Effects of prescribed fire and subcortical beetles on southern pines in Georgia

by

Jordan Lewis Burke

(Under the direction of Kamal J.K. Gandhi)

Abstract

My research objectives were as follows: 1) to evaluate efficacy of two insecticides for excluding subcortical beetles from pine trees (*Pinus* spp.), and of two trap heights (1.5 and 4 m) and designs (single- or double-pane window traps) in maximizing trap catches; and 2) to assess the effects of prescribed burning on subcortical beetles and mortality of pines. Carbaryl and bifenthrin were equally effective in excluding beetles. Bark beetles caught at two heights reflect known vertical partitioning on trees. Catches of single- and double-pane window traps were similar. Effects of fire on tree mortality with beetle exclusion could not be determined. Trees subjected to fires in 2009-2010 and girdled in 2011 indicated that beetle catches were lower and species composition different for trees burned in 2011. Stands burned in 2010 and 2011, respectively, had higher volume of logs and basal area of snags; trends did not correlate with beetle attributes.

Index words: Cerambycidae, loblolly pine, longleaf pine, Scolytinae, Prescribed burning

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B.S., University of Georgia, 2009

A Thesis Submitted to the Graduate Faculty
of The University of Georgia in Partial Fulfillment
of the
Requirements for the Degree

Master of Science

Athens, Georgia

2011

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December 2011

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December 9, 2011

Acknowledgments

I thank Jackson Audley, Brittany Barnes, Courtney Brissey, Kayla Brownell, Jamie Dinkins, Angela Mech, Sean Meadows, Lee Ogden, Dale Porterfield, and Jenny Staeben from the Forest Entomology Laboratory at the Warnell School of Forestry and Natural Resources, The University of Georgia for assistance in the laboratory and in the field. Scott Horn and Mike Cody from the USDA Forest Service, Southern Research Station, and Michael Clarke and Robert ”Scrubby” Rogers from the Fort Stewart Environmental Division, Forestry, provided critical assistance and equipment in the field. Dan Miller from the USDA Forest Service, Southern Research Station provided laboratory equipment, and Mike Hunter of the Warnell School of Forestry and Natural Resources permitted use of the Whitehall Experimental Forest. I also thank my parents, April Burke and Garrett Burke, for supporting me through the program. Funding for the project was provided by the Warnell School of Forestry and Natural Resources, The University of Georgia, McIntire-Stennis funds, and the USDA Forest Service Southern Research Station SRS-4522.

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Chapter 1

Introduction and Literature Review

1.1 Forests in the Southern United States

Forestry in the Southeastern United States is a major part of the regional and global economy. The southeastern region produces 58% of the timber in the United States, and about 16% of the world production (Wear and Greis, 2002). Currently, about 86 million ha of the southeastern United States is forested and contains 81 million ha of commercial timberland of which 89% is privately owned. Among the southeastern states, Georgia has the largest area of forest cover, with about 10 million ha, or 67% of the state. Loblolly (*Pinus taeda* L.), longleaf (*P. palustris* Mill.), shortleaf (*P. echinata* Mill.), and slash (*P. elliottii* Engelm.) pines cover 45% of the total forested area, of which about 60% is planted. The remaining forests are in the oak (*Quercus* spp.)-pine, oak-hickory (*Carya* spp.), and bottomland hardwood cover types (USDA Forest Service, 2004). These forests are also important ecologically as they contain the highest diversity of plant species in North America, along with thousands of indigenous amphibian, reptile, mammal, and bird species (World Resources Institute, 2010). Southeastern pine forests provide critical ecosystem services, and therefore, maintaining their sustainability and integrity is vital for the local economy of the region.

Since the European settlement of North America, southeastern forests have been disturbed through exploitative harvest, soil erosion, urbanization, fragmentation, and outbreaks of native and exotic pests and pathogens (Sharitz and Lee, 1990). The major change in the southeastern forests has been the drastic turnover of the dominant canopy pine species. Much of the forest in the southeastern United States, especially the Gulf Coast Region, was historically dominated by longleaf pine. Due to over-harvesting and deliberate replacement, most of the original longleaf forest has been replaced with loblolly and slash pine, which has resulted in a shift in understory plant species from diverse grassland to hardwood trees and shrubs. Additionally, animal species such as the red-cockaded woodpecker (*Picoides borealis* Vieillot) and the gopher tortoise (*Gopherus polyphemus* Daudin) which rely on these open longleaf/grass stands have since been added to the endangered species list (Outcalt, 2000). These forests are hypothesized to be impacted by global climatic shifts that will alter biotic communities unique to the region (Williams et al., 2007; USDA Forest Service, 2011).

In addition to the change in dominant overstory pine species, prescribed burning and harvesting have replaced wildfires as the major abiotic disturbance in the Southeast. Most pine species in the region are fire adapted, meaning that they can tolerate periodic low intensity fires in the understory that eliminate competition from hardwoods and in some cases initiate reproduction in serotinous species (Burns, 1983). Longleaf pines require fire to transition from the early-growth grass stage, in which growth is focused primarily focused on root system development to establish roots, and the seedling stage when aboveground biomass is added (Outcalt, 2000). In addition to natural fires, intentional burning was used in the southeastern pine systems by the indigenous people for $>$ 12,000 years to clear agricultural lands and keep the pine savannas open for wildlife (Carroll et al., 2002). This open and diverse understory was replaced by hardwood tree saplings and other shrubs as Europeans began suppressing natural fires (Van Lear et al., 2005). High intensity wildfires increased in frequency because the elimination of low intensity fires permitted fuel loads to accumulate over time (Stephens and Ruth, 2005).

1.2 Ecology of Subcortical Beetles

Subcortical beetles (Coleoptera: Curculionidae; Cerambycidae; Buprestidae) are major disturbance agents in forests around the world, contributing to tree decline and mortality (Dale et al., 2001; Logan et al., 2003). The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is the most destructive pest of western forests where it kills up to 50,000 ha per year of lodgepole pine (*P. contorta* Douglas) in British Colombia, Canada alone (Furniss et al., 1978; Unger and Wood, 1996). In the southern United States, the southern pine beetle (*D. frontalis* Zimmermann) caused over $254 million in timber losses from 1972 to 2007 in just the state of Georgia (Georgia Forestry Commission, 2007). Primary subcortical beetles are first to colonize conifer trees, and directly contribute to mortality through the destruction of tissues that transport water and nutrients. This process is accelerated when they attack trees in large numbers and overcome tree defenses. Secondary subcortical beetle species often require a tree in a weakened state, usually caused by biotic and abiotic factors including fungal infections, drought, flooding, fire damage, or mechanical wounding (Franklin et al., 1987), to successfully colonize a tree and reproduce (Connor and Wilkinson, 1983). Most primary subcortical bark beetle species are in the genus *Dendroctonus*, whereas secondary bark beetles are more diverse and include a few *Dendroctonus* spp. as well as *Ips* spp. and woodboring beetles in the Coleoptera families Cerambycidae and Buprestidae. In addition to being economically important, subcortical beetles are also ecologically important, as they aid in the breakdown of dead wood and thus cycling of nutrients in ecosystems. As a group, subcortical beetles are an integral part of forested ecosystems, and contribute significantly to forest successional patterns and ecological processes.

Georgia contains a complex of common pine bark beetles that coexist in stands, but have evolved to avoid competing with each other in a number of ways, most notably through vertical spatial partitioning on the boles of pines. These species include southern pine beetle, black turpentine beetle [*D. terebrans* (Olivier)], and the pine engraver beetles [*Ips avulsus* (Eichoff), *I. grandicollis* (Eichoff), and *I. calligraphus* (Germar)]. The two species of *Dendroctonus* can be distinguished by their size, with the black turpentine beetle being about 2-3 times as large at ∼6 mm, and found almost exclusively in the lower bole and base of trees (Wood, 1982). Southern pine beetle is usually found in the middle to upper part of the stem. The *Ips* species can also be distinguished by size, with *I. avulsus* averaging ∼2.5 mm in length, *I. grandicollis* averaging ∼3.5 mm, and *I. calligraphus* at ∼5 mm (Wood, 1982). The *Ips* species can also be distinguished by the number of spines on the declivity of the elytra, and general preferred location of colonization; *I. avulsus* has 4 spines and is found in the upper bole and branches, *I. grandicollis* has 5 spines is found mostly in the upper bole, and *I. calligraphus* has 6 spines and is found in the middle of the stem (Connor and Wilkinson, 1983). All of these species oviposit and feed in the phleom layer, and all create egg and larval galleries with the exception of black turpentine beetle, whose larvae feed in large contiguous feeding chambers as opposed to distinct galleries (Staeben et al., 2010).

Most if not all primary and secondary species of bark beetles are also associated with one or more species of fungi that coexist in a variety of symbiotic relationships (Hofstetter et al., 2006). These fungi can be carried in specialized structures called mycangia, or on the cuticle, and are inoculated into the tree when the insects bore into the stem, branches, or roots (Paine et al., 1997). These fungi are most often members of a group called blue-stain fungi (genus *Ophiostoma*), and they infect the woody tissue of trees and disrupt water and nutrient flux in the stem and assist the beetles in overcoming constitutive and induced tree defenses (Coulson and Witter, 1984). Beetles in the genus *Dendroctonus* especially have a wide variety of relationships with fungi. For example, some fungi are mutualists carried in mycangia, while other fungi are antagonistic carried phoretically on the cuticle and inhibit larval development [reviewed in Six and Klepzig (2004)]. The fungus *O. minus* (Hedgecock) interacts with the southern pine beetle in multiple ways; the fungus is mutualistic with attacking adults as it seems to aid in overcoming tree defenses (Paine et al., 1997), but inhibits larval development after the eggs hatch (Hofstetter et al., 2006). Fungal associates of *I. grandicollis* [*O. minus* and *O. ips* (Rumbold)] may influence parasitoid host-seeking behavior, although the bark beetle host must be present along with the fungus (Sullivan and Berisford, 2004).

1.3 Interactions Between Fire and Subcortical Beetles

Interactions between subcortical beetles and pine trees subjected to low- or high-intensity prescribed burning are complex and unclear at the present time. Prescribed burning has been historically used to reduce fuel-loads and eliminate habitat for subcortical beetles in many ecosystems in the United States. For example, after a 1999 windthrow event in the Superior National Forest in Minnesota, prescribed burning along with salvage-logging was used to reduce the threat of bark beetle outbreaks in the downed material (Gandhi, 2005; Gandhi et al., 2008). The number of bark beetles actually increased in the prescribed burned areas for one year after the burn, but was reduced 3-4 years thereafter.

There is also some indication that *Ips* spp. prefer feeding on tissues that have been damaged by fires (Lombardero et al., 2006), but subcortical beetles are not always attracted to burned stands. Amman and Ryan (1991) found that a large number of dead trees after a wildfire did not have evidence of any insect attack, suggesting that these trees were killed directly by fire. Belowground tissue damage (often measured by the level of fungal root pathogen infection) may be a better predictor of eventual mortality in pines than fire damage alone (Geiszler et al., 1984; Hanula et al., 2002). Hanula et al. (2002) found that the best predictor of tree mortality after a wildfire was the level of root damage in Florida.

Once the trees have been weakened by these fungi, insects such as *Ips* spp. may detect the decline (mostly through volatizing monoterpenes) and colonize the trees. Since bark beetles are attracted to damaged and weakened trees, they are almost always present in areas where fire damage and subsequent mortality has occurred. This may lead to a misleading conclusion that bark beetles may be killing pine trees subjected to prescribed burning, since fire-mediated tissue damage and belowground fungal infection are often conspicuous. Likewise, the association of certain fungi with fire damaged roots may also lead to a misleading conclusion about their role in the mortality of trees.

1.4 Research Objectives of the Thesis

The focus of my research was to determine whether prescribed-fire could kill pine trees in the absence of stem-colonizing subcortical insects. Despite the vast amount of research on fire ecology in pine ecosystems, it is unclear whether fire or bark beetles are the primary killing agents when trees die following a prescribed burn. Foresters and managers often find evidence of insect attack, superficially suggesting that subcortical insects are colonizing and killing the trees. But underlying effects from fire-damage, drought, and unseen biotic agents (such as root pathogens) may also play a role in the decline and death of these trees.

