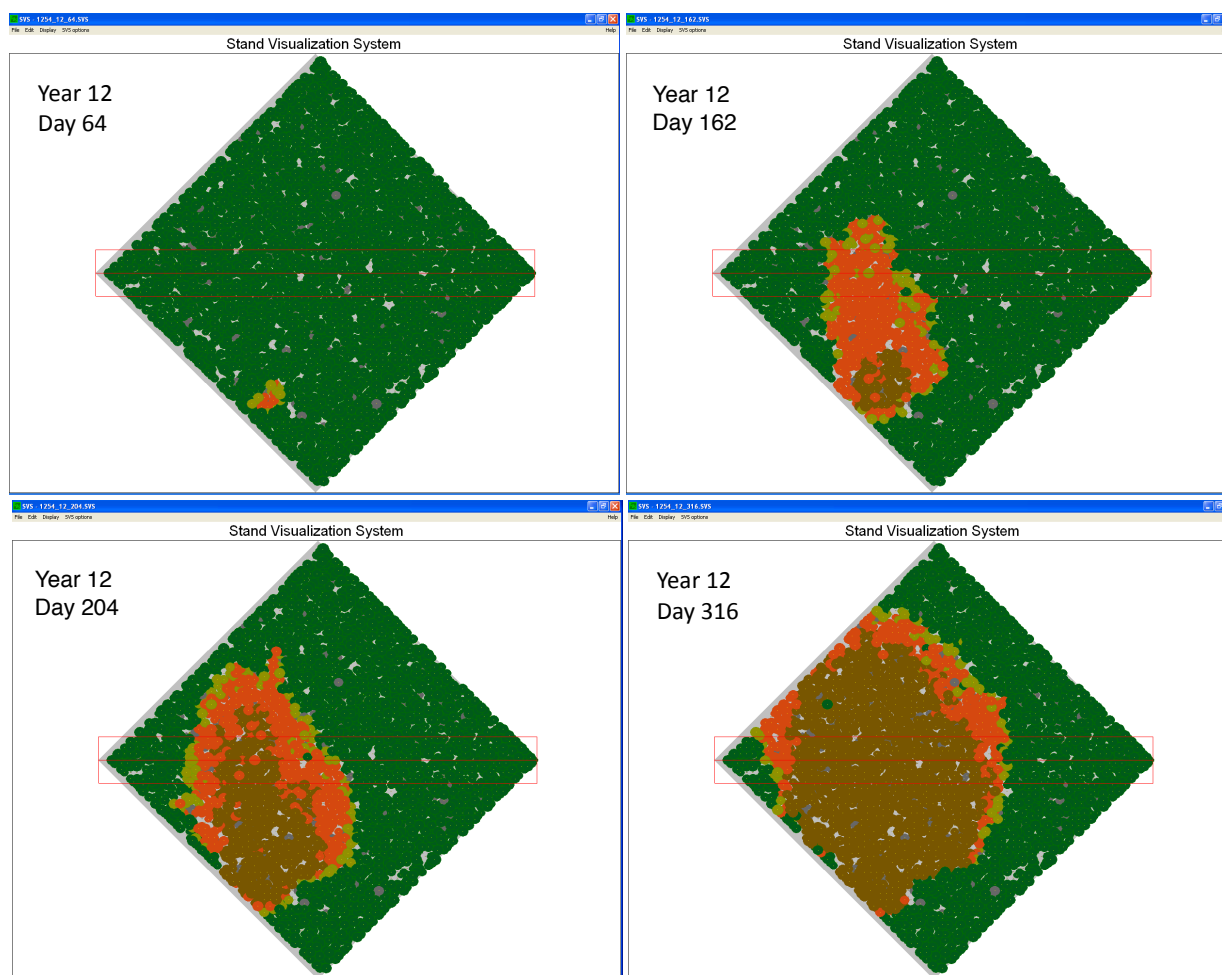


Figure 2—SPB spot in unmanaged stand (Example 1). Unmanaged stand regime 1 of pre-programmed regimes in SPBLOBTHIN. Stand was planted at 2,000 trees per acre to simulate planted seedlings and natural infill. The simulation realized its first southern pine beetle infestation at year 12 and the infestation is followed until day 316. As is typical in SPBLOBTHIN simulations (and in the real world), unmanaged stands realize extensive damage from SPB spots.

