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Three-dimensional Landscape Visualizations of Forest Restoration Scenarios for Southern Pine Beetle-Infected Forests

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ABSTRACT

Setting appropriate goals for projects is a primary challenge facing forest restoration. Not only is it difficult to achieve a complete restoration of an ecosystem, but deciding restoration goals that involves a set of values from diverse stakeholders is also very challenging. In this study, an integrated technique of geographic information systems (GIS), historic remotely sensed images, and three-dimensional (3-D) landscape visualization was used to construct a variety of realistic images and animations depicting effects following southern pine beetle (SPB) infestations on different forest restoration scenarios in the upper Piedmont of South Carolina. The alternative restoration treatments included prescribed burning, mechanical thinning, and the combined effect of both. We also compared the effect of species mixture: pure loblolly pine stands and mixed pine stands within the thinning treatment and thinning + burning treatment. The results indicated that 1) thinning treatment responded the best (i.e., least damage) to SPB infestation for both pure pine stands and mixed forest stands, 2) the presence of other pine or hardwood species would not affect the tree susceptibility but does alter the distance between susceptible trees, 3) the short-term effectiveness of prescribed burning was not obvious in our study, and 4) the thinning + burning treatment may have resulted in too much stress that increases the stand's susceptibility for SPB infestations. In addition, the spatial trends of infestation were illustrated by the photo-realistic geographical visualized medium to simplify the complicated information. This resulted in improvement of the representation and understanding of the SPB restoration scenarios for different decision makers without considerable training or experience with map reading and forest restoration.

Keywords: 3-D visualization, forest restoration, prescribed burning, SPB, thinning

INTRODUCTION

Disturbance always plays a critical role in impacting the composition and distribution of forest landscapes. However, some intensive and extended disturbances have accelerated soil erosion, fragmented forests, altered natural fire regimes, and promoted the loss of native species and their habitats (Noss and Copperrider 1994; Heilman *et al.* 2002). Those disturbances include logging, fire suppression, road building, live-stock grazing, mining, and exotic species invasions (Noss and Cooperrider 1994; Ricketts *et al.* 1999; DellaSala *et al.* 2003). Forest scientists, managers, and related stakeholders have recognized that there is an urgent need to restore these damaged forest ecosystems.

One of the primary challenges facing restoration is how to set appropriate goals (Throop 2004; Davis and Slobodkin 2004). Not only is it very difficult to achieve complete restoration of the ecosystem (Lockwood and Pimm 1999), but also it is even more difficult to know the original state, since there are seldom accurate historical records for determining the original ecosystem structure and composition (Hobbs 2004). Deciding on restoration goals also involves a set of theories requiring input from diverse stakeholder groups and other concerned publics (at local, regional, and national levels). Additionally, policy makers also struggle to define a decision-making procedure (Higg 1997). Therefore, in order to achieve a meaningful involvement of diverse stakeholders at all levels, an open, inclusive, and transparent decision-making process with recognition of and respect for differences should be developed (DellaSala *et al.* 2003). Meanwhile, the recognition and understanding of the objectives, concepts, and management strategies for forest restoration should be promoted to related stakeholders and interest groups who are typically not professionally trained and experienced in ecosystem dynamics or in responses to treatments (Mansourian 2005; Meitner *et al.* 2006).

Three-dimensional (3-D) landscape visualization

Over the past 30 years, advances in computer hardware and software have permitted managers and researchers to visualize the complex phenomena and dynamics of natural systems with a more perceptible and comprehensible computer-aided medium (Daniel and Meitner 2001; Wang *et al.* 2006a). 3-D landscape visualization is one of the outstanding innovations resulting from this technological advancement. It can be used as a comprehensive medium to aid in providing lay audiences with a general sense of forest stand composition and structure, in illustrating the properties of geographic information systems (GIS) and remotely sensed images, and in visualizing the consequences of different restoration alternatives (Orland 1994; McGaughey 1998). In addition, 3-D landscape visualizations are quantitative information-based techniques that can be used to illustrate stand succession, landscape transformation, and regional planning outcomes (Song *et al.* 2006; Wang *et al.* 2006a). Visualizing the past, present, and future conditions of the forest landscape provides the ability to display potential outcomes that are difficult to assess in the field and to allow the observation of forest landscapes without temporal and spatial limitations (Orland 1994; McGaughey 1998; Song *et al.* 2006).

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Original Research Paper

Southern Pine Beetle (SPB)

In this study, the technique of 3-D landscape visualization was used to generate realistic landscape restoration animations of alternative management scenarios following southern pine beetle (*Dendroctonus frontalis* Zimmerman, SPB) infestations in the upper Piedmont of South Carolina. The SPB is one of the most aggressive and destructive insect pest of pines in the southeastern United States. Although all southern pines may serve as hosts for SPB, loblolly pine (*Pinus taeda*) and shortleaf pine (*P. echinata*) are considered the most susceptible (Coulson 1980). From 1999 to 2003, outbreaks of SPB have severely attacked the southern pine forests in Alabama, Florida, Georgia, Kentucky, Tennessee, North Carolina, and South Carolina (Nowak *et al.* 2008). Increased susceptibilities of the forests in southeastern US have stand conditions similar to: 1) dominated by loblolly and shortleaf pine, 2) littleleaf disease, 3) overly dense stands, and 4) poorly drained and eroded soil (Hedden and Billings 1979; Coulson 1980; Moorhead *et al.* 2004; Fettig *et al.* 2007). Therefore, almost a million acres on forests were infected with estimated $ 1 billion in economic losses (Nowak 2004).

Restoration strategies

Because the SPB infestations caused great loss of forest resources, strategies to mitigate the damage and restore the forest ecosystems to its pre-settlement conditions have been developed. Forest restoration can help to repair habitat and restore forest structure and functions to the natural or historical condition (Stanturf 2004). There are two proposed treatments: thinning and prescribed burning. For overstocked stands, thinning can reduce the stand density and relieve the stresses related to living competition and drought. Also, thinning can: a) remove the more vulnerable hosts to increase stand resistance to initial attack by SPB, b) change stand structures to prevent favorable conditions for beetle outbreaks, and c) provide overall stand revitalization to reduce many linked biological hazards that ultimately support bark beetle outbreaks (Belanger 1980; Nebeker *et al.* 1983; Brown *et al.* 1987; Edmonds *et al.* 2001; Van Lear *et al.* 2004). Prescribed burning is another popular silvicultural operation to rehabilitate degraded forest ecosystems. It can: a) alter species compositions, b) remove more-susceptible and low-vigor species, and c) mimic the role of natural fire for restoring forested landscapes (Wade *et al.* 1989; Pyne *et al.* 1996; Edmonds *et al.* 2000; Fernandes and Botelho 2003). Therefore, we can control the frequency, intensity, and behavior of fire to achieve the expected stand situation.