The research objective of Chapter 2 was to compare the efficacy of two insecticides (carbaryl and bifenthrin) for preventing attacks by subcortical beetles on pine trees in Georgia. Both products have been tested in other forest ecosystems in the western United States, but I needed to be sure that the product I selected would protect whole trees from even light infestations for extended periods of time in the subsequent experiments to avoid confounding the results. In addition, I also tested two trap designs (single- and double-pane intercept traps) at two heights (0.5 and 4 m) to determine which trap-type combination would be most efficient for trapping beetles in subsequent studies. Traps also measured the colonization pressure on trees, and allowed me to ensure that treated trees were being visited by large numbers of subcortical beetles.

I had two major research objectives in Chapter 3. The first objective was to exclude beetles from the boles of trees that had experienced high intensity fires, and to compare their mortality to similarly burned trees that were not protected from insect attack [Prescribed Fire Beetle Exclusion (PFBE) Experiment], to determine the importance of insects in fire-mediated mortality. I assessed differences in the amount of resin produced after mechanical wounding between trees that were burned and unburned. The second objective of this chapter was to determine the effects of fire on the communities and populations of subcortical insects [Prescribed Fire Comparison (PFC) Experiment]. For this purpose, I girdled loblolly and longleaf pine trees in forest stands that had been burned in 2011 (current year), 2010, or 2009 (one and two years since burn). Loblolly pine has been planted extensively in southern Georgia for commercial production, but this area was originally dominated by longleaf pine. Due to increasing emphasis on longleaf pine restoration by foresters, I wanted to determine what effects overstory canopy replacement would have on pine-feeding beetles. I monitored beetle arrival at those pine trees using double-pane intercept traps and determined beetle abundance, and species diversity and composition. Also, I assessed the differences in amount of coarse-woody debris in FIA decay class 1 and 2 (USDA Forest Service, 2005) between stands that did or did not experience burning to provide mechanistic reasons for observed trends in subcortical beetle attributes.

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Chapter 2

Efficacy of Two Insecticides for Protecting Loblolly Pines *(Pinus taeda)* from Subcortical Beetles (Coleoptera: Curculionidae and Cerambycidae)[1]

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[1] J L Burke, Hanula J L, Horn S, Audley J P, and Gandhi K J K. submitted to *Pest Management Science* 12-Sept-2011

Abstract

We tested two insecticides (carbaryl and bifenthrin) for excluding subcortical beetles (Coleoptera: Curculionidae and Cerambycidae) from loblolly pine trees (*Pinus taeda* L.). Two trap designs (single- and double-pane window) and two trapping heights (1.5 and 4 m) were also evaluated. Fifteen loblolly pine trees were left unsprayed, or sprayed with carbaryl or bifenthrin. We caught 28,473 bark beetles in window traps, including *Ips avulsus* Eichoff, *I. grandicollis* (Eichhoff), *I. calligraphus* (Germar), and *Dendroctonus terebrans* (Olivier). Both insecticides significantly reduced colonization of the trees by bark beetles and woodboring beetles by 300-400%, with no differences in efficacy observed for the two insecticides. About 59% more *I. avulsus* were caught in double- than single-pane window traps, with no differences for any other species. Traps at 4 m caught more *I. avulsus* and *I. grandicollis* (290% and 153% respectively), while traps at 1.5 m caught more *D. terebrans* (215%).

Keywords: bark beetles, bifenthrin, carbaryl, loblolly pine, woodboring beetles

2.1 Introduction

Bark (Coleoptera: Curculionidae: Scolytinae) and woodboring beetles (Coleoptera: Cerambycidae) are a diverse and abundant group of subcortical insects that are ecologically and economically important in the southern United States (Wood, 1982; Lingafelter, 2007). They assist in decomposition and nutrient cycling of dead wood in forests, but they may also cause large-scale tree decline and mortality. For example, the Georgia Forestry Commission has calculated a total of $254,295,101 in timber losses from 1972 to 2007 in Georgia from the southern pine beetle (*Dendroctonus frontalis* Zimmerman) alone (Georgia Forestry Commission, 2007). The larvae of bark beetles feed primarily in the phloem tissue, whereas those of woodboring beetles feed on phloem and xylem tissues (Linsley, 1959). Feeding and construction of galleries by larvae and adults girdles the tree, thus disrupting photosynthate transfer and resulting in the eventual decline and death of the tree (Dunn and Lorio, 1992).

Forests in residential and recreational areas are important in providing environmental, aesthetic, and economic values. Coincidentally, trees located in urban and semi-urban sites are often susceptible to subcortical beetle attack due to stressful conditions associated with localized drought, overwatering, soil compaction, air pollution, and mechanical injury to either stems or roots (Haverty et al., 1998; Poland and McCullough, 2006). Although bark beetles such as pine engravers (*Ips* spp.) and black turpentine beetle [*Dendroctonus terebrans* (Olivier)] usually do not colonize healthy, uninjured trees, they do colonize and kill pine trees in urban areas where they can build up in slash, weakened, damaged, and drought-stressed trees (Connor and Wilkinson, 1983; Gandhi and Miller, 2009). Three major species of *Ips* are abundant in the southern pine forests, including *I. avulsus* Eichoff, *I. grandicollis* (Eichhoff), and *I. calligraphus* (Germar), that can attack apparently healthy high-value trees, and create a public safety hazard in urban areas (USDA Forest Service, 2005; Gandhi and Miller, 2009). The high cost of removing these trees and the aesthetic impacts on the property often makes protection of trees with insecticides an economically viable option (Fettig et al., 2006b).

A number of studies have tested the efficacy of carbaryl and bifenthrin in the protection of different species of pines trees from various bark beetle species (Hall et al., 1982; Haverty et al., 1985; Hastings et al., 2001; Fettig et al., 2006a). Most tests on the efficacy of carbaryl and bifenthrin in the southeastern and western United States have been conducted on members of the genus *Dendroctonus* that are considered major outbreak pests capable of killing live healthy trees. For example, Berisford et al. (1981) found that carbaryl was not effective on southern pine beetle, *D. frontalis* Zimmerman, likely due to metabolic processes that differ from most other bark beetles. Fettig et al. (2006a) tested carbaryl and bifenthrin on multiple insect and tree species combinations, and found both to be effective in the prevention of attacks by western pine beetle (*D. brevicomis* LeConte). Grosman and Upton (2006) and Grosman et al. (2009) tested the efficacy of systemic insecticides for the protection of loblolly pines (*Pinus taeda* L.) from *Ips* spp., cerambycids, and *D. frontalis* in the southern United States, and found that fipronil and emamectin benzoate were effective at varying levels in preventing mortality from subcortical insects. Similarly, Grosman et al. (2010) reported that systemic insecticides can protect ponderosa pines (*P. ponderosa* Dougl. ex Laws.) for up to three years from *D. brevicomis* in California, United States. However, systemic insecticides are expensive, bole injection can cause wounding on trees, and there is a lag period between treatment and effective control leaving trees vulnerable for a short time after application (Grosman and Upton, 2006).

Information is lacking on the use of non-systemic insecticides to prevent attacks by *Ips* and cerambycid beetles on mature loblolly pine trees in the southeast United States. Further, fewer tests exist for standing trees, as opposed to cut bolts (Strom and Roton, 2009). Our research objectives were: 1) to compare the relative efficacy of two sprayable insecticides with differing modes of action, carbaryl (acetylcholinesterase inhibitor) and bifenthrin (sodium channel disruption), in preventing colonization by subcortical beetles on loblolly pines; 2) to compare the efficacy of single- versus double-pane window trap designs for capturing subcortical beetles arriving at trees; and 3) to compare the efficacy of these two trap designs at two different heights on tree boles.

2.2 Methods and Materials

2.2.1 Study Sites

The study was conducted near Athens, Georgia, United States (N 33°53′18” W 83°22′21”) within the Piedmont region of the state. The study site was a 15 year old loblolly pine plantation with sweetgum (*Liquidambar styraciflua* L.), muscadine (*Vitis rotundifolia* Michx.), *Lespedeza* spp., and various species of grasses in the understory. The trees were growing in Madison clay sandy loam soil, and the mean annual precipitation in the region was ∼1124 mm (The University of Georgia, 2011). Stands in the study area were on a three-year prescribed burn cycle, with the last burn in our study site applied in early spring of 2009.

2.2.2 Tree Selection, Preparation, and Monitoring

Fifteen mid-rotation loblolly pines were randomly chosen that were similar in size (DBH = 29.4 ± 0.9 cm) and age (15 years). Trees were spaced > 15 m from each other to reduce the potential for drift contamination of nearby trees (Fettig et al., 2008). Three treatments randomly assigned to each of five pine trees were as follows: 1) unsprayed control; 2) 2.0% cabaryl [Sevin® 80 WSP (EPA Reg. No. 432-1226), 80% carbaryl by weight, Bayer CropSciences LP, NC, U.S.]; ; and 3) 23.4% bifenthrin [Onyx® (EPA Reg. No. 279-3177), FMC Corp., Philadelphia, PA, U.S.]. In mid-July 2009, each of the fifteen trees was girdled ∼ 0.5 m from the ground with a double girdle applied with a chainsaw. The lower girdle was then sprayed with 53.8% glyphosate herbicide [Foresters'® (EPA Reg. No. 228-381), Nufarm Americas Inc., Burr Ridge, IL, U.S.] to accelerate the death of the trees. The second girdle was used to prevent movement of the herbicide up the tree. The following day insecticides were applied to the boles of the assigned trees to a height of 12-15 m, which was approximately the height of the lowest branches in the tree crown, with a hydraulic sprayer. Insecticide was applied until runoff was observed, and each tree received the maximum amount of active ingredient allowed by the labels of the respective products (Sevin: 1.6% a.i., ∼11 L spray/tree; Onyx®: 0.06% a.i., ∼ 15 L spray/tree). An ±-ipsenol and an ±-ipsdienol bait pouch (ConTech Inc., BC, Canada) was hung on each tree at ∼1.5 and 4 m, for a total of four baits per tree. These semiochemicals were used to lure *Ips* engraver beetles into the general area to maximize colonization pressure on each tree (Miller et al., 2005). Tree mortality based on percent crown dieback was recorded every two weeks until 100% mortality was reached (due to girdling) for all trees in the third week of August 2009.

2.2.3 Subcortical Beetle Sampling

Once the insecticide dried on the trees, a single- and double-pane window trap were each installed at 1.5 and 4 m on the boles, for a total of four traps per tree. Traps were placed on each tree by randomly selecting a cardinal direction and then hanging the single-pane window traps on that side of the tree at each height. Double-pane window traps were then installed on the opposite side of the tree to reduce interactions between the two traps. Single-pane window traps consisted of a 17.6 X 26.4 cm panel of clear plexiglass with a 20 cm diameter collecting funnel (from a Lindgren funnel trap, Contech Inc, BC, Canada) attached to the bottom. A 9.5 cm diameter and 12 cm deep wet collection cup (also part of a Lindgren funnel trap) was attached to each funnel, and filled with 5 cm of non-toxic propylene glycol RV antifreeze. Double-pane window traps were constructed similarly, but had an additional plastic panel slotted in the middle of the first panel at a right angle to form a ”+” shaped barrier, thus increasing surface area. Traps were emptied every two weeks for four months from July to mid-October, 2009. All *Ips* and *Dendrotonus* bark beetles, and cerambycid beetles were identified to species using taxonomic keys (Wood, 1982; Lingafelter, 2007). Voucher specimens were deposited at the Georgia Museum of Natural History, University of Georgia, Athens.

Trees were sampled for evidence of beetle colonization five times during the study. During each sampling period, five 20 X 20 cm sections on each tree bole were selected at random heights and directions. These sections were inspected for evidence of insect colonization, which consisted of oviposition scars, entrance/exit/vent holes to galleries, and boring dust and frass. Small (1-3 mm) round entrance/exit/vent holes are typically created by bark beetles, and diamond-shaped oviposition scars and large round exit holes are typically created by woodboring beetles (Gandhi, 2005). In October 2009, when the traps were removed, we peeled bark from selected trees to visually assess gallery formation by colonizing beetle larvae and the extent of phloem degradation.

