USING A GIS-BASED SPOT GROWTH MODEL AND VISUAL SIMULATOR TO EVALUATE THE EFFECTS OF SILVICULTURAL TREATMENTS ON SOUTHERN PINE BEETLE-INFESTED STANDS

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Abstract—Many models are available for simulating the probability of southern pine beetle (*Dendroctonus frontalis* Zimmermann) (SPB) infestation and outbreak dynamics. However, only a few models focused on the potential spatial SPB growth. Although the integrated pest management systems are currently adopted, SPB management is still challenging because of diverse land ownership, dynamic forest landscapes, and uncertainty in spatial infestation pattern. In this study, we incorporated Geographical Information System (GIS)-based spot growth model into a three-dimensional visualization by using the visual simulator. The GIS maps of possible infestations were generated and used as the basis of three-dimensional visualizations to simulate spatial patterns of spot growth under various silvicultural treatments, including thinning, species mixtures, and different ages of stands. The results indicated these management practices, especially the thinning treatment, can reduce SPB infestation, particularly on the number of trees killed, but this does not necessarily result in a reduction of the infested area. We believe that GIS-based three-dimensional visualizations could provide more realistic landscapes without the spatial and temporal limitations for improving the SPB management decisionmaking process.

INTRODUCTION

The outbreaks of southern pine beetle [*Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae)] (SPB) have caused severe ecological and economical damages (Price and others 1998). Consequently, the cause and spread of SPB has been studied extensively and its impacts are quite well understood. Owing to these efforts, existing models can predict both the probability of infestation and spot growth well for managers to make management plans with a minimum cost (Clarke 2001, Hedden 1985, Stephen and Lih 1985). However, although there are several regression and mechanistic models developed for simulating SPB spot growth, most models focus on predicting the number of trees killed in an infestation, and only few models were developed for spatial spot growth within forest stands.

In order to control and reduce the damage from SPB, the integrated pest management (IPM) system was used. IPM can help us to reduce pest populations and maintain them at levels below causing ecological and economic damage through the following main strategies (Edmonds and others 2000, Hedden 1978, Vité 1990): (1) developing a damage threshold where pest suppression is considered necessary, (2) establishing a detection-population monitoring system, and (3) developing silvicultural techniques to lower the population by interfering with the host selection behaviors of dispersing beetles. Despite the implementation of these effective management strategies responding to bark beetle (*Ips typographus* L.) hazards, there are still millions of acres of forests impacted by SPB infestations every year (Clarke 2001, Oliver and others 1994, Stephens and Ruth 2005).

Some challenges still constrain the land managers' ability to accomplish comprehensive IPM programs (Clarke 2001, Coster 1981, Stark and others 1985, Stephens and Ruth 2005). The major constraints are: (1) diverse land ownership—they are responsible for the pest detection and control on their lands with varying objectives and economic resources (Clarke 2001, Oliver and others 1994, Pyne and others 1996) and make it difficult to manage or control SPB outbreaks before or after infestations occurred when this damage covered widespread forest lands; (2) dynamic forest landscapes—although SPB hazards are more serious on pine (*Pinus* spp.) forest stands than other types of forest, these pine stands are dynamic and regional stand conditions are highly variable to make higher uncertainties when detecting the infestation regions and spreading patterns of SPB outbreaks; (3) the uncertainty effect from pest strategies—it is difficult to predict consequences of specified management strategies, such as buffer strips or mechanical thinning, for lowering SPB hazards on ecological or social impacts, and it's even more challenging to determine how efficient to achieve a specified operation (Almo 2006, Coster 1981, Martell 2001). Due to these constraints, forest managers and researchers are still challenged to control SPB hazards, to recover these damaged forests, and to determine the best restoration strategy for forest ecosystem and public awareness (Moore and others 1999, Pollet and Omi 2002, Stephens 1998, Waters 1985). For these reasons, an improved IPM system is needed for combining different objectives and resources from diverse land ownerships; organizing dynamic temporal and spatial data and information; monitoring, analyzing, and evaluating the ecological and social impacts from alternative management operations; and finally representing a comprehensive and sophisticated communication to ameliorate the decisionmaking process (Coster 1981, Sheppard and Salter 2004).

