AUBURN UNIVERSITY
FOREST HEALTH
COOPERATIVE

RESEARCH REPORT 2013-01

BARK AND AMBROSIA BEETLE DIVERSITY AT THE OAKMULGEE RANGER DISTRICT, TALLADEGA NATIONAL FOREST, ALABAMA

by
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ABSTRACT

Over a two-year period, 85,876 insects were captured with three different trap types located in the Oakmulgee Ranger District in the Talladega National Forest in Alabama. *Hylastes salebrosus* was the most commonly collected bark beetle species, while *Dendroctonus frontalis* were captured infrequently. The ambrosia beetle *Gnathotrichus materiarius* was the second most commonly collected insect species. Differences in insect collection totals were observed between predicted loblolly decline plots versus predicted non-decline plots. No differences in insect collection were found between adjacent plot pairs that differed in slope and aspect. A strong positive relationship between insect collection numbers and higher foliar transparency was observed. Bark beetle species tended to be positively correlated with one another, suggesting that pine bark beetle outbreaks may be compounded by additional bark beetle species which often go unobserved. Many of these less studied species, particularly weevils and insects in the genus *Hylastes*, have been linked with pine decline that may in turn weaken tree resistance to subsequent insect attacks. In addition to providing a picture of bark and ambrosia beetle diversity at the Talladega National Forest, data collected over the two-year period could serve as pre-treatment data for any subsequent work performed in the plot locations.

INTRODUCTION

Insect attacks on pines have become widespread and severe in recent years (Western Forestry Leadership Coalition, 2009). In western North America alone, mountain pine beetle epidemics have killed over a million acres of forest trees (Robbins, 2008). Many bark and ambrosia beetles are poorly understood and thorough diversity studies may uncover previously obscure interactions between beetles and their host trees. It is important to fully understand bark beetles so their attacks can be either minimized or mitigated.

Most research exploring the relationships between forest health and insect attacks have concentrated on the few bark beetle species associated with widespread mortality and financial damage (Berisford, 1980). In the southeastern United States, *Dendroctonus frontalis* Zimmerman is associated with far more damage than any other species and have received more attention than other regional bark beetles. Their ability to kill healthy trees over large geographic areas has shaped forest ecology and forest management (Boyle et al., 2004). Insects within the genus *Ips* are also associated with economic damage and tree mortality. *Ips* species usually attack declining trees but can kill healthy trees during outbreaks that most often follow disturbances such as major storms or *D. frontalis* outbreaks (Erbilgen and Raffa, 2002).

Healthy trees are usually able to resist beetle attacks. In addition to physical defenses such as bark, trees employ chemical defenses such as chemical repellents and oleoresin (Hanover, 1975). When trees are stressed the effectiveness of these defenses is reduced. In particular, stressed pines produce lower resin and are less capable of flushing out bark beetles (Perkins and Matlack, 2002). Bark beetle attacks are also more successful following disturbances such as wind throw or lighting strike.

Many of the other bark and ambrosia beetle species are not associated with mortality and and rarely the direct focus of insect research. Recent studies, however, suggest they exert an influence on forest health. These beetles are capable of introducing pathogenic fungal associates into trees which may reduce tree resistance to subsequent insect attacks (Paine et al., 1997). *Hylastes tenuis* Eichhoff and *Hylastes salebrosus* Eichhoff have been observed to be more common in declining loblolly pine stands than non-declining stands (Eckhardt et al., 2007). Most studies devoted to *Hylastes* and other root and lower bole feeders have investigated their potential contribution to the pine decline complex.

Forest management practices can have powerful and widespread effects on tree resistance to insects and subsequent bark beetle populations. Excessively dense planting has been associated with greater insect attacks. Trees in thinned stands were found to be as likely to be attacked, but less likely to be killed by a mass attack (Safranyik et al., 2004b). Trees growing within thinned, less densely stocked stands, produced a greater quantity of defensive resin (Negron, 1998), which enhances resistance to insects. Bark beetle populations increase in the immediate aftermath of thinning but decline over the long-term (Werner, 2002). This short-term increase in beetle species diversity and bark beetle populations is due to the increase of coarse woody debris associated with thinning (Peltonen et al., 1998). Thinning may also cause changes in microclimate, such as increased wind and warmer temperatures that act to increase beetle diversity (Hindmarch and Reid, 2001). Attractant chemicals are spread over a broader range following thinnings but are less concentrated and are therefore more difficult for insects to detect (Thistle et al., 2005).

Loblolly pine is the most common commercially planted tree species in the southeastern United States and is the dominant tree species in many forests. Widespread premature mortality of these species has important ecological and economic repercussions. Trees begin to suffer decline symptoms at age 25 to 35 and die well before the expected lifespan of 120-275 years. The prospect that little studied bark and ambrosia beetles may be vectors in a disease complex make a broad insect survey in a declining area valuable. While testing possible associations between beetle capture and tree health indicators it will also be possible to test models estimating loblolly pine decline probability. Steeper slope (greater than 10%) and south and southeast facing aspect has been associated with pine decline in prior reports (Eckhardt and Menard, 2008), which would be expected to reduce insect resistance. Greater insect capture was therefore expected in predicted decline plots.

METHODS AND MATERIALS

Plot Measurements

Bark and ambrosia beetles were trapped at twenty-four research plots located in the Oakmulgee Ranger District of the Talladega National Forest in Perry, Chilton and Bibb Counties, Alabama. Study sites, selected on the basis of stand history, slope and aspect, were former agricultural lands converted to forest between 1973 and 1984. Each study plot included three subplots located 36.57 meters from plot center at bearings of 120, 240 and 360 degrees. Subplots were an array of circles with a radius of 7.62 meters. Plot design followed methods used in the USDA Forest Inventory and Analysis Program (Dunn, 1999).