In this paper, we visualize the SPB infestation by vivid foliage features, stereo viewsheds, and specially designed tree images for different SPB affected-stages and tree species. As a case study in the upper Piedmont of South Carolina, we incorporate GIS databases and historic remotely sensed images to visualize 3-D landscapes before and after the 2002 SPB outbreaks following the thinning and burning restoration treatments. We also compare the effects of species mixtures in stands (i.e., pure loblolly pine stands and mixed pine stands) under the thinning and thinning + burning stands to discuss the species influence on these forest restoration treatments and SPB disturbances. Our objective is to develop visual communication media to deliver the complex information to different stakeholder groups with varying needs and degrees of knowledge about forest restoration. We also delineate spatial and temporal changes in forest landscapes resulting from alternative forest restoration scenarios.

MATERIALS AND METHODS

Study area

The study area is located in the upper Piedmont of South Carolina, covering approximately 300 acres (**Fig. 1**) (1 acre = 0.4047 ha) primarily in the Clemson Experimental Forest (CEF). Before the first Europeans settlements here in 1790, the original landscape was covered by a mature, even-aged pine-oak-hickory dominated forest (McMinn and Ill 1999). The predominant species were white oak (*Quercus alba*), red oak (*Quercus falcata*), hickory (*Carya* spp.), chestnut (*Castanea dentata*), and southern pine species, including loblolly, shortleaf, and Virginia pine (*Pinus virginianna*) (Carroll *et al.* 2002; Van Lear *et al.* 2004). Originally (i.e., prior to the permanent European settlement), Native American burning practices and lightning ignited fires, with low-intensity and high-frequency, were major influences on the vegetation of the upper Piedmont (Owen 2002). From the late 18th through early 20th centuries, the European settlement and intensive agriculture practices resulted in highly modified forest ecosystems that were impacted by SPB in contemporary society (Nelson 1989; Van Lear *et al.* 2004; K. Cox pers. comm.).

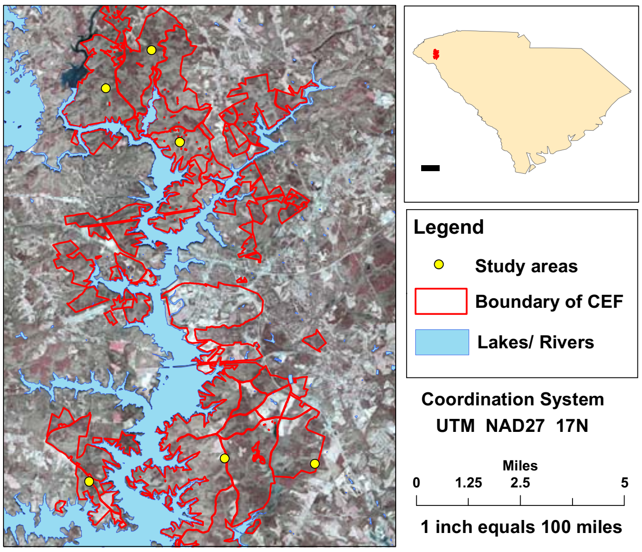

Fig. 1 SPB infestation study locations in the Clemson Experimental Forest (CEF). Six study areas were spreading in the CEF where is located at the northeast of South Carolina. The definition of study area: PP_T indicates the pure loblolly pine stand under thinning treatment; MP_T indicates the mixed pine species stand under thinning treatment; PP_TB indicates pure loblolly pine stand under thinning + burning treatment; MP_TB indicates mixed pine species stand under thing + burning treatment; PP_B indicates pure loblolly pine stand under burning treatment; PP_C indicates the un-treated controlled stand.

Accelerated soil erosion caused by poor agricultural practices resulted in significant loss of the soil capability to supply nutrients and moisture during droughts (McMinn and Ill 1999; Van Lear *et al.* 2004). In addition, successful fire suppression altered originally open and fire-maintained stands into overstocked stands with many small-diameter trees (McCullough *et al.* 1998; Harrington *et al.* 2000). The original disturbances (i.e., low intensity and high-frequency Native American burning practices and lightning ignited fires) were replaced by more severe SPB infestations.

For this study, one of the SPB infestations, the 2002 SPB outbreak (Boyle *et al.* 2004), was taken as a case study. The infected area was approximately 150 acres, and located in the CEF (**Fig. 1**). Six study sites were selected and under specified restoration scenarios. The affected forests were primarily loblolly pine and mixed pine stands in high to extremely high stand density (around 300 trees/acre) (**Fig. 1**). Mixed pine stands were dominated by loblolly pine mixed with other southern pine species (i.e. shortleaf and Virginia pines).

Data sources and processing

(1) GIS databases of disturbance history were collected from forest managers of CEF (K. Cox pers. comm.) and National Forest Fire Surrogate (FFS) Study at CEF (R. Phillips pers. comm.). Dates of interest were from 1999 to 2002. The GIS databases pro-

