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Southern Pine Beetle Infestations in Relation to Forest Stand Conditions, Previous Thinning, and Prescribed Burning: Evaluation of the Southern Pine Beetle Prevention Program

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Since 2003, the Southern Pine Beetle Prevention Program (SPBPP) (a joint effort of the USDA Forest Service and Southern Group of State Foresters) has encouraged and provided cost-share assistance for silvicultural treatments to reduce stand/forest susceptibility to the southern pine beetle (SPB) (*Dendroctonus frontalis* Zimmermann) in the southeastern United States. Until now, stand- and landscape-level tests of this program's efficacy were nonexistent. In 2012, SPB outbreaks occurred in the Homochitto and Bienville National Forests (NFs) in Mississippi. Parts of each NF were treated (thinned) using SPBPP management recommendations, whereas other areas were untreated (unthinned). In the Homochitto NF, 99.7% of SPB spots occurred in unthinned stands, whereas all SPB spots occurred in unthinned stands in the Bienville NF. Unthinned stands in both NFs had higher basal area, higher stocking, and lower growth rates over the last decade. Burning also resulted in a lower incidence of SPB infestation. Our retrospective study results validate the effectiveness of SPBPP treatments for reducing stand- and landscape-level susceptibility to SPB, which encourages proper silvicultural methods that increase tree spacing, growth, and vitality, while effectively altering the in-stand atmosphere enough to interfere with SPB pheromone communication, thus reducing susceptibility to SPB spot initiation and spread.

Keywords: bark beetles, *Dendroctonus frontalis*, forest management, *Pinus taeda*, silviculture, Southern Pine Beetle Prevention Program

The Southeast is the largest timber-producing region in the United States, with more than 202 million acres of commercial timberland (Smith et al. 2004). Production of wood and wood products is dominated by several southern pine species. Southern pine ecosystems are greatly influenced by natural disturbances, and landowners and managers rely heavily on silvicultural techniques such as preplanting site preparation, thinning, and fire to maximize production and mitigate the deleterious effects of disturbances (Guldin 2011). The southern pine beetle (SPB) (*Dendroctonus frontalis* Zimmermann) is a native pest of southern yellow pine forests that historically has had large-scale economic, ecologic, and social impacts (Coulson and Klepzig 2011). SPB is a major disturbance agent that has greatly influenced southern pine ecology and production with an estimated loss to producers of $43 million per year from the early 1980s through 2010 (Pye et al. 2011).

SPB outbreaks have occurred at least every century since the 1700s (Hopkins 1909, Fries et al. 1943) and frequently have occurred throughout the southeastern United States since 1960, when outbreaks began being systematically recorded (Price et al. 1992). Areas in southeastern Texas and southwestern Louisiana have been the most commonly affected, followed by the region comprising northwestern South Carolina,

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southwestern North Carolina, and extreme northeastern Georgia. Other areas in Alabama, Arkansas, Florida, Mississippi, Tennessee, and Virginia have all experienced SPB outbreaks, but at a lower frequency (Price et al. 1992). Major regionwide outbreaks occurred in the mid- to late 1970s and mid-1980s and 1990s. The last major multistate outbreak occurred from 1998 to 2002 in the southern Appalachian Mountains and affected more than 1 million acres of forest in five states at an estimated economic loss of more than $1 billion (Clarke and Nowak 2009). Such has been its importance that two comprehensive volumes have been dedicated to its biology, ecology, and management (Thatcher et al. 1980, Coulson and Klepzig 2011).

SPB can mass attack and kill live, healthy trees, and all pine species within the SPB's range are susceptible (Hain et al. 2011). Loblolly (*Pinus taeda* Linnaeus), Virginia (*Pinus virginiana* Miller) and shortleaf (*Pinus echinata* Miller) are preferred hosts in the southeastern United States, but longleaf (*Pinus palustris* Miller), slash (*Pinus elliottii* Engelmann), and Table Mountain (*Pinus pungens* Lambert) pine are also susceptible (Lafon and Kutac 2003, Veysey et al. 2003, Pureswaran et al. 2006, Martinson et al. 2007). SPB biology and ecology are well documented (Clarke and Nowak 2009, Hain et al. 2011, Sullivan 2011, and references therein). Adults choose host trees based on visual and chemical cues and can quickly overwhelm a tree's natural defenses. Up to seven generations can occur annually, and dispersal is largely dictated by semiochemicals. Brood development takes place within the cambium and inner bark. Vigorously growing trees can withstand low levels of SPB pressure, but even healthy trees can be overwhelmed by large beetle populations (Franceschi et al. 2005). The SPB has both latent (i.e., low-level) and outbreak population phases, which are governed primarily by local environmental and host conditions (Mawby et al. 1989).

Proper forest management has long been considered the most effective means of mitigating future impacts from this beetle (Guldin 2011). Stands with poor soils, increased susceptibility to drought, or highly susceptible tree species, and overstocked stands are at the greatest risk of SPB infestation (Lorio 1968, Lorio et al. 1982, Mason et al. 1985, Gan 2004, Birt 2011). Forest managers and forest health specialists often recommend prevention of outbreak populations and creation of forest conditions that lessen impacts once outbreaks occur (Belanger et al. 1993, Clarke 2003). Stand density is thought to be one of the most critical factors in determining the chances of SPB spot initiation and expansion within a stand. For overstocked stands (which, in general, are inherently stressed) a finite amount of sunlight, water, and nutrients are available in a given area. Thinning is particularly effective at reducing stand susceptibility to SPB (Nebeker and Hodges 1983, Burkhart et al. 1986, Brown et al. 1987, Schowalter and Turchin 1993), as it reduces stem density while simultaneously increasing tree vigor and growth rates (Haywood 2005). Thinning also increases air flow within a stand, which could result in dispersion, dilution, and disruption of SPB-mediated semiochemical pheromone plumes (Thistle et al. 2004). It is widely recommended that stands with a density greater than 120 ft^2 of basal area per acre should be thinned to less than 80 ft^2 per acre (Belanger and Malac 1980, Nowak et al. 2008).