outcomes from the NHB study reported in Brown and others (1987), Nebeker (1981), and Nebeker and Hodges (1985). As mentioned, the NHB study was conducted from 1978–80 and evaluated the impact of thinning intensity on the resulting stand damage (primarily tree mortality) caused by SPB within each year. The loblolly pine plantation used for the study was established at the Starr Memorial Forest, Mississippi State University, Mississippi in 1956 using a spacing of 10- by 10-feet. Stand basal area averaged 197 square feet per acre prior to initiation of thinning treatments in winter 1977-1978 at tree age 22. Thirty-six 1-acre plots were established, providing nine replicates for each of four thinning intensities [untreated (BA = 197, called “200” in the literature describing study results), 130, 100, and 70 square feet per acre]. Thinning began with the removal of every fifth row in each plot, except where high levels of fusiform rust (*Cronartium fusiforme* Hedge & Hunt) precluded this method from leaving enough residual trees to meet the BA target. In this case, infected trees

were preferentially removed in lieu of row trees. The fifth-row thinning was followed by secondary removal stages that consisted of “thinning from below” and removal of trees infected with fusiform rust between rows to reach the final BAs desired for individual plots (Brown and others 1987, Nebeker 1981).

Beginning in 1978, the NHB study challenged 12 plots per year with SPB. To promote attacks and evaluate spot initiation and growth, a single tree at each plot center was baited with SPB aggregation pheromone to provide an initial focal point. Beetle-infested logs and/or bark were placed at the plot center. In 1978, an estimated 5,000 SPBs were introduced on a single date to each plot (as brood). Because this provided a challenge that was less severe than desired, the number of SPBs was increased with the introduction of additional SPB brood material to 10,000-15,000 accumulating over multiple dates in 1979 and 1980.