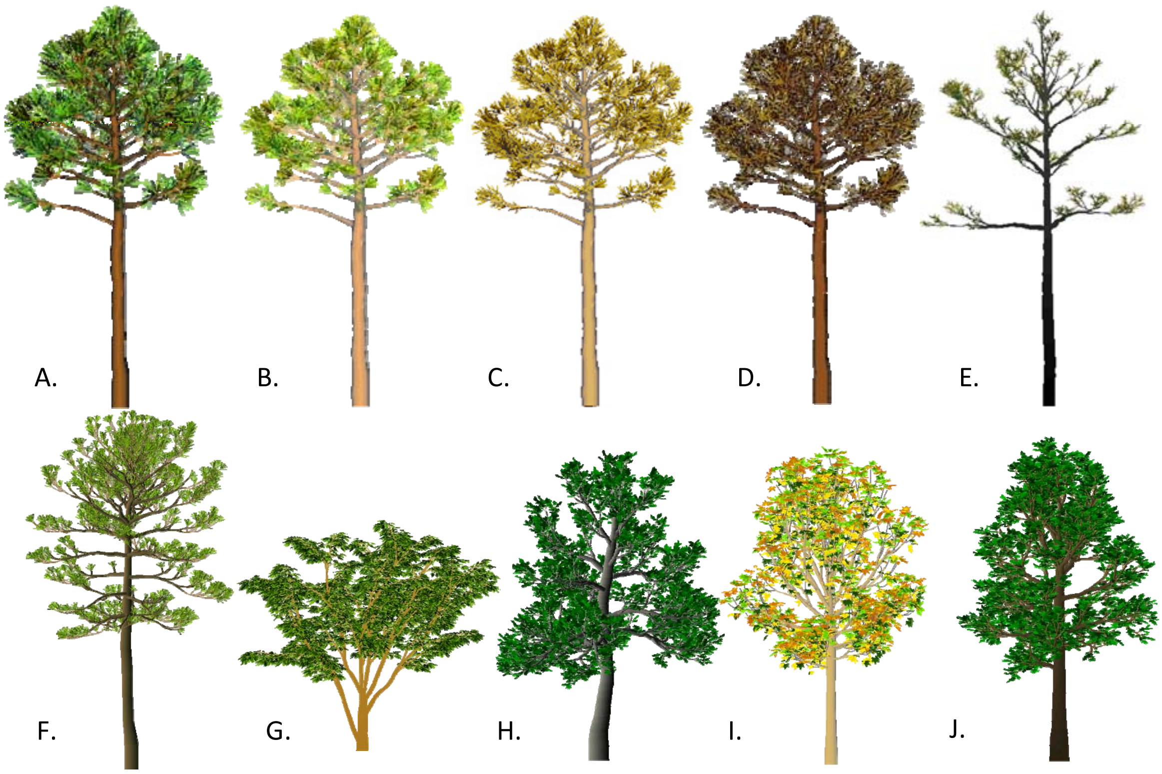

Fig. 2 Specific created tree images. (**A**) Pine species with green foliage in good condition. (**B**) Pine species with light green foliage under SPB freshly attack. (**C**) Pine species with brown foliage under intermediate conditions between SPB fresh attacks and developing beetle broods. (**D**) Pine species with red foliage subject to SPB developing beetle broods. (**E**) Pine species with grey foliage in dead condition. (**F**) Wax myrtle (*Myrica cerifera*). (**G**) Red oak (*Quercus rubra*). (**H**) Sugar maple (*Acer saccharum*). (**I**) White oak (*Quercus alba*).

vided stand data required as input parameters for landscape visualization: number of trees per acre, the percentages of different species, diameter classes and average heights. The disturbance records provided the occurrence date and size (i.e., the infected area and the number of trees killed/affected) of SPB infestations.

(2) The Digital Elevation Model (DEM) is the base data layer for computer terrain modeling. The DEM files are based on a 30 by 30 meter sample grid and correspond to 7.5-min quadrangle map series produced by the USGS (U.S. Geological Survey 1997).

(3) Remotely sensed images, in this study, were mainly collected from the ortho-rectified digital aerial photography coverage (Lillesand and Kiefer 2000) of the entire study area for periods before (1999) and after (2002) the SPB disturbance, which occurred during the summer of 2002 (Boyle *et al.* 2004). After these time-series images had been georectified, they were used to identify the forest types (i.e., pure loblolly pine, mixed pine species, and other hardwood stands) and stand condition (i.e., healthy or infected). In addition, the patterns of disturbances (i.e., the degrees of severity, the locations and the trends of infestations) were delineated from time-series aerial photographs with the reference to infestation records from the GIS databases (**Appendix I**).

Development of 3-D landscape visualization

(1) Creation of tree images: Realistic tree images of species are the most critical components for quality visualizations (Wang *et al.* 2006a). Because of the variety of tree features within individual species, as well as among different species, multiple foliage images are needed to represent the variation. Tree images can be photos taken in the field or designed digital images on a computer. In this study, computer-designed tree images were used and created through OnyxTree Professional (Onyx Computing Inc. 1992-2008, http://www.onyxtree.com). This approach is capable of synthesizing realistic-looking foliage images, including hardwoods, conifers, palms, bamboos, and shrubs (i.e., grass and flowers), by adjusting the variety parametric models through a user-friendly platform. The dozen of parametric models, which is based on the anatomy and growth of vegetation, including the structure and color of trunk and branch, leaf population, crown shape, and weather effect (i.e., sun light and wind). In this study, we generated five categories of foliage images for pine species under different SPB affected-stages and four foliage images for hardwood species (**Fig. 2**).

(2) Visualization of 3-D forest landscape: A terrain-modeling software package, Visual Nature Studio (VNS) (3D Nature Inc. 1991-2009, http://3dnature.com/), was used to construct 3-D landscape visualizations. A flowchart for generating the 3-D landscape visualization is shown in **Fig. 3**. The concepts of generating the 3-D landscape visualizations are: 1) displaying the base layer of landscape (i.e., terrain or landform), 2) delineating the boundaries of interest topic (i.e., the spatial arrangement of forest types, stand conditions, or degrees of infestation severity), and 3) rendering the image-based objects, such as foliage images, snags, deadfall, ground cover and other vegetation types for understory and overstory of forest stands, to realistically represent the composition and structure of the boundary of interest, as well as their spatial relationships to each other (**Appendix II**). After attaching these ecosystem components to the corresponding landscape patches and stands, we could then visualize various scenarios of SPB infestations under specified stand conditions.