The Southern Pine Beetle Prevention Program (SPBPP) began in 2003 with the goal of supporting the reduction of pine stand susceptibility to SPB through various silvicultural methods or the restoration of sites with less-susceptible pine species (Nowak et al. 2008). The SPBPP has helped treat more than 1.2 million acres in the southeastern United States[1] and has been widely hailed as a highly successful federal program for forest pest management in the United States.[2] A SPB outbreak in Mississippi, USA, in 2012 provided an opportunity to evaluate the efficacy of silvicultural treatments for SPB management at the landscape and stand levels. We hypothesized that SPB spots would be less likely to occur in thinned than in unthinned stands across a forested landscape. At the stand scale, we hypothesized that thinned stands would have smaller spots that were more likely to collapse without suppression treatment than unthinned stands. The outbreak also gave us the opportunity to examine SPB activity in unburned versus prescribed burned stands.

Methods

Study Area

In 2012 and 2013, we evaluated stands in the Bienville and Homochitto National Forests in Mississippi, USA (Figure 1). The Bienville National Forest (hereafter called BNF) contains more than 178,500 acres and is located in Jasper, Newton, Scott, and Smith counties in central Mississippi (32°17′ N and 89°30′ W). Mean annual temperature is 63.7° F with annual precipitation of nearly 60 inches. The Homochitto National Forest (hereafter called HNF) contains more than 191,800 acres and is located in Adams, Amite, Copiah, Franklin, Jefferson, Lincoln, and Wilkinson counties in southwestern Mississippi (31°30′ N and 90°59′ W). Mean annual temperature is 65.8° F with annual precipitation of nearly 66 in. The BNF and HNF are part of the southeastern mixed forest ecoregion and are composed of the loblolly-longleaf-shortleaf pine, oak-pine, and oak-hickory forest types. Forests were dominated by pine (*Pinus* spp.) and oak (*Quercus* spp.) and also contain spe-

Management and Policy Implications

This study shows that thinning and prescribed fire can protect stands on a landscape scale from low to high levels of southern pine beetle (SPB) infestations. Thinning is a recommended practice for reducing SPB impacts, and this study validates that recommendation. Prescribed burning to reduce understory competition has been allowed under the Southern Pine Beetle Protection Program (SPBPP) but is considered by some forest health specialists and forest managers to have at least short-term negative impacts on tree susceptibility to SPB. In this retrospective study, stands with more recent and more frequent prescribed fire had a significantly lower incidence of SPB infestation. This result, while unexpected, confirms that stands with frequent low-intensity fire, lower basal area, and more open growing conditions are more resilient to forest disturbance factors such as SPB. Based on these results, there will be an increased focus on burning through the SPBPP to reduce dense understory competition and promote open stand conditions, especially in conjunction with thinning to reduce stand basal area. The SPBPP is now in its 12th year of working with state forestry agencies, private landowners, and national forests to improve the resiliency of southern forests through an "all lands approach" on more than 1.2 million acres of forestland.