The main study objective was to provide three-dimensional visualizations to make the SPB management decisionmaking processes more effective. Three-dimensional visualizations are spatial representations and understandable

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communication techniques to help us to present different management alternatives and allow observation of forest landscapes without temporal and spatial limitations (McGaughey 1998, Orland 1994, Song and others 2006). Moreover, we used the Geographical Information System (GIS) maps of probable infestations as the basis of visual simulator to generate three-dimensional visualizations. Consequently, we aim to support a visual communication technique not only to deliver the complex information to different stakeholder groups with varying needs and degrees of knowledge on forest science, but also to delineate spatial and temporal changes in forest landscapes resulting from the multiple purposes and alternative SPB management operations (Sheppard and Salter 2004, Song and others 2006).

SIMULATION APPROACH

In this study, we simulated the spread probabilities of SPB spots in loblolly pine (*Pinus taeda*) stands within the southeastern Piedmont region of the United States. Spot growth was mapped by GIS-based SPB spot growth model using ArcObjects and Microsoft® Visual Basic for Applications in ArcGIS. Then, GIS maps of probable spot spread could be modified by initial stand characteristics for different SPB management practices, e.g., thinning, different species mixtures, and different ages of stands. Finally, these GIS maps of probable infestations were used as the basis of three-dimensional visualizations to simulate the trends of spot growth by using the Visual Nature Studio (VNS) software package (3D Nature 2002).

The Simulation of GIS-Based Southern Pine Beetle Spot Growth Model

Hedden and Billings (1979) developed the SPB spot growth model based on simple regression approach. We translated it into a GIS model. Because the SPB spot growth model was not originally designed for GIS base, we had to follow three steps to realize it (fig. 1, Chou and others 2008). In the first step, we determined the stand conditions, including species composition, stand area, stand density, average diameter at breast height (d.b.h.) and stand height, and spatial pattern of trees. The main patterns were uniform, random, and cluster, and these stand patterns would interact with silvicultural treatment effects. Silvicultural treatments influence the spatial pattern of trees and species mixture. In the second step, we calculated the dynamic of number of killed trees using SPB spot growth model for different affected stages during the period of infestation. In the last step, we built a spatial spreading module mainly based on the effects of nearest neighborhood, the susceptible species to pine beetle, season, and wind direction. Using the spatial spreading module within the ArcGIS programming environment, we could estimate the spatial arrangement of these infected trees as GIS maps. Therefore, according to this approach, we can generate any specified stand pattern by assigning the parameters of stand conditions.

Three-Dimensional Visualization of Southern Pine Beetle Spot Growth

A flowchart of the visual simulator (fig. 2) was generated for simulating the three-dimensional visual animations of