(3) Projection of 3-D visualizations among alternative restoration scenarios: In order to visualize the forest restoration scenarios for the SPB infected forests, we incorporate the DEMs, GIS maps (i.e., forest types and infestation patterns), and specified foliage images to visualize 3-D landscapes before and after the 2002 SPB outbreaks following the proposed restoration treatments (**Fig. 3**). Data from the FFS (Weatherspoon 2000; Phillips and Waldrop 2008) were used to compare treatments of thinning, prescribed burning, and the combination effect of thinning and burning with the untreated controlled stand in terms of SPB infestation and subsequent developments. Four types of treatments were designed by the FFS, which is a nationwide study funded by the Joint Fire Science Program to assess how forest ecosystem components and

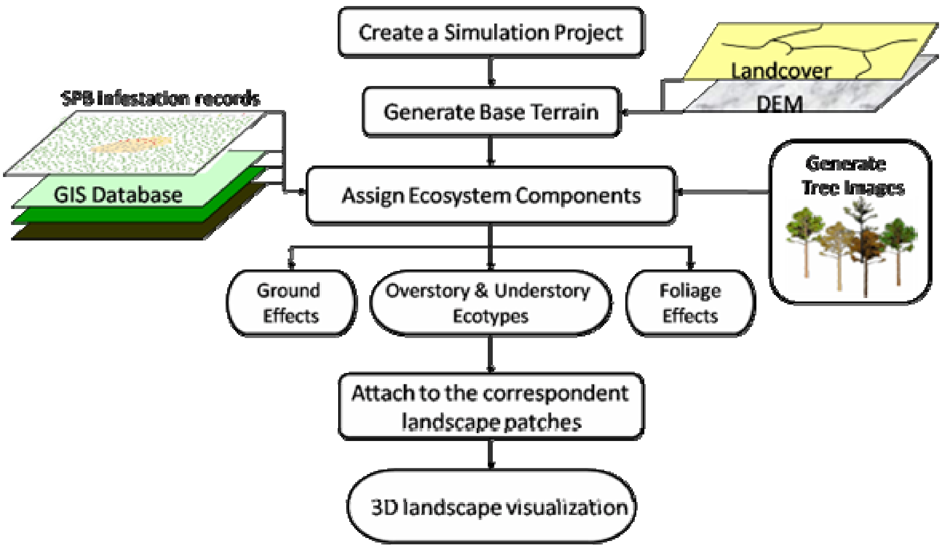

Fig. 3 Flowchart of 3-D landscape generation and visualization within VNS.

processes are affected by both fire and fire surrogate treatments (Weatherspoon 2000). In this study, four pure loblolly pine stands were selected for each of the treatments (indicated as PP_T, PP_B, PP_TB, and PP_C in **Fig. 1**) from the study area.

The effects of species composition to SPB infestations were also addressed within the stands under thinning treatment and thinning + burning treatment. Two mixed pine stands were selected and indicated as MP_T and MP_TB (**Fig. 1**) to be compared with two of the pure loblolly pine stands selected earlier and indicated as PP_T and PP_TB in **Fig. 1**, respectively.

In this study, we are interested in the visual comparison of SPB infestations among different restoration scenarios. The infestation patterns of the overstory horizontal arrangement and the variations of infestation severity were specially focused on the 3-D landscape visualizations. The regions outside of the infected stands were not visualized.

RESULTS

Comparisons of 3-D visualizations among alternative restoration scenarios

Through the comparison of SPB infestation effects among different treatments (**Figs. 4**, **5**), the most serious impacts occurred in the controlled stand. More than 85% of the forest was affected and about 70% of the forest was totally dead (**Table 1**). The existing loblolly pines were mostly killed and only hardwood species remained.

The second most serious impacts occurred in the thinning + burning treatment. Most of the loblolly pines (about 75%) were attacked, but the severity differed by stand locations (i.e., 64.38% of the forest were dead; 16.87% of the forest were moderately affected; 3.17% of the forest were slightly affected) (**Table 1**). The backside of the stand suffered the most serious damage, as shown by the grey foliage. This damage grew gradually less severe toward the front of the stand, as shown by the red to fading foliage (**Fig. 5D**).

However, the stand with the thinning treatment suffered the least damage from SPB infestation. In this stand, we can see more open spaces with minor attacks displayed as red foliages which were covering about 15% of the forest (**Table 1**). Most of the forest (about 75%) was not affected.

The prescribed burning treatment was also damaged by SPB infestations, although the damage was not as severe as within the stand subjected to the thinning and burning combination (**Fig. 5C; Table 1**). As a result, the spatial trends of infestation with diverse degrees of severity were revealed the locations (i.e., where would be attacked severely), the affected patterns (i.e., how it would correspond to the arrangement of forest landscapes), and the effects of restoration scenarios (i.e., which treatment could aid in the SPB infestation control).

Comparisons of 3-D visualizations under different species compositions

The effects of SPB infestation on different species compositions were visualized in thinned stands (**Fig. 6**). These 3-D visualizations provide distinctions between pure pine stands and mixed pine stands with shades of green foliage (**Fig. 6A, 6C**). Subsequent to the attacks from SPB, there were no obvious differences in the thinned treatments among the pure and mixed stands (**Table 1; Fig. 6B, 6D**). Only minor parts of the pine stands were attacked as shown by red foliage, and no area suffered severe damage (**Fig. 6B, 6D**).

Conversely, the impacts of SPB infestation on pure and mixed pine stands were clearly different in the 3-D visualization when the stands were subjected to the thinning + burning treatment (**Fig. 7A, 7C**). The pure pine stand was more uniform and regular, while the mixed pine stand was more diverse and fragmented. After the SPB outbreaks (**Fig. 7B, 7D**), the pure pine stand suffered severe damage throughout the landscape. In the mixed pine stand, however, the most severe damage was limited to those areas where loblolly

Table 1 Summary of the restoration scenarios under different degrees of SPB infestation (percentage of the forest area).