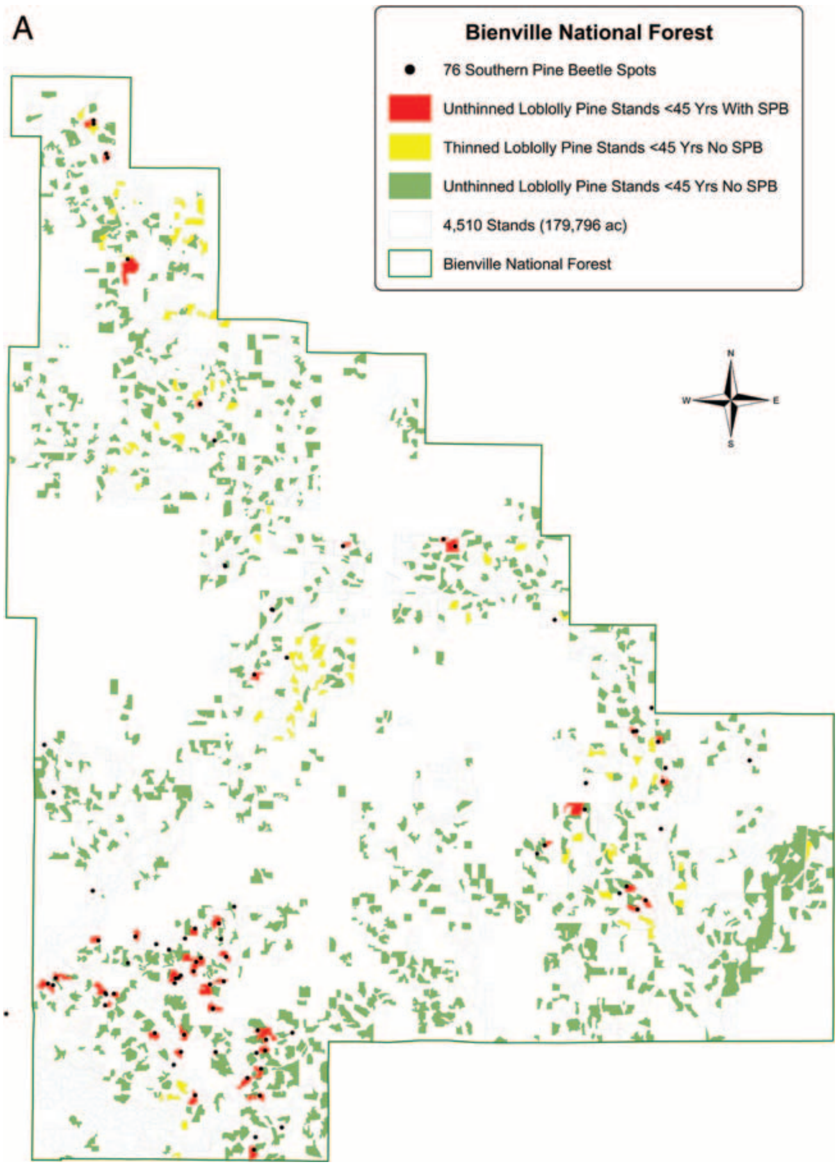

Figure 1. BNF (A) and HNF (B) showing all loblolly pine stands <45 years old that were either thinned with no SPB (green), thinned with SPB (orange), unthinned with no SPB (yellow), and unthinned with SPB (red) after an SPB outbreak in 2012. Within each NF, black dots represent SPB spots.

cies such as tulip poplar (*Liriodendron tulipifera* Linnaeus), sweetgum (*Liquidambar styraciflua* Linnaeus), tupelo (*Nyssa sylvatica* Marshall), hickory (*Carya* spp.), cherry (*Prunus* spp.), and magnolia (*Magnolia* spp.). Understory flora includes sassafras (*Sassafras albidum* [Nuttall] Nees), blackberry (*Rubus* spp.), catbrier (*Smilax* spp.), grapevines (*Vitis* spp.), and other grasses and ferns.

Study Design

Stands chosen and sampled for this study included the entire population of stands (on both national forests [NFs]) designated as loblolly pine forest type (and management type), <45 years old (i.e., the primary stand type targeted by the SPBPP). This particular subset of stand conditions was chosen because it also highlights areas where SPB problems were most prevalent. Our stand categories (treatments) were (1) unthinned, with a SPB spot, (2) unthinned, without a SPB spot, (3) thinned (either commercially or precommercially) during the last 6 years (2006–2011), without a SPB spot, and (4) thinned within the last 6 years, with a SPB spot. The BNF and HNF were each divided into five sampling blocks that represented different geographic areas of each NF. Stands in categories 1–3 were represented in each sampling block; however, thinned stands with SPB spots were practically nonexistent, thus preventing further stand-level analysis of this treatment.

Landscape-Level Treatment Evaluation

Using the Southern Pine Beetle Information System (SPBIS) database, the Field Sampled Vegetation (FSVeg) database, the US Department of Agriculture (USDA) Forest Service Activity Tracking System (FACTS), and forest geographic information system (GIS) data, we obtained the following information from each stand: the number, size (to the nearest 0.1 acre), and treatment of SPB spots; the stand age, size (acres), condition, and site index; and the year and type of thinning. We obtained stand burn history (i.e., the frequency and timing of prescribed burns occurring during the last 6 years) from local USDA Forest Service records.

We conducted landscape-level assessments of SPB activity among different stand types and ages and, in particular, provided a landscape perspective for comparisons among thinned and unthinned stands. Integrating these stand data with documented SPB spot data from the 2012 outbreak, across each NF, also provided setting and context to the nature and scope of SPB activity. This type of landscape assessment provided a forestwide quantification of what and how much was affected by SPB in both absolute and relative terms, as well as insight into what is susceptible and most at risk of SPB on both NFs. In addition, the broader assessment points toward those forest conditions more likely to require spot suppression measures and how much and where future management might be directed to prevent or mitigate risk of SPB.

To test the null hypothesis that SPB occurrence was the same for thinned and unthinned stands, a 2 × 2 contingency table was constructed with all stands classified according to thinning status and the presence of SPB for each NF (1,160 and 946 stands total in BNF and HNF, respectively). Fisher's exact test was carried out separately for each NF, and a Cochran-Mantel-Haenszel test for general association (controlling for forest) was applied to data from both NFs combined. SAS statistical software (SAS Institute, Inc., Cary, NC) was used for this and all subsequent analyses.

Fisher's exact test was also used to test the null hypothesis that SPB presence in a stand was as likely for stands that have been burned as for stands that were never burned.