Research plots were selected on the basis of whether or not they were in compartments in which loblolly pine decline occured. Nine of twelve plot pairs were within compartments considered to be experiencing loblolly pine decline on the basis of topography, stand age and management. Three pairs of plots were located in stands not expected to exhibit decline symptoms. Insect collection data from both predicted decline and predicted non-decline compartments could subsequently be compared. The 24 study plots were grouped into 12 pairs and plots within a pair were separated by topographical features with one plot located in a predicted high risk area (slope >10%) and an adjacent plot in a predicted lower risk area (slope<10%). Plots were randomly selected within predicted decline or predicted non-decline plots and slopes were confirmed with a clinometer at each research plot.

One hundred latitude and longitude plot center coordinates were measured and averaged per plot within the GPS unit (Garmin GPSMAP 76Cx, Garmin International Inc., Olathe, KS) before data was recorded. GPS measurements were accurate within 10 meters. Pitfall traps, panel traps and modified flight intercept traps were placed within each of the three subplots for a total of nine traps per plot.

Insect trapping

Three different trap types were utilized to capture the widest range of species. Intercept panel traps (Fig. 1a) and flight intercept traps (Fig. 1b) were installed to capture flying insects and pitfall traps were placed in the ground to capture root dwelling insects. Pitfall traps were placed at the center of each subplot, panel traps were located approximately 3 meters west of the pitfall trap and flight intercept traps were placed approximately 3 meters east of the pitfall traps. Intercept panel traps (APTIV Company, Portland, Oregon) were hung approximately two meters by wire from a metal pole kept in the ground by a metal sleeve. The bucket of each panel trap was filled with approximately 45 ml of a mixture of two parts distilled water to one part antifreeze to prevent the escape of captured insects.

Flight intercept traps consisted of a plastic gallon milk jug cut open on three sides with the fourth side attached to a pole approximately 0.60 meters above the ground. A 120 ml plastic cup attached to the lip of the milk jug served as the receptacle for insects. Two 5 cm long by 2 cm diameter pine stems were placed in the cup to attract and protect insects.

Pitfall traps consisted of 10 cm by 20 cm diameter of PVC plastic drain pipe with eight entrance holes equally spaced around the circumference. The traps were buried with the entrance holes within 5 cm of ground level at each subplot. A plastic skirt was fitted around the trap to reduce the risk of flooding (Menard, 2007). Two loblolly pine stems 5 cm by 2 cm were placed in the trap base. The cap was kept loose to facilitate access. Escape of captured insects was prevented though coating with a thin layer of liquid Teflon™ (Northern Products Woonsocket, RI) each collection period. Trapped insects remained in the cup until the following collection period.

All traps were baited with two 8 ml glass vials, filled either with 90% ethanol or steam- distilled southern pine turpentine. Bait vials were replenished every two weeks during insect collections. Intercept panel traps were also refilled with the diluted antifreeze during collections. The antifreeze deterred predaceous insects and prevented insect loss from intercept panel traps. Pine stems in the flight intercept and pitfall traps were replaced every two weeks. Insect collections began March 2008 and continued biweekly through February 2010. Captured insects were taken to the Forest Health Dynamics Laboratory at Auburn University (Auburn, AL, USA), sorted and identified to species.

Tree measurements

Crown rating - Live crown ratio, crown density, crown transparency, crown dieback, crown position and number of sides of crown sunlight exposure were measured on each of the three subplots and at plot center in accordance with Forest Health Monitoring (FHM) procedures (Dunn, 1999). Pine trees with DBH greater than four inches (10 cm) were evaluated. Three trees were randomly selected for resin and growth increment collection at center plot and the three subplots. Selected trees were spray painted with one pink band both above and below the tag in May 2009 to indicate leave trees in future thinning or biomass removal work so post-treatment data could be collected. Pine and hardwood basal areas were measured with a prism at the center plot of all research plots. Stem count within 7.32 meters of center plot and all subplots was determined in July 2009.

Additional tree measurements - Resin was collected from 12 trees per plot (three trees at center plot and all three subplots) in July 2009. Trees were wounded with a ½ inch arch punch (Osbourne No. 149) at a height of 1.37 m and 15 mL pre-weighed vials were hung below the wound. Vials containing resin were collected 24 hours later and weighed upon return to the Forest Health Dynamics Laboratory at Auburn University. Increment cores were collected from the selected trees during July and August 2009 and returned to the Forest Health Dynamics Laboratory where 5-and-10- year growth measurements were conducted to the nearest 0.01 mm with a Mitutoyo Digimatic (Mitutoyo Corporation, Maplewood, NJ) electronic ruler. Pine and hardwood basal area was measured with a prism.

STATISTICAL ANALYSIS

Statistical analysis was performed using SAS 9.1 (SAS Institute Inc., Cary, N.C.). Correlations between collected insect species and crown rating variables were obtained using Pearson correlations. Multivariate linear regression was used to determine significant relationships between insect numbers and crown rating, stem count, growth increment and resin production. Analysis of variance was used to determine differences between groups of plots stratified by forest health characteristics. A repeated measures General Linear Model (GLM) test using Tukey-Kramer analysis to obtain least-squared means was used to identify differences in totals between plots within and outside areas of predicted loblolly pine decline.

Insect collection totals within plots with slopes greater than 10 percent were compared with collections from plots with slopes less than 10 percent with a two-sided t-test. On the basis of National Forest data (stand age, slope, aspect and prior management), nine pairs of study plots were expected to undergo loblolly pine decline and three were not. Differences in insect collection totals between the eighteen study plots located within National Forest compartments considered to be experiencing loblolly pine decline were compared to insect collections in six plots from compartments considered to be outside the area of decline. Because of the unequal number of plots, a repeated measures General Linear Model (GLM) was used to test for differences in SAS 9.1. Least-squared means were obtained using Tukey-Kramer analysis. Alpha-levels of significance for these and all subsequently mentioned testing was set at $P \geq 0.05$.