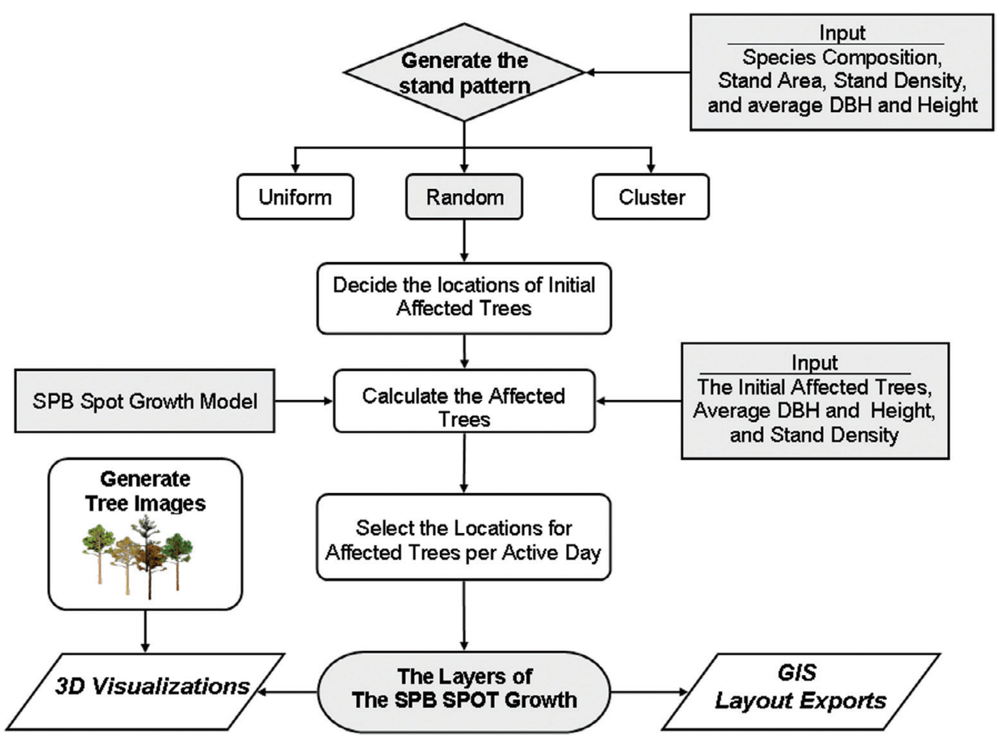

Figure 1—The simulation framework of the GIS-based southern pine beetle (SPB) spot growth model.

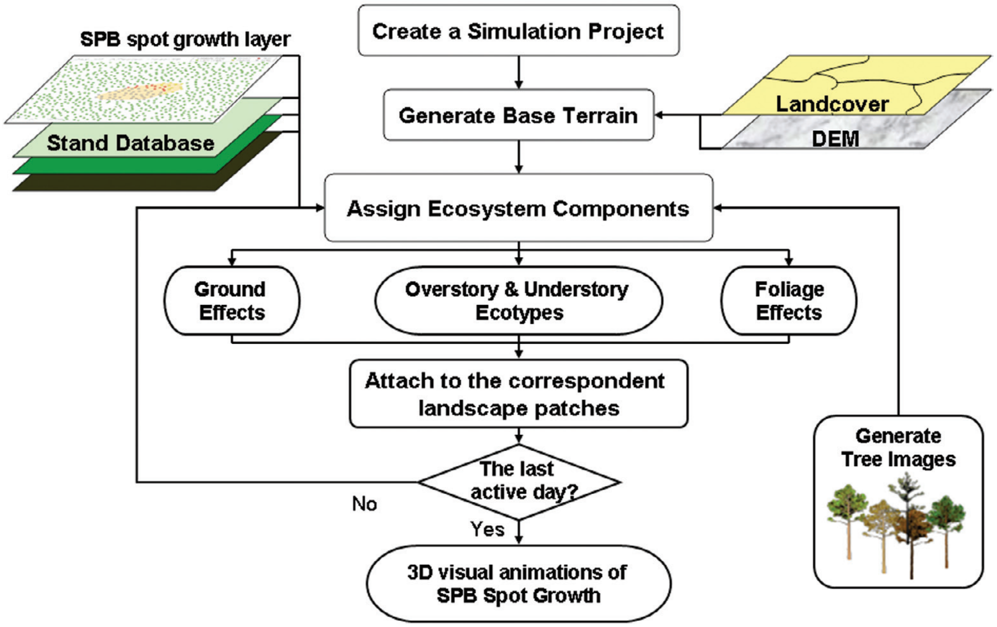

Figure 2—The flowchart of the visual simulator within Visual Nature Studio. (SPB = southern pine beetle, DEM = digital elevation model)

SPB spot growth. The environment of three-dimensional visualization is VNS, a three-dimensional, photorealistic, and landscape-visualization simulation software package (3D Nature 2002). Within it, we can directly import the landcover map and digital elevation model as our terrain base. Then, using the GIS maps of SPB spot growth, stand database, and specified tree images to assign the landscape patches (within VNS, they are called “ecosystem components”). The stand database includes stand density, stand average height, and species composition to support the required parameters for simulations. Moreover, we created specified photorealistic images to represent varied foliage effects from different affected stages and species with diverse colors and crown shapes (fig. 3).

