SHORT-TERM RESPONSE OF BARK BEETLES TO FUEL REDUCTION TREATMENTS IN THE UPPER PIEDMONT

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by

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ABSTRACT

Suppression of natural fire and reduction of anthropogenic fire over the past century have increased fuels throughout many forest ecosystems. These fuel increases have led to an unusually high degree of catastrophic wildfires. Thinning and prescribed burning are two silvicultural treatments that forest managers can utilize to reduce these fuel loads. This thesis is the Southeastern Piedmont entomological component of the National Fire and Fire Surrogate Study (FFS), a nationwide study whose main objective is to assess how forest ecosystem components and processes are affected by both fire and treatments which may act as surrogates for fire..

Prescribed fire and thinning can be used to reduce losses from the southern pine beetle (*Dendroctonus frontalis* Zimmerman) by increasing host tree vigor and widening spaces between host trees. However, it is hypothesized that these treatments will cause a short-term increase in bark beetle activity by inducing tree shock. Variables measured across treatment units included bark beetle numbers, infestation sizes, host radial growth, host resin flow, hazard-rating, and risk-rating data. Results indicate that bark beetle activity was not affected by either of treatments. Thinning improved the recent year radial growth, but had no effect on resin flow. There was a strong inverse correlation between beetle activity and total resin flow across a treatment unit. It is yet to be determined what long-term effects fire and thinning have on southern pine beetle spot occurrence and spot growth in the Piedmont. However, reduction in stand density along with increase in tree vigor should result in lower long-term susceptibility to an attack.

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INTRODUCTION

Historically, both natural and anthropogenic fires have shaped forested lands throughout North America. Evidence exists in fire scars, written documentation, and adaptations of certain plants to recurring burn regimes. Suppression of natural fire and reduction of anthropogenic fire over the past century have increased fuels throughout many forests. These fuel increases have resulted in recent catastrophic wildfires. Thinning and prescribed burning are two silvicultural treatments that forest managers can utilize to reduce these fuel loads.

This thesis is a component of the National Fire and Fire Surrogate Study (FFS), a nationwide study funded by the Joint Fire Science Program to assess how forest ecosystem components and processes are affected by both fire and fire surrogate treatments. Among 13 different locations throughout the United States, a set of core response variables was measured from different ecologic and economic conditions. Four types of treatments were used at each site. These included an untreated control, prescribed fire with periodic reburns, thinning, and prescribed fire with thinning. These four treatments span a useful range both in terms of realistic management options and anticipated ecological effects. The treatment units were replicated three times at each of the 13 research sites, using either a completely randomized or randomized block design. Objectives of the FFS are as follows (Executive Summary 2000):

1. Quantify the initial effects (first five years) of fire and fire surrogate treatments on a number of specific core response variables within the general groupings of (a) vegetation, (b) fuel and fire behavior, (c) soils and forest floor (including relation to local hydrology), (d) wildlife, (e) entomology, (f) pathology, and (g) treatment costs and utilization economics.

2. Provide an overall research design that (a) establishes and maintains the study as an integrated national network of long-term interdisciplinary

research sites utilizing a common "core" design to facilitate broad applicability of results, (b) allows each site to be independent for purposes of statistical analysis and modeling, as well as being a component of the national network, and (c) provides flexibility for investigators and other participants responsible for each research site to augment—without compromising—the core design as desired to address locally important issues and to exploit expertise and other resources available to local sites.

3. Within the first five years of the study, establish cooperative relationships, identify and establish network research sites, collect baseline data, implement initial treatments, document treatment costs and short-term responses to treatments, report results, and designate FFS research sites as demonstration areas for technology transfer to professionals and for the education of students and the public.

4. Develop and maintain an integrated and spatially-referenced database format to be used to archive data for all network sites, facilitate the development of interdisciplinary and multi-scale models, and integrate results across the network.

5. Identify and field test, in concert with resource managers and users, a suite of response variables or measures that are: (a) sensitive to the fire and fire surrogate treatments, and (b) both technically and logistically feasible for widespread use in management contexts. This suite of measures will form much of the basis for management monitoring of operational treatments designed to restore ecological integrity and reduce wildfire hazard.

6. Over the life of the study, quantify the ecological and economic consequence of fire and fire surrogate treatments in a number of forest types and conditions in the United States. Develop and validate models of ecosystem structure and function, and successfully refine recommendations for ecosystem management.

Sites selected for the FFS were judged to have historically short-interval, low to moderately severe fire regimes and be in danger of uncharacteristically severe wildfire due to heavy fuel loads. In the Southeastern Piedmont, these fire regimes were born from anthropogenic disturbance across the landscape. Native Americans, who entered into the Piedmont 12,000 years ago, used fire frequently in order to reduce undergrowth in the forests, clear land for cultivation, and improve habitat for game species. When European colonists arrived in the late 17th century, fire had become an important component of Piedmont ecosystems. Intensive agriculture practices from the time of European settlement until the Civil War dramatically altered the ecology of the Piedmont. Much of the land, which became abandoned after economic depressions of the 1880's and late 1920's, was highly eroded and reverted to natural succession. Fire exclusion had been the policy of most land management agencies throughout most of the 1900's. For the most part, prescribed fire is used today by government agencies and private industry. However, most of the forest land in the Piedmont is owned by nonindustrial private landowners. Generally, this group does not use fire for fuel reduction purposes.

The southern pine beetle (*Dendroctonus frontalis* Zimmerman) is the most aggressive and destructive of the bark beetle guild (Scolytidae) in the southeastern United States. In South Carolina alone, the beetle was responsible for $76 million worth of damage and the loss of almost 5 million pine trees during 2001. Increases in southern pine beetle activity appear to be closely related to changes in forest structure (Hedden 1978). The number of overstocked, pure pine stands is greater now than at any time in the past (USDA Forest Service 1988). These stand conditions, which favor southern pine beetle attack, can be attributed to abandonment of agricultural land and the exclusion of fire.

Throughout the range of the southern pine beetle, four other bark beetle species can cause significant, but usually restricted, damage to pines. These include the black turpentine beetle (*Dendroctonus terebrans* Olivier), and the 4-, 5-, and 6-spined engraver beetles (*Ips avulsus* Eichhoff, *I. grandicollis* Eichhoff, and *I. calligraphus* Germar).

Southern pine beetle population behavior consists of two distinct phases: spot occurrence and spot growth. Spot occurrence is the initial establishment of new spots, and it occurs primarily in the spring in the Piedmont of South Carolina. Spot growth is the phase after establishment where emerging generations of beetles attack other trees, causing an overall increase in spot size. Growth occurs during the summer months and can last through the fall. This phenomenon is unique to bark beetle behavior in the southeastern Unites States, where prolonged warm temperatures and ample pine growing stock provide conditions for beetle population expansion.

Silvicultural practices, including prescribed fire and thinning, can be used to reduce losses from the southern pine beetle (Belanger et al. 1993). Because the two population phases are related to different stand conditions, it is hypothesized that fire and thinning treatments will have distinct effects on beetles. Spot occurrence is closely related to stand disturbances that decrease tree vigor. Spot growth, on the other hand, is most related to pine density within a stand. The disturbances caused by these silvicultural techniques may cause short-term increases in spot occurrence due to short-term adverse effects on tree and stand vigor (Hedden and Belanger 1985). It is hypothesized, however, that thinning will cause short-term decreases in spot growth by widening the spaces between host trees.

The objectives of this study were to determine the short-term and long-term impact of thinning and prescribed fire on potential losses from bark beetles. Secondary objectives were to monitor stand, site, and host conditions.

LITERATURE REVIEW

There are five species of Scolytids that make up the southern pine bark beetle guild. These are the southern pine beetle (*Dendroctonus frontalis* Zimmerman), the black turpentine beetle (*D. terebrans* Olivier), the four-spined engraver beetle (*Ips avulses* Eichoff), the five-spined engraver beetle (*I. grandicollis* Eichoff), and the six-spined engraver beetle (*I. calligraphus* Germar) (Flamm et al. 1993). Unlike other beetles, these Scolytids colonize southern pines in order to construct egg galleries beneath the host bark (Beal and Massey 1945). Each of these bark beetles exhibits differing life history mechanisms. Infestations of engraver beetles usually occur in trees that have been damaged by lighting, windfall, logging, or snow breakage (USDA Forest Service 1985). The four-spined engraver prefers the slash of limbs and pine tops, but attacks can occur throughout the entire bole of a tree. The five-spined engraver prefers recently felled trees and slash, but can also be found in living trees as well. The largest of the southern U.S. *Ips* species, the six-spined engraver, attacks larger limbs, stumps, and trunks of recently felled trees. Attacks on living trees usually occur on the lower portions of the trunk. Throughout North America, species of the genus *Dendroctonus*—literally "killer of trees"—are the most destructive of all bark beetles (Stark 1982). Attacks by the black turpentine beetle are usually found below a height of two meters on the trunks of standing trees (USDA Forest Service 1985). This species is especially attracted to terpenes released by trees injured by fire and logging.

The southern pine beetle, which is the most important pest of declining southern pine forests (Cameron and Billings 1988; Belanger et al. 1993), can attack all species of pines within its range (Beal and Massey 1945). Shortleaf pine (*Pinus echinata* Mill.) and loblolly pine (*P. taeda* L.) are the preferred southern pine beetle hosts. This is mainly due to the physical properties of oleoresin within the two species (Hodges et al. 1979). When compared to resin of slash pine (*P. elliottii* Engelm.) and longleaf pine (*P. palustris* Mill.), loblolly and shortleaf oleoresin has a rapid rate of crystallization, a low viscosity, a low flow rate, and low volume.

Among other bark beetles, periods of severe outbreaks lasting two to three years are a unique population characteristic of the southern pine beetle (Thatcher 1960). Increased incidence and severity of beetle activity has been attributed to high pine basal area (Hedden and Billings 1979, Ku et al. 1980), reduced radial growth (Hicks et al. 1978), increased stand age (Belanger et al. 1993), poor site quality (Coster and Searcy 1981), and stand disturbance (Bennett 1971, Coulson et al. 1983). During periods of endemic population levels, the southern pine beetle is thought to attack only weakened or dying trees (Payne 1980). When population levels reach epidemic status, healthy trees become susceptibly to attack as well (Payne 1980).

Attributes of southern pine beetle population dynamics distinguishes this species from other *Dendroctonus* bark beetles in North America and are an important consideration in understanding the amount of timber volume loss that can accrue over a year. Most new beetle infestations are initiated during the spring (Belanger et al. 1993), when fat content in emerging adults is relatively high (Hedden and Billings 1977). According to Lorio (1986), this is during a time of year when water and nutrient supplies are abundant, the carbon budget is used in reproductive and vegetative growth, and little energy is put into resin synthesis. The oleoresin system of pines is considered the primary defense mechanism against attacking beetles (Hodges et al. 1979, Warren et al. 1999). Spot initiation generally occurs on a concentrated area of a stand that has been disturbed by logging or lightning, is of poor site quality, has overmature trees, or has overstocked trees (Coster and Searcy 1981, Hedden 1983).

In order to better understand the relationship between tree vigor and beetle activity, a description of several pine physiology models is needed. Oleoresin, a secondary metabolite produced during photosynthesis, is one of the primary defense mechanisms that trees have against invading organisms. Reeve et al. (1995) found that bark beetles have much greater reproductive success on trees with less resin. As beetles penetrate through the inner bark and expose the xylem tissue in order to construct egg galleries, resin acts as a physical and chemical barrier (Thatcher et al. 1980). Working from the growth-differentiation balance model proposed by Loomis (1932), Lorio (1986) postulated that during times of moderate water stress, resin flow (differentiation) is favored over tree growth and beetle attack is reduced. These moderate water deficiencies limit growth and result in a relatively large carbohydrate pool after the carbohydrate demands for growth have been met. Also, vertical resin ducts are formed with the transition from earlywood to latewood production in the late spring. As long as the earlywood is being produced, resin is physically blocked. Increased rainfall in the late spring or early summer can actually prolong the formation of earlywood and increase a trees susceptibility to a beetle attack (Lorio et al. 1990). A source-sink model proposed by Luxmoore et al. (1995) came to the same conclusion: growth is more sensitive to water stress than photosynthesis.

Little information is available regarding the effect of prolonged drought on oleoresin production. However, Lombardero et al. (2000) showed that induced resin flow increased during periods of fastest growth, or when soil conditions were well watered. Herms and Mattson (1992) postulated that by causing a total collapse of carbon, extreme water deficits would decrease the production of secondary metabolites.

Spot growth, which is the second phase of southern pine beetle population dynamics, occurs later in the growing season (Belanger et al. 1993). This phase is closely related to the numbers of beetles within a spot and the density of pines within the stand (Hedden and Billings 1979, Schowalter et al. 1981). Spot growth usually begins in the early summer, when growth has slowed in pines and more energy is allocated to resin production, or defense (Lorio 1986).

Biologically, the southern pine beetle is well adapted to periods of successful population explosions (Payne 1980). Like all members of the order Coleoptera, the southern pine beetle undergoes four major life stages—egg, larva, pupa, and adult. Adult beetles emerge from host trees and fly to a new host tree in response to other beetle pheromones and host odors. Adults mate and construct egg galleries within the host tree phloem. Eggs are laid throughout these galleries. Developing larvae feed within the phloem, widening the galleries at each successive molt. Mature larvae chew into the outer bark where pupal cells are built. Mature pupae emerge into callow adults, and cuticle hardening takes place. The fully developed adults construct exit holes through the outer bark, and, depending on environmental conditions, disperse to another host.

In the northern part of its range—northern Virginia and southern Pennsylvania—the southern pine beetle may have as few as three generations per year (Payne 1980). In Texas, seven or more generations may be completed in a year (Billings and Kibbe 1978). A summer generation, egg to adult, was reported to be 26 days long (Thatcher and Pickard 1967) and 37 days long (Billings and Kibbe 1978) in southeast Texas. A winter generation can take well over 100 days for completion (Billings and Kibbe 1978). Thatcher (1967) found that emerging adults are able to colonize new host trees when temperatures are above 15° C. If temperatures are too low, emerging beetles will not fly to new trees, but attack new areas of the same tree in which they developed (Thatcher and Pickard 1964).

Over the past 20 years, one of the most applied avenues of southern pine beetle research has been the integration of pest management with forest management (Lorio 1978, Hicks et al. 1980, Coster and Searcy 1981, Hedden 1984). This research has culminated in stand hazard and risk rating systems that forest managers can use to: 1) change priority settings for forest management, 2) monitor pest activity during endemic population levels, 3) schedule direct control treatments, and 4) determine outbreak and loss potential (Mason et al. 1985). Risk rating systems are generally designed to determine a stand's susceptibility to beetle occurrence; hazard rating systems are generally designed to determine a stand's vulnerability to spot growth (Hedden and Belanger 1985). Each major geographical province in the southeastern United States has a distinct stand rating system due to differing stand, site, and host characteristics (Coster and Searcy 1981).

In the Piedmont, site conditions such as higher than average clay content of the soil surface (0-15 cm) and plots on steep side slopes are considered high-risk areas for beetle infestations (Coster and Searcy 1981). These same site conditions are often associated with littleleaf disease (*Phytophthora cinnamoni* Rand.) (Oak and Tainter 1988). Belanger et al. (1977) postulated that these littleleaf sites would often become the locus point for initial beetle infestations. Coster and Searcy (1981) found the greatest difference between attacked and non-attacked plots in the Piedmont to be the proportion of shortleaf pine to loblolly pine. Almost 70% of attacked plots were dominated by shortleaf, while close to 56% of the non-attacked plots were dominated by loblolly. Shortleaf pine, which was the primary tree species to colonize infertile abandoned farmlands in the southern Piedmont 100 years ago, is more susceptible to littleleaf disease than loblolly or Virginia pine (*Pinus virginiana* Mill.) (Tainter and Baker 1996). However, on high-risk littleleaf sites loblolly pine declines are due to the same factors that cause the disease in shortleaf pine (Jacobi and Tainter 1988).

Susceptibility to southern pine beetle attacks in the Coastal Plain is more closely related to stand conditions than site factors (Coster and Searcy 1981). Attacked plots characteristically are more heavily stocked and had a higher pine component. In southern Arkansas, Ku et al. (1980) found shortleaf pine to be more susceptible to beetle attack than loblolly pine. They also found higher basal areas in attacked plots versus non-attacked plots.

Coster and Searcy (1981) found that basal areas did not differ much between attacked and non-attacked plots in the Piedmont. However, it is well understood that the southern pine beetle prefers densely stocked, slow growing stands throughout its range (Showalter and Turchin 1993). Stands in these conditions often exhibit reductions in annual radial growth increments (Coulson et al. 1974). Other factors that lead to reduced growth include extended periods of water deficit (Zahner 1968), site conditions that may predispose pines to littleleaf disease (Jacobi and Tainter 1988), and disturbance. These are factors that are similar to those found in areas highly susceptible to beetle infestations.

Silvicultural treatments, including prescribed burning and thinning, may be used to reduce losses from southern pine beetle attack (Belanger et al. 1993). However, short-term disturbances caused by these treatments on tree vigor can increase a stand's susceptibility to an attack (Hedden and Belanger 1985).

By reducing competition for resources, thinning increases the growth rate of residual stems. The fewer the residuals, the longer the tree will sustain a good growth rate and remain in high vigor (Zahner and Whitmore 1960). In most instances, host vigor (growth) is reduced immediately following thinning (Nebeker et al. 1983). The degree of decline is dependent on the intensity of the thinning operation and the overall soil damage within the stand.

Both simulation models (Hedden 1983, Burkhart et al. 1986) and field studies (Brown et al. 1987, Showalter and Turchin 1993) have been used to test the effects of thinning on stand susceptibility and host resistance to a southern pine beetle attack. In all these studies, results show that thinning can reduce losses from an attack. Ku et al. (1980) recommend thinning to a basal area below 23 m^2/ha. On the lower quality, high-risk sites, recommendations have been made to thin below 18 m^2/ha (Hicks et al. 1979).

By increasing the spacing between residuals, crown size and bole ratios are improved. Crown size has been shown to have a direct relationship with resin flow rates (Schopmeyer and Larson 1955, Lombardero et al. 2000). Mason (1971) found a reduction of resin flow rates from overstocking in a young (12-year old) pine plantation.

In more recent studies, Matson et al. (1987) and Ruel et al. (1998) found resin flow rates to be higher in trees from thinned stands than unthinned stands.

In addition to improving tree vigor, thinning can widen the spaces between host trees, making spot enlargement more difficult for the southern pine beetle. Attacked trees must be within six to eight meters of a source tree in order for beetles to detect pheromones (Gara and Coster 1968). During epidemic populations of the southern pine beetle, this "critical switching" distance may be increased because of the pheromone overload within an area.