Scenarios	Dead (%)	Degrees of SPB infestation			Total (acre)
		Moderately affected (%)	Slightly affected (%)	Non affected (%)	
Within pure loblolly pine stand					
Control	69.23	12.18	4.75	13.84	12.19
Thinning	2.47	6.3	15.33	75.67	13.75
Thinning + Burning	64.38	16.87	3.17	15.58	8.64
Burning	20.41	29.44	26.84	23.31	12.97
Within mixed pine stands					
Thinning	3.26	6.32	18.69	71.73	11.34
Thinning + Burning	16.29	3.77	14.49	65.45	13.86

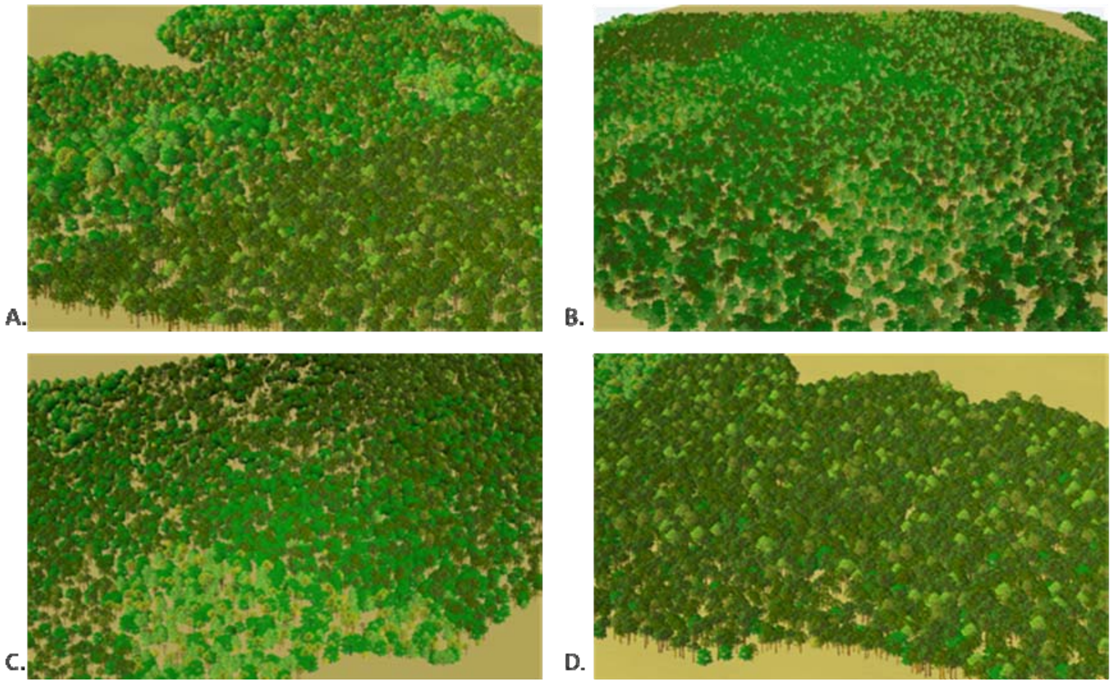

Fig. 4 3-D landscape visualizations among alternative restoration scenarios before 2002 SPB infestation. (**A**) Controlled treatment. (**B**) Thinning treatment. (**C**) Prescribed burning treatment. (**D**) Thinning + burning treatment. The darker green foliages represent the dominant loblolly pines and the lighter green foliages represent other pine species. The brighter and yellowish green foliages represent the hardwood species.

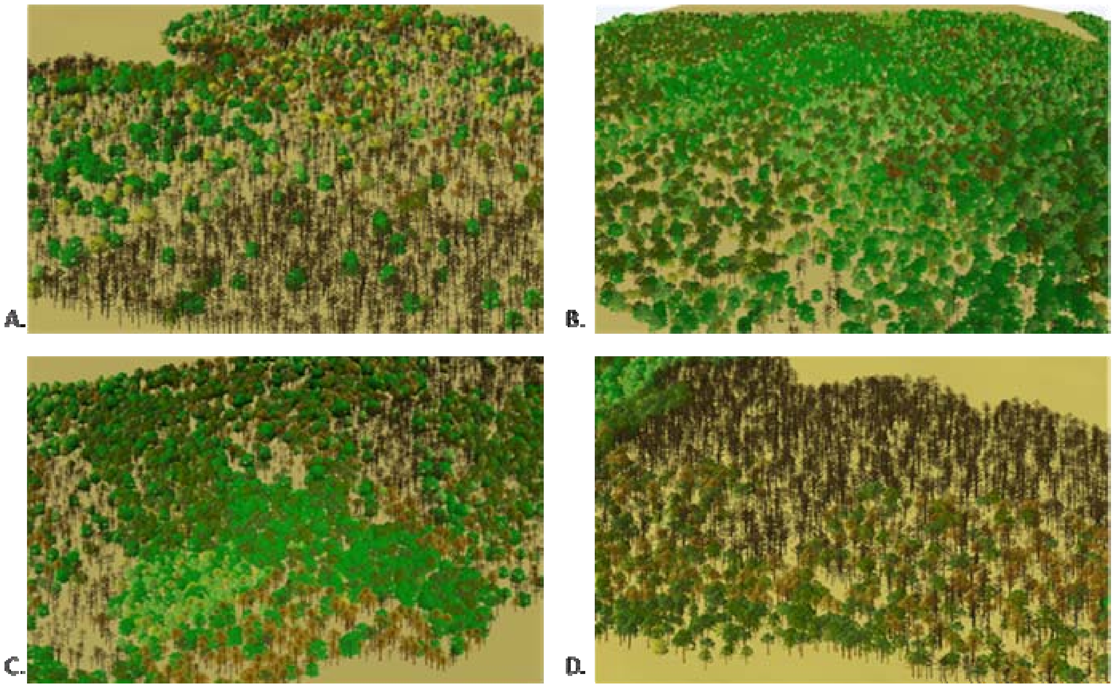

Fig. 5 3-D landscape visualizations among alternative restoration scenarios after 2002 SPB infestation. (**A**) Controlled treatment. (**B**) Thinning treatment. (**C**) Prescribed burning treatment. (**D**) Thinning + burning treatment. The red and brown foliages represent the affected trees and the images with little gray foliages represent the dead trees.

pines were dominant, and the other areas (approximately 65% of the forest, **Table 1**) were relatively unaffected by the infestations.

DISCUSSION AND FUTURE DIRECTIONS

Visual evaluations of alternative restoration scenarios after SPB attacks were developed in this study. The damaged area, pattern of spread, and the SPB infestation severity were successfully visualized.