2.2.4 Statistical Analyses

All statistical tests were performed using SAS© version 9.2 (SAS, 2007). Beetle colonization data were first checked for normality and constant variance across treatments. Since these data were non-normal, various transformations were performed that did not improve normality. Hence, we used non-parametric Kruskal-Wallis tests of Wilcoxon rank-sum scores to assess differences in beetle colonization activity among the three treatments (unsprayed, carbaryl sprayed, and bifenthrin sprayed trees) (Dowdy et al., 2004). The unit of replication was individual tree. Data points were means of five samples taken at each sampling interval, and pooled over the season. Analyses were performed separately for bark beetles and cerambycids. Means with 95% confidence intervals were calculated for each factor and compared graphically.

Beetle trap catches were pooled for each *Ips* and *Dendroctonus* species over the entire sampling season for analyses. The unit of replication was individual trap per tree (N = 60). Data were first checked for normality and equal variance. The three main factors in the model were insecticide treatments, trap type, and trapping height. A three-way analysis of variance test (ANOVA) was conducted to determine whether there were any significant interactions among the main factors (SAS, 2007). As all the interaction terms were insignificant ($p > 0.05$), the analyses were repeated without the interaction terms (Dowdy et al., 2004). Analyses were conducted separately on each bark beetle species under investigation; *I. avulsus*, *I. grandicollis*, *I. calligraphus*, and *D. terebrans*.

The three most abundant species of Cerambycidae [*Monochamus* spp., *Xylotrechus sagittatus* Germar, and *Acanthocinus obsoletus* (Olivier)] were tested separately using ANOVA. No significance was found for species-level trap data, so all Cerambycidae were pooled together and tested as a group using ANOVA.

2.3 Results

Kruskal-Wallis non-parametric tests indicated that there were significant differences in colonization activities among the three treatments for both Scolytinae ($\chi^2_2 = 29.820$, $p < 0.001$) and Cerambycidae ($\chi^2_2 = 28.623$, $p < 0.001$). To quantify this difference, we examined the means and their 95% confidence intervals and found that for both taxonomic groups untreated trees had significantly more attacks (ranging from 300 to 400% more), and there was no significant difference between the two insecticides (Figure 2.1). Visual assessment of the boles after peeling bark revealed no measurably galleries, due to extensive phloem degradation by Cerambycidae larvae and decay in untreated trees, and no galleries on treated trees. Treated trees had some evidence of attempted colonization (entrance/exit/vent holes and oviposition scars), but peeling bark revealed no gallery formation, even in areas where holes were present.

During July to mid-October 2009, we caught a total of 28,473 *I. avulsus, I. grandicollis, I. calligraphus*, and *D. terebrans* (Table 2.1). *Ips avulsus* was the most abundant beetle followed by *I. grandicollis, D. terebrans*, and *I. calligraphus*. Insecticide treatment was not a significant factor for *I. avulsus* and *I. grandicollis*, but it was for *I. calligraphus* (df = 2, F = 3.94, p = 0.025) and *D. terebrans* (df = 2, F = 5.09, p = 0.010). For *I. calligraphus*, fewer individuals were caught on trees treated with carbaryl than controls, but were not different from trees treated with bifenthrin. Addtionally, trees treated with bifenthrin were not different from controls. For *D. terebrans*, trees treated with carbaryl caught fewer individuals than both trees treated with bifenthrin and controls. Double-pane window traps caught 1.43 times more *I. avulsus* (df = 1, F = 4.44, p = 0.040) than single-pane traps while both trap designs were equally effective for the other three species (*I. grandicollis*: p = 0.124, *I. calligraphus*: p = 0.617, and *D. terebrans*: p = 0.129) (Figure 2.2 A). Traps placed at 4 m caught 2.9 times more *I. avulsus* (df = 1, F = 33.79, $p < 0.001$) and 1.53 times more *I. grandicollis* (df = 1, F = 8.07, p = 0.006) than those at 1.5 m. In contrast, traps at 1.5 m caught 2.15 times more *D. terebrans* (df = 1, F = 23.48, $p < 0.001$) than traps at 4 m. Trap height was not a significant factor in trapping *I. calligraphus* (p = 0.510) (Figure 2.2 B).

We caught a total of 503 cerambycid beetles in all traps. Trap height ($df = 1, F = 0.59, p = 0.4448$) and trap design ($df = 1, F = 0.59, p = 0.4179$) had no effect on trap captures of these beetles.

2.4 Discussion

Our results show that carbaryl and bifenthrin were effective in preventing colonization by subcortical beetles on loblolly pine trees. While our experiment was small-scale (we were limited in the number of trees that could be killed on site), the results were highly significant and the trends were clear enough to draw a conclusion. Studies performed on pines in the western United States. have shown similar results for carbaryl and bifenthrin on subcortical beetles, although most of these studies assessed colonization by *Dendroctonus* spp. and rarely by *Ips* spp. (Haverty et al., 1985, 1998; Fettig et al., 2006a).

Fettig et al. (2006a) tested carbaryl and bifenthrin to protect trees against *I. confusus* LeConte and *Dendroctonus* spp. in Nevada, Colorado, and Arizona using tree mortality as the response variable. This allowed evaluation of multi-year efficacy, but was not effective in areas where beetle abundance was too low to cause mortality with baiting alone. However, beetle pressure was sufficient in Nevada to show that both products were effective for two seasons. Tests in Colorado showed that both insecticides were effective for the first season, but in the second season there was not enough pressure to challenge the treatments, as none of the untreated trees died from *I. confusus* attack. The tests in Arizona had to be discontinued completely due to low beetle pressure and low tree mortality. For this reason, we decided to girdle and bait our trees to ensure that we got high beetle colonization pressure. This also meant that we could not test the efficacy beyond one growing season (as all the trees were dead), but ensured that there would be enough pressure to properly challenge the treatments. The total numbers of the most abundant bark beetle species in our traps (Table 1) suggests that our pressure was many times more than the natural level, even after a large disturbance [e.g. Hanula et al. (2002)]. Untreated trees were highly infested by beetles, and the bark came off in large (∼0.5 m^2) sections without any effort at the end of sampling. Trees that were treated with insecticides had essentially undamaged boles with intact phloem, and the bark had to be removed with a draw knife, despite the fact that the crowns were dead with no live needles.

This study also provided an opportunity to test different trapping methods for subcortical beetles on standing mature pine trees. Traps at different heights (1.5 and 4 m) caught different numbers of *I. avulsus, I. grandicollis, I. calligraphus*, and *D. terebrans.* It has been well documented that these beetles exhibit vertical partitioning behavior on the boles of pine trees to limit interspecific competition (Paine et al., 1981). Our trapping data reflected this behavior, as we caught higher numbers of *I. avulsus* in traps at 4m, and more *D. terebrans* in traps at 1.5m. *Ips avulsus*, the smallest of the *Ips* species in this complex, is usually found in the branches and upper bole, where the phloem is thinner. *Ips grandicollis* was also trapped with greater frequency in the 4 m traps. Since it is only slightly larger than *I. avulsus* it is also usually found in the upper area of the bole and in larger branches. *Dendroctonus terebrans* is the largest beetle of the group and is found in the lower bole and base of the tree where the phloem is thickest (Paine et al., 1981). If the objective is to sample only *Ips* spp., then the 4 m trapping height would be more accurate. However, with the inclusion of *D. terebrans* in the target group, a lower trap may be needed to get a more accurate sample of this species.

Double-pane window traps caught significantly more *I. avulsus* but both traps were equally effective for the other species. To maximize the number of beetles caught when using window intercept traps attached to trees, we recommend using the double-pane as opposed to the single-pane design as differences in material costs and construction times are negligible.

Our results could have been confounded by two factors: 1) volatiles produced from insecticide treated trees may have been different from untreated trees, thus affecting trap catches; and 2) potential colonizers of trees were removed during the trapping which may have affected results of the insecticide treatment. If the first confounding factor was true, then we would have observed significant interactions between insecticide treatment and trap types. For total catches of bark beetles, none of the second- and third-order interactions were significant (p= 0.351 - 0.960). At species-level, the treatment terms were significant only for *I. calligraphus* and *D. terebrans* (p= 0.025 and 0.010) respectively), but the interaction terms were not significant (p=0.251 - 0.845). Considering that these species accounted for only ∼3% of total catches, it is hard to draw final conclusions about their response to insecticides. In terms of the second confounding factor, it is not possible to test whether our traps skewed the colonization of beetles on trees, and thus affected the insecticide results. We used exactly the same trap designs and the sampling period on all trees allowing for comparison across treatments, and further our observations about insecticides are similar to those found in other studies that did not use traps on trees (Fettig et al., 2006a, 2008).

2.5 Acknowledgements

We thank Mike Cody (USDA Forest Service, Southern Research Station) for assisting with application of the insecticides and girdling trees, and Daniel Miller (USDA Forest Service, Southern Research Station) for providing baits. Brittany Barnes, Kayla Brownell, Michael Hunter, Lee Ogden, Jenny Staeben, and Dale Porterfield (University of Georgia) provided critical field and laboratory assistance. We thank anonymous reviewers for comments on a previous version of this manuscript. We are grateful for the funding provided by the USDA Forest Service, Southern Research Station SRS-4522, and the Daniel B. Warnell School of Forestry and Natural Resources, University of Georgia, Athens.

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Table 2.1: Total numbers of the most abundant bark and woodboring beetles caught in 2009 on loblolly pine in both single- and double-pane window traps.

DATE	***Ips avulsus***	***Ips grandicollis***	***Ips calligraphus***	***Dendroctonus terebrans***	***Monochamus* spp.**	***Xylotrechus sagittatus***
30-Jul-2009	8190	2406	46	193	69	43
13-Aug-2009	1675	1326	54	228	28	22
27-Aug-2009	3931	1141	53	113	42	29
10-Sep-2009	2816	440	84	45	57	16
24-Sep-2009	2177	74	76	27	71	11
9-Oct-2009	3317	30	28	3	30	8
TOTALS	**22106**	**5417**	**341**	**609**	**297**	**129**