Though absent from many fire regimes throughout the South during most of the 20th century, prescribed burning has once again become an important land management tool (Pyne et al. 1996). Compared to thinning, very little research has been done regarding the effects of burning on both incidence and susceptibility of stands to the southern pine beetle. In the Gulf Coastal Plain, both fire within the past year and fire after the past year did not have an effect on spot occurrence (Coster and Searcy 1981). In east Texas, spot occurrence was more frequent in loblolly pine stands that had been prescribed burned (Cameron and Billings 1988).

Like thinning, prescribed burning can have long-term positive effects on residual host tree vigor by reducing competition within a stand for water and nutrients. Short-term availability of nutrients following a prescribed burn is generally reduced due to volatilization. Pre-treatment availability of nitrogen, however, is regained following this initial loss (Knoepp and Swank 1997).

Prescribed burning can also have negative effects on host tree vigor. Lilieholm and Hu (1987) found that different levels of scorch cause reduction in radial growth. Reduction of crown size from scorch may also have damaging effects on constitutive resin flow.

Differing effects of thinning and prescribed burning on activity of the southern pine beetle are abundant throughout the literature. One of the limitations of many of these studies is the lack of available populations of beetles. When populations are endemic, there may not be enough beetles to test certain stand-level hypotheses. Furthermore, epidemic populations of the southern pine beetle behave in a different manner than endemic populations. Forest managers are most concerned with these epidemic population levels. Therefore, a study was conducted on the Clemson Experimental Forest to examine the effects of thinning and burning on southern pine beetle activity and stand, site, and host conditions. Specific objectives included:

1) Assessment of bark beetle populations among each thin and burn treatment.

2) Measurement of bark beetle spot infestation sizes among each treatment.

3) Determination of tree vigor characteristics—recent radial growth and resin flow.

4) Collection of stand, site, and host variables for risk and hazard rating models.

METHODS AND MATERIALS

Experimental Design

A randomized block design, with blocking on tree size, was used for this study in order to reduce the variability of tree size classes on treatment effects. Each of the three blocks (replicates) contained four sites (treatment units) that underwent a specific treatment. The four treatments called for by the National FFS included an untreated control, prescribed fire, thinning, and a prescribed fire with thinning. Weather conditions prevented the application of prescribed fire within the prescribed fire with thinning treatment units prior to the sampling period for this specific study. Therefore, two thinning treatments were compared against the prescribed fire and untreated control units.

Study Site

Twelve study sites, one for each treatment in a replicate, were located on the Clemson Experimental Forest in the upper Piedmont of South Carolina. These study sites were chosen on the basis of stand age, size, and management history. Each of the three replicates was dominated by different size-classes of trees. Replication 1 was dominated by pulpwood-sized trees (dbh 15-25 cm); replication 3 was dominated by sawtimber-sized trees (dbh >25 cm); and replication 2 was a mixture of both pulpwood and sawtimber-sized trees. All of the sites were predominately loblolly or shortleaf pines with a mixture of hardwoods in the under- and mid-story. Appendix A shows the location of each treatment unit (replicate and treatment) along with its respective cover type, size class, and acreage estimate.

Each treatment unit is comprised of a 10-hectare measurement area and a buffer of at least one tree length surrounding the measurement area (Figure 1). Within the measurement area, 40 permanent grid points were established. Distance and spacing between each grid point was 50 meters in one of the cardinal directions.

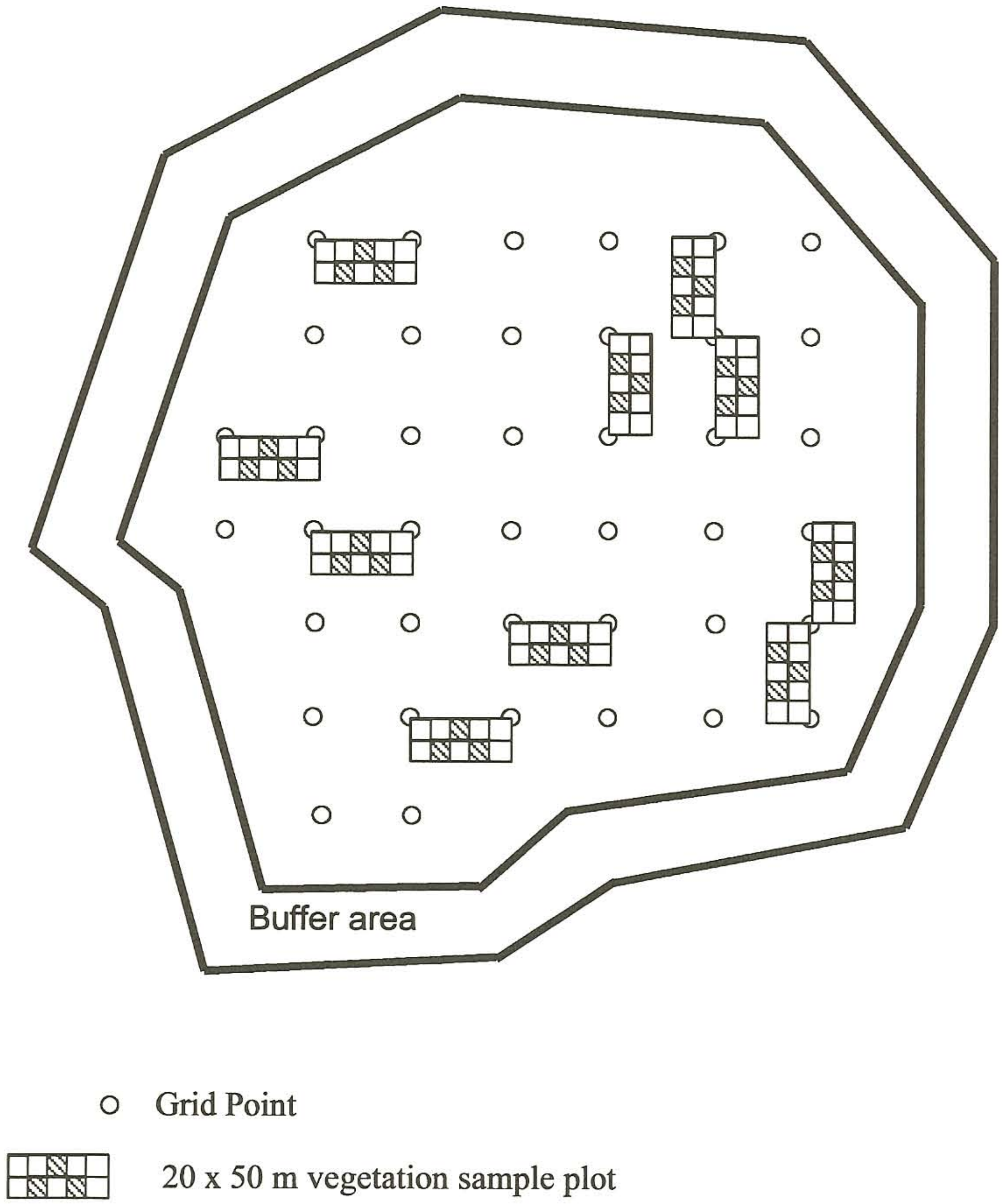

Figure 1. Typical treatment area layout for all sample and data collection.

Treatments

The levels of prescribed burning and thinning were defined by the protocols of the National Fire and Fire Surrogate Study to be sufficiently heavy so that if a wildfire occurred on a day with weather conditions at the 80th percentile during the wildfire season of the Piedmont of South Carolina (February through early April) 80% of the overstory trees would survive. Table 1 provides dates for each of the prescribed treatments in each of the treatment units. Thinnings were conducted from the winter of 2000 and 2001 to the spring of 2001. All prescribed burns were conducted in mid-April of 2001.

Table 1. Dates of prescribed treatments for each treatment unit.

Replication	Treatment	Dates
1	Thin A	8 March 2001 – 4 April 2001
2	Thin A	18 December 2000 – 18 January 2001
3	Thin A	5 February 2001 – 21 February 2001
1	Thin B	3 January 2001 – 18 January 2001
2	Thin B	25 January 2001 – 31 January 2001
3	Thin B	26 February 2001 – 7 March 2001
1	Burn	10 April 2001
2	Burn	12 April 2001
3	Burn	11 April 2001

Burning operations were conducted by the Clemson University Department of Forest Resources with assistance from USDA Forest Service personnel. A backing fire was set by hand along the northeast side of Replication 1 Burn to burn into the southwesterly wind. Strip headfires were set in parallel lines approximately 3 to 5 meters apart. Fire intensity was generally low with flame heights below 1 m. Heat-sensitive paints placed on tiles 1 m above ground showed temperatures generally below 150° Celsius throughout the treatment unit. Hot spots occurred in areas of southern pine beetle attacks. A backing fire was set by hand at the northern side of Replication 2 Burn to burn into the southerly wind. Strip headfires were set in parallel lines approximately 3 to 5 meters apart. Fire intensity was generally low with flame heights below 1 m. An area of high flame intensity occurred where erosion gullies created a chimney effect. This allowed flames to carry into the crowns of a few trees. A backing fire was set by hand along the northern side of Replication 3 Burn to burn into the southerly wind. Flanking fires approximately 10 meters long were set perpendicular to the backing fire and spot fires were set in areas not covered by the flanking fires. Fire intensity was moderate with flame heights generally between 1 and 2 m. Occasional hot spots occurred in areas where southern pine beetle attacks created high fuel loads.

Thinning operations were conducted by contract and were specified as a fifth-row thin with operator selection between rows. Small, merchantable-sized trees and diseased or insect-infested trees were selected in-between rows. A residual basal area of approximately 18 m^2/ha was desired on the thinned treatment units.

Bark Beetle Infestations

The presence and absence of bark beetles was monitored during the late fall of 2000 and 2001. At each grid point of a treatment unit, an ocular estimate of whether trees were infested with bark beetles was recorded. Signs of a bark beetle infestation included needle color change, pitch tubes along the bole of the tree, and wood dust in the crevices of bark or around the base of the tree. If it was determined that a tree or trees at a grid point was under attack, then the following data were recorded: tree species, bark beetle species responsible for mortality, and beetle attack stage.

Bark beetle species responsible for mortality were first determined by examining the location of pitch tubes along the bole of the tree and by peeling away an infected tree's bark to see the shape of egg galleries in the inner bark. Pitch tubes on trees attacked by black turpentine beetle are normally less than three meters from the base of the tree. Pitch tubes can be found at any distance on the bole of a tree attacked by the southern pine beetle or any of the three engraver beetles. Egg galleries constructed by the southern pine beetle follow an S-shaped, winding pattern. Galleries constructed by engraver beetles are often Y- or H-shaped. Galleries of black turpentine beetles follow no particular pattern. During the second year of monitoring bark beetle infestations, the species responsible for mortality was automatically determined to be the southern pine beetle.

Beetle attack stage was determined by examining the dominant color of infected pine needles at a grid point. Stage 1 trees had green needles and were those pines with new beetle attacks. Stage 2 trees usually contained developing broods of bark beetles and had needles fading from a light green or yellow to a light red. Pines that had been killed and recently vacated by bark beetles were stage 3 trees. Their needles were red in color.

The boundaries of beetle-infested spots from years 2000 and 2001 were mapped in February of 2002 using a GeoExplorer model 3 Global Positioning System (GPS) unit and GPS Pathfinder Office 2.70 software (Trimble Navigation Limited, Sunnyvale, CA). These areas were then overlaid in ArcView GIS 3.2 against existing treatment unit maps and size (hectares) was determined for each beetle infestation (Environmental Systems Research Institute, Inc, Redlands, CA).

Beetle Trapping

Collection of beetle specimens began in May of 2001 and ended in October of 2001. A total of 20 flight-intercept traps (Hines and Heikkenen 1977) were placed in each of the four treatments of a single replication for a seven-day period. In each treatment area, five grid points were randomly chosen for trap location. Following the seven-day trap period, traps were removed from the four treatments of that replication to the four treatments of the next replicate. Thus, for a three-week period, all treatment units had been sampled.

Each trap was constructed from two pieces of 30 by 40 centimeter medium-grade Plexiglas and one 30 cm diameter plastic funnel. Using a band saw, a 20 cm slit was cut into the long side of each of the pieces of Plexiglas. The two pieces were then connected at the slits and held together with epoxy glue. Four 2.5 cm slits, each at 90-degree angles from one another, were cut into the top of the rim of the plastic funnel using a band saw.

The connected pieces of Plexiglas were fitted and glued into these slits. Two small holes were drilled at the top of each of the two pieces of Plexiglas.

Traps were placed adjacent to a pine at a height that represented the average mid-bole height of the pines surrounding the particular grid point. A 25-pound test fishing line was tied to a metal weight and tossed over a live, thick pine branch. The end of the line was then tied through the holes at the top of the flight-intercept trap. A 125-milliliter plastic jar with a 3-cm wide mouth was half-filled with water and a drop of laundry detergent. The jar was fitted against the stem of the funnel, and the trap was hoisted in the air until a suitable height was reached. Lastly, the fishing line was tied to the bole of an adjacent tree. The trap was brought down after a week of sampling.

Contents of the plastic jar were examined in the laboratory. Only beetle species from the Scolytidae family were counted and only the five bark beetles of concern—southern pine beetle, black turpentine beetle, four-spined engraver, five-spined engraver, and six-spined engraver—were identified to species.

Oleoresin Flow

Oleoresin flow was measured during July 2001 on four randomly selected pines at the same five grid points per treatment unit that flight-intercept traps were placed. Using a 2.54-cm arc punch, one north-facing core and one south-facing core was drilled into the bole of the sampled tree at breast height. A piece of aluminum flashing was constructed into the shape of a funnel and placed below each of the circular tree cores. A pre-weighed 15-ml plastic centrifuge tube was placed below the flashing. After a 24-hour period of collecting resin flow, the tube was collected and weighed to determine the relative amount of resin flow in each pine over a 24-hour period (McCall 2000).

Tree Growth

Increment cores were removed during the winter of 2002 from the same four pines at each grid point that had been sampled for oleoresin flow. Each tree was cored to the pith using an increment borer (Haglof, Madison, WI). Mounting blocks were constructed out of 2.54 cm ponderosa pine shelving, cut into 32-cm x 2-cm dimensions. A 1-cm slot was routed out of the middle of each mounting block and two tree cores were glued into this slot. Once dried, the cores were sanded flat. Tree rings were counted to determine the age of the pines. A tree ring is comprised of a light colored ring—earlywood—and a darker colored ring—latewood. One ring represents one year's growth for that tree. The length of the past 10-years of earlywood and latewood growth was measured using a Bannister incremental measuring machine (Jacobi 1987).

Risk-Rating and Hazard-Rating

Risk and hazard-rating data were gathered on ten 50 x 20 meter sample vegetation plots within each of the treatment unit. These sample plots were established at grid points 2, 6, 10, 14, 18, 22, 26, 30, 34, and 38. Susceptibility of a treatment unit to an attack by the southern pine beetle (risk) was expressed as the estimated probability of infestation per acre (Hedden 1984). Data required included: pine type, percent slope, clay content of the surface soil, stand origin, disturbance information, radial growth during the last five years (mm), and 50-year site index (ft). Using these data, an appropriate stand condition score was calculated (Table 2). Pine type was determined by calculating the percentage of shortleaf pine to other pine species within the sample vegetation plot. These data were collected by a vegetation crew working for the Fire and Fire Surrogate Study. Slope percentage was determined at each of the ten sample plot grid points using a hand-held clinometer. Clay content of the surface soil was determined through personnel communication with the Fire and Fire Surrogate Study soil crew. Radial growth data were obtained from increment cores taken for the pine growth portion of the study. Because not all of the grid points where increment cores were taken matched up with where risk-rating data were taken, a five-year radial growth average from the 20 cored trees for each treatment unit was used. However, if the grid points

Table 2. Logistic models for determining probability of southern pine beetle infestations in the Piedmont of the southeastern US (Hedden 1984).

DISTURBED STANDS	UNDISTURBED STANDS
Natural Stand Score = 2.60 - .44(Pine Type) - .42(Slope) + .70(Clay) - .09(5-Year Radial Growth)	**Natural Stand Score** = 1.42 - .44(Pine Type) - .42(Slope) + .70(Clay) - .09(5-Year Radial Growth)
Planted Stand Score = 2.60 - .44(Pine Type) - .42(Slope) + .70(Clay) - .01(50-Year Site Index)	**Planted Stand Score** = 1.42 - .44(Pine Type) - .42(Slope) + .70(Clay) - .01(50-Year Site Index)
Pine Type: -1 if shortleaf pine > 50% of pine 1 if shortleaf pine <= 50% of pine Clay: 1 if clay content of surface soil > 28% -1 if clay content of surface soil <= 28%	Slope: -1 if slope >= 10% 1 if slope < 10%

were the same, an average of the four cored trees at that grid point was used. The 50-year site index was determined using the equation from Schumacher and Coile (1960):

LOG (site index) = LOG (average height of dominant and codominant trees in the stand) + 6.528 ([1/stand age] – [1/50])

The above mentioned vegetation crew collected tree height and stand age. The probability of an infestation was determined using the stand condition score and an adjustment factor for beetle population levels. This is a weighted factor used to obtain an absolute probability of infestation given a specified population level (Hedden 1984). The following equation was used to determine the adjustment factor:

Adjustment Factor = LN ([Number of infestations per 1000 acres of host type]/[1000 – Number of infestations per 1000 acres of host type])

The probability of infestation occurring per acre was determined using the following equation:

Probability = 1 – (1/[1 + e^{Adjustment Factor + Stand Condition Score}])

The potential for southern pine beetle infestation growth (hazard) was derived using the pine basal area per acre (Hedden and Billings 1979). Vegetation crews measured dbh on all trees within .05 ha of the 50 x 20 m sample vegetation plots. These measurements were used to calculate pine basal area for each of the plots using the following equation:

Basal Area = $([\{\text{Average pine dbh}/2\}^2](\text{pi}) \times (\text{number of pine trees})(20))/(2.471))$

Statistical Analysis

Simple regression analysis was used to determine correlations between host vigor characteristics and beetle activity across a stand level. Analysis of variance was used to determine treatment and replication differences. A multiple regression model, with numbers of southern pine beetles trapped and infestation area as the dependent variables, was developed to predict beetle activity. All statistical analyses were conducted with the SAS statistical software (SAS Institute Inc., Cary, N.C.).

RESULTS AND DISCUSSION

Bark Beetle Activity

Of the five targeted species of Scolytids, the southern pine beetle was by far the most abundant and influential within each of the treatment units (Figure 2). During the sampling period, populations of southern pine beetles throughout the Piedmont of South Carolina reached epidemic levels. Every bark beetle infestation discovered on the 12 treatment units was caused by the southern pine beetle. The overall number of southern pine beetles caught in flight-intercept traps throughout the six-month trapping period was 210 (Figure 2). Representatives of the other four targeted Scolytids were also caught during the trapping period, but in much smaller numbers compared to the southern pine beetle. Of the three species of Ips engraver beetles, the four-spined engraver was found in greater abundance (Figure 2).