Stratification methods

For each of the forest health characteristics measured resin production, 5-and-10-year growth increments, stem count, pine basal area, hardwood basal area, mean diameter at breast height (DBH), mean crown ratio, mean crown density, mean crown transparency, study plots were stratified into groups of the eight lowest, eight median and eight highest. Stratification was performed to uncover relationships in data that may be obscured (Randolph, 2006). Analysis of variation was used to test differences in insect populations between stratified groups.

RESULTS

Total number of insects

Between March 2008 and February 2010, 85,876 insects were collected and identified to species. Twenty-three different bark and ambrosia beetle species and two predator beetle species (*Thanasimus dubius* Fabricius (family Cleridae) and *Temnoscheila virescens* Fabricius (family Troggossidae) were captured (Table 1). *Hylastes salebrosus* was the most frequently collected insect during the study. *Ips grandicollis* Eichhoff was the second most common bark beetle. Few *D. frontalis* (n=23) were collected throughout this same period. Three weevil species were identified, *Pachylobius picivorus* Germar, *Hylobius pales* Germar and *Pissodes nemorensis* Germar. *Gnathotrichus materiarius* Fitch was the most numerous ambrosia beetle recovered. *Xyleborinus saxesenii* Ratzburg, *Xylosandrus crassiusculus* (Motschulsky) and *Xylosandrus mutilatus* (Blandford) were the next three most common ambrosia beetle species collected in the traps.

Correlations between insect species

Bark beetle species were closely associated with one another. *Hylastes salebrosus,* the most frequently observed species, was significantly correlated with more species than any other bark beetles captured. *Hylastes salebrosus* was positively correlated with *H. tenuis* (r^2= 0.4222, p-value=0.0399), *P. picivorus* (r^2=0.4592, p-value=0.0240), *D. terebrans* (r^2=0.6464. p-value=0.0006) and *I. grandicollis* (r^2=0.6542, p-value=0.0005) and *X. crassiusculus* (r^2=0.4200, p- value=0.0140). *Ips grandicollis* was positively associated with *D. terebrans* (r^2=0.4806, p-value=0.0174) (Table 2). In addition to their significant correlation to *H. salebrosus, H. tenuis* was positively correlated with the ambrosia beetle *X. crassiusculus* (r^2=0.4200, p-value=0.0410). *Pachylobius picivorus* had a positive correlation with *D. terebrans* (r^2=0.5882, p-value=0.0025).

Ambrosia beetles were less related to one another although there was a positive correlation between *X. saxesenii* and *G. materiarius* (r^2=0.4168, p-value=0.0427). The predator beetle *T. dubius* was negatively correlated with *H. salebrosus* (r^2= 0.5770, p-value=0.0032), *I. grandicollis* (r^2=-0.3971, p-value=0.0547), *X. crassiusculus* (r^2= 0.5113, p-value=0.0107) and *X. saxesenii* (r^2= 0.4167, p-value=0.0428). Relationships between *T. dubius* and other insect species were generally negative, an unexpected result given that *T. dubius* is a known predator of some of the other species, such as *Ips* beetles.

Multivariate analysis of insect collection numbers and tree measurements

Mean crown transparency was highly correlated with insect collection totals. Higher transparency was associated with greater collections of *H. salebrosus* (r^2=0.3465 p-value=0.0025), *H. tenuis* (r^2=0.2398, p-value=0.0152), *P. picivorus* (r^2=0.2820, p-value=0.0076), *D. terebrans* (r^2=0.2471, p-value= 0.0135), *I. grandicollis* (r^2=0.1808, p-value= 0.0384), *G. materiarius* (r^2=0.3023, p-value=0.0054) and *X. saxesenii* (r^2=0.1205, p-value=0.0161). Mean crown density was significant for *H. salebrosus* (r^2=0.0668, p-value=0.0336) and *X. crassiusculus* (r^2= 0.2459. p-value=0.0137). Other forest health variables were significant for only single species. Ten-year growth was significant for *X. saxesenii* (r^2=0.0690, p-value=0.0330). *Pachylobius picivorus* was negatively correlated with hardwood basal area (r^2=0.2585, p-value=0.0025) and *G. materiarius* was negatively associated with mean diameter at breast height (r^2=0.1031, p-value=0.0198). There was also a strong positive association between *X. saxesenii* and mean diameter at breast height per plot (r^2= 0.5102, p-value<0.0001). A full list of significant regression results is shown of Table 3.

Effects of prior thinning at research plots

Three pairs of the research plots were thinned in 1996 and two additional pairs were thinned in 1999. None of the remaining seven pairs underwent thinning. General linear model analysis was used to compare insect counts at the seven plot pairs that had never been thinned with the five plot pairs that had. Higher mean captures of *P. picivorus* (p-value= 0.0008) were observed at unthinned plots and insect counts were higher in thinned stands for *X. mutilatus* (p-value=0.0194).

The presence of pine decline may have confounded effects of prior thinning on insect presence. To account for this possibility, data from unthinned predicted decline stands were separated from that of unthinned, predicted non-decline stands. Insect totals from both plot groups were compared to those from those from thinned stands (n=10) with Tukey-Kramer comparisons using a General Linear Model Procedure. Significant differences were observed between thinned and unthinned predicted decline plots for *H. tenuis* (p-value=0.0494), *P. picivorus* (p-value= 0.0793), *X. saxesenii* (p-value=0.0429), *X. crassiusculus* (p-value=0.0198) and *P. flavicornus* (p-value= 0.0286). Differences were obscured between previously thinned predicted decline plots and previously unthinned predicted decline plots after plots in non- declining areas were separated as a potential confounding factor. No predicted decline plots had been thinned. After presence of possible pine decline was accounted for, several insect species were more common in predicted decline plots including *P. picivorus* (p-value=0.0003), *H. porculus* (p-value=0.0143), *X. crassiusculus* (p-value=0.0449) and *P. flavicornus* (p- value=0.0293). Only *X. mutilatus* (p-value= 0.0378) was more common in the thinned plots. When compared to the plots located in predicted non-decline compartments, the unthinned predicted decline plots generally had greater totals of several insect species (Tables 4 and 5)

Stratification method and results

The stratified groups consisted of the eight plots with the highest, median and lowest values for each forest health variable. The plots with the lowest resin production had the lowest number of *P. picivorus* and *X. crassiusculus* (Table 6). *Dendroctonus terebrans* was captured more frequently in plots with median resin production. *Gnathotrichus materiarius* and *X. saxesenii* were collected in greater numbers in plots that had greater five and ten-year growth. *T. virescens* was most common in the group of plots with the lowest five-year growth (Table 7).