Figures

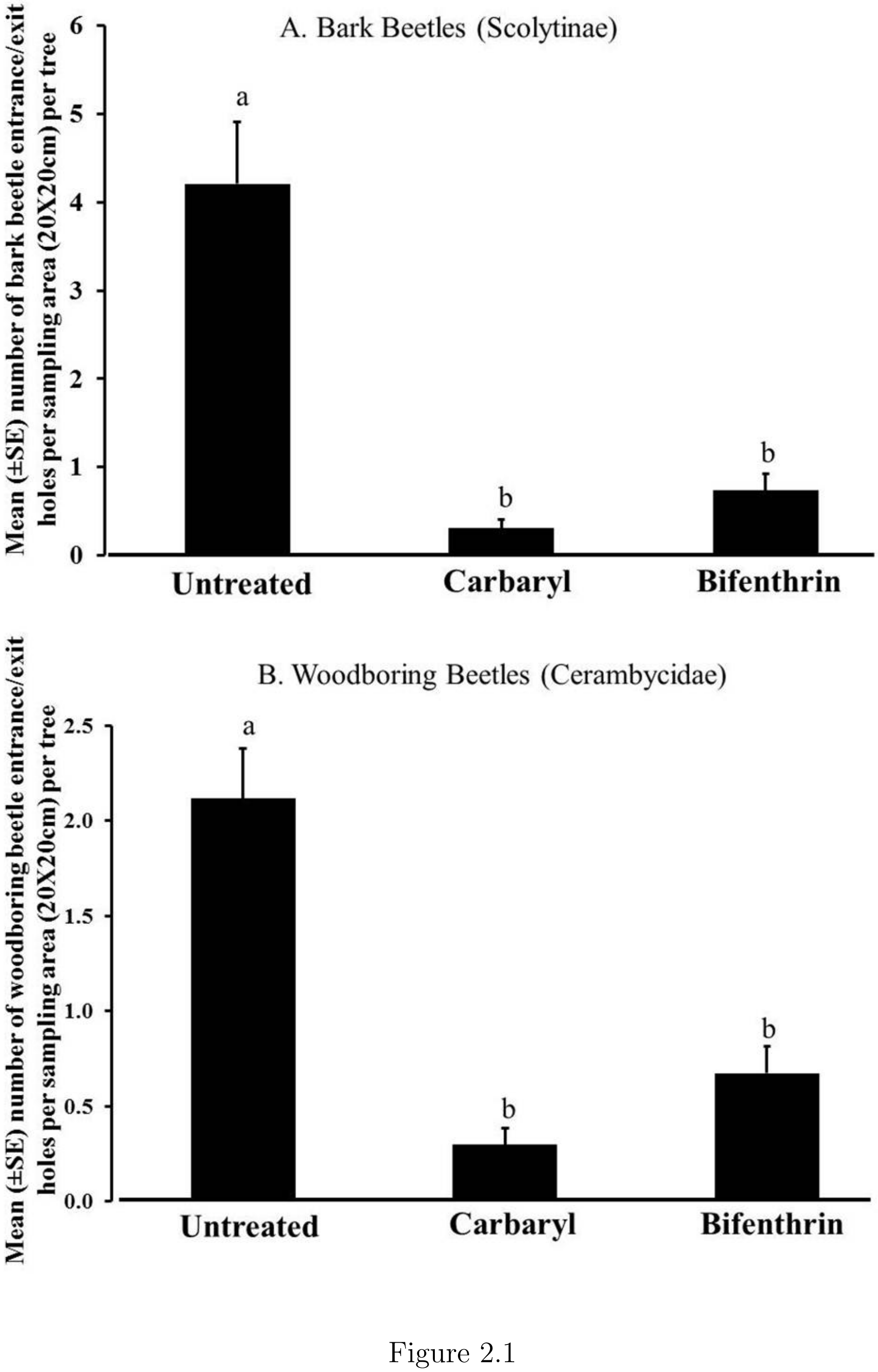
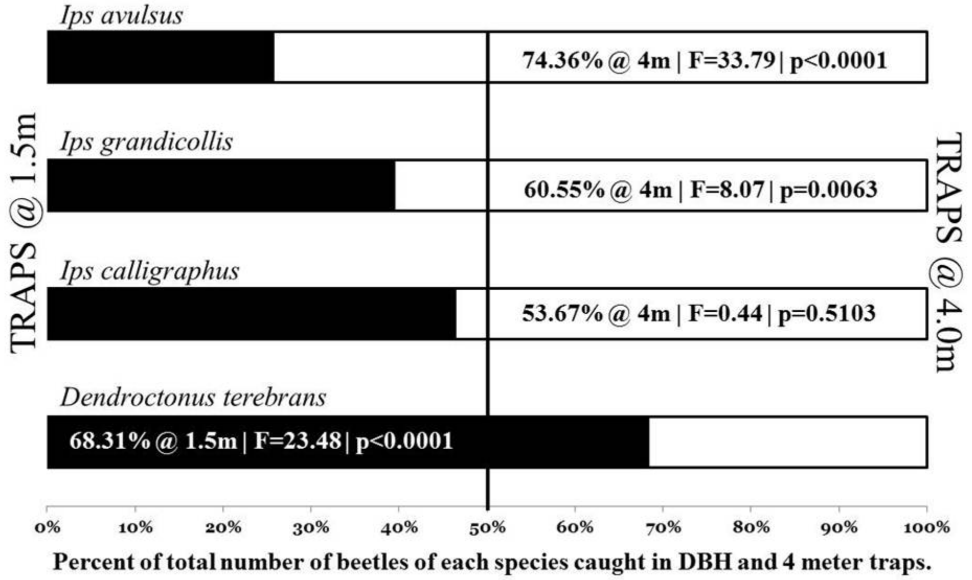
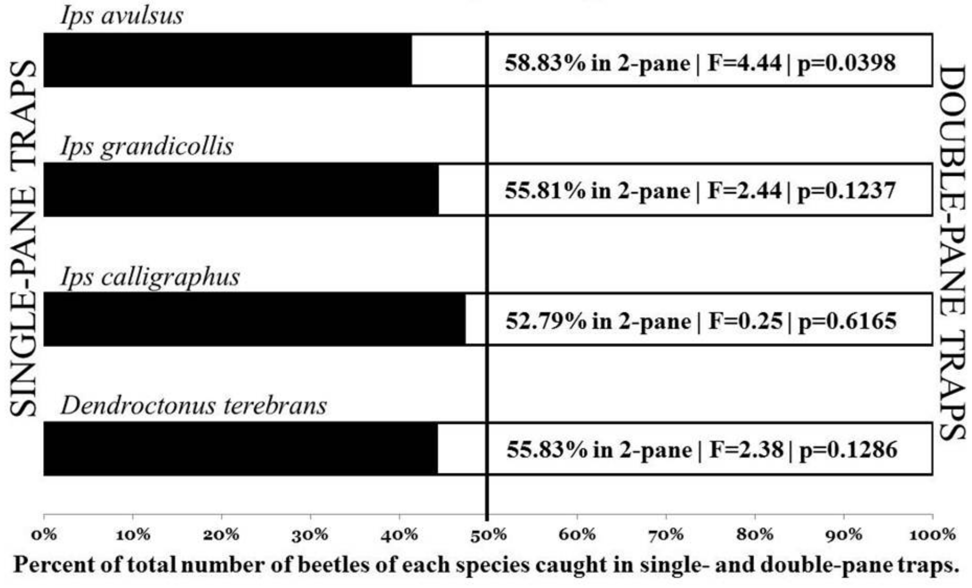

A. Bark Beetles (Scolytinae)
Mean (±SE) number of bark beetle entrance/exit holes per sampling area (20X20cm) per tree
0
1
2
3
4
5
6
a
b
b
Untreated
Carbaryl
Bifenthrin
B. Woodboring Beetles (Cerambycidae)
Mean (±SE) number of woodboring beetle entrance/exit holes per sampling area (20X20cm) per tree
0.0
0.5
1.0
1.5
2.0
2.5
a
b
b
Untreated
Carbaryl
Bifenthrin

Figure 2.1



A.Trap Height



B. Trap Design

Figure 2.2

Chapter 3

Interactions between prescribed fire, subcortical beetles (Coleoptera: Curculionidae and Cerambycidae), and southern pines (*Pinus* spp.) in Georgia [1]

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[1] J L Burke, Hanula J L, Horn S, and Gandhi K J K. To be submitted to *Forest Ecology and Management*

Abstract

Prescribed burning is widely used in pine (*Pinus* spp.) forests throughout the United States to manage forested lands, but in some instances fire can injure trees that are then subsequently colonized by subcortical beetles (Coleoptera: Curculionidae, Cerambycidae, and Buprestidae) . We conducted experiments to determine the effects of extensive bole and crown scorching during prescribed burning on the mortality of loblolly (*P. taeda* L.) and longleaf (*P. palustris* Mill.) pines when subcortical beetles are excluded from trees. We also measured subcortical beetle abundance, and species composition and diversity in stands burned in 2009, 2010, and 2011, and arrival of beetles to two species of pines (loblolly and longleaf pines). Pine mortality was low (5-10%) regardless of whether beetles were excluded or not, and induced resin flow was similar in unburned and burned trees. Fewer Scolytinae beetles were caught in flight-intercept panel traps on trees located in stands burned in 2011 than on similar trees located in stands burned in 2009 and 2010. Tree species had no effect on the numbers of beetles captured. Species diversity of Scolytinae beetles was not affected by time of burn or species of trap tree. Stands burned in 2011 had a significantly different composition of Scolytinae beetles than those burned in 2009 and 2010, while there was no differences between the latter two years. Time of burn did not affect Cerambycidae and Buprestidae beetles, and similar species were captured on loblolly and longleaf pines. Stands burned in 2010 had a higher volume of downed coarse woody debris, whereas stands burned in 2011 had higher basal area of standing dead wood; these trends did not correlate with any observed beetle attributes.

Keywords: Buprestidae, Cerambycidae, lobolly pine, longleaf pine, prescribed-burning, Scolytinae.

3.1 Introduction

Prescribed burning is a commonly used forest management technique to accomplish a variety of goals including maintaining the forest structure and composition of natural fire-adapted ecosystems, creating wildlife habitat, reducing understory competition for trees, in addition to reducing fuel loads to prevent severe wildfires (Davis, 1973). It has been estimated that up to 3 million ha of forest are intentionally burned in the southern United States each year (Wade et al., 2000). The southern forests have a number of fire-dependent species of pines, including longleaf pine (*Pinus palustris* Mill.), which require periodic fire for regeneration and growth (Burns, 1983). Prescribed burning is an important management tool for reducing overstocking of pine stands which may reduce subsequent outbreaks by the southern pine beetle (*Dendroctonus frontalis* Zimmerman) in the southern United States (Nowak et al., 2008).

While prescribed-burning is an effective tool, it is not implemented without risk. Cameron and Billings (1988) found that southern pine beetle spots were more frequent in stands that had been burned, and that the number of spots was directly correlated with pine basal area. Fire can be used to control understory plants and overstocking, but damage by fire may predispose trees to infestations. Fires often do not burn evenly across a landscape, so trees may experience severe scorching (Lilieholm and Hu, 1987). Such extensive scorching may stress trees making them susceptible to colonization by subcortical insects and wood-decaying fungi leading to further decline and mortality over time (Amman and Ryan, 1991; McHugh et al., 2003).

Several studies have examined the effects of bark beetles (Coleoptera: Curculionidae: Scolytinae) on the mortality of pines after fire in the Southeast. In general, trees exposed to intense fires are colonized by subcortical insects (Storey and Merkel, 1960; Hanula et al., 2002; Sullivan et al., 2003), and some *Ips* species are more likely to attack in areas of the bole that have been significantly charred as compared to uncharred areas (Lombardero et al., 2006). However, the direct role these insects play in the decline and mortality of pines after fires is not clear. For example, Hanula et al. (2002) and Campbell et al. (2008) suggested that tree mortality following wildfire and prescribed burns was due to the effects of the fires and not a result of bark beetle attacks. In addition, Hanula et al. (2002) found that after a large wildfire in Florida in 1998, traps in stands in the burned area, regardless of severity, captured fewer 5-spined engravers [*Ips grandicollis* (Eichoff)] and black turpentine beetle [*D. terebrans* (Olivier)] six months after the fire than those in unburned forest stands. The incidence of *Leptographium* spp. in trees that survived the fire for one year was much higher in areas where the fire damage was severe (Hanula et al., 2002), but there was no evidence of long-term tree mortality five years after the fire (Hanula, unpubl. data). Geiszler et al. (1984) found that percent root kill due to fire was the best predictor that bark beetles would infest fire-damaged lodgepole pine [*P. contorta* var. *latifolia* (Englem.)] in Oregon. Storey and Merkel (1960) attempted to use insecticide to exclude beetles from wildfire-damaged trees in Florida, although beetles were present on their trees before they initiated the experiment, leading to a confounding effect. However, they did report that there was no difference in mortality of untreated and insecticide-treated trees, again suggesting that some factor (related to fire damage) other than bark beetles was responsible for tree death (Storey and Merkel, 1960). Similarly, Amman and Ryan (1991) studied bark beetle infestations following a fire in Yellowstone National Park in 1988. They found a high number of uninfested, dead trees, suggesting that the damage inflicted by the fire may have been the leading cause of mortality in these stands.