Mapped southern pine beetle infestations can be found in Figures 3-6. The largest of these infestations was found in the following treatment units—Replication 2 Burn, Replication 1 Thin A, Replication 3 Thin B, and Replication 1 Control (Table 3).

Southern Pine Beetle Response to Treatments

Initial examination of spot infestation and trap catch data indicated that both prescribed burning and thinning had no effect on short-term incidence of southern pine beetles. Southern pine beetle infestations were found on all of 12 treatment units. The size of these infestations did not differ significantly among the four treatments ($p=.6248$) or the three replicates ($p=.4188$) (Table 4). Figure 7 illustrates the southern pine beetle trap catch in the four treatment units. Total number of southern pine beetles trapped in burn units was 25, thin A units was 43, thin B units was 48, and control units was 97. However, there were no significant differences in trap catch among treatments ($p=.4849$)

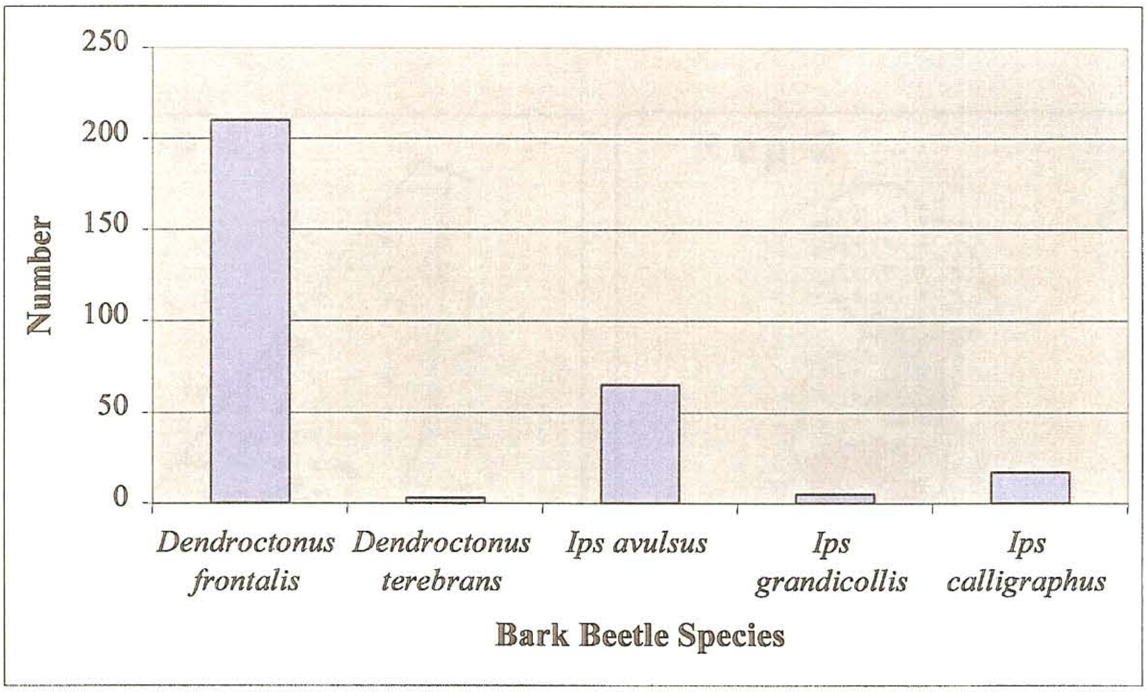

Figure 2. Total number of targeted bark beetles trapped in flight-intercept traps from May through October 2001.

Table 3. Area of southern pine beetle infestations in each of the 12 treatment units.

Rep	Treatment	2000 Infestation (ha)	2001 Infestation (ha)
1	Burn	0.00	0.29
2	Burn	2.06	3.31
3	Burn	0.64	1.31
1	Thin A	0.00	4.81
2	Thin A	0.00	0.49
3	Thin A	0.00	0.22
1	Thin B	1.16	0.00
2	Thin B	0.00	0.14
3	Thin B	1.36	1.26
1	Control	4.73	4.24
2	Control	0.00	0.78
3	Control	0.00	0.38

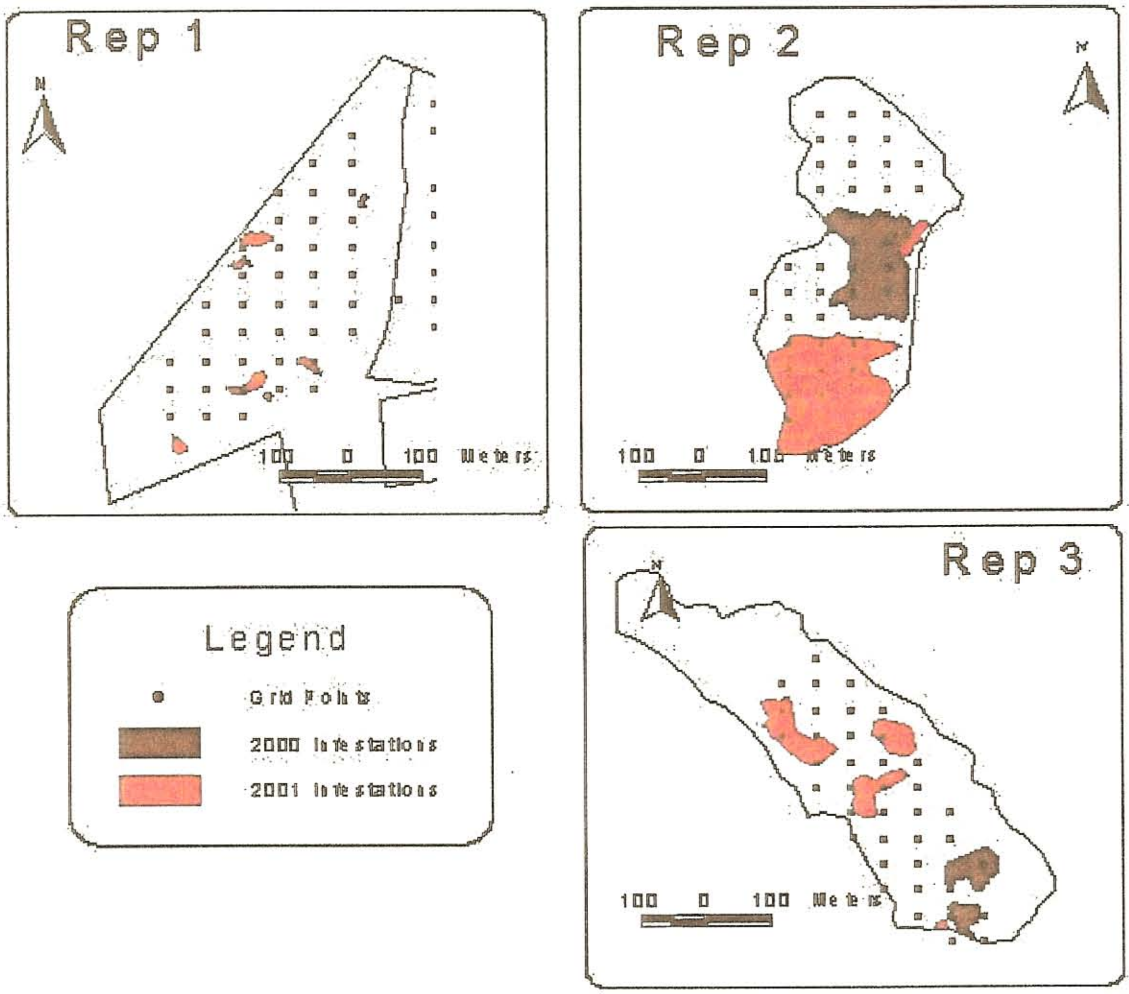

Figure 3. Southern pine beetle infestations from year 2000 and 2001 for each Burn unit.

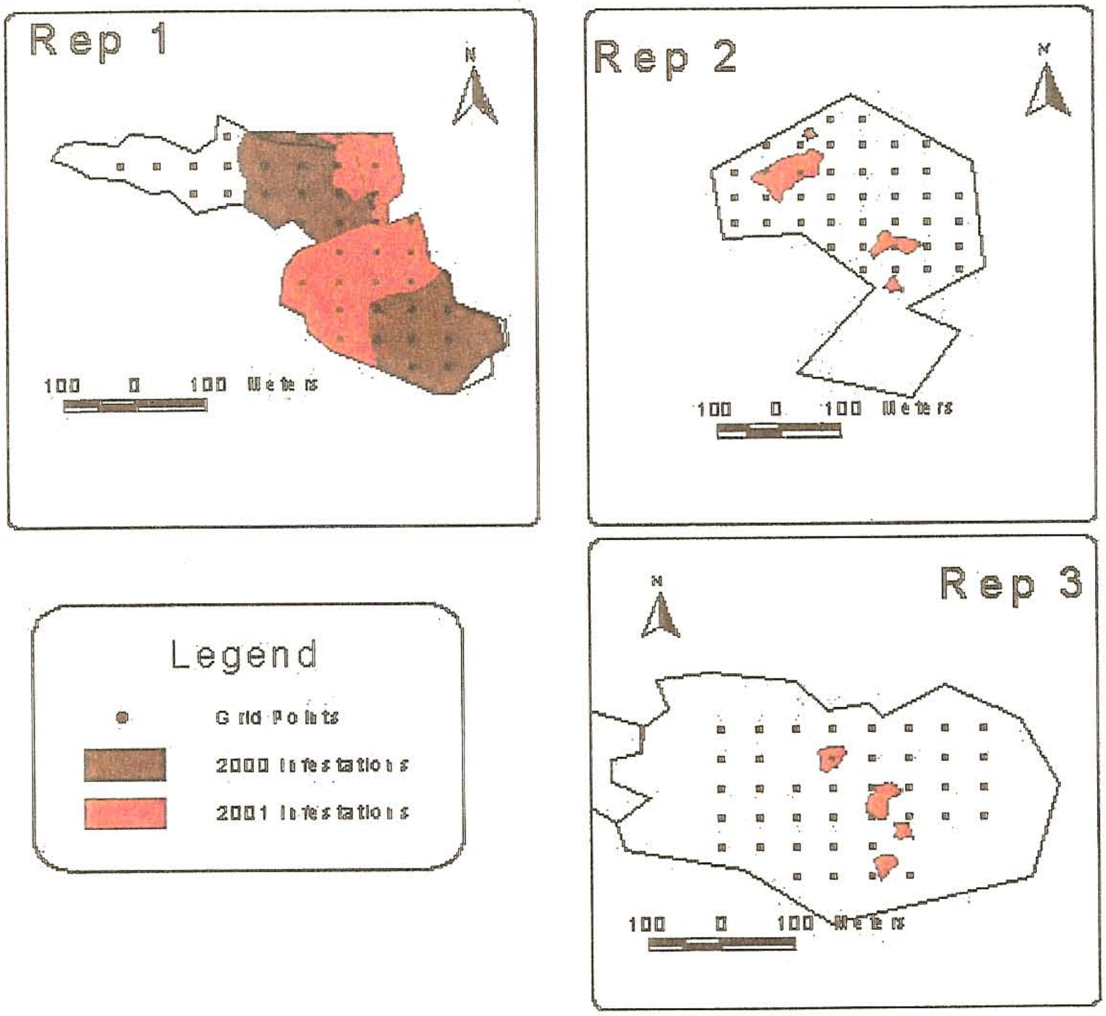

Figure 4. Southern pine beetle infestations from year 2000 and 2001 for each Control unit.

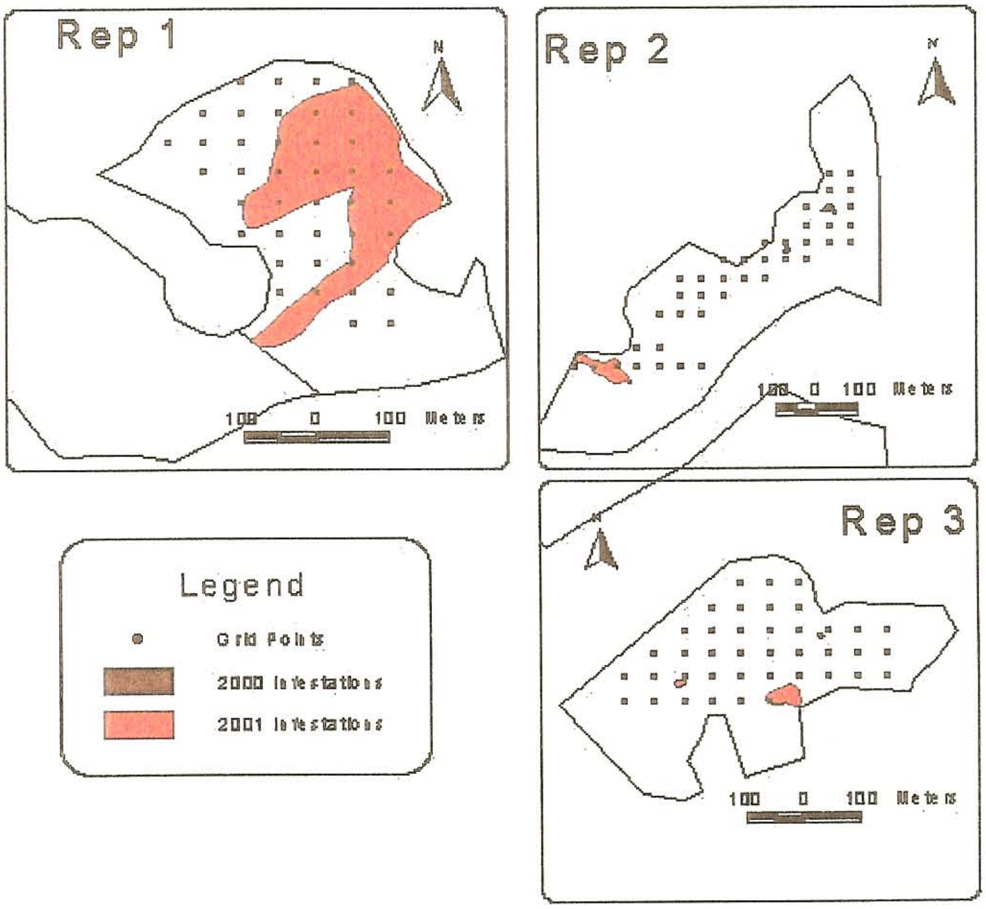

Figure 5. Southern pine beetle infestations from year 2000 and 2001 for each Thin A unit.

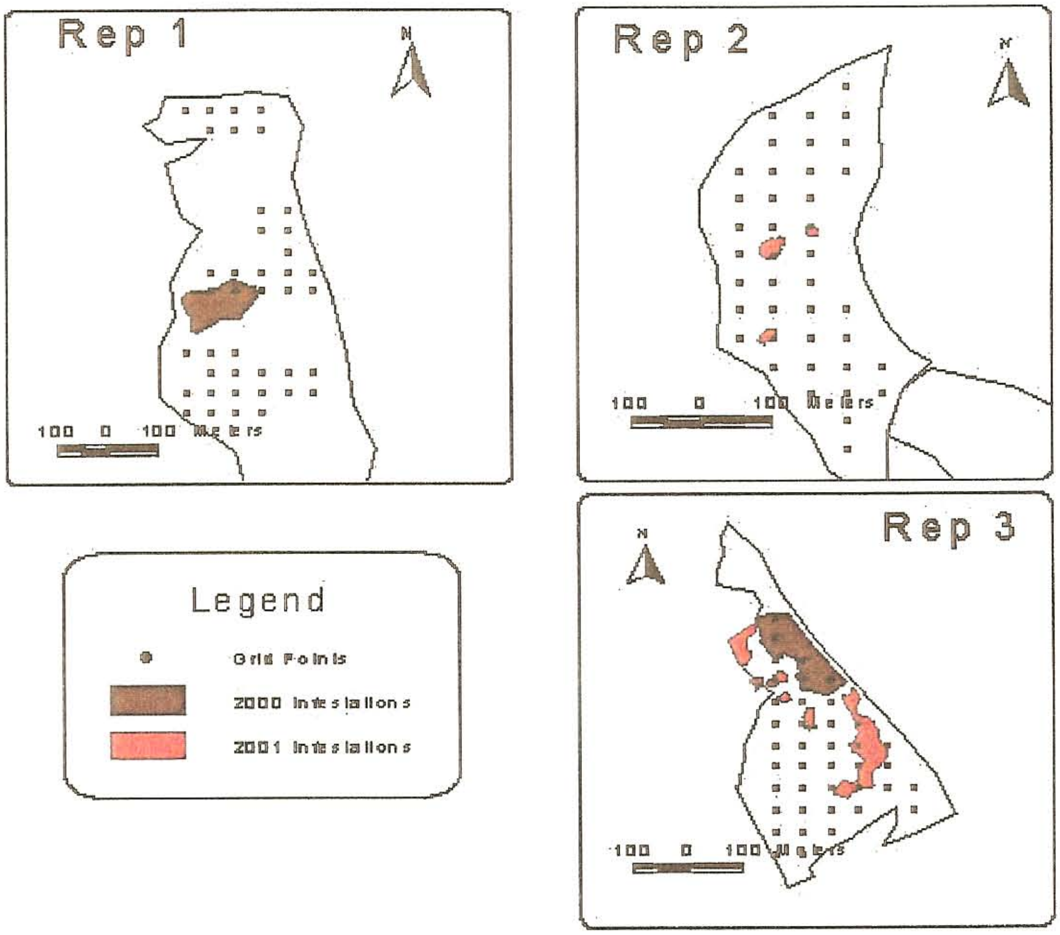

Figure 6. Southern pine beetle infestations from year 2000 and 2001 for each Thin B unit.

Table 4. Analysis of variance for southern pine beetle infestation sizes between treatments and replications.