Stands with the highest stem count were associated with the greatest numbers of *P. picivorus*, *D. terebrans* and *X. crassiusculus* while the stands with the lowest stem count had greater totals of *I. grandicollis* than the median stem count plots (Table 8 and 9). *Hylastes tenuis* was captured least frequently in the the low basal area plots (Table 10). The lowest hardwood basal area plots had the largest number of *H. salebrosus* and *D. terebrans*. More *G. materiarius* insects were collected at the lowest hardwood basal area plots than at the highest (Table 11).

Ips grandicollis was most frequently collected at plots with the lowest DBH. *Temnosheila virescens* was least frequently trapped at the plots with the highest DBH. *Xyleborinus saxesenii* was collected most in the plots with the greatest DBH, while *G. materiarius* was captured more at the highest DBH plots than at the lowest DBH (Table 12). Plots with the lowest mean live crown ratios (LCR) were associated with higher collections of *P. picivorus* and *X. crassiusculus*. Median LCR plots had the greatest numbers of *I. grandicollis* collected. *Hylastes salebrosus* was more common at low mean LCR plots than at median mean LCR plots while *T. virescens* was most often collected in the median than low LCR plots (Table 13).

Capture of *H. tenuis* and *X. crassiusculus* were lowest at plots with high mean crown densities. *Pachylobius picivorus* were captured more in stands with the lowest mean crown density plots compared to plots with highest mean crown density (Table 14). Plots with the highest mean crown transparency had the greatest number of *P. picivorus*, *D. terebrans* and *G. materiarius* collected. Plots with the greatest mean foliar transparency had significantly greater numbers of *I. grandicollis* and *X. crassiusculus* than plots with the lowest mean crown transparency. The plots with the lowest mean crown transparency had the fewest of *H. salebrosus* (Table 15).

Insect totals in predicted decline stands versus those in predicted non-declining stands

Hylastes tenuis, G. materiarius, X. crassiusculus, X. saxesenii and *T. virescens* were more frequently captured in the predicted decline plots than predicted non-decline plots. No differences occured between plots for *T. dubius, H. salebrosus, H. porculus, P. picivorus, H. pales, D. terebrans* or *I. grandicollis* (Table 16).

Timing of insect collection peaks

The majority of species showed a spring population peak, reduced numbers from June to August and few if any individuals from December through February. Some species, however, were captured during times of year in which traps are rarely utilized. *Gnathotrichus materiarius* was captured primarily during relatively warm periods during December through February when contents of the intercept panel trap collection bucket were not frozen. The two most common weevils, *P. picivorus* and *H. pales* were generally captured during different seasons. *Hylobius pales* were most frequently captured during March and September while *P. picivorus* was captured more frequently from May through August.

DISCUSSION

Predicted decline plots often had more insects recovered than predicted non-decline plots. Increased numbers of fungi-vectoring root feeders may be contributing to loblolly pine death within the stands believed to be in decline. One reported insect vector (*H. tenuis*) of *Leptographium* fungi associated with pine decline and several ambrosia beetle species were more common in predicted decline plots than predicted non-decline plots. Many trees in the predicted decline stands exhibited signs of stress and the elevated presence of ambrosia beetles provides additional evidence of poor tree health as ambrosia beetles have been reported to be more numerous in the increased presence of dead and dying trees (Gorsuch, 2003). Several ambrosia beetle species in this study, notably *G. materiarius* are known to benefit from the presence of dead and dying pines (Wood and Bright, 1992) and this appeared to be occurring here.

Crown characteristics in general were often more accuracte predictors of insect populations than non-crown measurements and mean foliar transparency were particularly associated with higher insect captures. Compared to trees within predicted non-declining plots, those within predicted declining plots were expected to show signs of distress including reduced resin production, slower growth, lower live crown ratios, lower live crown density and higher live crown transparency. Greater bark and ambrosia beetle capture had been expected at plots where trees showed those outward characters than where there were healthier looking trees. Higher mean crown density and live crown ratios were associated with fewer insect totals for observed bark and ambrosia beetle species when differences were detected. This finding was not surprising as distressed crowns are often apparent before loblolly pine death. Given that most ambrosia beetles and many bark beetle species avoid the defenses of healthy trees, greater collection totals of beetles was anticipated in declining plots.

Crown transparency was not strongly correlated with non-foliar tree measurements such as resin production, radial growth or basal area. Non-foliar tree measurements had weaker and less consistant relationships with insect collection counts. Resin production and growth rate were not strongly associated with insect collection totals despite a documented association between increased pine decline and slower growth (Eckhardt et al., 2007). This may be because those are earlier signs of distress than damage to needles and are not as directly associated with mortality. Pine and hardwood basal area did not appear to affect insect collections despite the documented preference of some ambrosia beetle species (such as *Monarthrum* sp.) for hardwoods. Measuring basal area with a hand prism may have artificially increased the basal area of loblolly pine at the expense of hardwoods given the greater diameter of pines at the plots.