We then assigned these “ecosystem components” by three divisions. First, the “ground effect” is visualized for the soil, litter, and other surface materials. Second, species composition, stand density, and average height are assigned for the “overstory and understory ecotype.” And third, specified photorealistic tree images are linked to the appropriate tree “foliage effects.” After attaching these ecosystem components to the correspondent landscape patches and stands, we can generate one scenario of SPB stop growth for 1 day. In order to simulate the trend of spot growth, we have to generate the three-dimensional visualizations for the whole period of spot growth by repeating the process of “assign ecosystem components” until the last day of the SPB spot growth simulation. Finally, we created the three-dimensional visual animations of SPB spot growth under the specified stand condition and generated other alternative SPB management operations by these procedures.

Comparing the Simulations of GIS Maps and Three-Dimensional Visualizations from Different Silvicultural Strategies

Following the above approach, we generated GIS maps and three-dimensional visualizations for comparing infestation sizes and spreading trends of SPB spot growth under different silvicultural strategies. First, we simulated stands [site index (SI) = 70, age = 40 years, height = 65 feet] with different stand densities, including low [basal area (BA) = 90 square feet per acre, d.b.h. = 7.76 inches], medium (BA = 120 square feet per acre, d.b.h. = 8.46 inches), and high (BA = 180 square feet per acre, d.b.h. = 9.15 inches) stand densities to see if stands with a higher density would cause more widespread damage. Second, we simulated a pure pine stand [natural loblolly pine (*Pinus taeda*)] and a mixed forest stand [mixture of loblolly pine, yellow-poplar (*Liriodendron tulipifera*), and white oak (*Quercus alba*)] within the same stand condition (SI = 70, age = 40 years, height = 65 feet, BA = 180 square feet per acre, d.b.h. = 9.15 inches) to determine whether different species compositions could affect the trends of spot growth. And third, we simulated infestation growth in a young loblolly pine plantation (about 15 years old, d.b.h. = 5.46 inches, height = 40 feet, SI = 55, BA = 120 square feet per acre) and mature loblolly pine stand (about 40 years old, d.b.h. = 8.46 inches, height = 65 feet, SI = 70, BA = 120 square feet per acre) to determine whether young stands are more resistant to SPB damage than mature stands. Using these simulation procedures, we compared both the number of trees killed and the infested area during 50 days among different management scenarios.