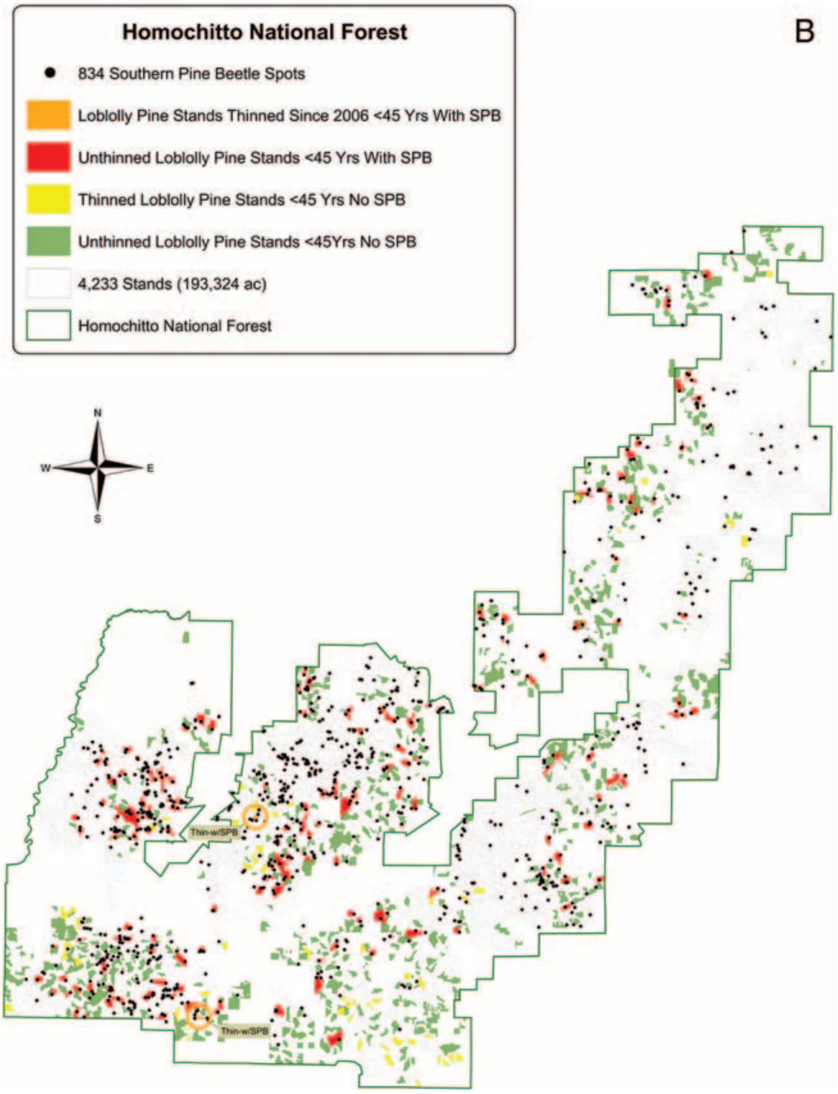

Figure 1. Continued.

Contingency table "exact" tests were carried out separately for each NF to test for association between SPB occurrence and number of burns and between SPB occurrence and years since last burn.

Treatment comparisons were carried out on the following measurements obtained from the SPBIS data for all stands in the sampling study (see Stand-Level Treatment Evaluation below): stand age, stand area, susceptible area (stand area less inclusions), site index, number of burns, and years since the most recent burn (or age if never burned). The mixed model included the fixed-effects forest, treatment and forest × treatment interaction, and random effects block (forest) and treatment × block (forest).

To investigate the best predictors of spot size and spot number, a model selection method (using Proc GLMSELECT) was applied to the entire set of measurements of tree size and density plus stand characteristics obtained for all stands in the sampling study, including the two thinned stands with spots in the HNF ($n = 164$). The selection method was stepwise, and the criterion used to terminate addition of variables was Mallows Cp. Forest was included in the list of potential predictors. Thinning status was not included in the list of predictors because this was one of the factors in the selection of stands in the sampling study and because it was of interest to assess the importance of various effects of thinning as reflected in tree growth and density. Spot number and size were regarded as 0 for stands with no SPB in these analyses. Variables were transformed where necessary to better meet model assumptions. The model selection was repeated on the subset of stands with spots ($n = 58$) to focus on factors that are related to the severity of infestation.

Stand-Level Treatment Evaluation

We sampled multiple stands per treatment on each NF ($n = 20$ per treatment from BNF and $n = 33$ per treatment from HNF). In addition, we sampled the only two thinned stands with a SPB spot that occurred on the HNF (Figure 1). Field sampling consisted of establishing three 10-factor basal area prism plots per stand (proximal to the SPB spot in stands with spots), with a minimum of 300 ft between plots and 100 ft from any stand edge. Within each plot, we recorded species and dbh of all trees >4 in. and height and previous 10-year radial growth increment (to the nearest in.) from one dominant or codominant loblolly pine tree per plot, selected based on being closest to plot center. These data allowed us to quantify differences in stand composition among the chosen stand types to determine how SPB outbreak occurrence was affected.

We compared dbh, height, 10-year radial growth, relative growth, basal area, pine volume, and tree density among treatments using a mixed-model analysis of variance (ANOVA) to account for the hierarchical design of the sampling study. Proc MIXED was used to fit a model with forest, treatment, and forest × treatment as the fixed effects and block(forest), treatment × block, and stand (block × treatment × forest) as random effects. The two thinned stands with spots in HNF were excluded from these analyses, and data were transformed when necessary to improve homogeneity of variance and normality of errors. Means were compared via orthogonal contrasts using the estimate statement to compare the thinned treatment with the unthinned treatment and the unthinned-without SPB treatment to the unthinned-with SPB treatment.

Correlations among stand means for plot-level and stand-level measurements were obtained to determine whether analysis of covariance should be carried out to assess differences among treatments after accounting for properties such as stand age and burn frequency. Results led to performing analysis of covariance on stand means for dbh, height, 10-year radial growth, relative growth, basal area, pine volume, and trees per acre with stand age as the covariate. The mixed-model fixed effects were forest, treatment, forest × treatment interaction, and the covariate stand age, and random effects

Table 1. Prevalence of SPB spots on thinned and unthinned loblolly pine stands <45 years old in the BNF and HNF in Mississippi, USA, during 2012.