Thinning generally benefits forest health and reduces susceptibility to insects (Werner, 2002). Thinning, for example, can be used to offset effects of loblolly pine decline by reducing competition between remaining trees. Following a thin, standing trees often have increased access to light and nutrition. Insect counts in thinned stands in this study were lower than insect counts in unthinned stands, suggesting that thinning of stressed trees may have improved tree insect resistance even within predicted decline areas. On private land, this may serve to keep loblolly pine trees alive long enough to be more profitably harvested. Many land managers practice thinning for their own economic benefit in order to increase growth during rotations. Private land owners do not grow loblolly pine to its full age during commericial rotation and thinning may enable loblolly pine plantations to enhance their revenue even within areas of loblolly pine decline. In non-commercial forests, such as the study sites, growing alternate species that may be more site-appropriate, such as longleaf pine may be a better long-term strategy.

Because many bark beetle species coexist in the same habitat, some insect species were expected to be associated with each other and their associated predators. Bark beetle species were often found together but associations between ambrosia beetles were less strong. Correlations between ambrosia beetle species were expected to be weaker because ambrosia beetles often live in dead or dying material and exploit a broader range of tree species. Some ambrosia beetle genera, such as *Xylosandrus* and *Xyleborinus* include many species that are capable of feeding on dozens of tree species, both softwood and hardwood (Wood and Bright, 1992). Surprisingly, the predator species *T. dubius* was negatively correlated with all other insect species with which it had a significant relationship. This was inconsistent with the hypothesis that *T. dubius* feeds on its prey in a density dependant manner (Turchin et al., 1999). However, if *T. dubius* is more specifically attracted to frontalin, the primary attractant chemical of southern pine beetle (*D. frontalis*) the low numbers of southern pine beetle captured during the survey may have influenced *T. dubius* numbers. Additionally, many of the more common bark beetle species (in genus *Hylastes*) live much of their life cycle underground, whereas the predator beetles captured in this study feed primarily on in beetles associated with other areas of the tree.

Overall bark and ambrosia beetle capture was heavily weighted towards members of genus *Hylastes* and the ambrosia beetle *G. materiarius*. These species represented over half of the total insect captures. The seemingly high number of correlations between *Hylastes salebrosus* and other bark beetles may have simply been a function of how many individuals were captured. The *Hylastes* species and weevils captured are known vectors of fungi associated with loblolly pine decline and their high capture may be an indicator of the widespread problems with loblolly pine decline in the District (Eckhardt et al., 2007). The fact that only *Hylastes tenuis* among these species appeared to be greater in predicted decline plots was perhaps because bark beetles tend to live in living trees rather than dead material. The greater collection of ambrosia beetles at the predicted decline plots supported the accuracy of the decline model and the low insect resistance of many trees expected to be in decline (Table 2.15). This conclusion was supported by the distressed foliage at predicted decline plots. Total capture of *D. frontalis* was low and insect diversity during a southern pine beetle outbreak would be expected to be considerably different.

The southern pine beetle (*D. frontalis*) was rarely collected in the study. These observations were in line with regional observations of low southern pine beetle (SPB) activity in 2008, with SPB captured in only 1,433 spots recorded in the southeastern United States, compared to 60,000 spots in 2000 (Billings, 2008). Southern pine beetle levels in 2009 were expected to remain at 2008-levels in most states and to decline in Alabama (Billings, 2008). Southern pine beetle population patterns are erratic and a sudden outbreak of SPB would have provided an opportunity to document the extent of *T. dubius* population growth following an increase in prey population. Another possibility in the aftermath of a *D. frontalis* outbreak would be an upsurge of activity by bark beetles such as *Ips* and ambrosia beetles with the capability to exploit the increased potential habitat of dead and dying trees following a mass attack.

Insects captured in this study were similar to insects captured in Lindgren funnel traps during other trapping surveys in the southeastern United States. In prior studies, native species predominated among bark beetle collections whereas many of the ambrosia beetles encountered were non-native (Oliver and Mannon, 2001). This was true in this study as well (Table 2.1). While the most commonly observed bark beetles were native, several invasive ambrosia beetle species were prominent. In other studies conducted in different areas of the southeastern United States, *X. saxesenii* and *X. crassiusculus* were the most common ambrosia beetles rather than the native *G. materiarius* (Miller and Rebaglia, 2009). At three hardwood stands in Tennessee invasive *X. saxesenii* was the most abundant species (nearly half of all insects observed) with *X. crassiusculus*, *M. fasciatum*, *M. mali*, *X. atratus*, *Xyleborus pelliculosus* Eichoff and *Ambrosiodus tachygraphus* Zimmerman the other species with greater than 100 total individuals collected (Oliver and Mannion, 2001). The biggest difference between the findings of this study and previous studies of ambrosia beetles was that this project captured a disproportionately high number of *G. materiarius*.

Although insect collection totals were generally lower from November through February, insects were captured throughout the year. Many *G. materiarius* were captured in winter trapping that which detected population peaks during months not surveyed by earlier work. Extending the length of the trapping season appears to show that several species, including some that carry fungi associated with loblolly pine decline (Eckhardt et al., 2007) have been previously undercounted. This finding affirms results from earlier studies by Zanzot et al. (2010) who observed September peaks of several species, most frequently *H. tenuis* and *H. pales*, that supplemented more commonly detected spring peaks.