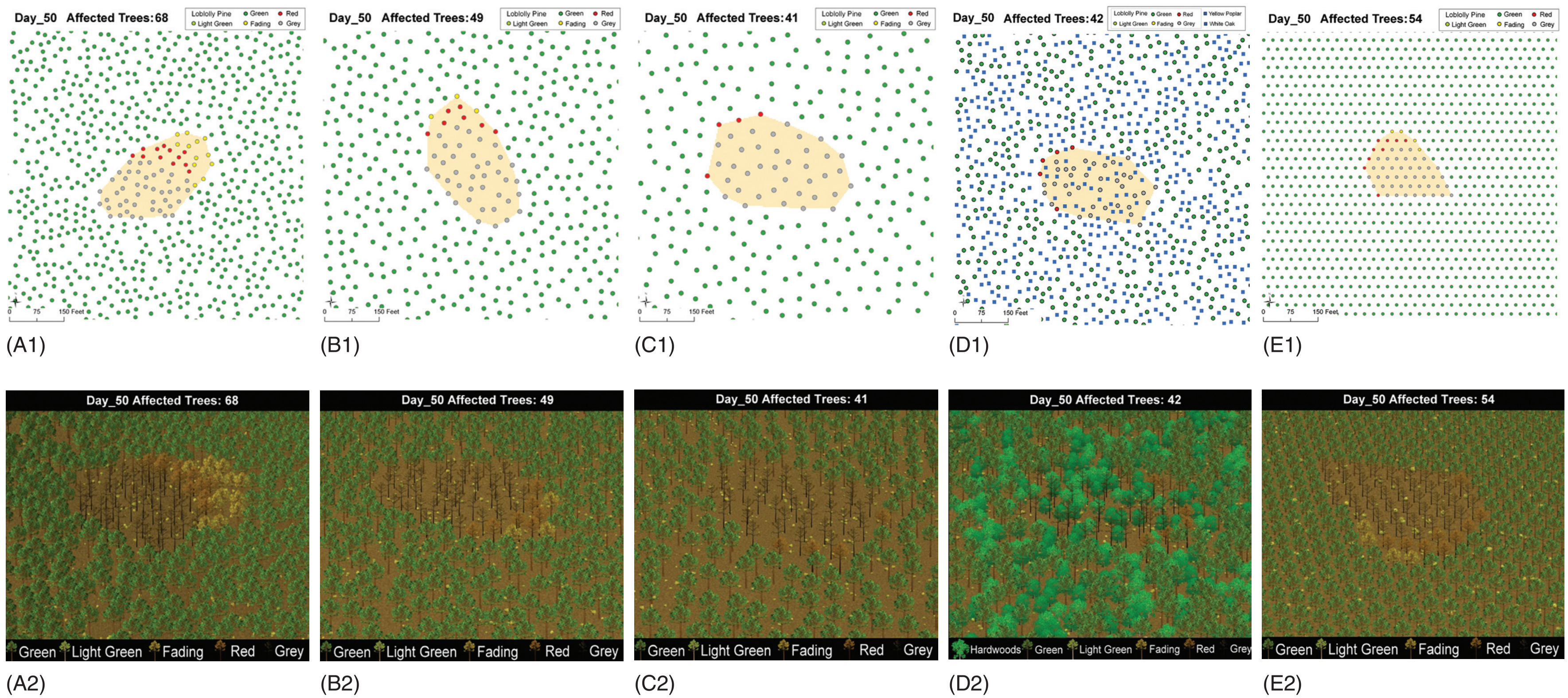

Figure 3—The comparisons of simulated GIS maps and three-dimensional visualizations of SPB spot growth in five different silvicultural treatments during 50 days. “a1” and “a2” were simulated for the high-density pine stand, “b1” and “b2” were simulated for the medium-density pine stand, “c1” and “c2” were simulated for the low-density pine stand, “d1” and “d2” were simulated for the mixed pine-hardwood forest stand, and “e1” and “e2” were simulated for the young loblolly pine plantation. “a1,” “b1,” “c1,” “d1,” and “e1” are GIS maps of SPB spot growth. “a2,” “b2,” “c2,” “d2,” and “e2” are three-dimensional visualizations of SPB spot growth.

RESULTS AND DISCUSSION

Through the simulation approach, we generated five different scenarios, including natural mature loblolly pine stands with high-, medium-, and low-stand density, a mixed forest stand with loblolly pine, white oak, and yellow-poplar, and a young loblolly pine plantation with medium-stand density. Simulation outputs for these five management scenarios were represented as GIS maps and three-dimensional visualizations.

The Comparison of Visualizations among Different Stand Densities

During the simulations, we generated three different kinds of stand densities in the mature loblolly pine stands (fig. 3). In the end of the spot growth simulation (day 50), the spot intensity (number of trees killed) in the high-density stand is the greatest (68, 49, and 41 affected trees for the high-, medium-, and low-density stand, respectively). However, the infested areas are larger in medium- and low-density stands (0.110, 0.137, and 0.177 acres for the high-, medium-, and low-density stands, respectively). The largest area occurred in the low-density stand.