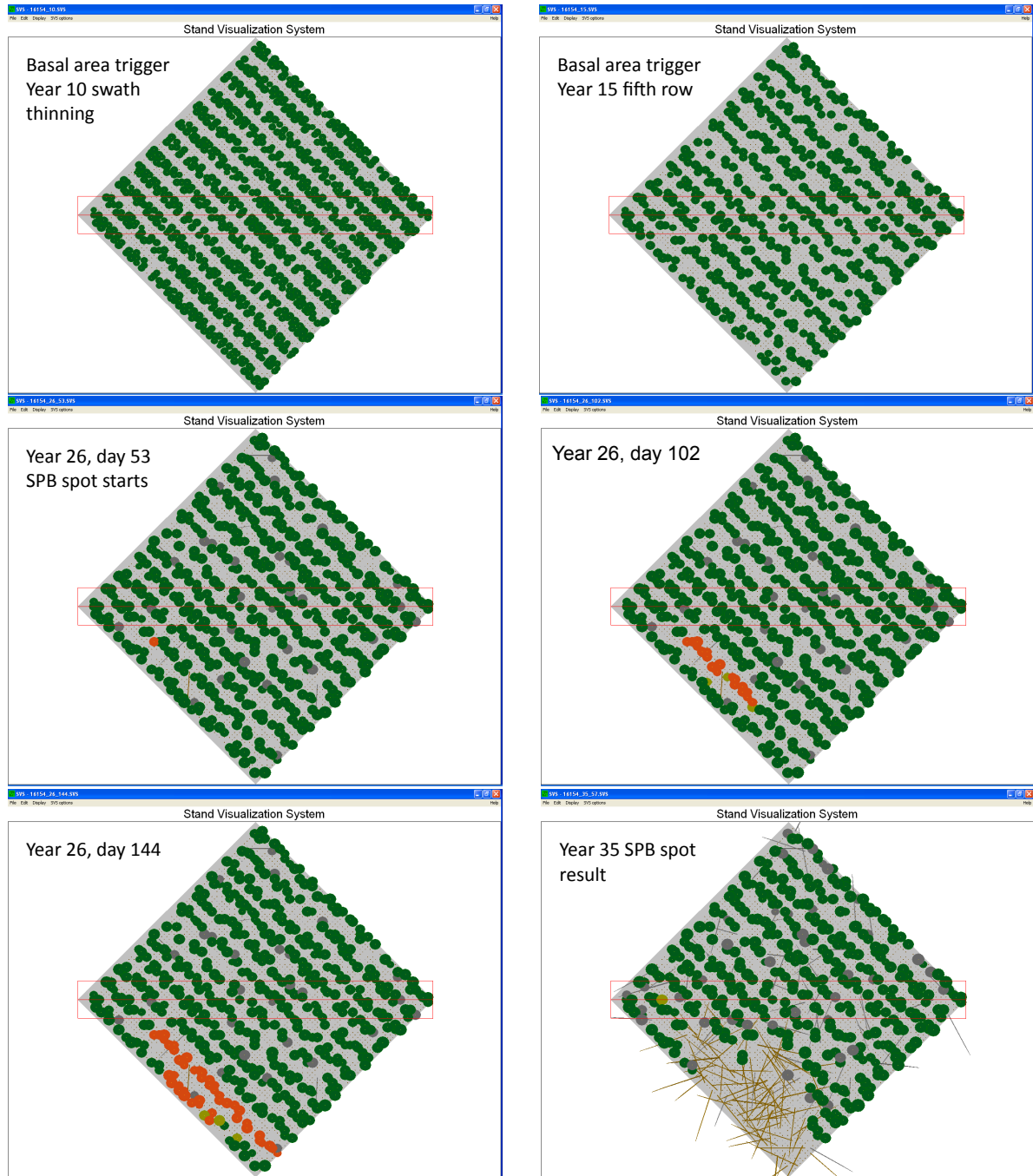


Figure 3—Example 2 showing densely planted loblolly pine as in Figure 2, but with precommercial thinning at year 10 and commercial thinning at year 15. During year 26 the first SPB spot was observed at day 53 and it is followed until day 144. Tree mortality progressed along a single swath of residual trees before extending across to a second swath of residual trees. Year 35 is also provided to show the depiction of fallen (attacked) trees in SVS.

Feral SPBs also moved via immigration throughout the NHB plots, but no data are provided to estimate their numbers (e.g., from trapping). As we discuss later, immigration of SPB into the plots was critical for the 1979 results to be realized by simulation. In each plot, the total number of trees killed by SPB was tallied (Brown and others 1987, Nebeker 1981), and these data were used to make the primary comparisons between results from NHB and corresponding SPBLOBTHIN simulations. Secondary data also were recorded, including estimates of SPB attacks, brood production, and other selected variables (Nebeker 1981).

Stand inputs to SPBLOBTHIN simulations followed as closely as possible the data and procedures reported by the NHB study. Each simulated 1-acre stand was “planted” using 10- by 10-foot spacing. Stand site index was defined to be 70 feet at base age 25 [about equivalent to the 110 feet at age 50 (Hamilton 2000) used by NHB]. To check these approximations, we simulated 100 independent, unthinned stands, each with 10- by 10-foot spacing and SI = 70. These showed an average BA value of 194.4 ± 4.08 square feet per acre (mean $\pm$ standard deviation) at age 22 compared to an overall average of 197.0 square feet per acre computed from the NHB data (Nebeker 1981). Simulated plots were then challenged with SPB by infesting a central tree with a sufficient number of SPBs to kill it. Each treatment combination (four levels of stand density) was simulated over 500 independent trials with the mean number of trees killed per plot being tallied.

In addition to tree mortality, Nebeker (1981) reports the total brood emergence for each of 17 trees killed by SPB in plots during the critical year of 1979. These field results were compared to brood emergence results from SPBLOBTHIN (1,500 simulations, 336 killed trees) by employing a chi-square test with four degrees of freedom; brood counts were first binned into five ordinal categories following the procedures of Hogg & Tanis (2001).

RESULTS

Objective 1

In the first example, SPB-caused tree mortality in an unmanaged stand was first observed in year 12 at day 64 (fig. 2). As the model updates, spot growth is obvious, depicting a spot head advancing in a northwesterly direction with expanding flanks and culminating on day 316 with much of the stand being lost to SPB.

In the second example (fig. 3), the high-density stand initially underwent a precommercial thinning followed later by a commercial thinning, both dictated by the user-selected regime 39. Figure 3 begins with the first thinning, conducted as a precommercial swath

thinning, at year 10. This was triggered “automatically” in SPBLOBTHIN by the established precommercial thinning parameters. At age 15, the first commercial thinning treatment was employed (fifth row perpendicular to previous swath thinning), this time by the model’s automatic commercial thinning trigger. The stand grew until year 26, when a SPB spot first appeared with a single dead tree at day 53. The spot expanded in a pattern that we often see in simulations produced by the model (and occasionally in the field)—tree mortality progressing along rows of more closely spaced trees until attacking beetles spread across the swath of removed rows. Ultimately, the simulation culminated with SPB-killed trees being present in a multiple row spot, and by year 35 scattered elsewhere, with SVS pictorially showing the attacked trees as fallen (fig. 3).

Objective 2

The primary objective of the NHB study was to evaluate the effect of thinning treatments on tree mortality and consequent losses of timber volume. For convenience, table 1 provides the yearly tree mortality data by BA class observed in the NHB study (Brown and others 1987). In our simulations, we resorted each year to a “trial and error” method of choosing the model immigration parameter (*parimmi*) values that produced the best approximations to the NHB field observations (table 2). It is evident from table 1 that tree mortality was greater in 1979 than in the other years, especially at the higher BAs. We found that the extent of these two results from 1979, greater tree mortality and a nonlinear, positive relationship between the number of trees killed by SPB and BA, were unique to that year and were the key factors necessary for successfully simulating the NHB results.