Survey accuracy is also influenced by how effectively traps capture target insect species. As in earlier studies, aerial traps captured the broadest diversity of insects. Window, panel intercept and funnel traps are typically used in general population surveys and studies aimed at invasive species. Pitfall traps are considered a supplemental tool in general insect surveys (Hyvarinen et al., 2006) but have been the primary trap used in surveys of root feeding beetles. A relatively high proportion of *P. picivorus* and *H. pales* in this study were collected in pitfall traps, apprearing to confirm the attraction of these weevil species to roots given the greater effort required for these relatively large species to enter the smaller entrances of the pitfall traps. *Pachylobius picivorus* was four times more frequently collected in pitfall traps than at flight intercept traps in Wisconsin but in Louisiana *P. picivorus* was collected twice as often in flight intercept traps than pitfall traps (Erbilgin et al., 2001). This variation appears to validate the use of multiple traps. Collections from Wisconsin pine plantations and the Kisatchie National Forest in Louisiana reported many species captured in this study. While different traps were more effective in different regions, many of the same insect species were captured as at the Oakmulgee Ranger District (Erbiligin et al., 2001). Previous studies that have trapped bark beetles through pitfall trapping have also captured large proportions of *Hylastes* and weevil species (Zanzot, et al., 2010). The appropriateness of different traps types appears to be a function of the range and habitat of target species.

Biomass removal of woody debris may become more common given environmental and social pressures for the development of alternative fuels. This treatment, essentially a thin from below that removes smaller diameter vegetation, may also be used for some wildlife management. Under a biomass removal regime, trees selected for fuel harvest would be completely removed from the plot. The effects of this treatment have not been tested on bark and ambrosia beetle populations and it is uncertain whether biomass removal would either increase or decrease insect numbers. While a temporary increase in release of attractant chemicals could draw bark beetles to the experimental plots the removal of potential habitat could reduce long term bark and ambrosia beetle populations. Also, following the treatments, trees would be released from competition with each other and expected to be more insect resistant. Effects of biomass removal may vary by insect type. Ambrosia beetles largely rely on declining and dead trees for habitat and their numbers would be expected to decline. Root dwelling beetles and insects would still have some habitat when roots are still around but many of those species are usually found on living hosts (Wood and Bright, 1992). Finally, *T. dubius* and *T. virescens* feed largely on these bark and ambrosia beeltes and their population numbers could be expected to mirror those of their prey.

CONCLUSION

The large numbers of *Hylastes* species collected at the plots indicate that they may play a more important role in forest health than previously believed. Slope and aspect differences between adjacent plots impacted insect population numbers. Crown condition was the most positive indicator of insect collection totals, as stands with more dense and less transparent tree crowns were associated with fewer insect numbers. Many bark beetle species were positively correlated with both poor crown condition and each other. If these correlations consistently hold, the populations of many bark and ambrosia beetles are likely to increase during southern pine beetle outbreaks.

A wider spectrum of insects was captured by collecting all year with a variety of traps. Panel intercept traps appeared to successfully capture a wide range of species, including those such as in the genus *Hylastes*, that are generally associated with roots. Deployment of the traps year round resulted in rarely observed peaks of some species (such as *G. materiarius*). Wider employment of year round trapping could provide for a more accurate idea of insect population and species richness.

The findings from the studies provided confirmation of the decline model at the Oakmulgee Ranger district. That a greater total of root and lower bole feeding beetles were captured at the stands considered to be in decline provides additional evidence that these species are involved in the loblolly pine decline complex. Previous thinning appeared to reduce the presence of some insect species, perhaps indicating that long-term resistance of trees within thinned stands has been enhanced. Subsequent biomass removal performed at the plots will test how bark and ambrosia beetle populations respond to these experimental treatments.

Figure 1. (a) Intercept panel trap and (b) flight intercept trap deployed on plots at the Oakmulgee Ranger District, Talladega National Forest

Table 1. Total bark, ambrosia and predator beetles trapped over two years (March 2008-February 2010).

Species	**Habitat role**	**Total capture**
Hylastes salebrosus	Bark beetle	23,030
Gnathotricus materiarius	Ambrosia beetle	21,283
Ips grandicollis	Bark beetle	8,004
Hylastes porculus	Bark beetle	4,612
Hylastes tenuis	Bark beetle	3,927
Xyleborinus saxesenii	Ambrosia beetle	3,748
Temnoscheila virescens	Predator beetle	3,720
Thanasimus dubius	Predator beetle	2,848
Xylosandrus crassiusculus	Ambrosia beetle	2,242
Hylobius pales	Weevil	2,044
Pachylobius picivorus	Weevil	2,027
Dendroctonus terebrans	Bark beetle	1,994
Xylosandrus mutilatus	Ambrosia beetle	1,989
Playpus flavicornis	Ambrosia beetle	1,616
Xyleborus atratus	Ambrosia beetle	896
Orthotomicus caelatus	Bark beetle	676
Pissodes nemorensis	Weevil	248
Monarthrum faciatum	Ambrosia beetle	135
Hylastes opacus	Bark beetle	125
Xylosandrus compactus	Ambrosia beetle	111
Ips avulsus	Bark beetle	99
Xylosandrus germanus	Ambrosia beetle	51
Ips callugraphus	Bark beetle	25
Dendroctonus frontalis	Bark beetle	23

Table 2. Significant Pearson correlation results between bark and ambrosia beetles species (α=0.05)

Species	Correlated species	R-sq.	P-value
H. salebrosus	*P. picivorus*	0.4592	0.0240
H. salebrosus	*D. terebrans*	0.6464	0.0006
H. salebrosus	*I. grandicollis*	0.6542	0.0005
H. salebrosus	*X. crassiusculus*	0.4949	0.0140
H. salebrosus	*T. dubius*	-0.5770	0.0032
P. picivorus	*D. terebrans*	0.5882	0.0025
H. tenuis	*X. crassiusculus*	0.4200	0.0410
D. terebrans	*I. grandicollis*	0.4806	0.0174
X. saxesenii	*G. materiarius*	0.4168	0.0427
X. saxesenii	*T. dubius*	0.4167	0.0428
X. crassiusculus	*T. dubius*	-0.5113	0.0107

Table 3. Multivariate analysis regression results for comparisons between bark and ambrosia beetles and forest health measurements. (α= 0.05).