NF	Stand thinned?	SPB spots present?	No. stands	% of total	Total ac	% of total ac	Total spots	% of total spots
BNF	Yes	Yes	0	0	0	0	0	0
		No	87	7.5	3,394	8.2		
	No	Yes	46	4.0	2,276	5.1	76	100
		No	1,027	88.5	39,317	87.4		
Total			1,160		44,987		76	100
HNF	Yes	Yes	2	0.2	38	0.1	2	0.3
		No	58	6.1	2,594	6.4		
	No	Yes	163	17.2	9,246	22.7	832	99.7
		No	723	76.4	28,759	70.7		
Total			946		40,684		834	100

were block(forest) and treatment × block(forest). In addition, to account for burn status (burned or not), a second mixed-model analysis was performed with fixed effects forest, treatment, burn, and all interactions and random factors block(forest) and treatment × block(forest). Treatment contrasts were evaluated separately by forests for stands that had or had not been burned.

Results and Discussion

The USDA Forest Service definition of SPB "outbreak" status is met by having >1 SPB spot per 1,000 acres of host type, and severe outbreak is defined as >3 SPB spots per 1,000 acres of host type (Price et al. 1998). By this definition, SPB activity on the BNF was considered low and not at outbreak levels with only 76 total spots in 145,310 acres of susceptible host type (0.52 spot per 1,000 acres of host type) (Figure 1A). In contrast, SPB activity on the HNF was considered high and well over severe outbreak levels with 834 spots in 170,000 acres of host type (4.9 spots per 1,000 acres of host type) (Figure 1B). Because of the low number of spots on the BNF (and lower average spot size: BNF = 0.88 acres and HNF = 2.31 acres), it was reasonable to believe that the SPB spots were confined to only the most susceptible (i.e., unthinned) stands. However, with the relatively high number of spots on the HNF, much more beetle activity was expected in less susceptible stands (Mason et al. 1985) as there was high SPB activity uniformly across the NF. Although there were some infestations in low- to moderate-hazard forest types (i.e., 33 spots or 4% of infestations), the overwhelming majority of spots occurred in loblolly pine forest type (i.e., 637 spots or 76% of all spots on the HNF). Other highly susceptible forest types (i.e., loblolly pine-hardwood, shortleaf pine, and mixed yellow pine including loblolly, shortleaf, and longleaf pine) accounted for only 164 (20%) of all spots. Within the loblolly pine forest type on the HNF, more spots (382) occurred in stands (227) that were <45 years old than in older loblolly stands (255 spots and 182 stands, respectively). In addition, in those stands <45 years old with SPB, average spot size was greater (2.05 versus 0.82 acres), and a higher percentage of spots required suppression measures (58% versus 26%) than spots in the older cohort of loblolly stands. Based solely on the beetle activity that occurred on the HNF, loblolly stands <45 years old incurred the greatest impact from SPB.

In the loblolly pine stands <45 years old that we examined in this study, we found that thinned stands were much less likely to incur SPB damage on either NF (Table 1). SPB spots were not present in thinned stands anywhere on the BNF, whereas SPB spots occurred on only 0.2% of stands that had been thinned in the past 6 years on the HNF. The proportion of stands (unthinned and thinned) that contained SPB spots was greater on the HNF (17%) than on the BNF (4%). Comparing thinned and unthinned stands separately for each NF, the proportion with SPB spots was significantly greater for unthinned stands for both the BNF ($P = 0.044$) and the HNF ($P = 0.001$). This difference is not surprising given that only 2 of 910 spots occurred in stands thinned in the previous 6 years before the SPB activity. Individual thinned stands might be less susceptible to SPB as shown by a number of studies, no studies have shown that recently thinned stands would virtually escape attack from SPB, even during high SPB activity, as occurred on the HNF. The two stands that had been attacked had been thinned 5 and 6 years previously and were therefore representative of the oldest thinning treatment examined. Plot data and tree metrics from these two thinned stands with SPB failed to reveal any obvious indicators of increased susceptibility, although they were older and contained larger pines than the averages of thinned stands without SPB.

We examined several individual tree metrics that provide a picture of stand characteristics and individual tree health and vigor (Table 2). As expected, there were significant differences between the thinned stands and unthinned stands in several tree and stand metrics (Table 2). The thinned stands on both national forests had significantly lower trees per acre (pine and all species combined) and significantly lower basal area (pine and all species combined) than the unthinned stands (Table 2). The average pine basal areas for the thinned stands was <90 ft^2/acre, close to the recommended thinning target for SPB prevention (80 ft^2/acre), and >120 ft^2/acre for the unthinned stands, the trigger point to recommend thinning to prevent SPB infestation (Nowak et al. 2008). Pine dbh was significantly greater in the thinned versus unthinned stands on the HNF, but not on the BNF, reflecting the expected patterns associated with the timing of thinning (e.g., at commercial age on the HNF versus numerous precommercial thinnings on the BNF). Pine height of thinned stands was significantly less than that of unthinned stands on the BNF, again, presumably due to the emphasis on precommercial thinnings at relatively younger ages. However, 10-year radial growth was greater in thinned stands than in unthinned stands on the BNF. Unthinned stands were significantly older than thinned stands on the BNF, but there were no significant differences in stand age on the HNF. Because the thinned stands on the BNF were younger than unthinned stands, this may account for the lack of differences in pine dbh and pine volume.