Because there are no field data from which to realistically base the immigration parameter in SPBLOBTHIN (*parimmi*), we employed a range of positive immigration values to the 1979 BA 130 and BA 200 plots. Results are displayed in table 2 using 450 landed female SPBs per tree (the number that SPBLOBTHIN simulations show were most probably present in NHB) and range from 0.004 (BA 130) to 0.008 (BA 200). We note that if field-based information becomes available to indicate values the immigration parameter should take, they can easily be specified in SPBLOBTHIN because *parimmi* is user-defined.

A trend readily apparent in results observed in both the NHB field experiment and our model simulations is that denser stands—those with higher BAs—tend to experience larger spots than do stands with lower BA values. This trend was observed in earlier studies of SPB spot growth in east Texas (Cameron and Billings 1988, Hedden and Billings 1979) and was the primary finding from the NHB field study. Likewise, similar

Table 1—Observed yearly mean numbers of trees killed per plot in each combination of year and BA as derived from Table 4 of Brown and others (1987)

Year	BA Values			
	70	100	130	200
Mean numbers of trees killed per plot				
1978	0	0.33	1.0	2.67
1979	0.67	1.0	2.67	11.33
1980	0.33	1.0	0.67	2.67

Table 2—Mean numbers of trees killed per plot in simulations of 1979 (age 23) plots having 450 ‘Landed’ SPB assigned to a single, initially infested tree (as per Nebeker, 1980). For BA groups 130 & 200, the non-zero immigration parameter values in these simulations were chosen through trial and error in order to approximate the mean numbers of trees reported by Nebeker (1980) and Brown and others (1987) as having been killed by SPB in 1979

Post-Thin BA Values	70	100	130	200
Immigration parameter parimmi	0.0	0.0	0.004	0.008
Simulated mean #s of trees killed	0.59	1.28	2.70	10.93
NHB data from Table 1	0.67	1.00	2.67	11.33

behavior observed in the simulations, whether or not beetle immigration occurred, further validates the SPBLOBTHIN model code.

In addition to tree mortality, we compared NHB counts of SPB brood from trees killed in the NHB study in 1979 to average brood counts obtained from SPBLOBTHIN simulations. Nebeker (1981) reports total brood emergence for each of 17 trees killed by SPB in the 12 experimental plots infested during 1979, and we evaluated brood emerged from 336 trees killed by SPB in 1,500 simulation runs of SPBLOBTHIN in this experiment. As indicated earlier, our test of the hypothesis H_0 , that the field and model distribution functions for brood counts were the same, was conducted by employing a chi-square test with four degrees of freedom. Because the sum (4.46) was less than the critical value for 5 percent significance (9.49), H_0 was not rejected, and the brood numbers from SBPLOBTHIN were deemed an acceptable representation of the field results.

DISCUSSION

The process model SPBLOBTHIN was employed to generate results and images to demonstrate the model’s flexibility, utility, and performance. Example output illustrates that thinning treatments followed the

expected pattern of row and between-row tree removals (fig. 3). In addition, development of SPB infestations (spots) seemed also to follow expected patterns (figs. 2 and 3). Simulation of SPB spots showed attacked and dead trees to be aggregated, damage to increase over time, and damage to be more severe in unmanaged stands. In thinned stands, when SPB spots did occur, they frequently extended along rows where distances to adjacent trees were shortest. This expected behavior is sometimes observed in the field, but spatially explicit field data to test this behavior are lacking.

Current pest management recommendations for thinning loblolly pine stands are primarily based upon the NHB study (Brown and others 1987, Nebeker 1981, Nebeker and others 1985). To compare field and model results, we employed SPBLOBTHIN to simulate the interaction between SPB and loblolly pine under the conditions reported for the NHB field study. Mean levels of field tree mortality by year of the NHB study are shown in table 1. Similar results were produced by SPBLOBTHIN for the years 1978 and 1980 (table 1). The exceptions in year 1979 are the untreated (200 square feet BA) and 130-square-foot BA stands, which were recognized as anomalies within the NHB study as well (table 1). For SPBLOBTHIN to effectively simulate the NHB field data on tree mortality in 1979, the realization

of two phenomena was necessary. First, immigration of SPB adults into the stand was required for 1979 (immigration rate greater than zero in that year), and second, immigration rates needed to be higher in denser (higher BA) stands (table 2). The likelihood of these phenomena being reasonable is discussed below.