Insect species	Forest health variable	Partial R-square	P-value
Hylastes salebrosus	Mean crown transparency	0.3465	0.0025
Hylastes salebrosus	Resin	0.0668	0.0336
Hylastes tenuis	Mean crown density	0.2398	0.0152
Pachylobius picivorus	Mean crown transparency	0.2820	0.0076
Pachylobius picivorus	Mean crown transparency	0.2585	0.0025
Dendroctonus terebrans	Mean crown transparency	0.2471	0.0135
Ips grandicollis	Mean crown transparency	0.1808	0.0384
Gnathotrichus materiarius	Mean crown transparency	0.3023	0.0054
Gnathotrichus materiarius	Mean crown density	0.2731	0.0014
Gnathotrichus materiarius	DBH	0.1031	0.0198
Xylosandrus crassiusculus	Mean crown density	0.2459	0.0137
Xyleborinus saxesenii	DBH	0.5102	0.001
Xyleborinus saxesenii	Mean crown transparency	0.1205	0.0161
Xyleborinus saxesenii	10-year growth	0.0690	0.0330
Temnoschila virescens	Mean crown density	0.1528	0.0341

Table 4. Comparison of mean bark beetle collections per plot at thinned predicted decline plots, unthinned predicted decline plots and unthinned predicted non-decline plots. Different letters within a row represent significant differences (α= 0.05).

Species	Thinned decline (n=8)	Unthinned declined (n=10)	Unthinned non-decline (n=6)
Hylastes salebrosus	737	1181	815
Ips grandicollis	307	339	339
Hylastes tenuis	146 ab	186 a	131 b
Hylastes porculus	127	175	131
Dendroctonus terebrans	59	109	68
Pachylobius picivorus	40 ab	122 a	79 b
Hylobius pales	70	91	88
Pissodes nemorensis	10	12	10

Table 5. Comparison of mean ambrosia and predator beetle collections per plot at thinned predicted decline plots, unthinned predicted decline plots and unthinned predicted non-decline plots. Different letters within a row represent significant differences (α= 0.05).

Species	Thinned decline (n=8)	Unthinned declined (n=10)	Unthinned non-decline (n=6)
Gnathotrichus materiarius	877	836	630
Xylosandrus crassiusculus	70 b	135 a	54 b
Xyleborinus saxesenii	172 a	172 ab	104 b
Xylosandrus mutilatus	111 a	62 b	80 b
Monarthrum mali	14	22	13
Monarthrum fasciatum	4	6	8
Platypus flavicornis	49 b	95 a	45 b
Thanasimus dubius	130	100	128
Temnochila virescens	180	155	121

Table 6. Mean insect collection totals per plot within eight highest, median and lowest resin collection plots. Different letters within a row represent significant differences (α= 0.05) within a species.

Species	High (2.64 – 4.79g) (std error = 0.76)	Median (2.01 – 2.58g) (std error = 0.73)	Lowest (1.19 – 1.99g) (std error = 0.58)
H. salebrosus	22 a	20 a	16 a
H. tenuis	3 a	4 a	3 a
H. porculus	4 a	4 a	4 a
P. picivorus	2 a	2 a	1 a
H. pales	1 b	2 b	2 a
D. terebrans	1 ab	2 a	1 b
I. grandicollis	7 a	7 a	6 a
G. materiarius	13 b	20 a	19 a
X. crassiusculus	2 a	2 a	1 b
X. saxesenii	3 a	3 a	3 a
T. dubius	2 a	3 a	2 a
T. virescens	3 a	4 a	2 b

Table 7. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to five-year radial growth increment (mm). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (37-51)** (std error = 0.52)	**Median (33-37)** (std error = 0.15)	**Lowest (27-33)** (std error = 0.28)
H. salebrosus	19 a	20 a	18 a
H. tenuis	3 a	4 a	3 a
H. porculus	4 a	4 a	4 a
P. picivorus	2 a	2 a	2 a
H. pales	2 a	2 a	2 a
D. terebrans	1 a	2 a	1 a
I. grandicollis	6 b	7 ab	8 a
G. materiarius	21 a	16 b	15 b
X. crassiusculus	1 b	2 ab	3 a
X. saxesenii	4 a	3 b	3 b
T. dubius	2 a	3 a	2 a
T. virescens	2 b	3 a	4 a

Table 8. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to ten-year growth increment (mm). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (65-82)** (std error = 0.18)	**Median (60-64)** (std error = 0.47)	**Lowest (48-59)** (std error = 0.52)
H. salebrosus	21 a	18 a	18 a
H. tenuis	3 a	3 a	3 a
H. porculus	4 a	4 a	4 a
P. picivorus	2 a	2 a	2 a
H. pales	2 a	2 a	2 a
D. terebrans	2 a	2 a	1 a
I. grandicollis	7 a	6 a	7 a
G. materiarius	21 a	18 ab	14 b
X. crassiusculus	2 ab	2 b	2 a
X. saxesenii	4 a	3 b	3 b
T. dubius	2 a	3 a	2 a
T. virescens	3 a	3 a	3 a

Table 9. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to stem count (stems/acre). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (48-59)** (std error = 1.94)	**Median (36-46)** (std error = 0.93)	**Lowest (12-34)** (std error = 4.79)
H. salebrosus	21 a	17 a	20 a
H. tenuis	3 a	3 a	3 a
H. porculus	4 a	4 a	4 a
P. picivorus	2 a	1 b	2 ab
H. pales	2 a	2 a	2 a
D. terebrans	2 a	1 b	1 ab
I. grandicollis	7 ab	5 b	8 a
G. materiarius	18 a	18 a	17 a
X. crassiusculus	2 a	2 ab	2 b
X. saxesenii	3 a	4 a	3 a
T. dubius	2 a	2 a	2 a
T. virescens	3 a	3 a	3 a