Although Lombardero et al. (2006) demonstrated that some *Ips* spp. attack burned portions of the bole more frequently than unburned portions, studies that included trapping data found that beetles are not always more abundant in stands that have been burned; they are simply more likely to attack burned trees due to their weakened state (Sanchez-Martinez and Wagner, 2002; Zausen et al., 2005; Lombardero et al., 2006). Others have found that fires can reduce bark beetle abundance through burning of their habitat (Smith et al., 1983; Stock and Gorley, 1989). Sullivan et al. (2003) found that the abundance of secondary colonizers (e.g. *Xyleborus pubescens* Zimmerman, *Hylastes* spp., and Buprestidae beetles) was increased in small plots that were burned versus unburned plots. These beetles are usually opportunists on dead or dying material but neither cause mortality nor are considered significant pests of longleaf pine (Coulson and Witter, 1984; Sullivan et al., 2003). *Ips grandicollis* and *D. terebrans*, which can potentially kill live trees, were not attracted to the burned plots in this study (Sullivan et al., 2003). In contrast, Hanula et al. (2002) found more *I. grandicollis* and *D. terebrans* present outside of a wildfire-burned area in Florida than inside the burn. These studies indicate that there is high variability in responses of pine trees and subcortical beetles to prescribed-burning across landscapes.

Little is known about how burning affects the assemblage of bark beetle and woodboring species following prescribed fires in the southeastern United States. Campbell et al. (2008) investigated the effects of burning, thinning, herbicide, and combination treatments on the abundance and species richness of saproxylic beetles in Alabama. They found that treatments that included burning had higher species richness one and two years post-treatment. Further, burn-only and burn plus thinning had similar numbers of species. Since the burn only treatments had fewer dead trees than the burn and thin treatment, they concluded that the increase in beetle species richness was not due to an increased volume of large dead trees. The abundance of smaller dead pine and hardwoods in these stands may have had some effect on species richness, and it is unclear how fire influences beetle assemblages, but it is an important question considering how often stands are burned (1-3 year fire interval) in the southeastern United States.

To better understand the interactions between prescribed burning, pine trees, and subcortical insects in southern forest stands, we conducted two experiments with research objectives as follows; 1) to investigate the direct role of subcortical insects and prescribed fire on the decline and mortality of southern pines; and 2) to determine the effects of prescribed burning along a chronosequence of burns from 2009 to 2011 on the abundance, species diversity, and species composition of subcortical beetles colonizing two ecologically and economically important southeastern conifer species [longleaf and loblolly *P. taeda* L. pines].

3.2 Methods

3.2.1 Study Sites

Our study sites were located at the Fort Stewart Military Installation in southeastern Georgia, United States (N 31°52′, W 81°36′) (Figure 3.1). Fort Stewart is the largest United States military installation in the eastern region, and is home to the 3rd Infantry Division and the 1st Battalion, 75th Ranger Regiment of the United States Army. The installation is present in Bryan, Evans, Liberty, Long, and Tattnall Counties. A majority of the 113,311 ha of Fort Stewart is mature loblolly, slash (*P. elliottii* Englem.), and longleaf pine forests. Fort Stewart is divided into training areas and these are subdivided into subsidiary training areas (STA) which are used as burn units (Fort Stewart staff, *personal communication*). Our experiments were conducted in STA's in the western part of the installation located in northern Long County, Georgia (N 31°57′, W 81°50′).

3.2.2 Prescribed Fire Beetle Exclusion (PFBE) Experiment

Five plots were established in STA's that were prescribed burned during the last week of March 2011. Plots were located in stands with high levels of fire damage. Burned trees were selected according to the following criteria: 1) $> 50\%$ of the bole was scorched; 2) there were no remaining green needles in the crown; 3) there was no evidence of previous insect activity (e.g. entrance/exit/vent holes, boring dust, and/or frass of bark and woodboring beetles); and 4) trees were a part of the dominant overstory layer. Trees were > 15 m from each other to reduce the effect of insecticide spray drift (Fettig et al., 2008).

In April 2011, sixteen trees were randomly selected in each plot based on the above criteria and each tree was then randomly assigned to be treated with insecticide to exclude subcortical insects from the bole, or to be left untreated. A carbaryl emulsifiable concentrate formulation (Sevin® SL, Bayer CropScience LP, North Carolina, United States) was applied at the maximum rate (2% solution) to the boles of insecticide treated trees with a hydraulic sprayer to a height of ~ 15 m or to the first live branches from the ground ($\sim$15 L spray/tree, see Chapter 2).

After the insecticide solution dried, one double-panel flight intercept trap was installed at a height of 2.5 m on a randomly selected side of the bole. Traps consisted of two clear plastic panels (17.6 X 26.4 cm) slotted perpendicular to each other with one funnel and a wet collection cup from a Lindgren funnel trap (ConTech Inc., British Colombia, Canada) attached to the bottom to collect insects intercepted by the panels. Traps were filled with propylene glycol potable water system antifreeze (Peak® RV & Marine Antifreeze, Old World Industries, Northbrook, Illinois, United States) to prevent evaporation and decomposition of insects. Trees were to be monitored every three weeks from April to August 2011 for signs of decline or mortality. All monitoring was discontinued in July 2011 after it was determined that there was not enough tree mortality.

Induced resin response by trees to fire damage was also measured. Half of the experimental trees were tapped for resin for a period of 24 hours in May 2011. To assess the effects of fire, we measured induced resin response by unburned trees located in the same general area that were not exposed to high intensity fire, as determined by the presence of green needles and no bole scorching. A 15mm round metal punch was used to remove outer bark and phloem at breast height at a random cardinal direction on the bole at breast height, exposing the xylem. Resin was directed into a collection vial using a molded plastic sampling unit designed specifically for sampling pine oleoresin (Karsky et al., 2004). After 24 hours the vials were removed from the sampling units and sealed, and each vial was weighed and recorded. A subsample of 50 unused vials was weighed before the experiment to determine the average vial dry weight, and this weight was subtracted from the total weight of the filled vials to determine the weight of the pine resin collected per tree.

3.2.3 Prescribed Fire Comparison (PFC) Experiment

Two plots were each established in April 2011 in STA's that were prescribed burned in 2009, 2010, or 2011. Three trees located more than 10 m from each other to reduce trapping interactions were selected in each of the six plots. Each tree was double-girdled, and the bottom girdle (∼15cm from the ground) was sprayed with ∼0.5 L of 53.8% glyphosate herbicide [Foresters'® (EPA Reg. No. 228-381), Nufarm Americas Inc., Burr Ridge, IL, U.S.] to kill the trees quickly. The top girdle (∼50cm from the ground) was made to prevent the glyphosate from moving up the bole where it might affect insect activity. One double-panel flight intercept trap was attached to the bole of each tree at breast height. Insects captured in the traps were collected at three weeks intervals from April to August 2011. All Scolytinae, Cerambycidae, Buprestidae, and their predators (Cleridae, Histeridae, Trogossitidae) were identified to species-level using appropriate keys (Wood, 1982; Anderson, 2002; Lingafelter, 2007), and a voucher collection was deposited in the Georgia Museum of Natural History at the University of Georgia in Athens, Georgia.

A survey of downed coarse woody debris (DCWD) and standing coarse woody debris (SCWD) was conducted to estimate the amount of potential subcortical beetle habitat in each plot. Methods were adapted from the USDA Forest Service Forest Inventory and Analysis Program (FIA) protocol (USDA Forest Service, 2005). Three transects were established in each stand starting at the centermost study tree and radiating out at $30°, 150°$, and $270°$

azimuth. Three circular, 181.46 m^2 (radius = 7.6 m) area subplots were established along these transects at 17.6, 35.2, and 52.8 m (10 m apart) from the center. A log was recorded as DCWD if it was $\geq$ 7.6 cm diameter within the subplot and if it was: 1) $\leq$ 1 m from the ground; 2) in FIA decay class 1-2 (suitable habitat for primary and secondary subcortical beetles); and 3) they were leaning at $\leq 45°$ from the ground, if still rooted in the ground. Diameter at both ends of the DCWD ($\geq$ 7.6 cm) was recorded, as was the total length of the log section. The volume of each piece was estimated using a cylindrical model (length x π x r^2, where r is the average radius calculated from the largest and smallest end). To survey SCWD, DBH ($\geq$ 7.6 cm) of all standing dead trees in decay class 1-2 were recorded to get an estimate of basal area.

3.2.4 Statistical Analyses

Analysis of variance (ANOVA), Kruskal-Wallis tests of Wilcoxon rank sums, and analysis of normality and equality of variance were performed using SAS© version 9.2 (SAS, 2007). Shannon-Weiner and Simpson's diversity indices were calculated using the vegan package in R 64-bit version 2.13.1 (www.r-project.org) (R Development Core Team, 2005). Nonmetric multidimensional scaling (NMS) were conducted to assess differences in subcortical beetle composition using PC-ORD™ version 5.31 (McCune et al., 2002), and associated p-values using the multiresponse permutation procedure (MRPP).

PFBE Experiment

No analyses were conducted on these date due to low numbers of beetles arriving at trees and low tree mortality. Induced resin response measurements were non-normal, and various transformations did not improve normality. We therefore assessed differences in induced resin response between unburned and burned pine trees using Kruskal-Wallis tests of Wilcoxon rank sum scores.

PFC Experiment

Trap catch data for total numbers of Scolytinae, numbers of individual Scolytinae beetle species (when total catches comprised $\geq 2.5\%$ of total catches), and total numbers of Cerambycidae and Buprestidae combined (since buprestid catches were low), were checked for normality and constant variance. If the data were non-normal, they were transformed with either the log10(x+1) or the square root (x+0.5) transformations. ANOVA were conducted with the time of burn, species of trap tree, and their interactions as the main factors. If the interaction terms were not significant, and subsequently if one of the remaining two factors was not significant, they were excluded from the final model (Dowdy et al., 2004). Tukey's HSD test was used to conduct pairwise comparisons among levels for significant factors.

Shannon-Weiner and Simpson's diversity indices were calculated for pooled beetle catches for each taxonomic group from each trap tree. These data were also not normally distributed and transformations did not improve normality. So, we compared species diversity among treatment combinations using Kruskal-Wallis tests of Wilcoxon rank sum scores for the time of burn and species of trap tree.

NMS ordination was performed for Scolytinae and Cerambycidae/Buprestidae separately. Data for both groups was checked for skewness, kurtosis, and coefficient of variance. For both groups, coefficient of variance was <100%, so no transformations were needed. A preliminary NMS ordination was conducted on six axes using random coordinates and the Sorenson distance measure. Fifteen iterations were used to evaluate stability, with a stability criterion of 0.0005. 250 iterations at 0.2 step lengths and step down dimensionality were used to run 50 iterations of real data for both groups. To find the correct number of dimensions, final stress *versus* the number of dimensions was plotted, and stability of the solution was checked using the plot of stress *versus* number of iterations for both groups. Final NMS ordination analysis was run using two dimesnsions for both groups, with one run of real data and 250 iterations. An ordination graph for each group was created using the mean

(±SE) distance scores for each treatment combination, along the two final hypothetical axes. MRPP was conducted to make pairwise comparisons of NMS ordination distances between treatments.

DCWD and SCWD data were not normally distributed and transformations did not result in normal distributions. These data were analyzed using Kruskal-Wallis tests of Wilcoxon rank sum scores.

3.3 Results

3.3.1 PFBE Experiment

Monitoring of the traps was discontinued in plots 1, 2, and 5 since there was no tree mortality after three months and trap catches of beetles were low. Plots 3 and 4 had ∼5-10% mortality depending on size class taken into consideration, so we continued trapping in those plots. Only 4 of the 80 treatment trees died during the experiment. There were no significant difference in the amounts of resin collected between trees that experienced high fire intensity and controls ($\chi^2_1 = 1.308, p = 0.253$).

3.3.2 PFC Experiment

We caught a total of 15,605 Coleoptera in window intercept traps during the PFC experiment (Table 3.1). The nine most abundant Coleoptera species were *X. ferrugineus* (Fabricius), *Myoplatypus flavicornis* (Fabricius), *X. pubescens*, *D. terebrans*, *Gnathotrichus materiarus* (Fitch), *Orthotomicus caelatus* (Eichoff), *H. porculus* Erichson , *I. grandicollis*, and *I. calligraphus* (Germar). In addition, we also caught 273 bark beetle predators in the Coleopteran families Cleridae, Histeridae, and Trogossitidae.