Source	DF	Sum of Squares	Mean Square	F value	Pr > F
Model	5	13.11	2.62	0.78	.5993
Error	6	20.21	3.37		
Corrected Total	11	33.32			

R-Square	Coeff. Var.	Root MSE	Infestation Mean
.3935	136.71	1.84	1.34

Source	DF	Type I SS	Mean Square	F value	Pr > F
Treatment	3	6.31	2.10	0.62	.6248
Replication	2	6.80	3.40	1.01	.4188

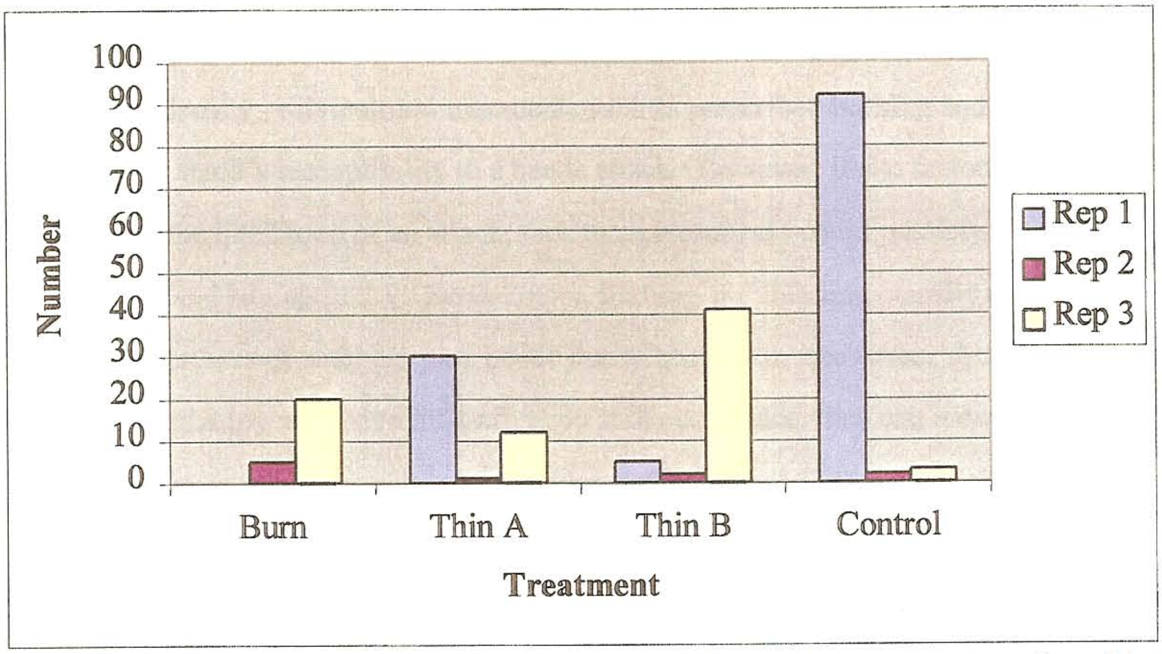

Figure 7. Total number of southern pine beetles trapped in flight-intercept traps from May to October in each of the 12 treatment units.

and among replications (p=.1671), and there was no interaction between treatments and replications (p=.1260) (Table 5). Figure 8 illustrates the total trap catch averaged over replication per treatment unit with associated standard deviations. The non-homogeneous variance in these data was explained by presence or absence of a flight-intercept trap in the path of an active southern pine beetle spot head. If a trap was not up when an active spot head moved through a grid point, then trap catch numbers were much lower than if the trap had been up when the spot moved through. This may help to explain why trap catch numbers were so disparate between treatment units that had large southern pine beetle infestation sizes—Replication 1 Control, Replication 1 Thin A, Replication 2 Burn, and Replication 3 Thin B. Complete trap catch data are found in Appendix B.

Coster and Searcy (1981) reported that site factors, rather than stand condition, were related to the occurrence of infestations of southern pine beetle in the Piedmont. These site factors include percent of clay in the soil surface, slope percentage, and specific tree density. Silvicultural treatments such as prescribed burning and thinning may reduce a stand's susceptibility to a beetle attack. However, if site factors are present that increase the likelihood of an attack, then these treatments could possibly play no part in reducing stand susceptibility. Furthermore, burning and thinning actually can cause short-term increases of southern pine beetle due to short-term tree stress. Although, burning and thinning may have little effect on spot occurrence, they can reduce overall beetle losses by reducing pine density (Hedden and Billings 1979).

Resin Flow and Beetle Activity

Oleoresin flow was not affected by any of the treatments (p=.7251) (Table 6). Total amount of resin sampled during the mid-summer of 2001 in each of the treatment units can be found in Table 7. There did appear to be a stand level relationship between southern pine beetle activity and total oleoresin flow. A regression analysis, using the logarithm of total 24-hour resin weight within a treatment unit as the independent

Table 5. Analysis of variance for southern pine beetle trap catch between treatments, replications, and treatment by replication.

Source	DF	Sum of Squares	Mean Square	F value	Pr > F
Model	11	1830.33	166.39	1.53	.1528
Error	48	5228.40	108.93		
Corrected Total	59	7058.73			

R-Square	Coeff. Var.	Root MSE	Trap Catch Mean
.2593	288.57	10.44	3.62

Source	DF	Type I SS	Mean Square	F value	Pr > F
Treatment	3	270.60	90.20	0.83	.4849
Replication	2	404.63	202.32	1.86	.1671
Treatment * Replication	6	1155.10	192.52	1.77	.1260

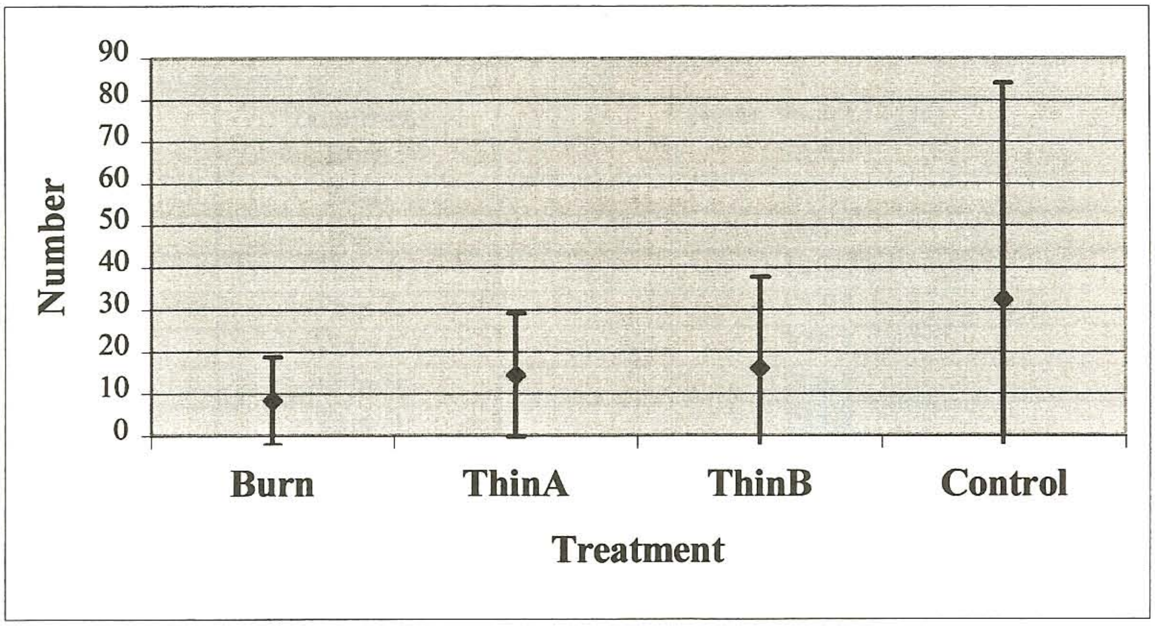

Figure 8. Average and standard deviation of southern pine beetles caught in each treatment type of the three replicates from May through October 2001.

Table 6. Analysis of variance between total oleoresin flow (gm) and treatments.

Source	DF	Sum of Squares	Mean Square	F value	Pr > F
Model	3	621.51	207.17	0.44	.7251
Error	56	26355.35	470.63		
Corrected Total	59	26976.86			

R-Square	Coeff. Var.	Root MSE	Resin Mean
.023	59.09	21.69	36.71

Source	DF	ANOVA Sum of Squares	Mean Square	F value	Pr > F
Treatment	3	621.51	207.17	0.44	.7251

Table 7. Total 24-hour resin weight from the sample of 20 trees in each treatment unit during the mid-summer of 2001.

Rep	Treatment	Resin Weight (gm)
1	Burn	158.9
2	Burn	123.2
3	Burn	266.9
1	Thin A	116.0
2	Thin A	183.4
3	Thin A	320.3
1	Thin B	206.1
2	Thin B	193.9
3	Thin B	151.0
1	Control	86.8
2	Control	159.0
3	Control	237.3

Table 8. Analysis of variance for the regression model (trap catch = log of total resin weight).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	2619.50	2619.50	5.41	.0424
Error	10	4845.42	484.54		
Corrected Total	11	7464.92			

Root MSE	22.01	**R-Square**	.3509
Number Mean	17.58	**Adj. R-Square**	.2860
Coefficient of Variation	125.19		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t value	Pr > t
Intercept	1	233.04	92.88	2.51	.0310
Log Resin Weight	1	-96.30	41.42	-2.33	0.0424

Table 9. Analysis of variance for the regression model (infestation size = log of total resin weight).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	18.99	18.99	14.85	.0032
Error	10	12.78	1.28		
Corrected Total	11	31.77			

Root MSE	1.13	**R-Square**	.5977
Infestation Size Mean	1.44	**Adj. R-Square**	.5574
Coefficient of Variation	78.68		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t value	Pr > t
Intercept	1	19.78	4.77	4.15	.0020
Log Resin Weight	1	-8.20	2.13	-3.85	.0032

variable, was run against both the total numbers of southern pine beetles trapped in a treatment unit, and the overall size of 2001 infestations (Tables 8 and 9). There was a significant relationship between numbers of beetles trapped and the log of total resin weight ($p=.0424$, $R^2=.3509$) (Figure 9) and between the size of beetle infestations and the log of total resin weight ($p=.0020$, $R^2=.5977$) (Figure 10). The observed pattern suggests that as total resin flow across a treatment unit increased, beetle activity within that stand decreased. The three treatment units with the largest beetle infestations in year 2001—Replication 1 Control, Replication 1 Thin A, and Replication 2 Burn—had the lowest total resin weight of all treatment units. These results are consistent with the previous understanding that the oleoresin system of pines is the primary defensive mechanism against attacking beetles (Paine et al. 1997).

Radial Growth, Tree Age, and Beetle Activity

Average radial growth data and tree ages for each of the treatment units can be found in Table 10. Younger stands, such as Replication 1 Thin A, Replication 3 Thin B, Replication 1 Thin B, and Replication 1 Control, had higher 5- and 10-year growth rates than stands with older trees. Latewood percentages for both recent 5- and 10-year growth bands can also be found in Table 10. As expected, there was a significant inverse relationship between tree age and radial growth (Figures 11 and 12). Hicks et al. (1978) determined that recent 5-year radial growth, adjusted for both age and the reciprocal of age, could be used as a measure of tree vigor. They found that radial growth was reduced in trees attacked by southern pine beetles compared to unattacked trees. Recent 5-year and 10-year radial growth patterns did not show the same relationship with beetle activity in this study (Figures 13 and 14). No significant relationship was noticed between numbers of beetles trapped and recent 5- and 10-year radial growth ($p=.2599$ and $p=.1734$, respectively). When tree age was taken into account, a significant correlation was noticed ($p=.0297$ and $p=.0665$, respectively) (Figures 15 and 16).

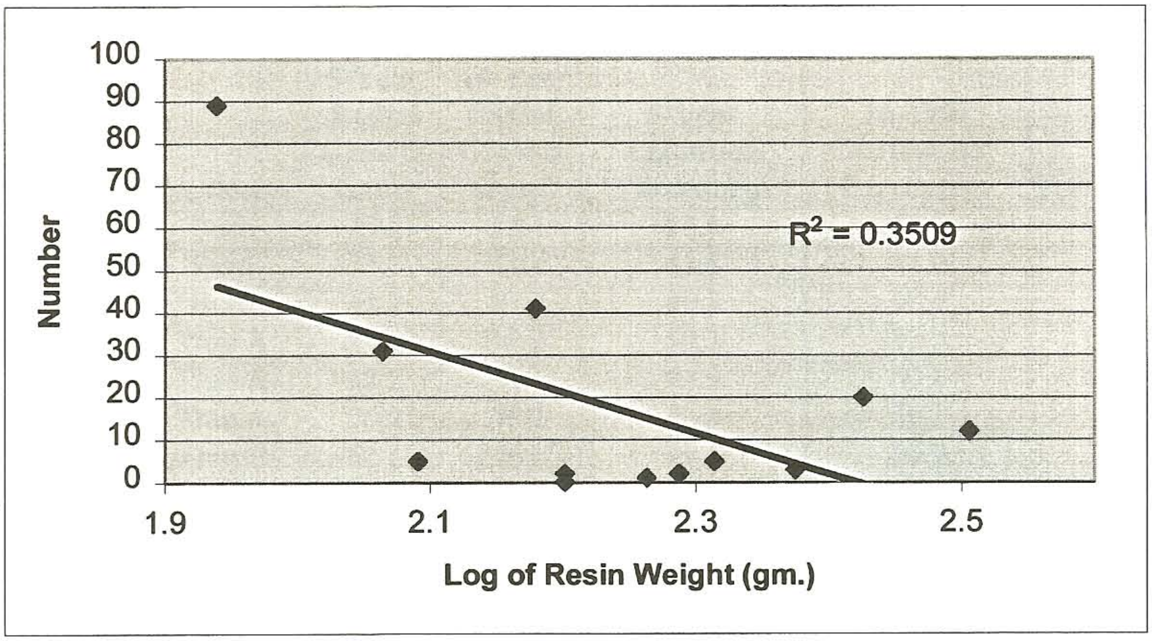

Figure 9. Total number of southern pine beetles trapped in each treatment unit compared to the log of 24-hour total resin weight in each treatment unit.

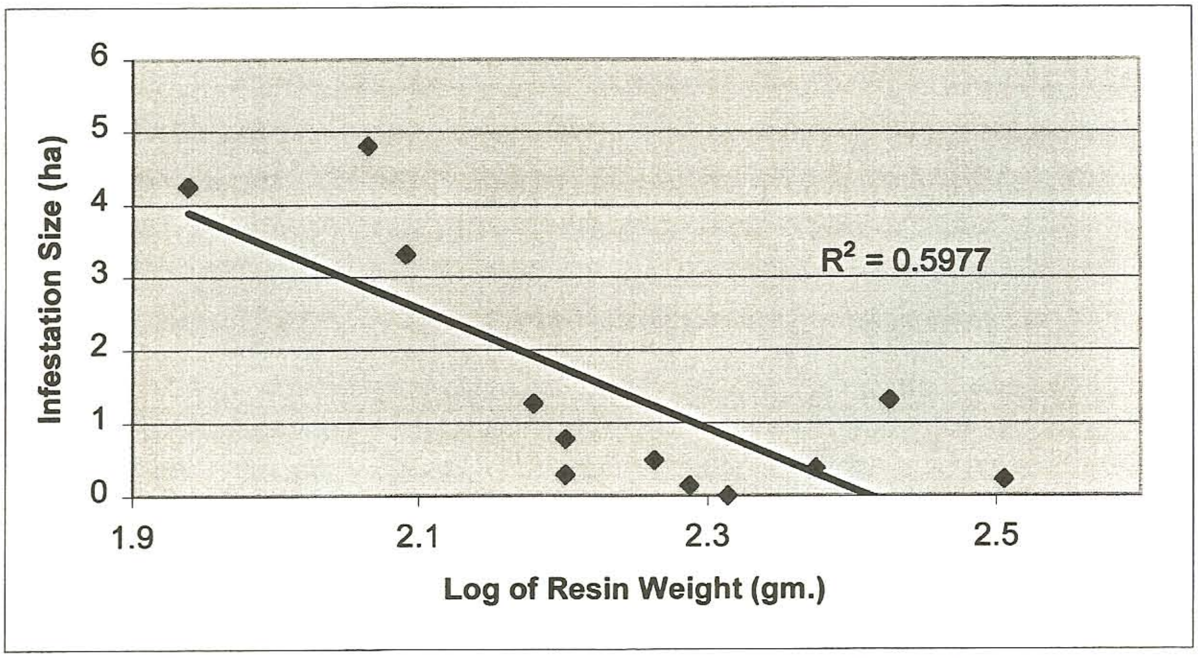

Figure 10. Total size of 2001 southern pine beetle infestations within each treatment unit compared to the log of 24-hour total resin weight within each treatment unit.

Table 10. Mean radial growth data taken from 20 pines per treatment unit.

Rep	Treatment	5-Year Radial Growth (mm)	10-Year Radial Growth (mm)	5-Year Latewood Percentage	10-Year Latewood Percentage	Tree Age
1	Burn	25.8	53.1	43.3	45.6	45
2	Burn	32.1	71.4	41.8	44.0	45
3	Burn	41.2	87.4	46.3	48.5	34
1	Thin A	81.6	216.2	39.3	33.5	13
2	Thin A	38.2	82.6	44.9	50.1	43
3	Thin A	36.2	79.2	46.9	50.1	34
1	Thin B	52.2	126.2	49.5	50.9	20
2	Thin B	29.4	60.8	43.8	46.9	46
3	Thin B	60.5	148.5	45.1	41.1	18
1	Control	40.1	108.3	40.2	44.5	20
2	Control	34.1	72.0	44.1	48.4	35
3	Control	27.7	65.8	51.8	54.5	35

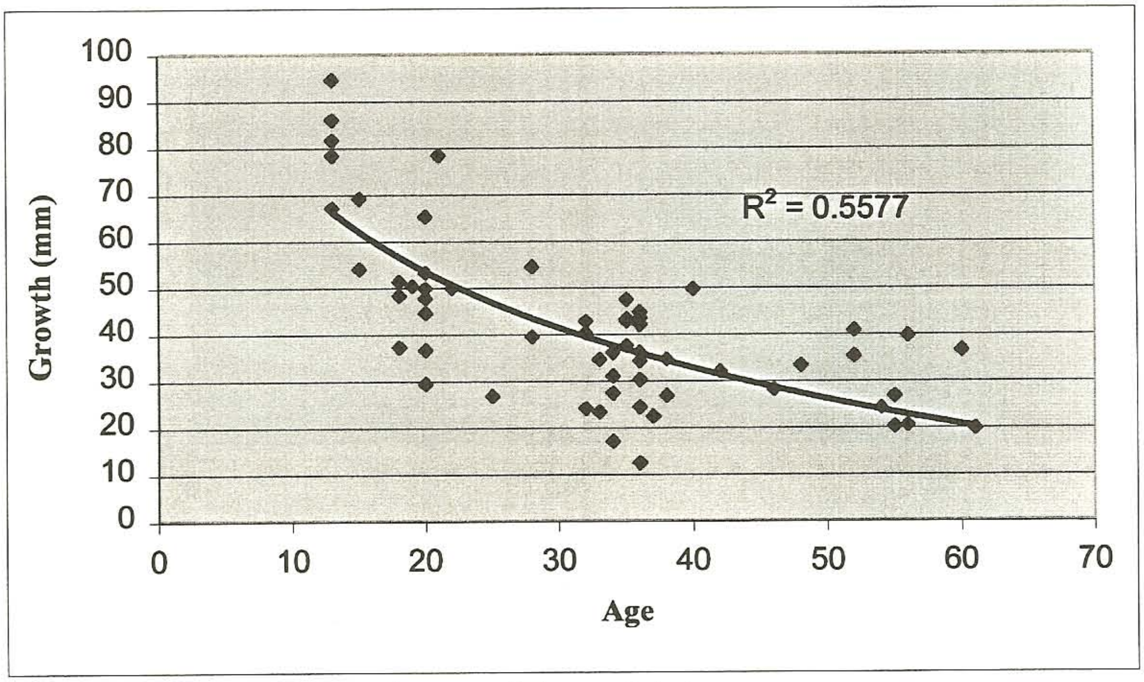

Figure 11. Relation of recent 5-year radial growth to tree age.