Table 10. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to pine basal area (sq. ft./acre). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (120-170)** (std error = 2.00)	**Median (90-110)** (std error = 0.95)	**Lowest (30-90)** (std error = 2.18)
H. salebrosus	15 b	22 a	20 ab
H. tenuis	4 a	4 a	3 b
H. porculus	4 a	4 a	4 a
P. picivorus	1 b	2 a	2 ab
H. pales	2 a	2 a	2 a
D. terebrans	1 b	2 a	2 ab
I. grandicollis	6 a	6 a	8 a
G. materiarius	15 a	18 ab	19 a
X. crassiusculus	2 b	3 a	1 b
X. saxesenii	3 a	4 a	3 a
T. dubius	3 a	2 a	2 a
T. virescens	3 a	3 a	3 a

Table 11. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to hardwood basal area (sq. ft./acre). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (30-60)** (std error = 1.28)	**Median (0-20)** (std error = 0.73)	**Lowest (0-0)** (std error = 0.0)
H. salebrosus	16 b	16 b	25 a
H. tenuis	3 ab	3 b	4 a
H. porculus	3 a	5 a	4 a
P. picivorus	1 b	2 b	3 a
H. pales	1 a	2 a	2 a
D. terebrans	1 b	1 b	3 a
I. grandicollis	7 ab	6 b	8 a
G. materiarius	15 b	17 ab	20 a
X. crassiusculus	2 ab	1 b	2 a
X. saxesenii	3 a	4 a	3 a
T. dubius	2 a	3 a	2 a
T. virescens	4 a	2 b	3 ab

Table 12. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to mean diameter at breast height (in). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (9-11)** (std error = 0.28)	**Median (8-9)** (std error = 0.15)	**Lowest (7-8)** (std error = 0.09)
H. salebrosus	19 a	20 a	19 a
H. tenuis	3 a	3 a	3 a
H. porculus	4 a	4 a	3 a
P. picivorus	2 a	2 a	2 a
H. pales	2 a	2 a	2 a
D. terebrans	1 a	2 a	2 ab
I. grandicollis	6 b	6 b	8 a
G. materiarius	20 a	17 ab	15 b
X. crassiusculus	2 a	2 a	2 a
X. saxesenii	4 a	2 b	3 b
T. dubius	2 a	3 a	2 a
T. virescens	2 b	4 a	3 a

Table 13. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to mean live crown ratio (percent). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (35-47)** (std error = 0.58)	**Median (30-34)** (std error = 0.58)	**Lowest (25-29)** (std error = 0.58)
H. salebrosus	19 ab	14 b	24 a
H. tenuis	3 b	3 a	4 a
H. porculus	4 a	3 a	4 a
P. picivorus	1 b	1 b	2 a
H. pales	1 a	2 a	2 a
D. terebrans	2 a	1 a	2 a
I. grandicollis	8 a	5 b	7 a
G. materiarius	16 a	18 a	18 a
X. crassiusculus	1 b	2 b	3 a
X. saxesenii	3 a	3 a	3 a
T. dubius	2 a	3 a	2 a
T. virescens	4 a	3 b	3 ab

Table 14. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to mean live crown density (percent). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (37-43)** (std error = 0.67)	**Median (33-37)** (std error = 0.44)	**Lowest (29-33)** (std error = 0.49)
H. salebrosus	18 a	21 a	18 a
H. tenuis	3 b	4 a	3 a
H. porculus	4 a	4 a	3 a
P. picivorus	1 b	2 ab	2 a
H. pales	2 a	2 a	2 a
D. terebrans	1 a	2 a	2 a
I. grandicollis	7 a	7 a	6 a
G. materiarius	17 b	21 a	15 b
X. crassiusculus	1 b	2 a	2 a
X. saxesenii	3 b	4 a	3 b
T. dubius	3 a	2 a	3 a
T. virescens	3 a	3 a	3 a

Table 15. Mean insect collection totals per plot within eight highest, median and lowest plots with regard to mean live crown transparency (percent). Different letters within a row represent significant differences (α= 0.05) within a species.

Species	**High (35-38)** (std error = 0.29)	**Median (33-35)** (std error = 0.27)	**Lowest (30-33)** (std error = 0.37)
H. salebrosus	23 a	20 a	14 b
H. tenuis	4 a	3 a	3 a
H. porculus	4 a	4 a	4 a
P. picivorus	2 a	1 b	1 b
H. pales	2 a	1 a	2 a
D. terebrans	3 a	1 b	1 b
I. grandicollis	8 a	7 ab	5 b
G. materiarius	23 a	15 b	14 b
X. crassiusculus	2 a	2 ab	1 b
X. saxesenii	3 a	3 a	3 a
T. dubius	2 a	2 a	3 a
T. virescens	4 a	3 a	3 a

Table 16. Differences in pooled insect collection totals between plots in stands suffering from loblolly pine decline (n=18) and plots outside of decline area (n=6). "Predicted loblolly pine decline (LPD)" and "predicted non-loblolly pine decline (non-LPD)" refer to mean insect collection per plot per collection. (α= 0.05).

	Predicted LPD	**Predicted non-LPD**	**F-value**	**P-value**
Hylastes salebrosus	17	20	2.15	0.1432
Hylastes tenuis	3	3	7.61	0.0059
Hylastes porculus	4	4	0.01	0.9386
Pachylobius picivorus	2	2	0.33	0.5659
Hylobius pales	2	2	0.41	0.5198
Dendroctonus terebrans	1	2	1.08	0.2998
Ips grandicollis	7	7	0.05	0.8260
Gnathotrichus materiarius	15	18	4.82	0.0283
Xylosandrus crassiusculus	1	2	11.73	0.0006
Xyleborinus saxesenii	2	3	10.29	0.0014
Thanasimus dubius	3	2	0.26	0.6090
Temnoscheila virescens	2	3	4.41	0.0359