Scolytinae abundance was significantly affected by the time of burn ($F_{2,16} = 7.84, p =$

0.005) (Figure 3.2). Trap catches of beetles in stands burned in 2009 and 2010 were similar, and caught 2-3 times more beetles than those in stands burned in 2011. Individual species of Scolytinae showed similar trends (Table 3.2). *D. terebrans*, *I. calligraphus*, and *Xyleborus pubescens* were caught in higher numbers in stands burned in 2009 than in similar stands burned in 2011 but captures in stands burned in 2010 were not significantly different from either 2009 or 2011. Fewer *X. ferrugineus* were captured in 2011 burned stands than in either of the other two burn years. Traps in 2011 burned stands caught significantly fewer *M. flavicornis* than those in 2010 burned stands but not those in 2009 burned stands. Species of trap tree was significant only for *I. grandicollis* where more beetles were caught on loblolly (44.78 ± 19.5) than longleaf pine trees (9.12 ± 2.32) ($F_{1,16} = 7.48, p = 0.019$). Interaction between the time of burn and species of trap tree was significant only for *D. terebrans* ($F_{2,16} = 5.73, p = 0.020$), and *X. pubescens* ($F_{2,16} = 4.83, p = 0.031$). For *D. terebrans*, loblolly pines burned in 2009 caught eight times more individuals than longleaf pines, but 2010 and 2011 longleaf pines caught three and six times more individuals than loblolly pines, respectively. For *X. pubescens*, loblolly pines burned in 2009 and 2010 both caught two times more individuals than longleaf pines, but in 2011 longleaf pines caught three times more individuals than loblolly pines (Table 3.3).

Total numbers of Cerambycidae and Buprestidae were unaffected by the time of burn ($p = 0.084$) or species of trap tree ($p = 0.733$) and there was no interaction ($p = 0.401$) between these factors. Time of burn, species of trap tree, and their interaction were also not significant factors for any of the individual species of Cerambycidae and Buprestidae ($p = 0.135 - 0.817$).

The Kruskal-Wallis tests of Wilcoxon rank sum scores for species diversity of Scolytinae were not significant for the year of burn (Shannon-Weiner: $\chi^2_2 = 1.6, p = 0.449$, Simpson's: $\chi^2_2 = 1.907, p = 0.385$), nor the species of trap tree (Shannon-Weiner: $\chi^2_2 = 0.750, p = 0.387$, Simpson's: $\chi^2_2 = 1.333, p = 0.248$). Diversity of Cerambycidae and Buprestidae were also not significant for the year of burn (Shannon-Weiner: $\chi^2_2 = 5.635$, p = 0.060, Simpson's: $\chi^2_2 = 4.915, p = 0.086$) or species of trap tree (Shannon-Weiner: $\chi^2_2 = 1.565, p = 0.211$, Simpson's: $\chi^2_2 = 0.148, p = 0.700$).

NMS ordination and MRPP pairwise comparisons indicated that the community of beetles captured arriving at trees in stands burned in 2011 was significantly different from that of stands burned in 2009 ($p = 0.015$) and 2010 ($p = 0.007$). Similar to beetle abundance, beetle community composition of 2009 and 2010 trees were not different from each other ($p = 0.320$) (Figure 3.3 A). Species of trap tree did not affect species composition of the Scolytinae ($p = 0.379$). For the Cerambycidae and Buprestidae, both time of burn ($p = 0.060 - 0.894$) and species of trap tree ($p = 0.304$) did not affect species composition (Figure 3.3 B) .

Time of burn was found to be a significant factor for DCWD in decay class 1 or 2 ($\chi^2_2 = 11.173, p = 0.004$). Plots burned in 2010 had 25.5 times more DCWD than those burned in 2009 and 9.8 times more than those burned in 2011 (Figure 3.4). Time of burn was also found to be a significant factor for SCWD ($\chi^2_2 = 6.0882, p = 0.048$), with 2011 plots having 3.2 times more SCWD in decay class 1-2 than in 2010 plots, and no dead standing trees were found in 2009 plots (Figure 3.5).

3.4 Discussion

Pine trees used in the PFBE experiment all showed signs of exposure to high severity fire in the form of stem char height and absence of green needles. Surprisingly, very few trees died in our experiment, and all but three trees began growing new needles almost immediately. Campbell et al. (2008) found that longleaf pine mortality after a growing season prescribed burn was not different from unburned controls in Alabama. However, mortality in longleaf pine in South Carolina following a high severity backing fire did not produce significant mortality until more than two years after the burn (Sullivan et al., 2003). Since our study was limited to one growing season, it is possible that mortality will occur in subsequent years, but our SCWD data suggests that highest mortality from prescribed burns in the study area occurs during the first year. Likewise, Hanula et al. (2002) found that most tree mortality following a wildfire in Florida occurred during the first year and there was very little additional mortality detected five years after the fire (JLH, unpubl. data).

Induced resin response of unburned and burned pines was similar. Previous efforts to measure the effects of burning on resin flow have shown both increased and decreased resin flow depending on the time of burning (Santoro et al., 2001; Lombardero et al., 2006; Perrakis and Agee, 2006). As we did not observe any changes in the amount of induced resin, it is unlikely that trees with extensive stem char and needle mortality were affected physiologically. This suggests that loblolly and longleaf pines are resilient and well-adapted to a short-interval fire rotation period, which correlates well with the presettlement natural and artificial (by indigenous peoples) fire rotation interval of 2-5 years in these southern forests (Outcalt, 2003).

In the PFC experiment, we observed fewer Scolytinae beetles arriving at trees located in stands burned in 2011 as compared to trees in stands burned in 2009 - 2010. Futher, the Scolytinae beetle community on trees burned in 2011 was unique from those burned in 2009 and 2010, suggesting a turnover of species with time since burn. Specifically, fewer individuals of *D. terebrans, I. calligraphus, P. flavicornis, X. ferrugineus*, and *X. pubescens* were found on trees burned in 2011 compared to those burned in 2009 and an intermediate number were captured in 2010. It is possible that these Scolytinae beetles were either directly affected by the fire through mortality, or indirectly by movement of beetles into other forest stands. *Ips* spp. and *D. terebrans* in the southern regions of their ranges are known to overwinter under the outer bark of their host trees in phloem galleries (Wilkinson, 1963; Godbee and Franklin, 1976; Lombardero et al., 2000). Individuals who had not yet emerged from overwintering stages may have experienced direct mortality due to heat in dead wood on the ground, although this effect is likely to occur in standing trees only from very high temperatures, which would contribute to tree mortality (Stock and Gorley, 1989). Sullivan et al. (2003) and Lombardero et al. (2006) reported that while burned trees are more susceptible to attack by Scolytinae, primary colonizing species (*D. terebrans, I. pini*, and *I. grandicollis*) were not more abundant in burned stands, as compared to unburned stands. Instead, they suggested that these beetles find hosts through random landing across the landscape, and that they detect fire-damaged material only after physical contact.

We did not observe similar effects of the time of burn treatment on the Cerambycidae and Buprestidae, and little or no species turnover with time. In our study, trees in stands burned in 2011, which had the highest basal area of standing dead wood, had similar Cerambycidae captures to 2009 and 2010 stands. Similarly, Hanula et al. (2002) did not observe any differences in woodboring beetle catches in relation to fire severity, which was directly correlated with tree mortality. In contrast however, Campbell et al. (2008) found that Cerambycidae captures increased with the number of dead trees, which were found in burned treatments only when paired with either thinning or herbicide treatment. Burning alone had similar tree mortality to thinning only and untreated controls. Burning alone seems not to produce enough mortality to cause an increase in Cerambycidae abundance.

We hypothesized that the effects of fire on subcortical beetle abundance may have to do with the amount of habitat in the area, mainly the volume of coarse woody debris (CWD). Standing dead trees and recently downed woody material are optimal habitat for bark and ambrosia beetles, and populations of *Ips* can build up in slash and other similar woody material (Connor and Wilkinson, 1983; Coulson and Witter, 1984). We measured the volume of intact [FIA decay class 1-2, (USDA Forest Service, 2005)] downed CWD, and basal area of standing CWD in all the sites for the PFC experiment. We found that the volume of downed CWD and the basal area of standing CWD differed significantly between treatments, but these data did not correlate with the beetle species abundance or composition data. Sites burned in 2010 had significantly more downed CWD than those burned in 2009, and there was no difference in abundance between these sites. Sites burned in 2011 had significantly more standing CWD than either of the other treatments (2009 sites had none at all), yet they had the lowest abundance of beetles. Hence, we conclude that the effect of fire on abundance is not due to the volume of potential habitat, at least in our sampled stands.

Shannon-Weiner and Simpson's diversity indices indicated that neither the time of burn nor species of trap tree had any significant effect on species diversity of subcortical beetles. Similar species were expected on loblolly and longleaf pines, as these two tree species have coevolved and coexisted with beetles for a long period of time. Extensive longleaf pine forests were cut during the development of the region. When these areas were eventually replanted, loblolly pine was used because it's easy to establish and grows quickly in the coastal Southeast. However, during the last few decades, there have been efforts to restore the longleaf pine to its native range (Van Lear et al., 2005). Our results indicate that similar subcortical beetle diversity will be maintained when loblolly pines are replaced with longleaf pines. This is supported in the literature, where almost all bark and woodboring beetles caught in our study are recorded from both loblolly and longleaf pine (Wood, 1982; Lingafelter, 2007). Wood (1982) reports that *I. calligraphus* is not found in longleaf pine, but more recent literature has reported otherwise (Sullivan et al., 2003). Of the Cerambycidae, two species, *Elaphidion mucronatum* (Say) and *Leptostylopsis planidorsus* (LeConte), are associated with hardwoods and not conifers (Lingafelter, 2007). As we only caught 8 and 4 individuals respectively, it is likely that these beetles were incidental captures in our traps placed on pine trees.

Overall, our results indicate that there was little mortality of southern pines under a three-year rotation prescribed fire regimen, and it was not possible in this study to disentangle the effects of fire and subcortical beetles on pine health. Further, prescribed burning may decrease populations of Scolytinae beetles, and there was a distinct chronosequence where the species-complex of Scolytinae beetles changed in burned areas over time.

3.5 Acknowledgements

We thank Michael Clark, Robert "Scrubby" Rogers, and the Fort Stewart Environmental Division, Forestry Department for technical assistance and use of equipment. Mike Cody from the USDA Forest Service, Southern Research Station assisted in the application of insecticide. Dale Porterfield, Courtney Brissey, Sean Meadows, Brittany Barnes, and Lee Ogden from the Forest Entomology Lab at the Warnell School of Forestry and Natural Resources at The University of Georgia provided assistance in the field and in the lab. Funding was provided by the USDA Forest Service, Southern Research Station SRS-4552 and The University of Georgia.

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Table 3.1: Total number of each subcortical beetle species caught in 2011 in window intercept traps, by time of burn treatment and species of trap tree at Fort Stewart, Georgia, U.S.