In addition to comparing thinned versus unthinned stands, this study examined individual tree metrics between unthinned stands without SPB (No thin–no SPB) and unthinned stands with SPB (No thin–with SPB) (Table 2). There were several significant differences between the No thin–no SPB stands and the No thin–with SPB stands. On both NFs, the No thin–no SPB stands had significantly smaller pine dbh, tree height, and pine volume than the No thin–with SPB stands. These differences may be explained by the fact that the No

Table 2. Stand characteristics of the BNF and HNF during 2012–2013.

				P value	
NF	Thin–no SPB	No thin–no SPB	No thin–with SPB	Thin–no SPB vs. No thin–no SPB	No thin–with SPB vs. No thin–no SPB
BNF					
Dbh, pine (in.)	9.5	9.4	10.5	0.331	0.026
Dbh, all species (in.)	9.6	9.4	10.2	0.619	0.056
TPA, pine	237	397	318	0.010	0.143
TPA, all species	243	433	387	0.002	0.419
BA, pine	86	135	145	0.001	0.332
BA, hardwood	2.6	7.6	9.9	0.013	0.415
BA, total	89	143	156	0.001	0.282
Height (ft)	61	68	75	0.001	0.006
Pine volume ($x^{1/3}$)	2.36	2.43	2.70	0.052	0.024
10-yr radial growth (in.)	1.8	1.2	1.2	0.001	0.347
Stand age (yr)	20.4	25.7	30.5	0.001	0.002
Stand size (ac)	41	41	45	0.724	0.471
Site index	93	87	89	0.062	0.586
HNF					
Dbh, pine (in.)	11.8	9.7	10.8	0.001	0.004
Dbh, all species (in.)	11.5	9.7	10.6	0.001	0.009
TPA, pine	145	391	314	0.001	0.069
TPA, all species	173	422	365	0.001	0.201
BA, pine	89	158	149	0.001	0.299
BA, hardwood	5.8	6.9	10.1	0.164	0.149
BA, total	95	164	159	0.001	0.598
Height (ft)	77	71	79	0.287	0.001
Pine volume ($x^{1/3}$)	2.9	2.5	2.8	0.002	0.007
10-yr radial growth (in.)	1.24	1.18	1.17	0.264	0.824
Stand age (yr)	25.6	23.6	26.2	0.499	0.023
Stand size (ac)	47	43	53	0.685	0.029
Site index	97	98	98	0.794	0.818

TPA, trees per acre; BA, basal index.

thin–no SPB stands were significantly younger than the No thin–with SPB stands on both NFs (by 4.8 ± 1.5 years on the BNF and by 2.67 ± 1.2 years on the HNF). However, even with adjustment for age, pine volume was lower in the No thin–no SPB stands than in the No thin–with SPB stands on both NFs, probably a reflection of SPB's propensity for larger trees. Older pine stands have sometimes been considered to be more susceptible to SPB (Hicks et al. 1980), even though some studies have indicated no such pattern (Zhang and Zeide 1999, Friedenberg et al. 2007). Hicks et al. (1980) reported that the average age of attacked stands was 39 and 44 years old. In this study, there were differences due to age of stands with and without SPB spots, but even the tree age differences were relatively small, <5 years on average (Table 2). However, as discussed earlier, more SPB occurred in the stands <45 years old than in stands >45 years old. Perhaps other stand characteristics (e.g., time since last thin, tree size, or stand density) are more important than age to stand susceptibility. Further research and data analysis on the 2012 HNF outbreak might clarify the relationship between SPB attack and stand age.

We also compared differences in percentage of stands burned, number of burns per stand, and time since the last burn occurred between the No thin–no SPB and No thin–with SPB stands. The two forests exhibited different burning regimes based on the stands sampled, with only about one-quarter of the stands (27%) burned on the BNF versus nearly one-half (47%) of the stands burned in the last 6 years on the HNF. There were no significant differences between the two treatments for any of the SPB measures on the BNF. However, on the HNF, there were significant differences among treatments ($P = 0.008$) in percentage of stands burned with and without SPB spots. A significantly higher percentage ($P = 0.002$) of No thin–no SPB stands were burned (67%) than No thin–with SPB stands (28%) (Figure 2A). In addition, the percentage of recently burned stands (in the previous 2 years) was significantly higher ($P = 0.003$) for No thin–no SPB stands (55%) than for No thin–with SPB stands (19%) (Figure 2B). Finally, the percentage of stands burned at least twice was higher ($P = 0.005$) for No thin–no SPB stands (57%) than for No thin–with SPB stands (28%).

When burn versus unburned was factored in for all treatments, there were few burn × treatment effects. In comparing the results for burned and unburned stands with those in Table 2, similar patterns emerged with respect to the direction and significance of the difference for most measurements. An exception is hardwood basal area, one measurement for which the treatment × burn interaction was significant ($P = 0.011$). In both NFs, hardwood basal area was significantly greater in the No thin–with SPB stands than in the No thin–no SPB only for burned stands (Figure 3), whereas the reverse trend was seen (although nonsignificant) for unburned stands. As a result, there was a significant treatment × burn interaction for the No thin–no SPB versus the No thin–with SPB comparison. When burn status is ignored (see Table 2) the contrast (No thin–no SPB versus No thin–with SPB) is not significant for hardwood basal area (Figure 3).