Moreover, through the simulation of SPB spot growth in 50 days, we also generated animations for the SPB infestation dynamics with different stand densities. From these animations, we can see that the infested area in the low-density stand is the biggest, although its spreading speed of spot growth is always the lowest. Hence, not only can we figure out the trend of spot growth and compare their spreading speeds among different stand densities, but also, we can detect that the changing patterns of infested areas among them.

Therefore, the visualizations of GIS maps could show us the overall spatial pattern with abstract symbols (fig. 3). In addition, three-dimensional visualizations allow us to observe the same phenomena with more vivid foliage features, stereo viewshed, and specially designed tree images for different affected stages and tree species (fig. 3). Based on three-dimensional visualizations, we can see the trend of spot growth in the high-density stand is aggregated and extensive. In contrast, the spot spread trends are sparser and slower for medium- and low-density stands. Then, we can see that the number of trees killed has high positive correlation with stand density. However, the infested area has a negative relationship with it.

The Comparison of Visualizations between Loblolly Pine Stand and Mixture Forest Stand

When we compared the simulations of SPB spot growth in the pure loblolly pine stand and mixture forest stand (fig. 3), infested area in the pure pine stand (0.137 acres) is slightly smaller than the mixture species stand (0.129 acres); the spot intensity of the former is significantly greater than the latter (68 and 42 affected trees for pure pine and mixture forest stand, respectively).

Besides, if we are concerned more about the timber harvest in economy, the losses from SPB attacking in pure pine stand must be more serious than in the mixture forest stand since, in the pure pine stand, the speed of spot growth is faster and keeps growing. Although the infested area in the mixture forest stand is larger, its spot grows slowly. Therefore, if our concern is economic impact, we will be more interested in spot intensity than infested area.

Furthermore, from these GIS maps, it's difficult to represent different species by specified symbols. It is easier to identify different tree species in the three-dimensional visualizations. In VNS, we can use different foliage effects to represent diverse tree species, ages, and seasons by specified foliage colors, crown shapes, and form structures. Compared to the GIS maps, three-dimensional visualizations give a better and more realistic representation for the trend of spot growth in forest stands with different species compositions.

The Comparison of Visualizations between the Mature Loblolly Pine Stand and Young Pine Plantation

When comparing the simulations between the mature stand and young plantation, the number of trees killed in young pine plantation (54 affected trees) is a little bit larger than the mature stand (49 affected trees). The infested area in the latter (0.110 acres) is significantly greater than the former (0.066 acres). Here indicates that younger stand is not necessarily highly resistant to the SPB attacking, if the stand is still dense. Trends of spot growth between the mature and young loblolly pine stands are distinct in both the GIS maps and three-dimensional visualizations. One is more dense, and tall, and the other is more regular and small. Although, both of them have fast speed of spot spreading in dense stand. As a result, we can get a conclusion that the stand density, especially the distance between pines, is an important factor when we consider the spot intensity.

The Comparison of Spot Intensities and Infested Areas among Different Silvicultural Treatments

Furthermore, in this study, we emphasize the silvicultural treatments—the thinning, species mixture, and stand regeneration—could reduce the damage from SPB infestations especially when the duration of spot growth is longer, the effect of treatments would be more significant. From the figure of comparison of spot intensity (fig. 4), at the beginning, the differences among these treatments are not strong. Then, when the spots continue to grow, the differences among them become obvious.

Moreover, the reduction in stand density and the mixture in species composition can reduce the spot intensity. However, the reductions in the spot intensity do not necessarily result in a reduction in the area of the stand affected. From the figure of infested area comparison (fig. 5), the low-density stand always has the greatest infested area, and, next are medium-density and mixed-species stands. Therefore, when we aim to modify losses from SPB attacks by silvicultural treatments, we not only have to think about the effects on the spot intensity, but also the spatial impact of the infested area.