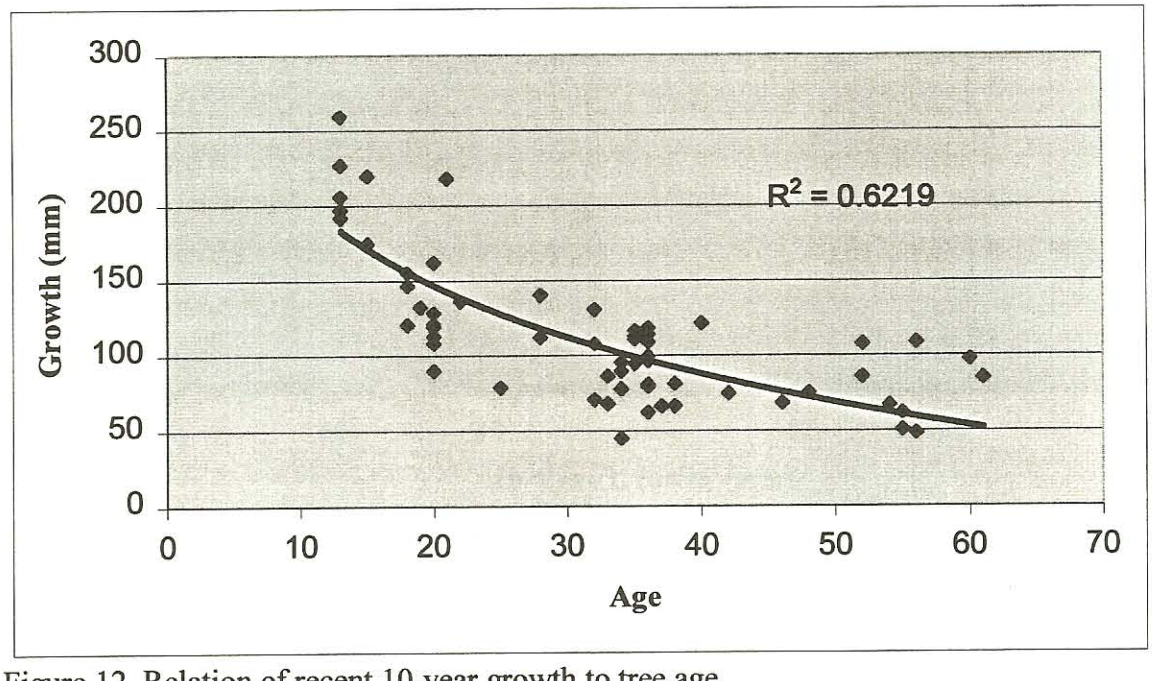

Figure 12. Relation of recent 10-year growth to tree age.

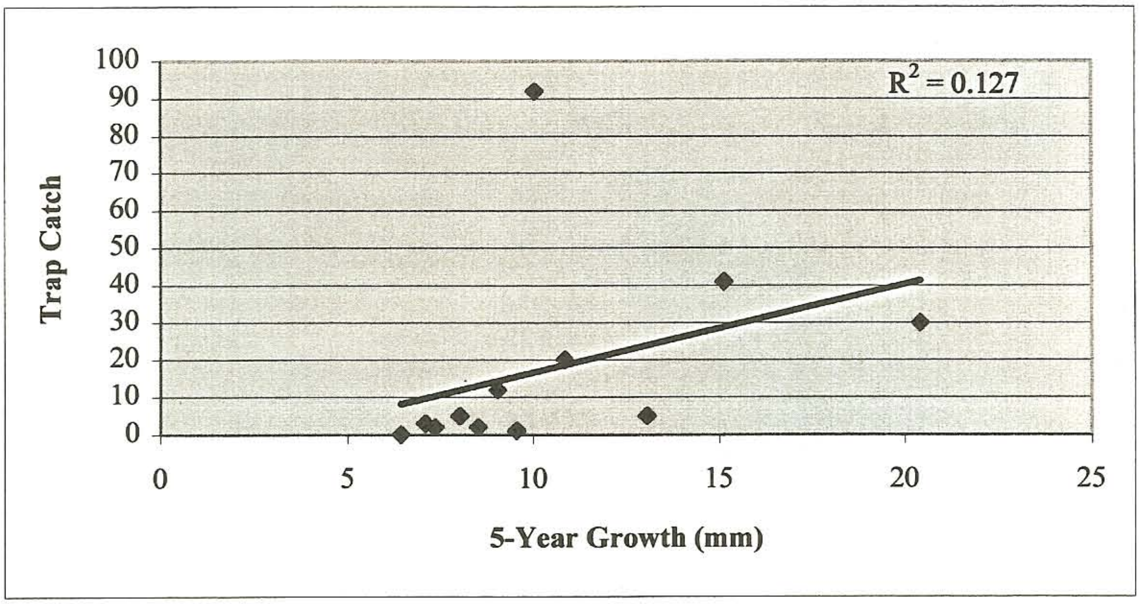

Figure 13. Relationship of number of southern pine beetles trapped to mean recent 5-year radial growth.

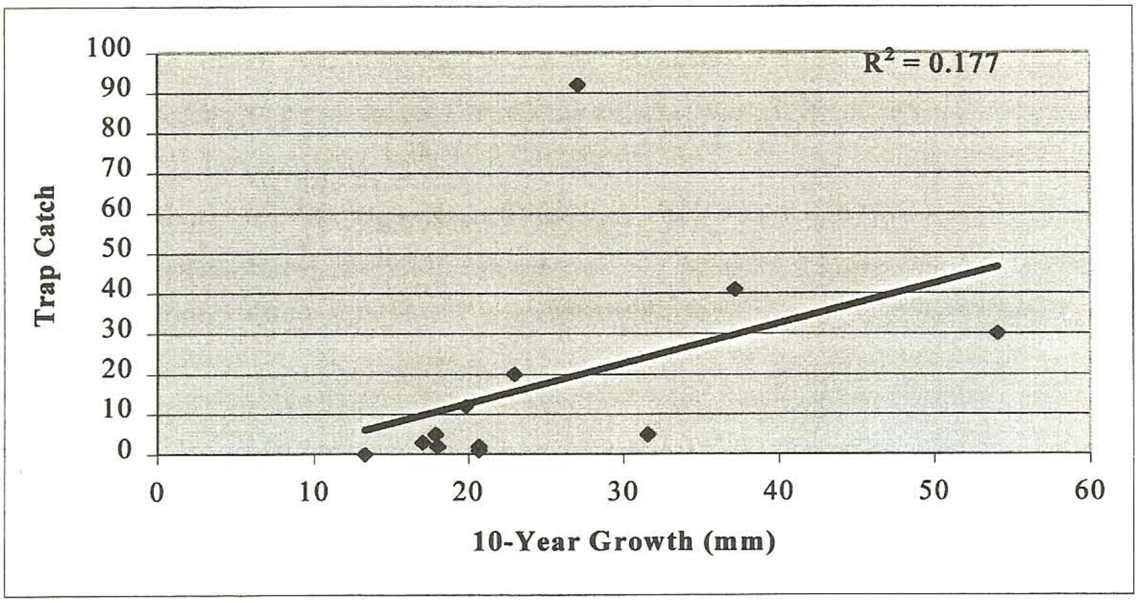

Figure 14. Relationship of number of southern pine beetles trapped to mean recent 10-year radial growth.

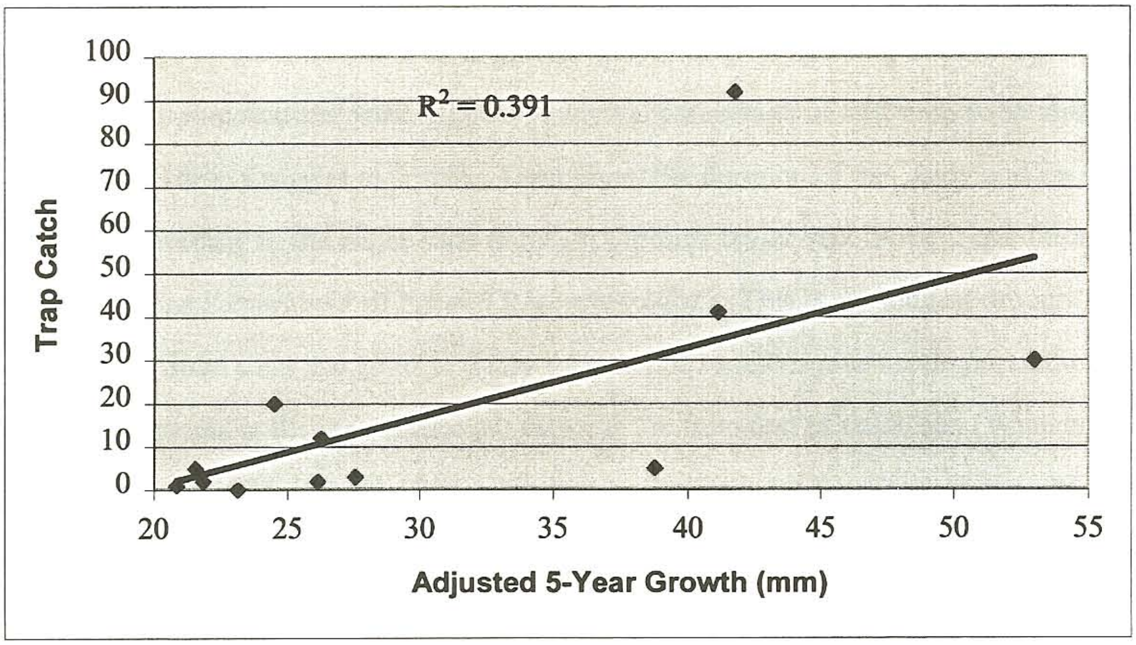

Figure 15. Relationship of number of southern pine beetles trapped to mean recent adjusted 5-year radial growth. The formula for adjusted 5-year radial growth is y = (5 year radial growth – (800.8/age + 11.78)) x -1.

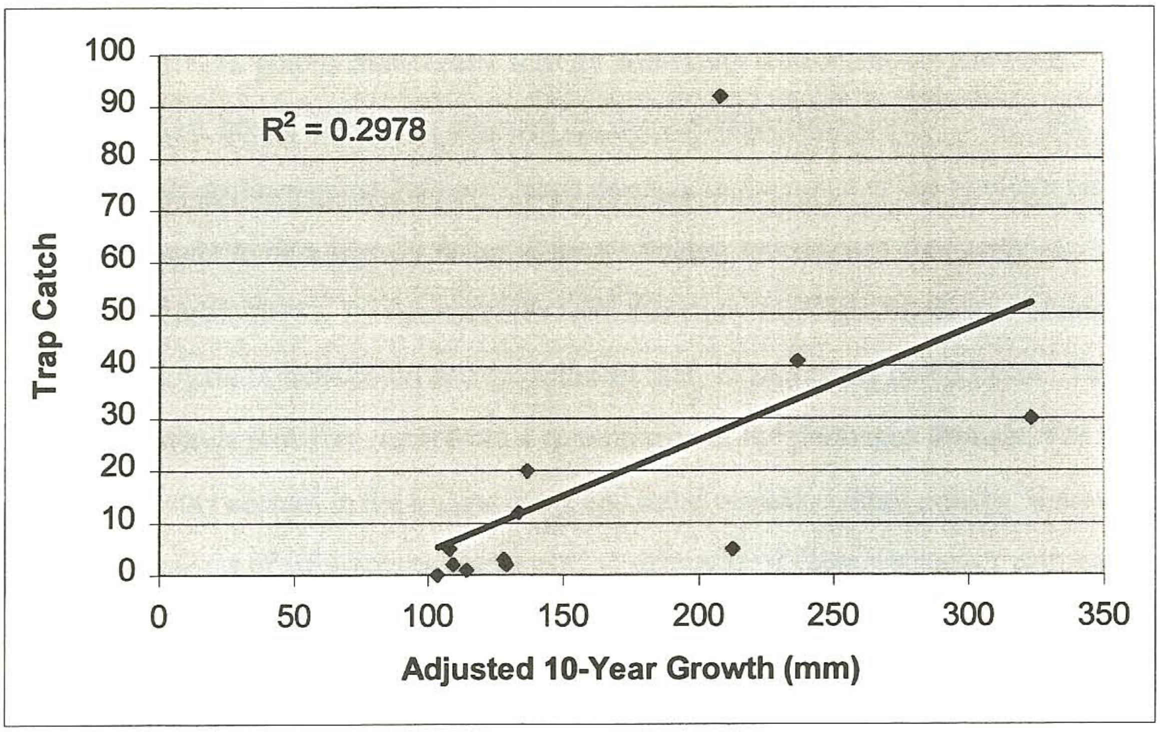

Figure 16. Relationship of number of southern pine beetles trapped to mean recent adjusted 10-year radial growth. The formula for adjusted 10-year radial growth is y = (10 year radial growth – (3271.4/age + 17.45)) x -1.

Amount of latewood was measured for recent 5- and 10-year bands and expressed as a percentage of the total width of an annual growth ring. It has long been thought that periods of extreme summer water deficits lower the percentage of latewood in an annual ring (Zahner 1968, Cregg et al. 1988). Throughout the duration of this study and for the two years preceding it, the entire state of South Carolina underwent drought conditions (South Carolina Department of Natural Resources 2002). This is the longest drought period in the State since the 1950's. Early accounts of southern pine beetle populations report that drought is the most important factor in the initiation of outbreaks (Wyman 1924, Craighead 1925, Hetrick 1949). It was hypothesized that the effect of drought would manifest itself more clearly in the latewood bands of the past five years. Averages of latewood percentages across treatment units were obtained from the radial growth data. A regression analysis, using recent 5-year latewood percentages as the independent variable, was run against both the total numbers of southern pine beetles trapped in a treatment unit ($p=.1197$) and the overall size of the infestation ($p=.0044$) (Figures 17 and 18). Although both graphs show beetle activity decreasing with increased latewood percentage, 2001 beetle infestation size was the more statistically significant variable.

Growth declines in natural pine stands throughout the range of the southern pine beetle are thought to be a primary factor in the increasing severity and frequency of outbreaks (Hedden 1978). Increment cores from this study highlight the degree of poor growth. Only 13% of trees cored had grown more than 15 mm in the past 5 years. These poor growth trends probably result from a combination of the prolonged drought, site factors (high clay content in the soil surface), and stand condition (high pine basal area).

An analysis of variance was conducted to determine if there were any treatment or replication differences in the past year's radial growth (Table 11, Figure 19). Overall, the thinned treatments experienced more radial growth during year 2001 than any other treatment. Belanger et al. (1993) suggested thinning as a way to reduce a stand's susceptibility to a southern pine beetle attack. Increased tree growth may also reduce the rate of spot growth due to increased vigor. While thinning may have increased radial

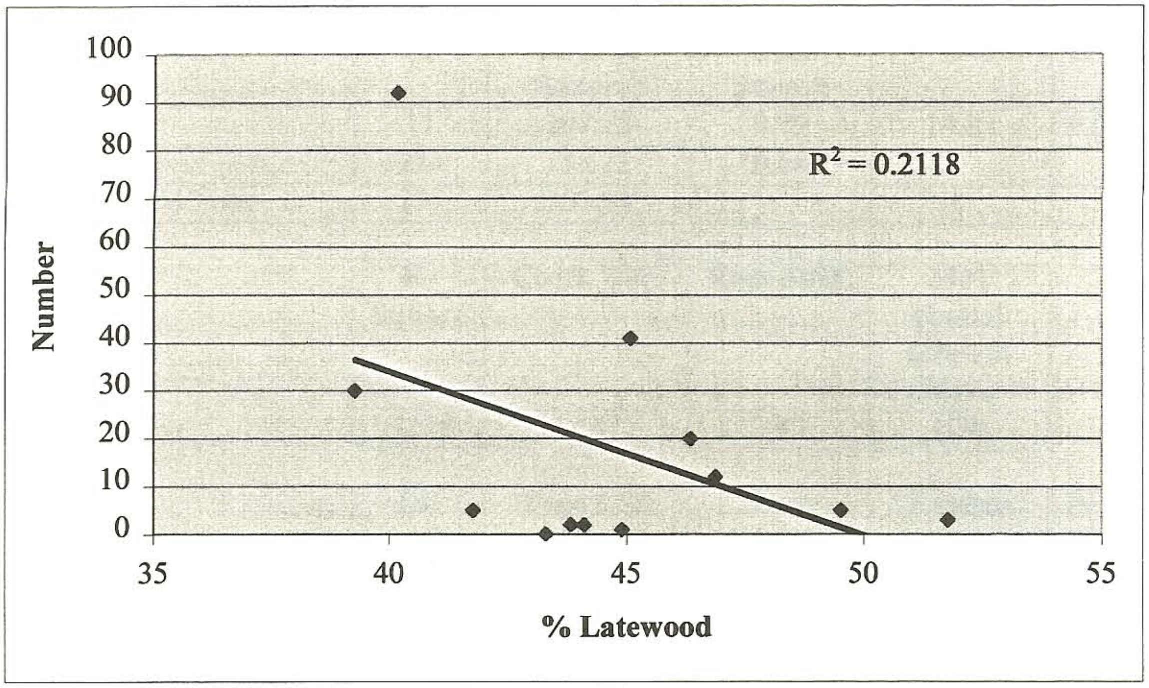

Figure 17. Total number of southern pine beetles trapped compared to the mean latewood percentages across each treatment unit.