We also examined correlations between average spot size and the number of SPB spots per stand compared with those for other stand variables, including pine diameter, pine volume, pine trees per acre, and burning history. This analysis was performed for both forests combined ($n = 58$ spots). The only correlations found to be significant were between average spot size and pine height ($P = 0.0104$). The model selection procedure (PROC GLMSELECT) was applied to data for all stands ($n = 164$) to identify combinations of variables that are associated with spot size and number of spots. The model selected to describe average spot size (square root transformed) based on data from all stands included the predictors height, stand size, total basal area, and time since the last burn. The fitted model explained 27% ($R^2 = 0.\ 27$) and the coefficient for each predictor was positive, indicating that spot size tended to increase with tree height, stand size, total basal area, and years since the last burn. Similar results were obtained for number of spots per stand ($R^2 = 0.27$). Number of spots per stand tended to increase with pine height, stand size, total basal area, and years since the last burn. Stand size was significantly greater for unthinned stands with SPB than for stands without SPB on the HNF ($P = 0.029$), suggesting that patch size has a positive influence on the success of SPB.

Although the benefits of thinning to reduce SPB impact on individual stands have been documented, the relationship between

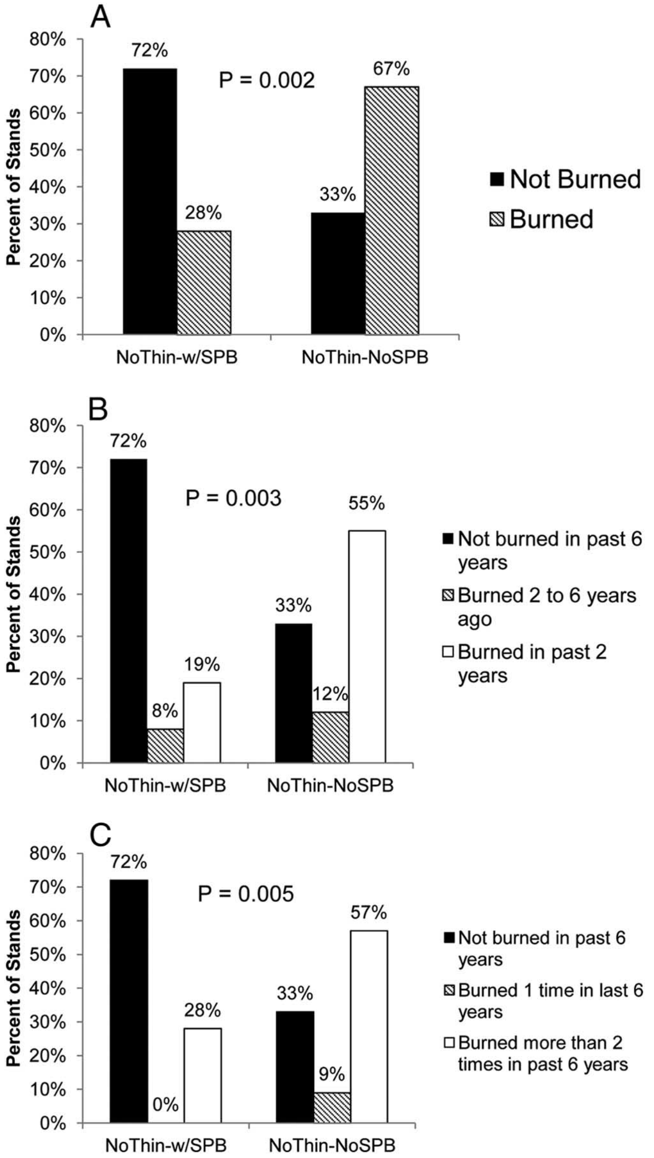

Figure 2. Percentage of stands on HNF in two treatments (No thin–with SPB and No thin–no SPB) that were burned or not burned in the previous 6 years before the study in 2012 (A); not burned in the past 6 years, burned in only in 2–6 years before or burned in the past 2 years before the study in 2012 (B); and not burned in the past 6 years, burned once in the past 6 years, or burned more than 2 times in the past 6 years prior to the study in 2012 (C). Reported *P* values are from the χ^2 analysis comparing No thin–with SPB and No thin–no SPB.

SPB impacts and prescribed fire is less certain (Fettig et al. 2007). In one of the few published studies examining the relationship between SPB and prescribed burning, Cameron and Billings (1988) reported that prescribed fire in young (<10 years old) loblolly and slash pine plantations in east Texas were associated with increased SPB incidence during an outbreak. Other studies on bark beetles and prescribed fire in the southern United States (Santoro et al. 2001, Sullivan et al. 2003) have had mixed results with no demonstrated link between bark beetles and tree mortality, even though some bark beetle activity may have increased. Burning can change stand structure, as does thinning, and the amount of competition for resources (Cain 1993), both factors that have been shown to reduce a stand's susceptibility to SPB (Gara and Coster 1968, Johnson and Coster 1978, Hodges et al. 1979, Brown et al. 1987, Nebeker et al. 1992). Furthermore, reducing competing vegetation through prescribed fire could also increase residual pine tree vigor (Knebel and Wentworth 2007), which is often associated with increased tree resistance to SPB.

Reduced tree density and stand basal area as a result of thinning can increase tree vigor as defined by tree growth and stand productivity. An increase in growing space and greater access to resources (e.g., water, nutrients and light) has been shown to result in greater tree defense capabilities against bark beetles. Increased tree vigor, oleoresin exudation pressure, and/or oleoresin flow associated with thinning is believed to potentially have a positive relationship with a tree's defensive capabilities against SPB attack (Hodges et al. 1979, Brown et al. 1987, Nebeker et al. 1992, Strom et al. 2002). Resin characteristics, such as increased flow rate and total volume, can help trees avoid SPB attacks (Hodges et al. 1979, Strom et al. 2002). Resin duct production has been shown to be associated with tree growth rate (DeAngelis et al. 1986), which in turn can affect tree susceptibility to SPB infestations (Coulson et al. 1974).