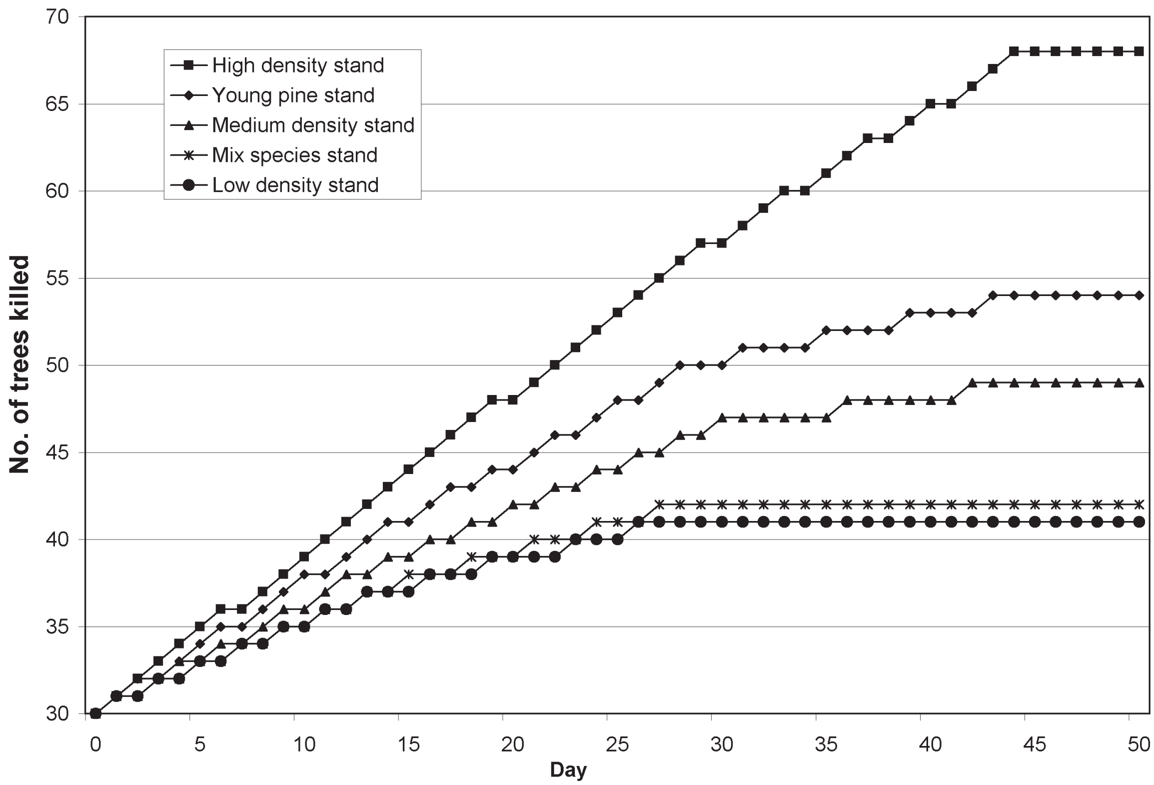

Figure 4—Comparisons of the number of trees killed (spot intensity) among five different silvicultural treatments during 50-day period of SPB infestation. The number of trees killed on the initial day (day 0) is 30 trees.