These 3-D landscape visualizations (**Figs. 4**, **5**) clearly communicate the forest composition and structures, including species composition, stand densities, and the arrangement of patches, in a simple yet comprehensive manner to the audiences. Those audiences are not familiar with the study area and without considerable training or experience with map reading and forest restoration. In addition, the damage area, pattern of spread, and the effects of restoration treatments to SPB infestation has been visually compared by combining the tabular infestation records, spatially GIS maps with object-oriented classification, and realistic foliage images in the medium of 3-D landscape visualization.

By moving through these 3-D landscape visualizations

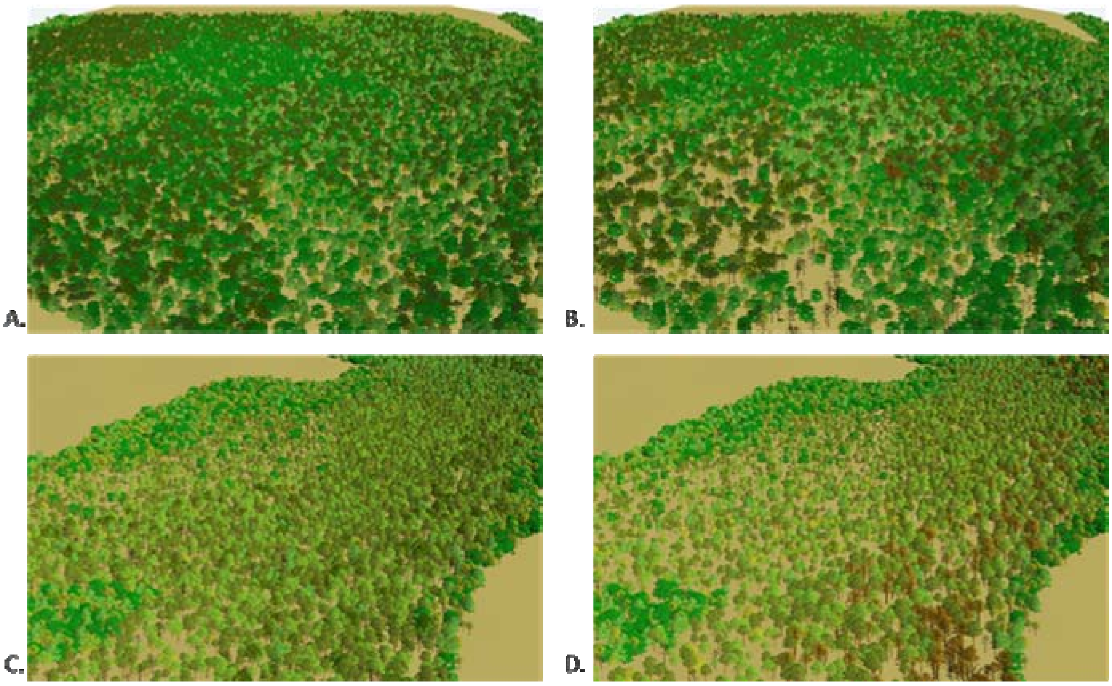

Fig. 6 3-D landscape visualizations of stands with different species composition subject to thinning treatment during two periods. (**A**) Pure loblolly pine stand before 2002 SPB infestation. (**B**) Pure loblolly pine stand after 2002 SPB infestation. (**C**) Mixed pine species stand before 2002 SPB infestation. (**D**) Mixed pine species stand after 2002 SPB infestation.

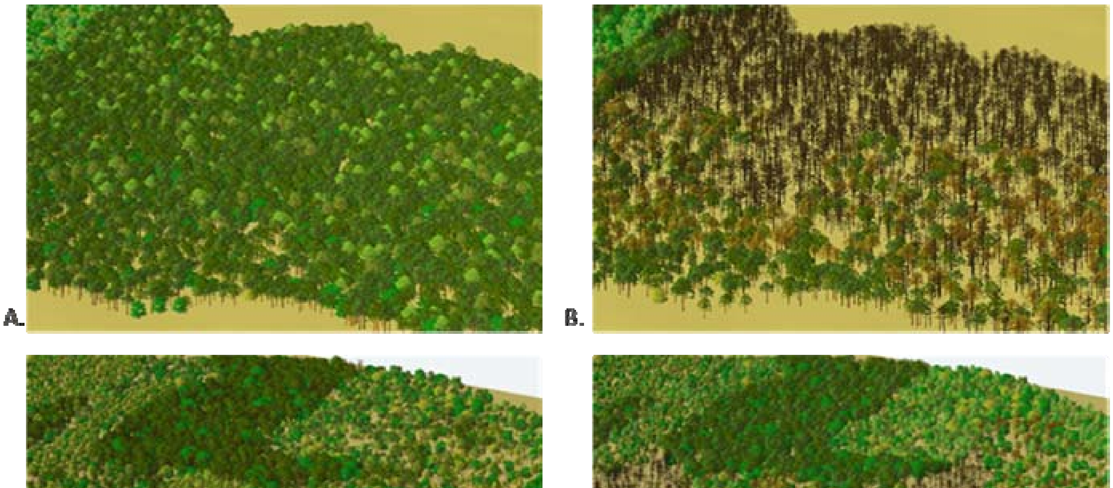

Fig. 7 3-D landscape visualizations of stand different species composition subject to thinning + burning treatment during two periods. (**A**) Pure loblolly pine stand before 2002 SPB infestation. (**B**) Pure loblolly pine stand after 2002 SPB infestation. (**C**) Mixed pine species stand before 2002 SPB infestation. (**D**) Mixed pine species stand after 2002 SPB infestation.

before and after the 2002 SPB infestation (**Figs. 4-7**), the audiences can gain a perception of the various ecological communities within the study area, the structural impacts of the SPB infestation, and more generally, the ability of GIS maps to detect these changes. In addition, these geographical visualized representations combine the applications of GIS maps and visualization to precisely locate the objects and to visually represent the tabular information.