In addition to effects on tree vigor and tree resistance, thinning (and potentially prescribed burning) may reduce a stand's susceptibility to SPB due to the resulting increased distances between host stems (Gara and Coster 1968) and changes in the stands microenvironment through changes in pine and hardwood basal area (Thistle et al. 2004, 2011, Strand et al. 2009). Gara and Coster (1968) found that intertree distance is an important factor influencing the spread of infestations and is most likely associated with the distance that a pheromone plume can remain intact from a source. In fact, they concluded that SPB spot expansion was unlikely in stands that had an intertree spacing of 20–25 ft. Mean intertree pine spacing in this study ranged from 10.5 ft (397 trees per acre) in unthinned stands to 17 ft (145 trees per acre) in thinned stands on the HNF (Table 2). Johnson and Coster (1978) further examined these factors and found that the probability of attack decreased with the distance between trees in small- to moderate-sized infestations with only one or a few pheromone plume sources (i.e., clusters of newly infested trees at the edge of a spot, "spot heads"). They did not find a relationship between intertree distance and the probability of attack in large infestations with multiple pheromone sources or spot heads. Nebeker and Hodges (1985) concluded that infestations initiated in stands of <70 ft^2/ac of basal area rarely expanded beyond 5 trees. Finally, studies have shown that more open stands allow greater dissipation and disruption of SPB pheromone—like gases (used as a surrogate) via increased wind speed and turbulence, solar radiation, and temperature (Thistle et al. 2004, 2011).

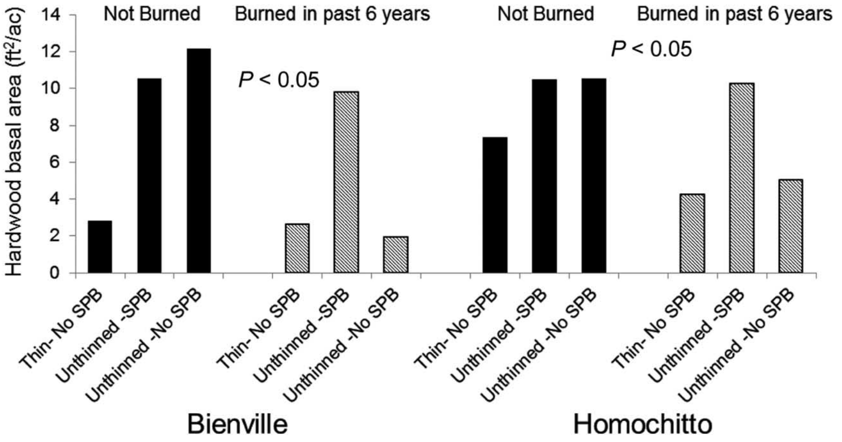

Figure 3. Hardwood basal area on the BNF and HNF in three treatments (Thin–No SPB, No thin–with SPB, and No thin–no SPB). Within each NF, the difference between not burned and recently burned is significant ($P < 0.05$).

They surmised that opening the stand by thinning would make it more difficult for SPB to find the source of the aggregation pheromone and lead to lower spot initiation and success.

Conclusions

Our study shows landscape-level effects of stand management on the incidence of SPB outbreak dynamics and strongly supports thinning and perhaps prescribed burning as effective management techniques to promote forest health and vitality. SPB was significantly less likely to attack and affect stands that had been thinned in the past 5–6 years during latent SPB activity on the BNF and under severe outbreak conditions on the HNF. Differences in stand density, stand age, and stand size were shown to be associated with the lack of SPB in stands. In addition, this study showed that prescribed burning was associated with less SPB activity in unthinned stands on the HNF, where prescribed burning was frequently used, but not on the BNF. These data show that implementation of areawide SPBPP practices that reduce basal area and increase intertree spacing through thinning or prescribed burning can have both stand- and landscape-level impacts on SPB activity.

Proper stand management, including thinning and prescribed burning, has long been accepted as crucial to the vitality of forest resources. Our results have implications throughout North American forests. As SPB is currently affecting nontraditional areas (e.g., the northeastern United States, particularly New Jersey and New York), stand management will continue to be the best management strategy against this forest pest. Thinning and prescribed fire are management tools often associated with western bark beetle species, and the implementation of these management activities has been shown to be beneficial in creating healthy forests and reducing losses from several species of bark beetles, including the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), western pine beetle (*Dendroctonus brevicomis* LeConte), and spruce beetle (*Dendroctonus rufipennis* [Kirby]) (Zausen et al. 2005, Fettig et al. 2007, Wallin et al. 2008). Further, our results could also be applied to management of nonnative forest pests, such as the Sirex woodwasp (*Sirex noctilio* F.), a significant pest of southern yellow pines planted in the Southern Hemisphere (Haugen et al. 1990) and currently established in the northeastern United States (Dodds et al. 2010). Thinning to reduce stand basal area and increase interspacing as recommended for SPB has also been shown to be a significant management tool for *S. noctilio* (Haugen et al. 1990) and would likely be a primary management tool to combat *S. noctilio* if it were to become established in the southeastern United States (Chase et al. 2014).

Endnotes

1. For more information, see www.fs.usda.gov/detail/r8/forest-grasslandhealth/insects-diseases/?cid=stelprdb5448137.
2. For more information, see www.srs.fs.usda.gov/compass/2012/09/12/secretarys-honor-award-for-southern-pine-beetle-prevention-program/.

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