FAMILY	**BEETLE SPECIES**	**2009**		**2010**		**2011**		**TOTAL**
		Loblolly	**Longleaf**	**Loblolly**	**Longleaf**	**Loblolly**	**Longleaf**	
Buprestidae	*Buprestis lineata* Fabricius	1	3	1	2	1	5	13
Buprestidae	*Chalcophora georgiana* (LeConte)	7	0	7	1	0	0	15
Cerambycidae	*Acanthocinus nodosus* (Fabricius)	16	2	8	9	0	7	42
Cerambycidae	*Acanthocinus obsoletus* (Olivier)	19	15	46	8	2	12	102
Cerambycidae	*Arhopalus rusticus* (L.)	16	6	6	6	1	0	35
Cerambycidae	*Elaphidion mucronatum* (Say)	5	0	1	1	1	0	8
Cerambycidae	*Leptostylopsis planidorsus* (LeConte)	1	1	0	0	1	1	4
Cerambycidae	*Monochamus titilator* (Fabricius)	5	20	16	0	3	27	71
Cerambycidae	*Prionis pocularis* Dalman	0	0	1	0	0	0	1
Cerambycidae	*Xylotrechus saggitatus* (Germar)	51	12	26	33	16	9	147
Cleridae	*Thanasimus dubius* (Fabricius)	0	1	0	0	0	1	2
Curculionidae	*Dendroctonus terebrans* (Olivier)	771	96	205	730	21	125	1948
Curculionidae	*Dryoxylon onoharaensum* (Murayama)	0	0	2	0	0	0	2
Curculionidae	*Gnathotrichus materiarius* (Fitch)	459	117	394	286	18	179	1453
Curculionidae	*Hylastes porculus* Erichson	273	200	235	144	33	215	1100
Curculionidae	*Hylastes salebrosus* Eichoff	0	0	2	0	0	0	2
Curculionidae	*Hylastes tenuis* Eichoff	44	47	140	11	41	24	307
Curculionidae	*Ips avulsus* (Eichoff)	2	6	21	2	2	3	36
Curculionidae	*Ips calligraphus* (Germar)	84	180	79	27	5	60	435
Curculionidae	*Ips grandicollis* (Eichoff)	49	36	298	18	56	19	476
Curculionidae	*Myoplatypus flavicornis* (Fabricius)	739	60	937	870	116	91	2813
Curculionidae	*Orthotomicus caelatus* (Eichoff)	558	12	177	352	14	82	1195
Curculionidae	*Xyleborinus saxeseni* (Ratzeburg)	1	0	2	0	0	0	3
Curculionidae	*Xyleborus ferrugineus* (Fabricius)	751	219	699	920	153	207	2949
Curculionidae	*Xyleborus pubescens* Zimmermann	635	328	491	258	94	282	2088
Curculionidae	*Xylosandrus crassiusculus* (Motschulsky)	19	0	57	9	1	1	87
Histeridae	*Hister* spp. A	3	9	4	34	2	22	74
Histeridae	*Platysoma attenuata* LeConte	12	18	65	2	0	13	110
Histeridae	*Platysoma cylindrica* (Paykull)	13	7	17	0	0	9	46
Trogossitidae	*Temnochila virescens* (Fabricius)	9	13	2	9	1	7	41
TOTAL (# of species)		**4543 (26)**	**1408 (23)**	**3939 (28)**	**3732 (22)**	**582 (21)**	**1401 (23)**	**15605 (30)**

Table 3.2: Mean (±SE) number of abundant Scolytinae beetle individuals by the year of burn treatment. Values with the same letter are not significantly different between year of burn treatments.

SPECIES	**2009**	**2010**	**2011**	**p-value**
Dendroctonus terebrans	173.4 ± 64.3^{a}	155.8 ± 63.3^{ab}	24.3 ± 9.2^{b}	0.026
Gnathotrichus materiarius	115.2 ± 31.4^{a}	113.3 ± 64.3^{a}	32.8 ± 17.9^{a}	0.148
Hylastes porculus	94.6 ± 25.8^{a}	63.2 ± 22.8^{a}	41.3 ± 19.5^{a}	0.106
Ips calligraphus	52.8 ± 18.4^{a}	17.7 ± 11.2^{ab}	10.8 ± 7.5^{b}	0.038
Ips grandicollis	17.0 ± 4.4^{a}	52.7 ± 29.7^{a}	12.5 ± 3.6^{a}	0.616
Orthotomicus caelatus	114.0 ± 46.7^{a}	88.2 ± 49.4^{a}	16.0 ± 7.9^{a}	0.259
Platypus flavicornis	159.8 ± 55.2^{ab}	301.2 ± 94.4^{a}	34.5 ± 12.3^{b}	0.004
Xyleborus ferrugineus	194.0 ± 40.7^{a}	269.8 ± 53.6^{a}	60.0 ± 14.3^{b}	0.001
Xyleborus pubescens	192.6 ± 37.7^{a}	124.8 ± 37.4^{ab}	62.7 ± 16.1^{b}	0.011
ALL SCOLYTINAE	$\mathbf{1137.2 \pm 244.4^{a}}$	$\mathbf{1227.7 \pm 355.2^{a}}$	$\mathbf{307.0 \pm 85.4^{b}}$	**0.005**

Table 3.3: Mean (±SE) number of beetles caught in traps in 2011 PFC Experiment for two species, *Dendroctonus terebrans* and *Xyleborus pubescens*, that showed significant interactions between time of burn and species of trap tree treatments.

Dendroctonus terebrans			*Xyleborus pubecens*		
Year of Burn	**Spp. of Trap Tree**	**Mean ± SE**	**Year of Burn**	**Spp. of Trap Tree**	**Mean ± SE**
2009	loblolly	257.00 ± 69.40	2009	loblolly	211.67 ± 46.69
	longleaf	48.00 ± 26.00		longleaf	164.00 ± 53.00
2010	loblolly	68.33 ± 27.47	2010	loblolly	163.67 ± 71.70
	longleaf	243.33 ± 107.93		longleaf	86.00 ± 18.36
2011	loblolly	7.00 ± 5.57	2011	loblolly	31.33 ± 2.33
	longleaf	41.67 ± 9.70		longleaf	94.00 ± 17.69

Figures


TENNESSEE
SOUTH CAROLINA
ATLANTA
ATHENS
ALABAMA
GEORGIA
SAVANNAH
FORT STEWART
ATLANTIC OCEAN
FLORIDA

Figure 3.1

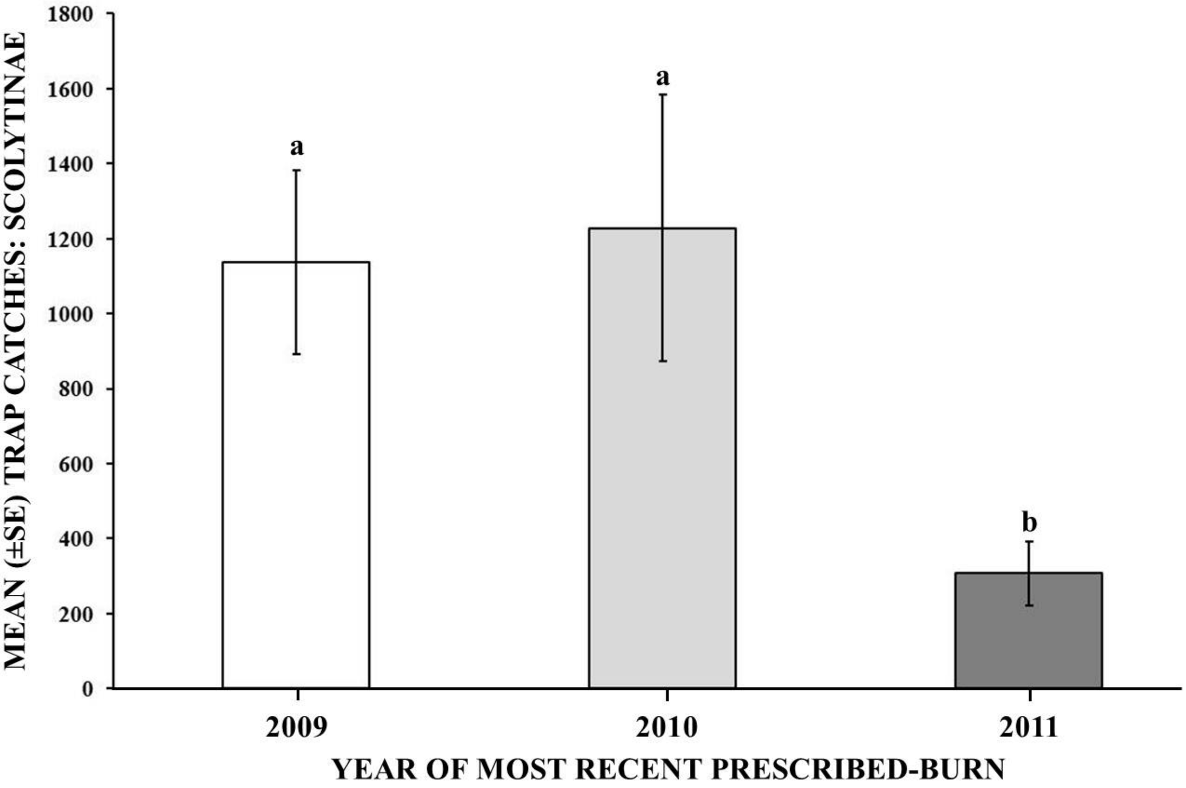
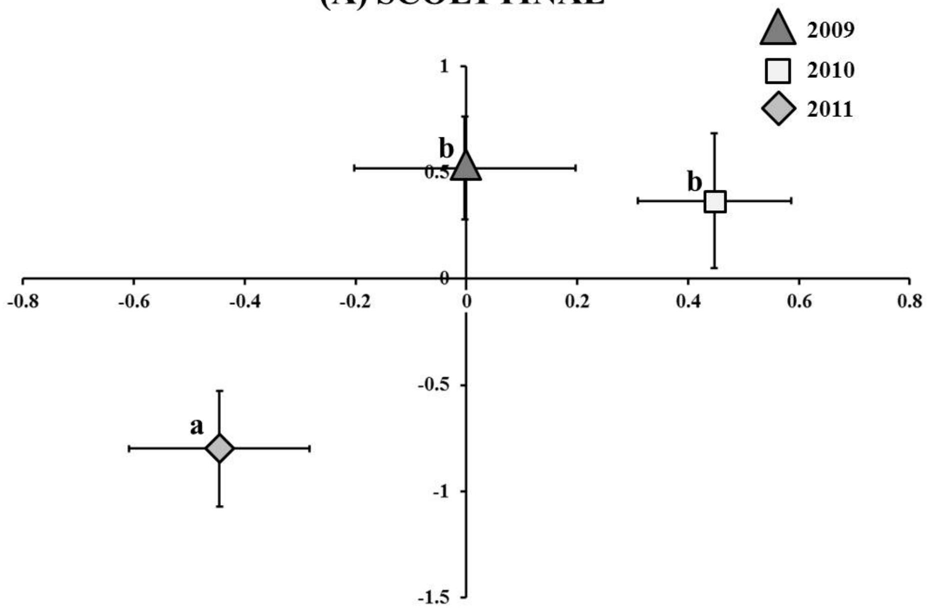

MEAN (±SE) TRAP CATCHES: SCOLYTINAE
1800
1600
1400
1200
1000
800
600
400
200
0
a
a
b
2009
2010
2011
YEAR OF MOST RECENT PRESCRIBED-BURN