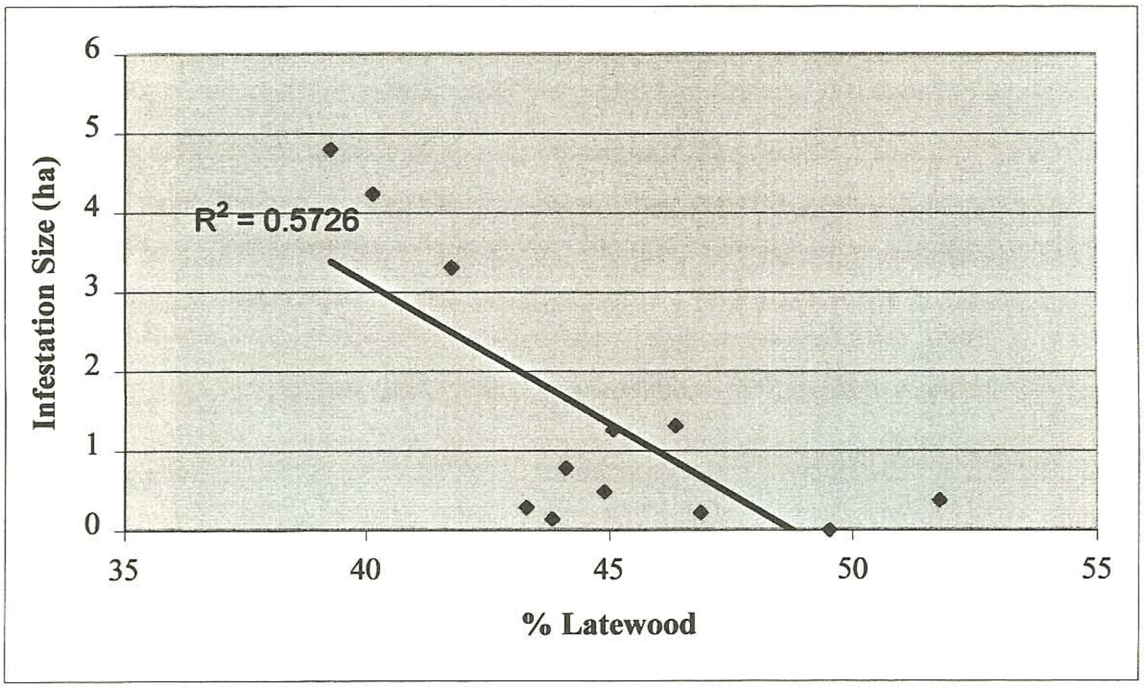

Figure 18. 2001 southern pine beetle infestation size compared to the mean latewood percentages across each treatment unit.

Table 11. Analysis of variance between 2001 radial growth patterns and different treatments, replications, and treatments by replications.

Source	DF	Sum of Squares	Mean Square	F value	Pr > F
Model	11	107.72	9.79	14.32	<.0001
Error	224	153.22	0.68		
Corrected Total	235	260.94			

R-Square	Coeff. Var.	Root MSE	2001 Radial Growth Mean
.4128	47.67	0.83	1.74

Source	DF	Type I SS	Mean Square	F value	Pr > F
Treatment	3	50.64	16.88	24.68	<.0001
Replication	2	15.95	7.98	11.66	<.0001
Treatment * Replication	6	41.12	6.85	10.02	<.0001

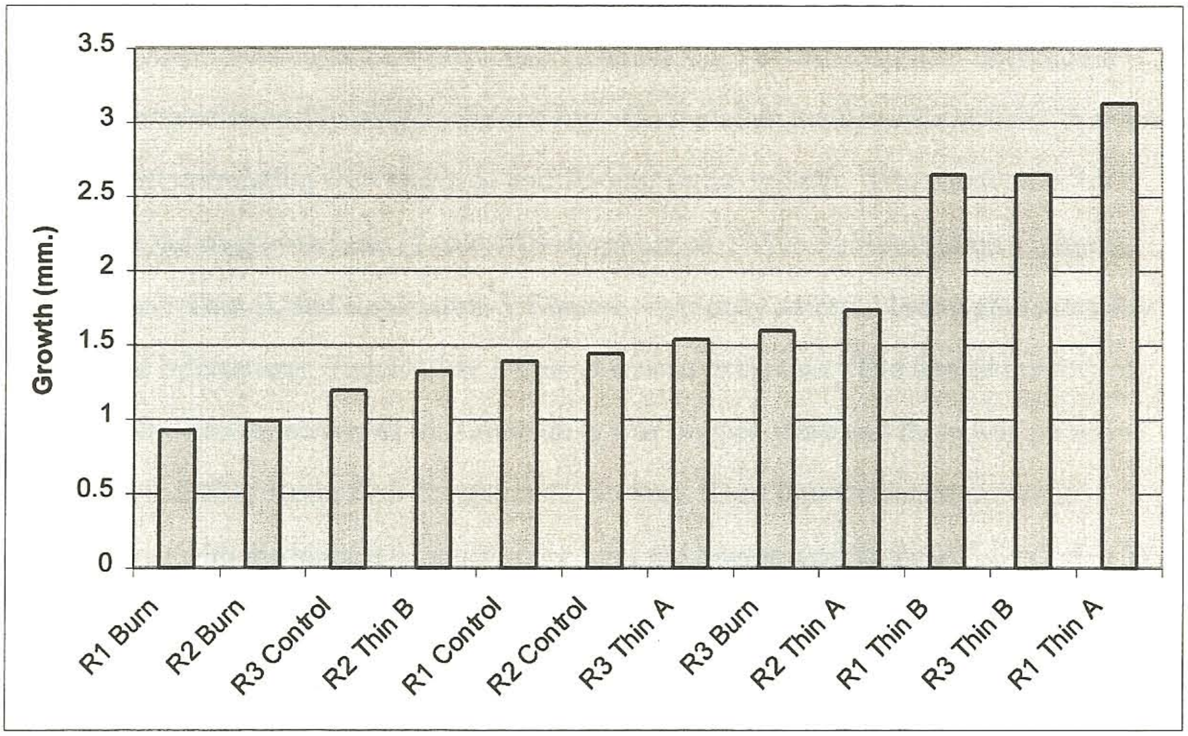

Figure 19. Mean 2001 radial growth for pines (n=20) in each of the 12 treatment units.

growth during the past year, it is yet to be seen whether this treatment will have long-term effects on the reduction of beetles within a stand. As this study illustrates, radial growth increases will not ensure reduced beetle activity during epidemic population levels.

Growth-Differentiation, Water Stress, and Tree Resistance

Most southern pine beetle infestations are established in the spring. During this time of year, water and nutrient availability to trees is relatively high. When water is not limited, photosynthate is primarily allocated to tissue expansion and not into resin production. Therefore, initial infestations, which usually consist of few pines, can be easily established by a relatively small number of emerging pioneer beetles. As spring turns to summer, both seasonal and diurnal water deficits facilitate the allocation of photosynthate to resin production as growth slows down. During this time of year, beetles will mass attack trees adjacent to those inhabited during the spring. By reducing resin production, extreme drought can increase the likelihood of successful mass attack.

As mentioned earlier, 24-hour resin flow averaged across treatment units had a strong inverse relationship with beetle activity. On the other hand, beetle activity showed a mild direct correlation with recent 5- and 10-year radial growth. Treatment units with the highest radial growth rates (Table 10)—Replication 1 Thin A, Replication 1 Thin B, Replication 3 Thin B, and Replication 1 Control—typically suffered heavy pine mortality from beetle infestations. Replication 1 Thin B was an exception. The fewest number of southern pine beetles across all treatment units was trapped there and there was no active infestation in 2001. Resin flow comparisons between these four treatment units show that the three with the highest beetle activity have the lowest total 24-hour flow (Table 7). Replication 1 Thin B had one of the highest flow rates.

Effects of prolonged drought on beetle incidence are complicated and not well understood. In this study, a decline in late spring and early summer rainfall probably caused an early transition from earlywood to latewood. This would have provided the pines greater resin defense earlier in the season compared to years with adequate late spring rainfall. However, the extreme drought conditions may have resulted in an overall reduction of secondary metabolites which would cause an increase in tree susceptibility to a beetle attack.

Stand Condition and Beetle Activity

The degree of stand vulnerability (risk) and susceptibility (hazard) was expressed as an index of potential loss. This index was a product of the estimated probability of infestation per acre (Hedden 1984) and the pre- and post-treatment basal areas (Table 13). As Coster and Searcy (1981) found in the Piedmont of Georgia, regression analysis revealed no basal area differences between treatment units with high and low beetle activity.

During this study, stands were found with differing risk- and hazard-rating ranks. Increased slope percentage has been attributed to spot occurrence within the Piedmont. However, Replication 1 Thin A had one of the lowest average slope percentages and one of the most active beetle populations. Another thinned stand, Replication 3 Thin B, had the highest average slope percentage and very little southern pine beetle activity. Reductions in basal area from thinning may have had some impact on spot growth. Replication 1 Thin B was the only stand to not develop a beetle infestation in 2001 despite having one in 2000. Decreases in basal area from year 2000 to year 2001 in Replication 2 Burn and Replication 3 Thin B did not seem to slow spot activity within these stands.

The long-term effects of thinning on potential loss from the southern pine beetle can be seen by comparing the index of potential loss before treatment with the index of potential loss more than one year after treatment (Table 13). Potential loss in thinned stands is less than one-half that in the unthinned stands. Disturbance effects from thinning occur during the year after treatment as pines recover from thinning shock. Afterwards, the benefits of reduced stand density on spot growth and tree vigor take effect.

Table 12. Risk and hazard rating means across treatment units. The index of potential loss is a product of the estimated probability of infestation per hectare and the basal area. Logistic models for determining the estimated probability of infestation can be found in Table 2. A disturbance factor is part of this equation. Probability A recognizes thinned and burned stands as a non-disturbance; probability B recognizes thinned and burned stands as a disturbance. Basal area estimates are given in m^2/ha.

Replication	Treatment	Basal Area Year 2000	Basal Area Year 2001	Index of Potential Loss—Pre-treatment (BA Year 2000*Probability A)	Index of Potential Loss—One-Year Post-treatment (BA Year 2001*Probability B)	Index of Potential Loss—More Than One-Year Post-Treatment (BA Year 2001*Probability A)
1	Burn	12.59	12.36	0.51	1.58	0.50
2	Burn	23.30	19.89	0.59	1.62	0.51
3	Burn	23.17	18.69	0.20	0.62	0.19
1	Thin A	22.28	16.38	2.38	5.36	1.76
2	Thin A	15.39	11.21	0.37	0.94	0.30
3	Thin A	18.45	14.53	0.23	0.59	0.18
1	Thin B	24.64	15.87	0.07	0.14	0.04
2	Thin B	27.20	16.07	1.30	2.19	0.70
3	Thin B	23.17	16.26	0.05	0.12	0.04
1	Control	26.31	26.34	0.24	0.24	0.24
2	Control	23.97	23.85	0.45	0.44	0.44
3	Control	24.33	23.91	0.71	0.69	0.69

CONCLUSIONS

Objectives of this study were successfully met and results are summarized below:

1) Fire and thinning had no short-term effects on reducing or increasing southern pine beetle incidence of attack.
2) Total resin flow from host trees in treatment units was inversely related to both the total numbers of southern pine beetles trapped and infestation sizes.
3) Radial growth from host trees in treatment units had a moderate direct correlation with total numbers of southern pine beetles trapped and infestation sizes. However, number of southern pine beetles and infestation growth were inversely related to latewood percentage.
4) Both pre-treatment and post-treatment basal areas were not correlated with beetle activity in 2000 and 2001.

In this study, drought conditions may have played an important role in decreasing host vigor. Numerous stressed trees throughout the landscape could have provided an increased habitat for pioneer beetles at the start of the outbreak in 2000. Due to the tremendous amount of beetles within the area, any factor resulting in further tree stress could have caused a spot occurrence. In addition, the larger number of beetles would have made it easier for spots to grow.

Further studies such as this one would benefit from monitoring beetle activity on the landscape level. Variables such as size and proximity of infestations to test study sites could be used to further test hypotheses regarding treatment effects. Perhaps infestation proximity was why data regarding beetle trap catch were disparate between treatments in this study.

It is yet to be determined what long-term effects fire and thinning have on southern pine beetle spot occurrence and spot growth in the Piedmont. However, reduction in stand density along with increase in tree vigor should result in lower long-term susceptibility to southern pine beetle attack.

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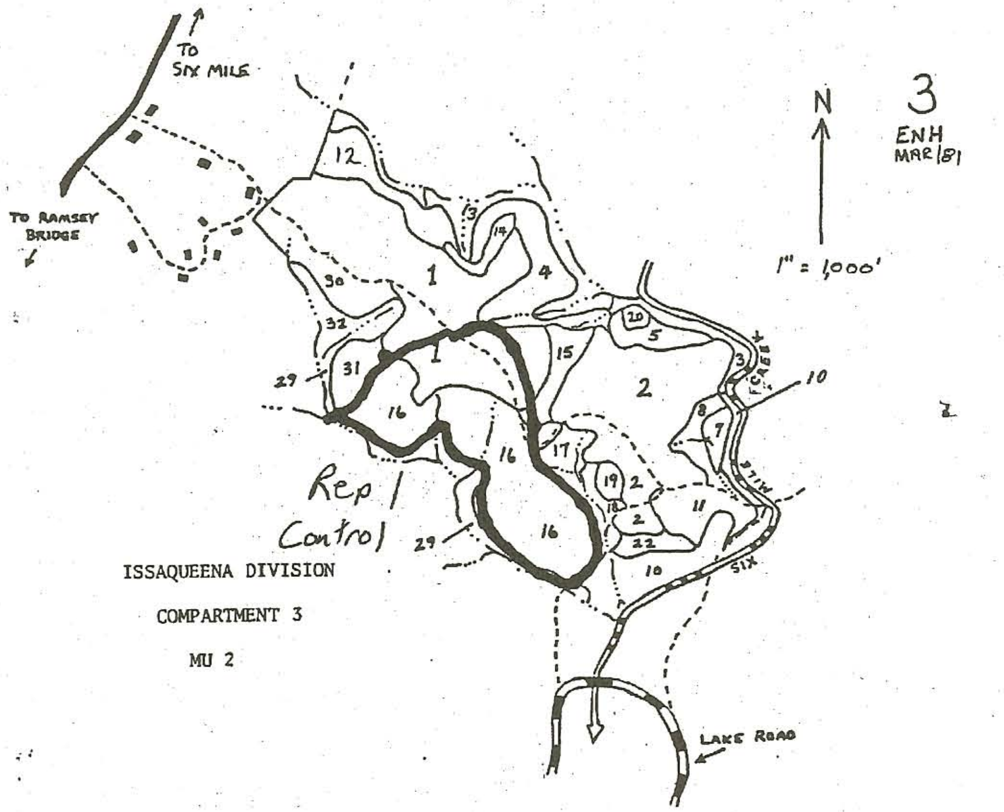
APPENDICES

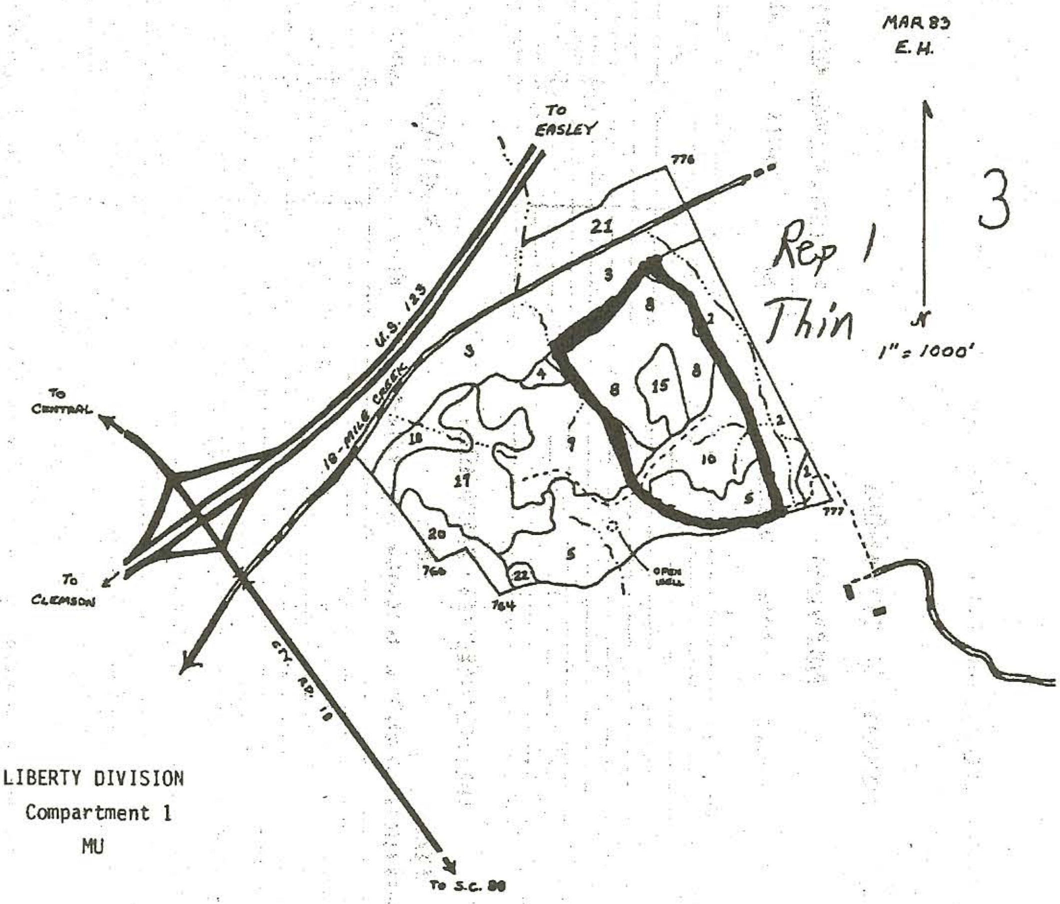
Appendix A

Treatment Unit Location, Stand Type, and Acreage Estimation*



STAND NO.	TYPE	SIZE CLASS	ACREAGE	STAND NO.	TYPE	SIZE CLASS	ACREAGE
1	Lop Plt.	Poles - Stds.	35.1	16(23,24, 25,27,28)	Lop Plt.	Seedlings	27.8
2	Lop Plt.	Poles - Stds.	25.1	17	Cove Hw	Poles - Stds.	4.6
3	Cove Hw	Saps - Vets	12.1	18	Shp	Poles - Stds.	1.4
4	Up Hw	Saps - Stds.	10.2	19	Up Hw	Poles - Stds.	1.1
5(6)	SHPHW	Saps - Stds.	2.8	20	Lop Plt.	Poles - Stds.	.7
7	Wildlife		1.8	22	Pine Hw	Saps - Poles	2.1
8(9)	Cove Hw	Poles - Stds.	2.6	29	Cove Hw	Poles - Stds.	7.9
10(26)	Bottom	Saps - Vets.	11.4	30(33,34)	Shp	Seedlings-Stds.	5.3
11(21)	Lop Plt.	Seedlings - Saps	5.1	31	Shp	Poles - Stds.	3.4
12(13)	UP PHW	Saps - Stds.	6.3	32	Up Hw	Poles - Stds.	3.9
14	Shp Shelterwood	Seedlings - Stds.	1.8				
15	Shp	Poles - Stds.	3.3				
						TOTAL	175.8

*Thin treatment units are referred to as "Thin A" and Thin and Burn treatment units are referred to as "Thin B" throughout this thesis.