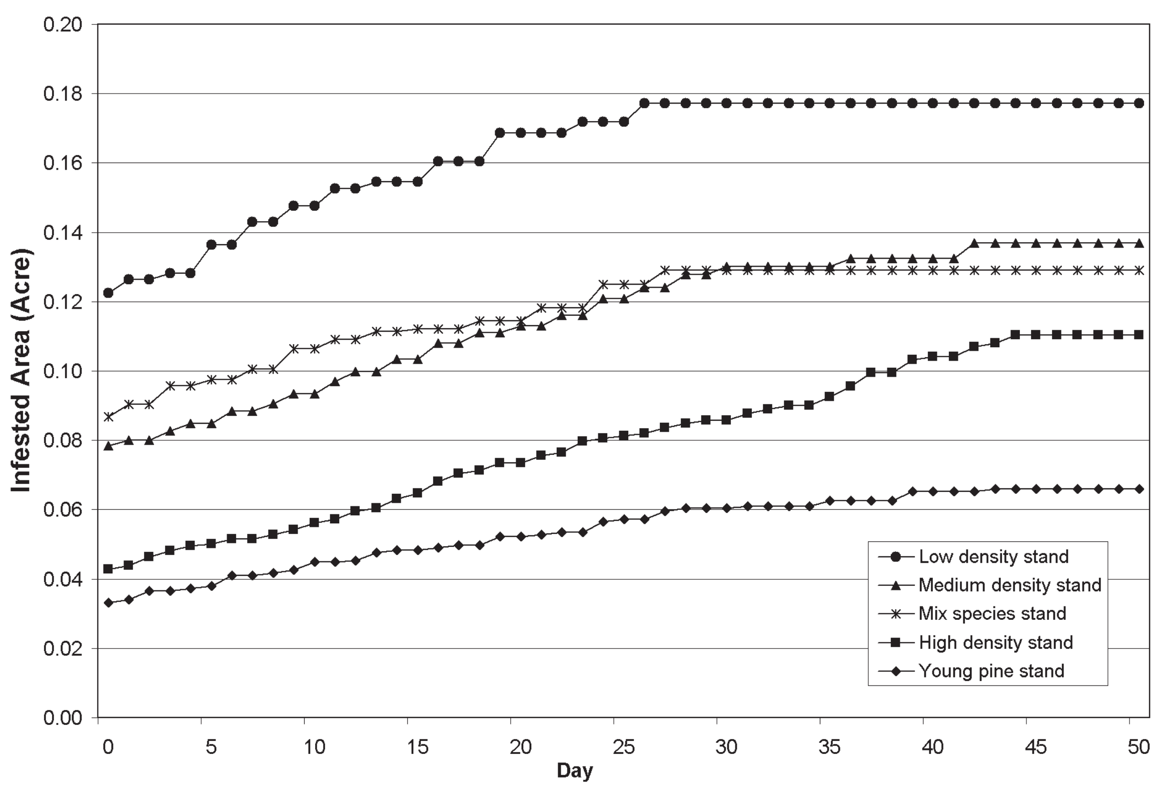

Figure 5—Comparison of the infested area among five different silvicultural treatments during 50-day period of SPB infestation.

CONCLUSION

According to the flexible and various representative styles of three-dimensional landscape visualizations, we can simulate time-series visualizations to compare influences of disturbance on different forest stands, monitor the infestation spot growth as three-dimensional visual animation for an instant short-term outbreak, or evaluate the response and efficiency from different management strategies on three-dimensional visual landscape panoramas.

In a summary, silvicultural treatments undoubtedly can modify the impacts from SPB infestations, especially the thinning and species mixture strategies. In this study, we emphasize the following conclusion—GIS-based visualizations indeed can be a comprehensive communication media to simplify the complicated information, and to provide multiscale visualizations with diverse spatial and temporal dimensions, and improve the representation and understandability for different decisionmakers with diverse backgrounds.

Finally, in the future, we would aim to apply the GIS-based spot growth model on the more practical scenarios to predict the trends of spot growth and improve the comparisons of simulated spot growth from different silvicultural treatments in real stand situations. Furthermore, in addition to simulating the instant outbreaks from SPB infestation among different silvicultural treatments, we also intend to link our model with other expert ecological prediction models and more available GIS database to predict the future patterns after SPB infestations in the long-term effects. Eventually, multispatial and temporal three-dimensional visualizations would be expected to improve the SPB decisionmaking process by combining the GIS-based spot growth model and visual simulator.

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