The results from the comparisons among alternative restoration scenarios and different species compositions indicated that the thinning treatment responded the best (i.e., least damage) from SPB infestation for both pure pine stands and mixed forest stands. While, from the comparisons of SPB infestation under different specie composition, the presence of other pine or hardwood species would not affect the tree susceptibility but does alter the distance between susceptible trees (Schowalter and Turchin 1993). However, although prescribed burning is frequently used to reduce competition in southern pine forests (Wade *et al.* 1989; Fettig *et al.* 2007), its short-term effectiveness was not obvious in our study. Specifically, the combination of thinning and burning may have resulted in too much stress for the stands prior to the SPB infestations. Therefore, further efforts and long-term studies on the relationship between prescribed burning and SPB damages are needed to understand these complex interactions (Boyle *et al.* 2004; Ayres *et al*. 2008; Xi *et al*. 2009).

The technical accuracy of 3-D geographical representations and their correspondence to the real landscapes are essential when applying this visual computer-aided technique to forest restoration management (Daniel and Meitner 2001; Sheppard and Salter 2004). Generally, accuracy depends on a visual scale and the proper resolution, extent, and quality of available data. Data quality also relies on the objectives and scale of the visualization (Wang *et al.* 2006a; Salter *et al.* 2009). In this study, we focused on generating the stand scale visualization among different restoration treatments. The data required was accurate stem density, species composition, and tree height and life condition. Within VNS, the landscape patches can be visualized according to the quality and accuracy of the required data. The accuracy of visual perception is altered by the realistic quality of foliage images (Sheppard and Salter 2004; Wang *et al.* 2006b). In the future, we can compare static views of the projected landscape visualization with known photo-realistic viewpoints in order to improve the quantitative analysis of accuracy assessment (Orland *et al.* 2001).

Although, we only developed the overstory visualizations, the understory cover, such as shrubs, herbs, and forest floor, should also be considered when visualizing a forest stand. Because forest stands are the basic management units for ecosystem restoration (Stage and Wykoff 1998; Avery and Burkhart 2002; Husch *et al.* 2003). The vertical structure, the interactions among species, and the stand dynamics, including stand density, species composition, and species growth, have been focused on stand scale visualization in the following studies: Karjalainen and Tyrnäinen (2002), Dunbar *et al.* (2005), Wang *et al.* (2006b), and Chou *et al.* (2010). VNS has been used as the 3-D visualization simulator for these studies, because it can project multiple scale visualizations for both stand-level and landscape-level scales. While the landscape scale visualization focuses on horizontal variations, spatial patterns, and landscape transformations (Dunbar *et al.* 2005; Wang *et al.* 2006a). Therefore, different studies focus on different visual scales to appropriately and efficiently represent the point and extent of the viewshed. In order to accurately and effectively generate forest visualization, we have to clearly define the objectives and subjects of interest for determining the most suitable visual scale (Paar *et al.* 2008; Wergles and Muhar 2009).

One of the most powerful applications from 3-D landscape visualization is visualizing the future conditions of the forest landscape to convey potential consequences of alternative restoration scenarios that are difficult to assess in the field (Meitner *et al*. 2006; Chamberlian and Meitner 2009; Lange and Hehl-Lange 2010). Based on the historical remotely sensed images and disturbance GIS database, we can visualize the landscape before, during, and after an infestation. Although it is comparatively easy to collect the required remotely sensed data after infestations, the precise disturbance records at the stand scale were absent in our study area. In the future, if we aim to generate landscape visualization of long-term recovery after infestation, we can rely on ecological restoration simulation models (**Appendix III**). They can help to predict the impacts and effects of disturbances and management strategies. However, there are many criteria and limitations that must be considered when applying specific models since the output parameters may not meet the requirements for developing high quality visualizations (Ghadirian and Bishop 2008; Xi *et al*. 2008; Castrillón *et al.* 2011).

The integrated technique of 3-D landscape visualization with GIS databases and remotely sensed images improves the understanding and representations of complicated information with diverse spatial and temporal dimensions (Stotlman *et al.* 2007; Allen and Madden 2009). It can aid in improving the decision-making process by facilitating communications among scientists, managers, and the general public with diverse backgrounds (Seely *et al.* 2004; Sheppard and Meitner 2005; Lange and Bishop 2005). In the future, we will aim to strengthen the varying temporal and spatial visualizations to satisfy different study purposes. More reliable spatial data and appropriate ecological simulation models will be required to visualize landscape as our needs evolve through time.

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APPENDIX I – GIS IN REFORESTATION

GIS is a computer program that allows one to efficiently manage, process, analyze, and represent data with the spatial reference to any thematic attribute that is connected to a location on the earth (Mach and Petschek 2007; Bolstad 2008). With GIS, one can utilize information from field or remotely sensed data to help clas-sify different land cover types. GIS can also identify the detailed forest stand characteristics, including cover type, tree species, crown diameter, and stand height and density. Remote sensing images, including aerial photography and satellite imagery, cons-titute the basis for the creation of a variety of spatial data. By interpreting remote sensing images, we can identify, recognize, and delineate land cover maps on multilevel land cover classifica-tion systems (U.S. Geological Survey 1997). With appropriate resolution, land cover maps can be used to support different land-scape scale management on a nationwide, interstate, or county-wide basis (Chandra and Ghosh 2006). In addition, when com-paring remote sensing images across times, we can not only des-cribe the type of landscape changing (Brandt *et al.* 2000; Dunbar *et al.* 2005), but also simulate the phenomena of ecological dyna-mics.

Object-oriented approach is used to classify the time-series images that had been georectified. Object-based classification allowed the images to be classified into forest/tree cover, non-forest, road/building structure, and water classes. It can also simplify the discrimination of land cover and enhances the practicality for landscape visualizations (de Kok *et al*. 1999; Geneletti and Gorte 2003; Dunbar *et al.* 2005).

In this study, we used the technique of photointerpretation to classify the forest types, stand conditions, and the patterns of disturbances. Photointerpretation was based on the typical elements of the remotely sensed image (Wolf 1974; Chandra and Ghosa 2006), including size, shape, tone, texture, pattern, shadow, association, and site, to delineate different land covers. We delineate the pure pine stands and mix forest stand based on their distinguished patterns. The pattern of pure pine stands is more regular than the pattern of mix forest stands. The variations of crown texture are important to the identification of species and stand condition. For instance, hardwood stands have s tufted appearance, while pine stands look like billowy. In addition, the foliage color changes under SPB infestation, and the infestation expanding area is easily detected from aerial photographs (Paine 1981; Lillesand and Kiefer 2000).