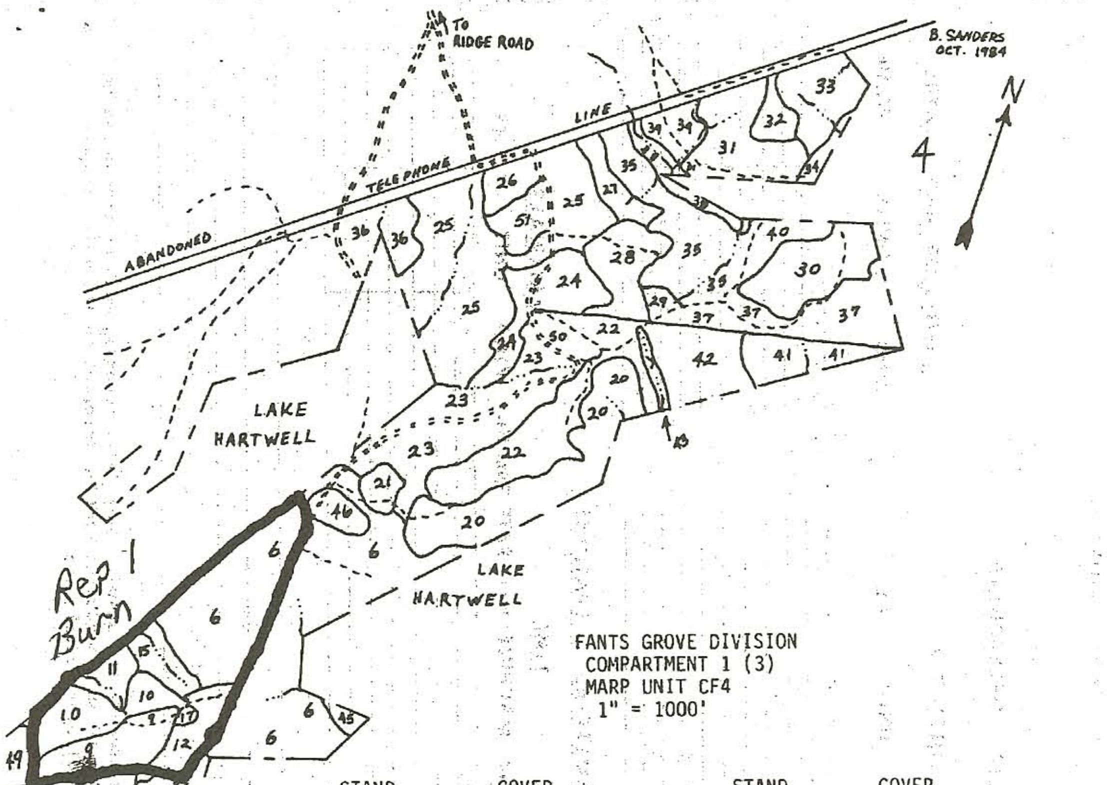


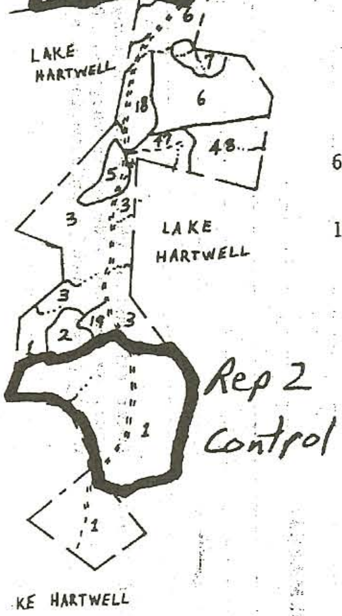
LIBERTY DIVISION

Compartment 1

MU

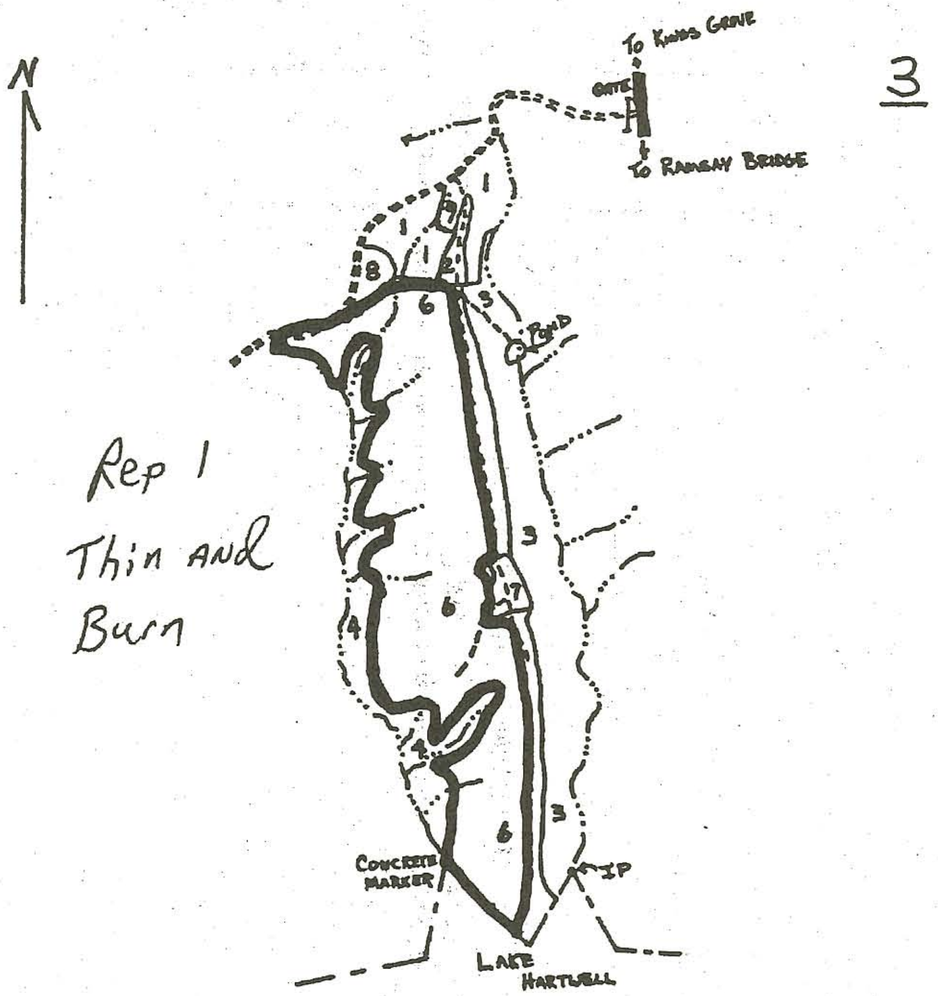
STAND NO.	COVER TYPE	SIZE CLASS	ACRES	STAND NO	COVER TYPE	SIZE CLASS	ACRES
1	SHP	POLES-STDS	1.5	10 (14)	UP-OAK	POLES-STDS	10.1
2 (11)	CO-YLP OAK	POLES-VETS	14.0	15	UP-OAK	STDS	3.6
3	BO-YLP SWG	POLES-STDS	22.0	17 (19)	SHP	POLES-STDS	13.7
4	SHP-VAP	POLES-STDS	.9	18	CO-YLP OAK	POLES-STDS	2.1
5(6,7,16)	SHP-VAP	SAPS-STDS	18.9	20	SHPHW	POLES-STDS	4.0
8 (12,13)	SHP-VAP	POLES-STDS	18.1	21	BO-RBR SYC ASH	STDS	9.9
9	CO-YLP OAK	POLES-STDS	15.9	22	SHP-VAP	POLES-STDS	.6
						TOTAL	136.4





FANTS GROVE DIVISION
COMPARTMENT 1 (3)
MARP UNIT CF4
1" = 1000'

STAND NO.	COVER TYPE	ACRES	STAND NO.	COVER TYPE	ACRES
1	LOP UPHW	29.8	29	SHP UPHW	1.0
2	LOP PLT	2.3	30	LOP PLT	9.0
3 (4)	UPHW	17.3	31	SHP LOP	~~10.3~~ 8.7
5	LOP PLT	2.2	32	LOP PLT	2.6
6 (8,13,44)	SHP VAP	58.4	33	UPHW	6.4
7	COVE HW	1.6	34	LOP PLT	1.2
9	LOP UPHW	7.1	35	UPHW	13.4
10 (14,16)	SHP VAP	7.0	36	COVE HW	3.8
11	UPHW	2.4	37	LOP PLT HW	13.2
12	SHP VAP	4.4	38	COVE HW	4.2
15	SHP HW	2.3	39	SHP VAP	~~1.6~~ 3.2
17	LOP PLT	0.7	40	UPHW	1.6
18	SHP UPHW	3.6	41	UPHW	6.0
19	SHP VAP	1.5	42	SHP VAP	8.6
20	SHP VAP	16.8	43	COVE HW	2.2
21	UPHW	2.8	45	UPHW	0.8
22	SHP VAP	14.8	46	UPHW	2.3
23	SHP VAP	19.0	47	UPHW	2.6
24	LOP PLT	7.9	48	SHP	5.3
25	SHP LOP	26.8	49	UPHW	2.4
26	LOP PLT	3.3	50	LOP PLT	2.3
27	SHP VAP LOP	3.7	51	LOP	3.7
28	LOP PLT	6.4		TOTAL	346.6

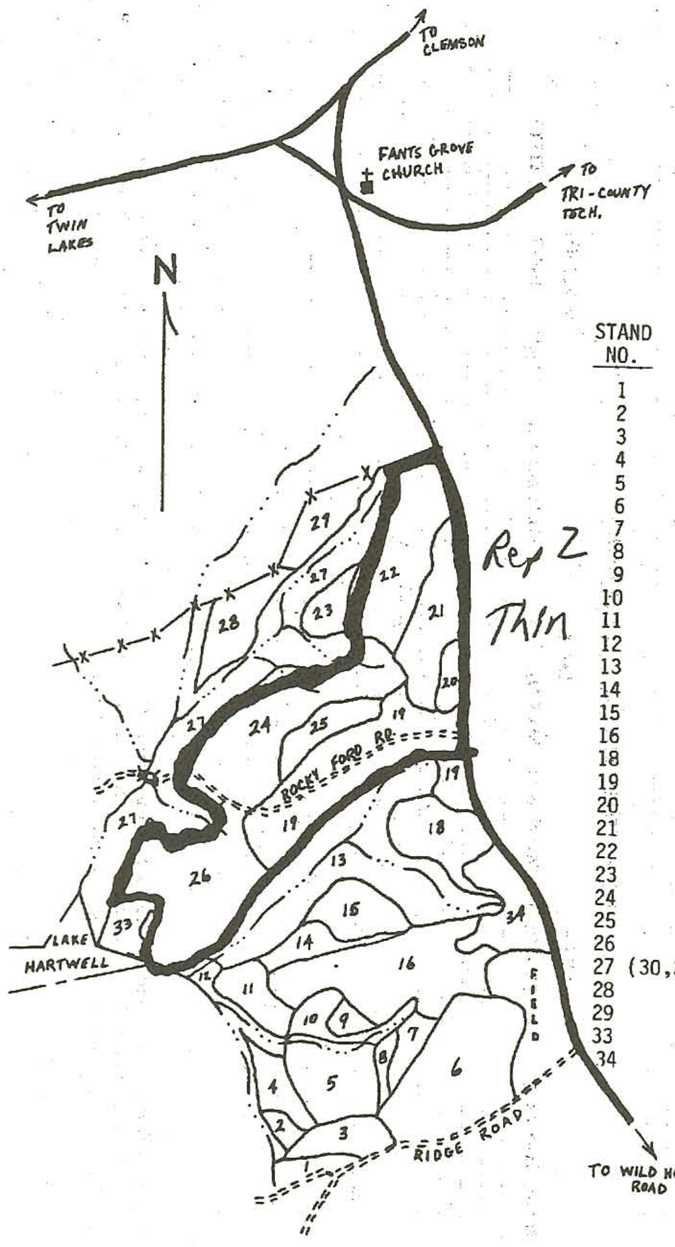


ISSAQUEENA DIV COMPARTMENT 13
Protection Forest II

STAND NO.	COVER TYPE	SIZE CLASS	ACRES
1	UP HW	SAPS-POLES	9.3
2	WILDLIFE PLOT	---	2.3
3(5)	COVE HW	POLES-STDS	29.5
4	COVE HW	SAPS-STDS	14.3
6	LOP	SDLGS	65.9
7	WILDLIFE PLOT	---	2.7
8	WILDLIFE PLOT	---	2.5
9	LOP	SDLGS	1.0
			127.5

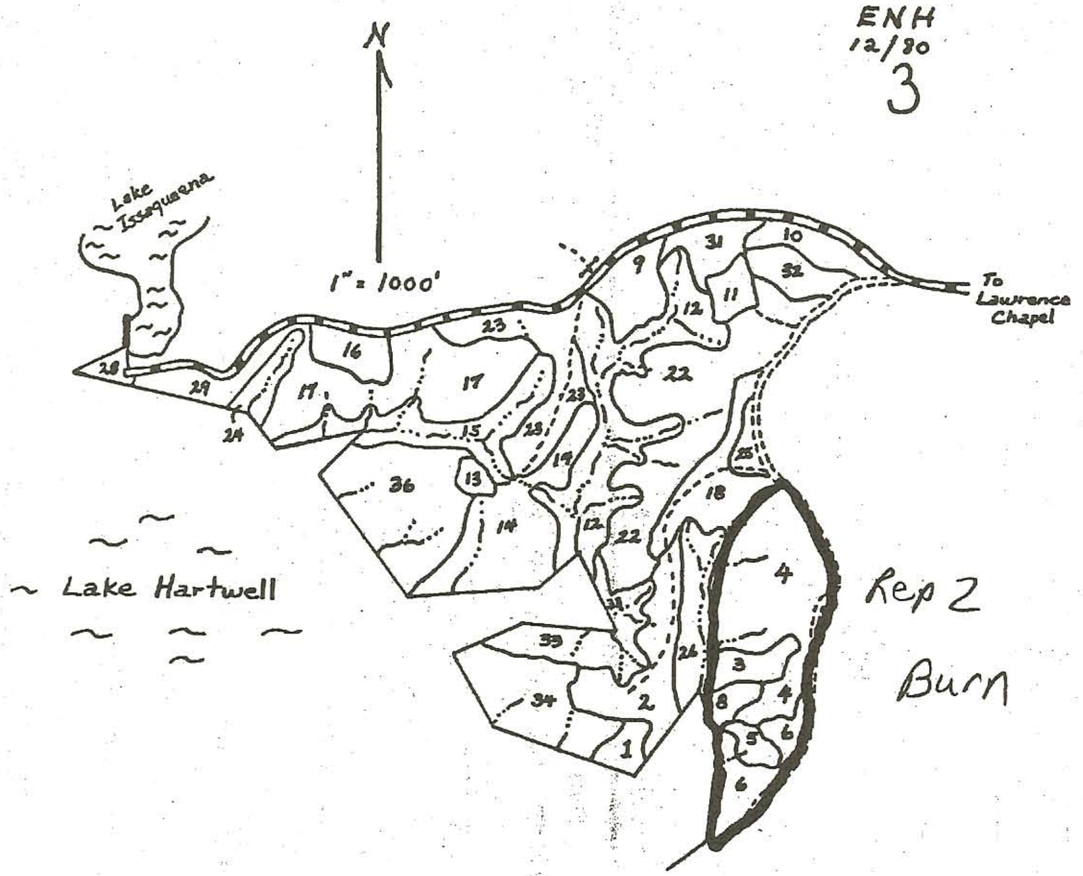
B. SANDERS
DEC. 1984

4



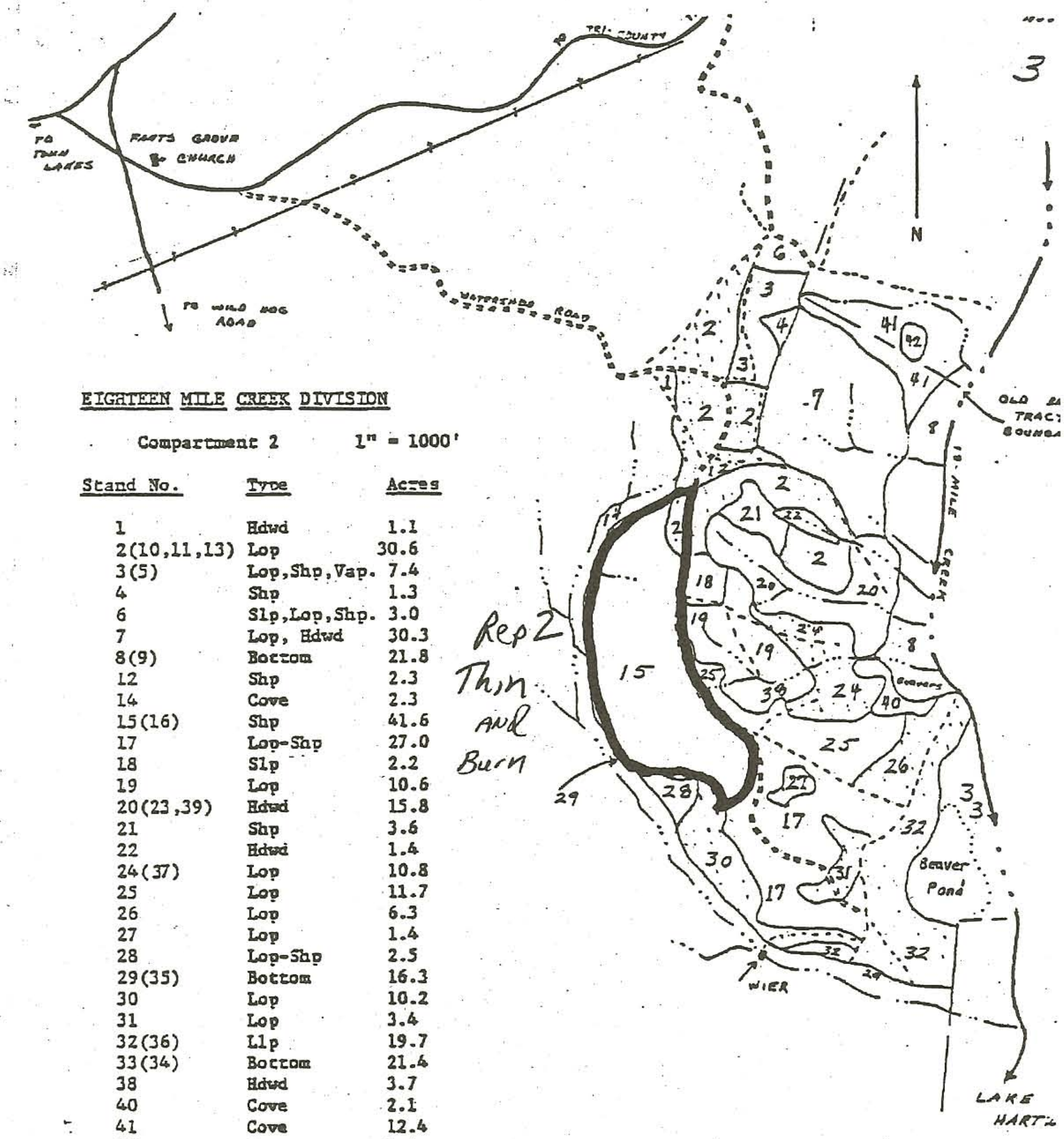
FANTS GROVE DIVISION
COMPARTMENT 10
MARP UNIT CF3
1" = 1000'