Figure 3.2

(A) SCOLYTINAE



(B) CERAMBYCIDAE/BUPRESTIDAE

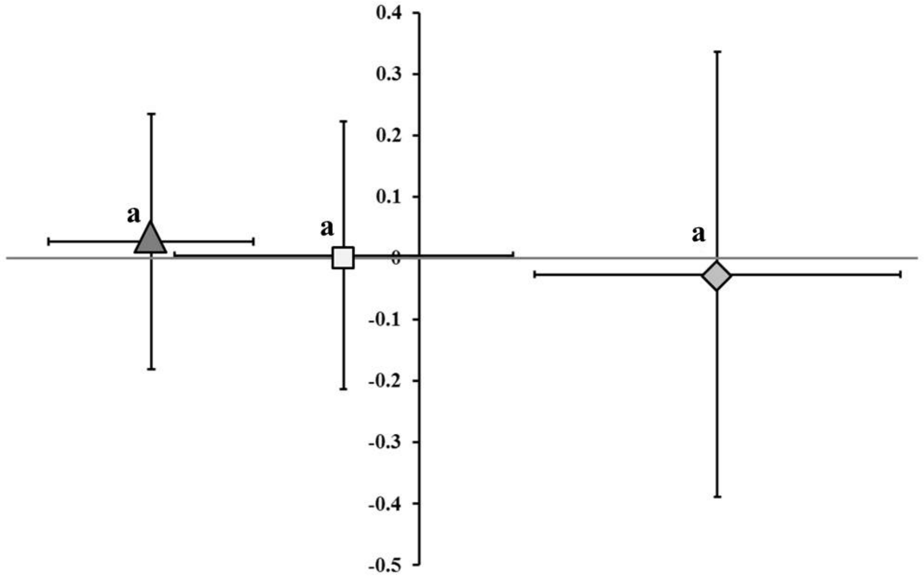
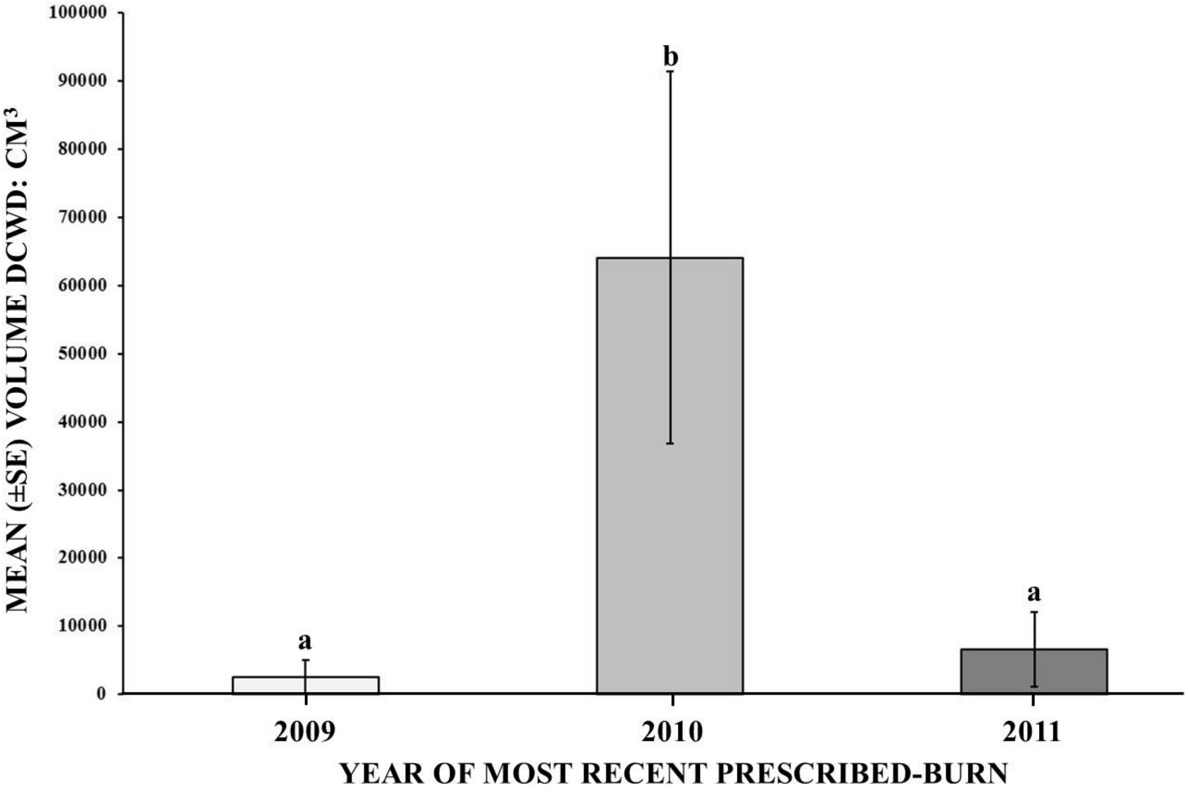
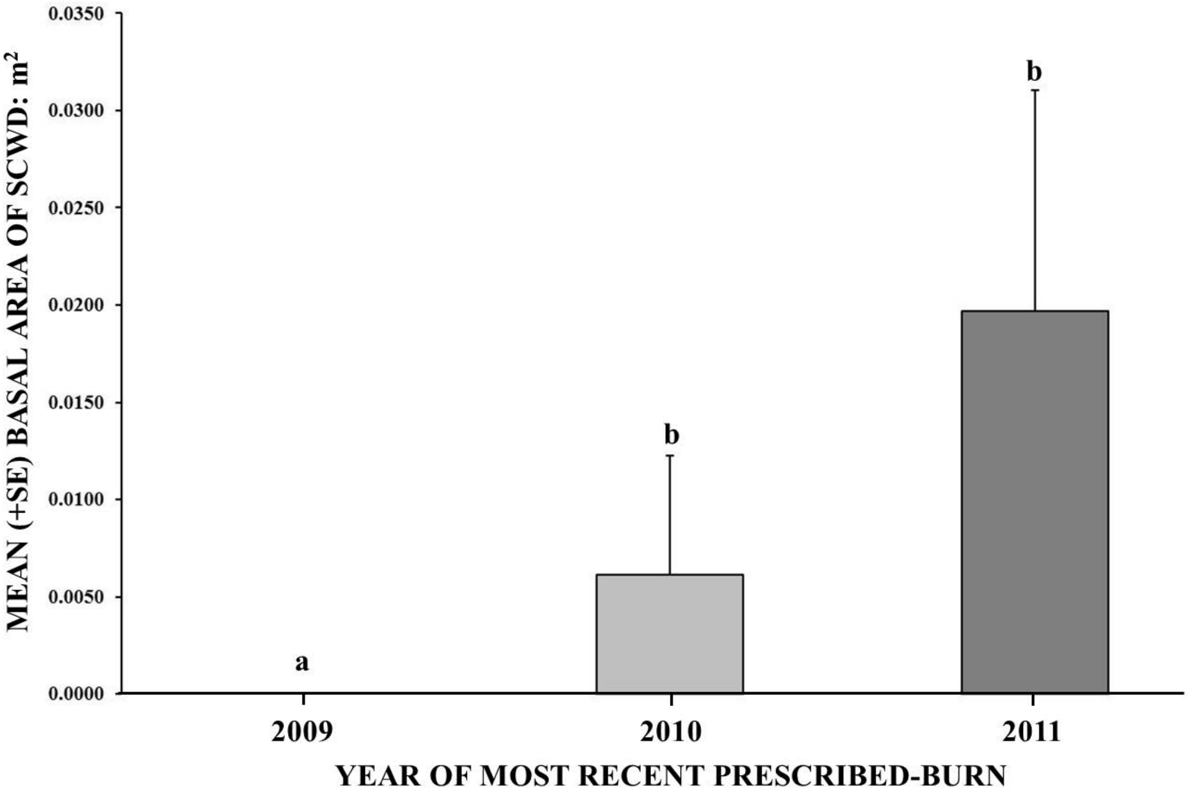


Figure 3.3



MEAN (±SE) VOLUME DCWD: CM³
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
a
b
a
2009
2010
2011
YEAR OF MOST RECENT PRESCRIBED-BURN

Figure 3.4



0.0350
0.0300
0.0250
0.0200
0.0150
0.0100
0.0050
0.0000
MEAN (+SE) BASAL AREA OF SCWD: m²
a
b
b
2009
2010
2011
YEAR OF MOST RECENT PRESCRIBED-BURN

Figure 3.5

Chapter 4

Thesis Conclusion

Prescribed-fire is a commonly used management tool to manage forests around the world, but sometimes fire may cause mortality of desirable tree species. Trees that are weakened by high temperature fires may get colonized by subcortical (bark and woodboring) beetles that contribute to the decline and mortality of trees. As pine trees are an important component of the economy in Georgia, understanding the interactions between subcortical insects and prescribed fire are essential to sustainability of pine plantations and other managed forests. I performed experiments to investigate the importance of subcortical beetles in the decline and mortality of pines after fire. First, I tested two insecticides for the protection of loblolly pine (*Pinus taeda* L.) from subcortical beetles (Chapter 2). I also compared the health of loblolly pines that had been subjected to burning and protected from subcortical, bole-colonizing beetles by insecticides to similar trees that had not been protected, to assess the importance of the beetles in the decline of trees [Chapter 3, Prescribed Fire Beetle Exclusion (PFBE) experiment]. Additionally, I assessed the abundance and species composition and diversity of subcortical beetles attracted to loblolly and longleaf pine (*Pinus palustris* Miller) trees in stands that had been burned in 2011 (same year), 2010 and 2009 (one and two years post-burn). I also measured coarse woody debris (CWD) to assess the potential habitat for subcortical beetles that may be present immediately, and one and two years after a fire [Chapter 3, Prescribed Fire Comparison (PFC) experiment].

The results of Chapter 2 were similar to other studies that have tested carbaryl and bifenthrin in forested ecosystems (DeGomez et al., 2006; Fettig et al., 2006). Although efficacy was found for both carbaryl and bifenthrin, the first compound was chosen due to lower cost and ease of use. Double-pane intercept traps were slightly more effective than single-pane intercept traps in catching subcortical beetles. The observed difference in species composition between the two height treatments on tree boles was similar to known vertical partitioning behavior of bark beetles.

The PFBE experiment of Chapter 3 had to be discontinued due to low levels of tree mortality and beetle catches. We measured induced resin response to mechanical injury in half of our experimental burned trees in the PFBE experiment, and also in adjacent controls (with no fire damage) to determine the level of fire injury. The effects of stem charring on resin response have been investigated in ponderosa (*P. ponderosa* Dougl.) (Perrakis and Agee, 2006; Agee and Perrakis, 2008) and lodgepole (*P. contorta* Dougl.) pines (Jakubas et al., 1994), with mixed results that were highly dependent on site and species. We found no differences in resin flow between unburned and burned trees, suggesting that our trees were not significantly injured by fire.

The PFC experiment in Chapter 3 investigated the effects of prescribed fire on subcortical beetle populations. Scolytinae beetle trap catches were reduced on trees in stands that had been burned in 2011 as compared to those burned in 2010 and 2009; catches on trees burned in 2010 and 2009 were also not different from each other. This suggests that either the Scolytinae abundance was reduced immediately after a fire and/or that they were not attracted to prescribed burned areas. Other studies on the effect of burning on subcortical beetles that included trapping data do not also show an increase in beetle abundance (Sanchez-Martinez and Wagner, 2002; Zausen et al., 2005; Lombardero et al., 2006). Hanula et al. (2002) found that the trap catches of secondary and ecologically important species *Ips grandicollis* (Eichoff) and *Dendroctonus terebrans* (Olivier) were reduced inside the burned areas after the 1998 Florida wildfire as compared to the unburned areas.

We hypothesized that the amount of potential subcortical beetle habitat in the study sites may influence the effect of fire on beetle captures we observed. CWD is often habitat for subcortical beetles, and populations can increase in logs and branches (Connor and Wilkinson, 1983; Coulson and Witter, 1984). We measured the volume of intact [FIA decay class 1-2, (USDA Forest Service, 2005)] downed CWD, and the basal area of standing CWD in all the sites for the PFC experiment. We found significant differences between treatments, but these did not correlate with the species abundance data. We conclude that the effect of prescribed fire on beetle captures is not due to the volume of potential habitat in our study sites.

Time since burning had a significant effect on the communities of Scolytinae beetles. There is evidence that natural and prescribed fire affects insect diversity, often with increased diversity in forest ecosystems (McCullough et al., 1998). Results of the NMS ordination showed that Scolytinae species composition of sites burned in 2011 were different from those burned in 2010 and 2009, but the latter two were not different from each other. In contrast to our prediction, neither the timing of burning nor the species of trap trees affected species diversity of bark and woodboring beetles. It is unclear why beetles were not attracted to fire-injured stands, although there is some evidence beetles may prefer to colonize fire-injured material (Lombardero et al., 2006). It is possible that defensive chemical production is lower after fire injury, since trees must devote more resources to repairing injured and damaged tissues, including burned needles (Herms and Mattson, 1992).

Future areas for research on the interactions between fire and subcortical beetles in the southern pine forests may include an assessment of the effects of fire on the constitutive defenses of pines. These include monoterpene chemicals in the bark and phloem, which are used to repel and kill insects. These chemicals are also used by insects to detect suitable hosts and in some cases synthesize pheromones and kairomones. At present, it is unclear how fire affects the production and persistence of these chemicals. It is likely that the effects of fire will vary between species of pine trees, and research may need to be region specific and conducted in multiple regions where prescribed fire is used to maintain commercial plantations and/or natural stands.

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