In this study, SPB infestation is classified into five stages on the basis of foliage colors of infected trees, which changed with the time from initial attack (Billings and Kibbe 1978): Stage 0 (non-infected, live trees; green trees), Stage 1(freshly attacked, light green trees), Stage 1~2 (from freshly attacked to developing beetle brood, fading trees), Stage 2 (developing beetle brood, red trees), and Stage 3 (inactive trees, no live beetle brood, gray trees).

APPENDIX II – 3-D FOREST LANDSCAPE VISUALIZATION

VNS is used to project the 3-D landscape visualizations. It is a premium photo-realistic and landscape-visualization software package. It was chosen for the following characteristics: 1) integration with georeferenced GIS datasets, 2) flexibility of land-cover development, and 3) use of raster and vector formats to render vegetation components (Dunbar *et al.* 2005). Because of these characteristics, we can then import terrain and land-cover data from numerous raster- or vector-based formats to generate vivid photo-realistic foliage images. Raster-based formats are considered as a rectangular grid of pixel and represented by n × m array of numbers where different numbers represent different spatial entities; i.e., images (.BMP, .JEPG, .TIFF, etc) and DEMs or USGS data types. Vector-based formats are used to represents geographic features or entities as points, lines or polygons; i.e., ArcGIS Shapefiles.

The following are the processes of 3-D landscape visualization within VNS:

(1) Import the DEM and landcover map as landscape foundation (i.e., base terrain): The imported landcover GIS layers with different attributes for each polygon are assigned as appropriate land cover.

(2) Assign the landscape patches: It is called "*Ecosystem Components*" within VNS. We assign it by three divisions (**Fig. 3**):

a) Ground effect assignment: The soil, litter, snags, deadfall, and other surface materials are visualized by giving the pattern, texture, and tone of the materials.

b) Overstory and understory assignment: The species composition (i.e., the numbers of species, the percentage of each species), stand density, and average height of each patch are assigned.

c) Foliage effects assignment: specified tree images are linked to the appropriate foliage effects for each overstory and understory species.

Therefore, the forest landscape visualization is manipulated to cover largest possible area, the landscape level, and to show the general spatial arrangement of landscape elements and the overall structure of the functional land cover units. At the stand scale, the vertical distribution of species and the shape of individual trees are shown to enhance the visualization quality.

APPENDIX III – A LIST OF ECOLOGICAL SIMULATION MODELS

Model type	Reference	Model name	Model application: Advantages	Model application: Limitations	Spatial-scale
Stand growth model	Ritchie (1999)	CACTOS (California Conifer Timber Output Simulator)	Simulate the effects of silvicultural treatments (i.e., harvesting and thinning) and wood products, then reports biomass.	Specifically for simulating the growth and dynamics of multiple species on a 5 year growth; without spatial explicitness.	Stand-level (Overstory and Understory)
	Arney and Milner (2000)	FPS (Forest Projection System)	Simulate the diameter distribution and local competition. Model can be linked to the ArcInfo and MapInfo GISs.	Simulator uses a library to summarize stand situation and response surface, rather than using equations or models.	
	Crookston and Stage (1999)	FVS(forest vegetation simulator)	Simulate the effects of silvicultural regimes, planted regeneration, and natural regeneration and disturbances.	Specifically simulating the major forest tree species.	
	Hann *et al.* (1997)	ORGANON (Oregon growth Analysis and Projection)	Simulate the growth for both even-aged and uneven-aged mixed-species stands of conifers and hardwoods.	Without the ability to be changed as necessary to accommodate new situations (i.e., different geographic areas and populations).	
	Mason, Bruce and Girard, Inc. (1988)	SPS (Stand Projection System)	Simulate the effects of silvicultural regimes (i.e., fertilization, thinning, and harvest).	Without the ability to simulate the forest dynamics from the regeneration or disturbances.	
GAP model	Botkin *et al.* (1972)	JABOWA	Project the dynamics of forest composition and simulate the interaction between environment factors and forest growth.	Without spatial explicitness. Specifically for stand-scale and short-term simulation.	Stand-level (Overstory)
	Shugart (1984)	FORET	Simulate the dynamics of forest distribution and the relationship between soil attributes and tree growth.	Without spatial explicitness. Specifically for stand-scale and short-term simulation.	
	Pacala *et al*. (1996)	SORITE	Predict the long-term (i.e., 2000 years) dynamics of transition and simulate competition among tree species, tree dispersal, establishment, growth, mortality, and fecundity. The spatial resolution (10 x 10 m^2 grid).	Specifically for northern oak hard woods forests, USA.	
	Miller and Urban (1999)	ZELIG	Simulate forest patterns by integrating climate, fire, and soil nutrient. Spatial resolution (15 x 15 m^2 grid).	Overestimating the tree mortality by overestimating fire intensity of grass-fueled fires.	
Landscape model	Baker (1992)	DISPATCH	Simulate the interaction between the climate change and landscape structure. Spatial resolution (200 x 200 m^2 grid).	Without the ability to simulate the forest dynamics.	Landscape-level (Overstory)
	Baskent (1997)	LANDMAN	Simulate the structural effects of initial landscapes and different harvest patterns for landscape fragmentation.	The spatial extent and resolution are not flexible and only set as 43 km^2.	
	Liu and Ashton (1998)	FORMOSAIC	Simulate tree location, regeneration, growth, death, spatial interaction and environmental factors. Spatial resolution (10 x 10 m^2 grid).	Specifically for the interaction between fine-scale changes in tropical forests.	
	He and Mladenoff (1999)	LANDIS	Simulate the forest succession and the interaction between disturbances and landscape pattern. Spatial resolution (10 x 10 km^2 grid).	Specifically for the simulation of large-scale and long-term forest landscape processes.	
	Scheller *et al*. (2007)	LANDIS II	Upgrade the LANDIS and include the biomass estimation. Spatial resolution (50 x 50 m^2 grid).	Specifically for the simulation of long-term forest landscape processes.	

Note: We here briefly describe some candidate models for each of these three types of models. Ritchie (1999), Robinson and Monserud (2003), and Xi *et al*. (2009) are very good sources for further information about many of these models.