The probability that greater SPB immigration could have taken place in the NHB field plots in 1979 is supported by two lines of evidence. First, Nebeker (1981) provides estimates of the number of attacking beetles and the number of beetles emerging from the bolts and bark brought into selected plots to challenge trees. By comparing the number of SPBs brought into the plots to the number of attacking beetles, an indication is given as to whether immigration of beetles into plots was necessary to produce the observed level of beetle activity. To do this, we limited our comparison to the first 30 days after attacks were first observed so that brood adults could be excluded from consideration. This approach did not account for parent adult reemergence, but the discrepancy between the number of SPB attacks and the estimated brood emergence in BA = 200 (unthinned) plots is too great for reemergence to account for the difference observed. In 1979, as in each year of the study, three unthinned plots were challenged. In plot 18, Nebeker (1981) estimates that 11,121 SPBs were released into the plot and that 24,808 attacked 9 trees in the plot by day 28. Similarly, in plot 20, counts indicated that 16,356 beetles were released and 38,466 attacked 12 trees by day 21. Finally, in plot 29, there were an estimated 14,439 SPBs released and 24,700 beetles attacked 10 trees. These estimates support that immigration into the unthinned plots in 1979 was necessary to account for the level of SPB activity observed.

In addition, records of SPB spot abundance at the county level (Pye and others 2008) support a higher probability of immigration into plots in 1979. Historical data on spot numbers from Oktibbeha County, MS (where the NHB study was located), indicate that in 1978, SPB spots were present below outbreak levels, between 0.1 to <1.0 spot per 1,000 acres of host type. In 1979, the county transitioned to severe outbreak status (≥ 3.0 spots per 1,000 acres), suggesting that area-wide beetle populations were abundant and that active spots would initially serve as sinks for dispersing SPB because there were fewer competing spots in the surrounding landscape to draw beetles from the plots. By comparison, in 1980, during the second year of severe outbreak levels of SPB activity, attractive (competing) spots would more likely already be present and relatively abundant in the landscape. In 1981, the county was again below outbreak levels. These records are consistent with a pattern of the greatest numbers of dispersing beetles being present in the exponential

population growth phase during the transition into a severe outbreak (Clarke 2012).

Available evidence from field studies also supports the indication from SPBLOBTHIN simulations that the immigration rate is higher for denser stands as determined by the number of trees killed. A recent study by Nowak and others (2015) on the Homochitto and Bienville National Forests (MS) investigated SPB spots that occurred during 2012. Of the 910 spots evaluated, only 2 (0.22 percent) were found in recently (past 6 years) thinned stands. In addition, research on the movement of air in thinned versus unthinned loblolly pine stands has demonstrated that the latter provides a meteorological environment that promotes structural integrity of gas plumes (Thistle and others 2011). Such an environment should allow easier semiochemical tracking by beetles during the host-finding process.

The biological process model SPBLOBTHIN performed well by the measures investigated in this study. Linkage with SVS provided pictorial evidence that simulated thinning operations resulted in appropriate patterns of tree removal and retention, and target residual basal areas being achieved. The model has great flexibility to simulate a wide variety of conditions and actions as specified by the user. Our simulations that mimicked conditions in the NHB study, performed from 1977–80 on trees planted in 1956, provided valuable insight into the number of landed SPBs necessary for tree mortality to be consistent with that observed in the field (450 female beetles per tree) and led to the conclusion that immigration behavior must have occurred in 1979. This was heretofore unrecognized from the field study. The model appears to be a useful tool for investigating joint population dynamics of SPB and loblolly pine. SPBLOBTHIN may be particularly valued for its flexibility and as a surrogate for large-scale field studies, which are difficult to implement and inflexible over the space and time needed to answer SPB/loblolly pine interaction questions at the stand level. It is probable that multiple factors favor host trees over beetles when stands are thinned, but our lack of knowledge about stand-beetle interactions contributes to uncertainty in predicting the impact of thinning regimes, especially as they evolve with changes in forests and forestry practices. Simulation models allow the flexibility necessary for navigating through changes that occur at a pace faster than long-term field studies can accommodate. They also help to identify knowledge gaps, provide a tool for preliminary evaluation of proposed operational treatments for field studies, and provide estimates of outcomes in interim periods before field studies are completed. Although irreplaceable, long-term field studies are expensive, burdensome to maintain, and difficult to replicate. As an alternative, we propose the use, application, and continued refinement of

process models such as SPBLOBTHIN to guide and assist decisionmaking for field studies and timber management operations.

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