STAND NO.	COVER TYPE	SIZE CLASS	ACRES
1	VAP SHP	POLES-STDS	2.1
2	SHP LOP	POLES	1.1
3	VAP	STANDARDS	3.0
4	SHP VAP	POLES-SM. STDS	3.4
5	COVE HW	SAPS-STDS	6.3
6	UP HW	SAPS-SM. STDS	15.7
7	VAP SHP	SAPS-STDS	2.0
8	SHP VAP	POLES-STDS	1.1
9	SHP VAP	POLES-STDS	1.6
10	UP HW	SAPS-STDS	3.7
11	SHP VAP	SAPS-POLES	3.9
12	COVE HW	POLES-STDS	4.9
13	COVE HW	SAPS-STDS	24.4
14	LOP HW	POLES-STDS	3.0
15	LOP	POLES-STDS	4.7
16	LOP PLT	POLES-STDS	16.2
18	SHP LOP	SAPS-STDS	7.7
19	LOP	POLES-STDS	18.6
20	LOP	SAPS-SM. POLES	2.0
21	LOP	STANDARDS	9.0
22	SHP LOP	POLES-STDS	14.1
23	SHP	POLES-STDS	3.2
24	SHP VAP	SAPS-POLES	18.9
25	SHP VAP	POLES-STDS	4.0
26	SHP VAP	SAPS-STDS	17.5
27 (30,32)	COVE HW	SAPS-VETS	23.6
28	SHP	POLES-STDS	6.8
29	SHP	POLES-STDS	5.2
33	LOP PLT	SAPS-SM. POLES	3.8
34	LOP PLT	SM. POLES	6.1
		TOTAL	237.6



LAWRENCE CHAPEL
COMP. 7
MULTIPLE USE I

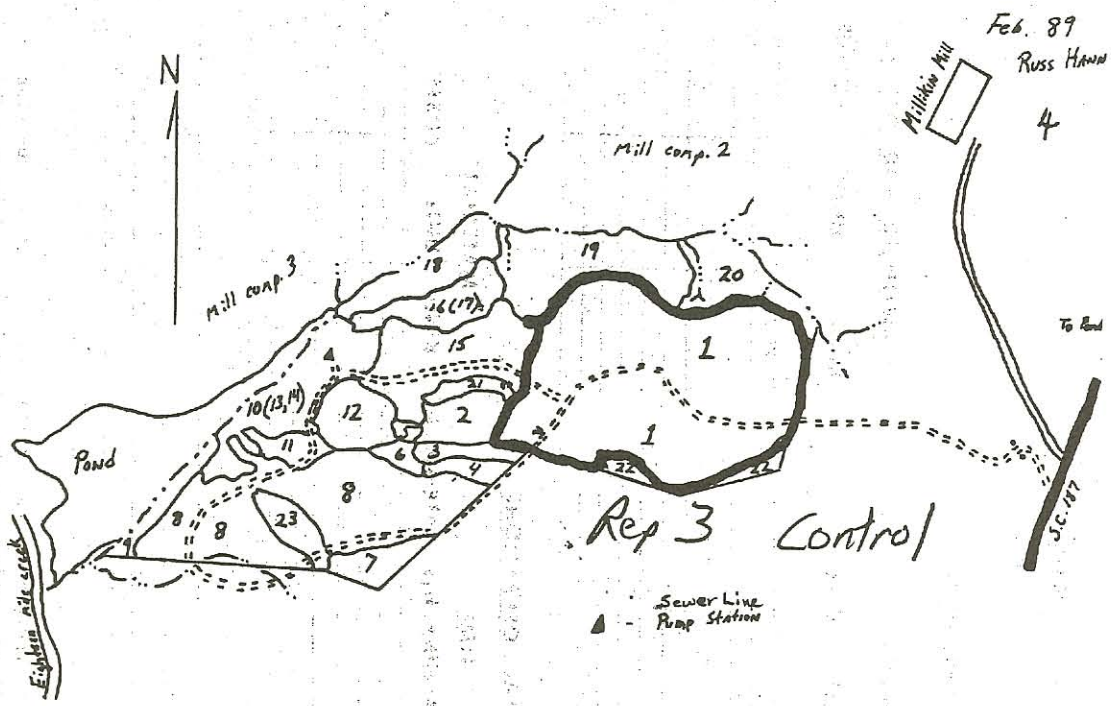
STAND NO.	TYPE	SIZE CLASS	ACRES	STAND NO.	TYPE	SIZE CLASS	ACRES
1	BB Kill	---	1.9	17	SHPHW	Saps-stds	17.7
2(7,20)	LOP	Seed-saps	10.0	18	BB Kill	---	7.0
3	SHPHW	Saps-stds	3.6	22(30)	SHPHW	Stds	22.7
4(19,21)	LOP	Seed-saps	18.0	23	SHPHW	Poles-stds	10.4
5	SHP-LOP	Saps-poles	2.0	24	COVE HDWD	Poles-stds	2.4
6	SHPHW	Poles-stds	5.5	25	WILDLIFE PLOT	---	1.4
8	SHPHW	Poles-stds	1.1	26	COVE HDWD	Poles-stds	6.7
9(27)	OLD HOUSE SITE	---	5.3	28	SHPHW	Saps-stds	2.0
10	WHP	Stds	4.2	29	UP HDWD	Poles-stds	3.3
11	WILDLIFE PLOT	---	2.2	31	UP HDWD	Poles-stds	4.4
12	COVE HDWD	Poles-stds	19.3	32	MXD PINE	Poles-stds	3.8
13	LOP	saps-poles	1.1	33	COVE HDWD	Poles-vets	8.0
14	SHPHW	Poles-stds	13.3	34(35)	SHPHW	Poles-vets	10.7
15	COVE HDWD	Poles-stds	9.5	36	SHPHW	Saps-stds	15.2
16	MXD PINE	Poles-stds	3.3				



EIGHTEEN MILE CREEK DIVISION

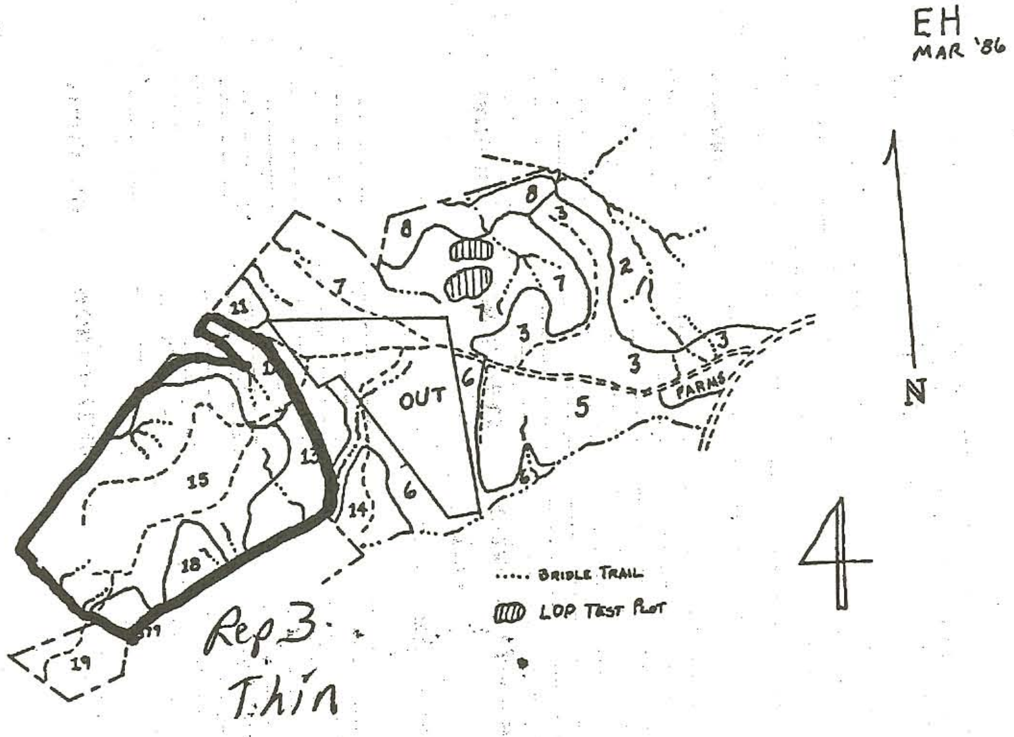
Compartment 2 1" = 1000'

Stand No.	Type	Acres
1	Hdwd	1.1
2(10,11,13)	Lop	30.6
3(5)	Lop,Shp,Vap.	7.4
4	Shp	1.3
6	Slp,Lop,Shp.	3.0
7	Lop, Hdwd	30.3
8(9)	Bottom	21.8
12	Shp	2.3
14	Cove	2.3
15(16)	Shp	41.6
17	Lop-Shp	27.0
18	Slp	2.2
19	Lop	10.6
20(23,39)	Hdwd	15.8
21	Shp	3.6
22	Hdwd	1.4
24(37)	Lop	10.8
25	Lop	11.7
26	Lop	6.3
27	Lop	1.4
28	Lop-Shp	2.5
29(35)	Bottom	16.3
30	Lop	10.2
31	Lop	3.4
32(36)	Llp	19.7
33(34)	Bottom	21.4
38	Hdwd	3.7
40	Cove	2.1
41	Cove	12.4
42	Shp	1.4
	Total	325.6



MILL DIVISION
COMPARTMENT 1
MARP UNIT PF4
SCALE 1"=1000'

STAND NO.	COVER TYPE	SIZE CLASS	ACRES
1	MIXED PINE	POLES AND STDS	54.4
2	LOP	SAPS	4.5
3	LOP	STDS	1.8
4	LOP SHP	SAPS TO STDS	1.7
5	LOP	POLES AND STDS	0.8
6	SHP HW	POLES AND STDS	1.3
7	YLP OAK	STDS	3.2
8	LOP	POLES AND STDS	28.0
9	SHP HW	STDS	2.4
10 (13,14)	YLP OAK	POLES TO VETS	10.1
11	SHP HW	POLES TO VETS	1.9
12	MIXED PINE	POLES AND STDS	5.4
15	LOP	SAPS	12.6
16 (17)	MIXED PINE	POLES AND STDS	5.4
18	MIXED OAK HC	POLES TO VETS	6.0
19	OAK HC BCH	STDS AND VETS	12.4
20	YLP OAK	POLES TO VETS	6.8
21	LOP HW	POLES AND STDS	1.5
22	YLP OAK	POLES TO VETS	2.3
23	LOP	SAPS	2.7
		TOTAL:	165.2



FANTS GROVE DIVISION

COMPARTMENT 9

MARP UNIT CF4

1" = 1000'

STAND NO.	COVER TYPE	SIZE CLASS	ACRES
1	FARMS DEPT.	-----	2.3*
2	UP HW	SAPS TO STDS	9.4
3 (4, 21)	VAP	SAPS & POLES	20.3
5	SHP	POLES & STDS	15.4
6 (22)	UP HW	POLES & STDS	10.3
7 (9, 10)	UP HW	SAPS TO VETS	29.8
8	COVE HW	SAPS	6.9
11	LOP HW	POLES	1.8
12 (16)	SHP HW	POLES & STDS	9.4
13	MXD PINE	POLES	9.0
14	SHP	POLES & STDS	4.4
15 (17, 23, 24)	LOP HW	POLES & STDS	36.5
18	SHP-LOP	POLES	3.4
19 (20)	SHP-VAP	POLES	7.3
		TOTAL:	163.9

* NOT INCLUDED IN COMPARTMENT TOTAL

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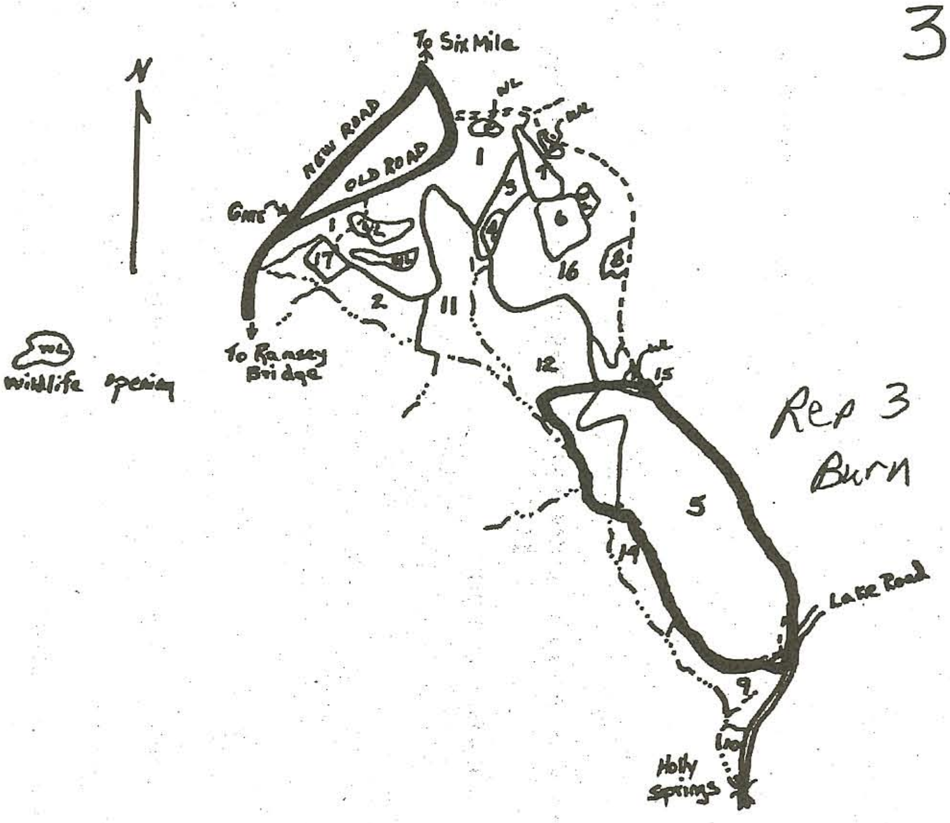
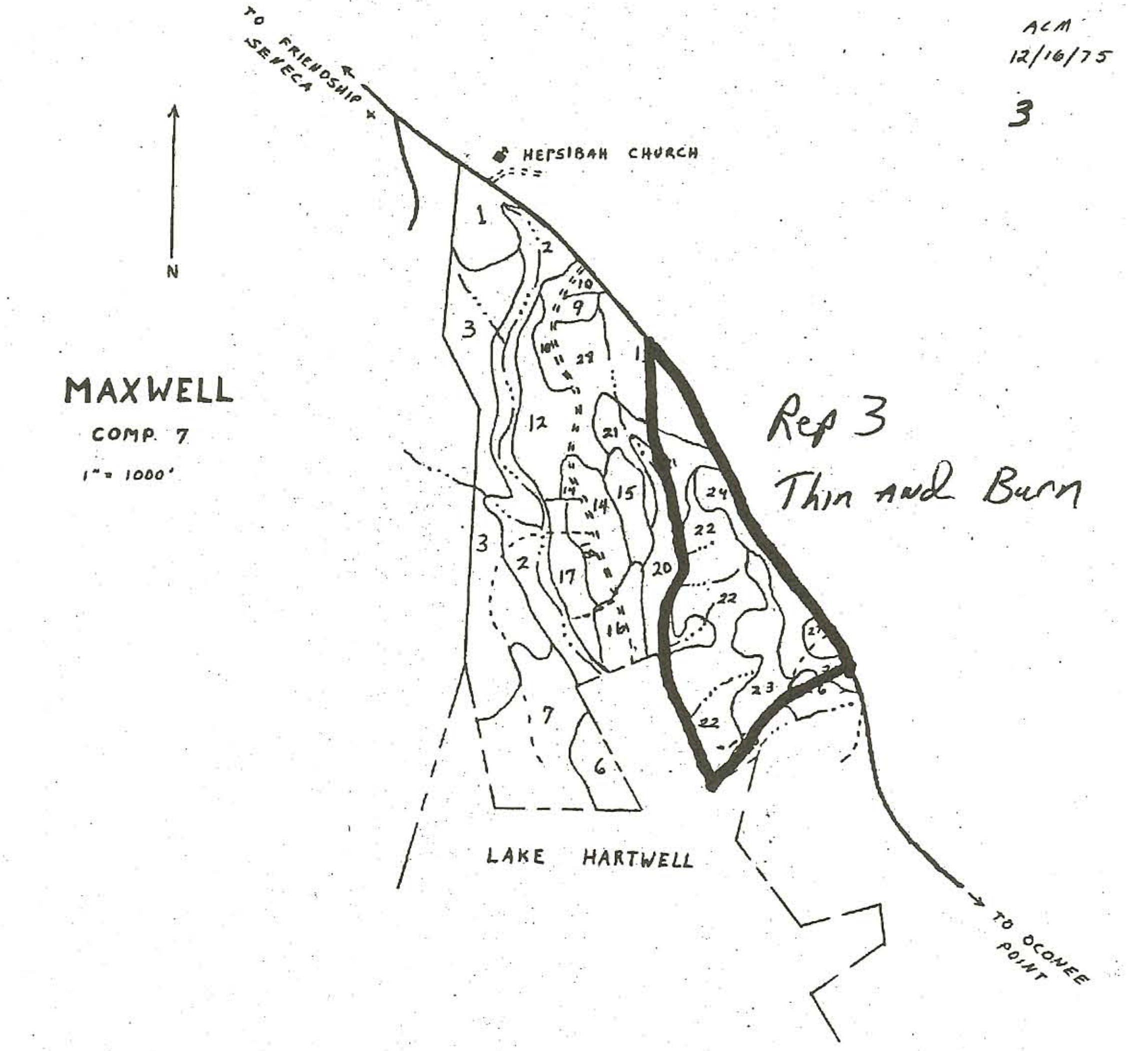


ISSAQUEENA DIVISION
COMP. 7
MU II

STAND NO.	COVER TYPE	SIZE CLASS	ACRES
1	LOP	Poles - Stds	15.1
2	MISC HW	Poles - Stds	6.1
3	WHP	Pole - Vet	1.7
4	MISC HW	Wildlife Plot	0.7
5	LOP	Saps - Vets	30.8
6	PTO BJO	Poles - Stds	2.6
7	SHP	Standards	1.7
8	MISC HW	Saps - Vets	0.7
9	WHO SRO BLO	Standards	3.9
10	MISC HW	Poles - Stds	1.2
11	MIXED OAK HC	Poles - Stds	8.5
12(13)	LOP	Seedlings	15.4
14	MISC PHW	Poles - Saps	3.2
15	MISC PHW	Saps - Poles	1.7
16	LOP	Saps - Stds	16.7
17	MISC PHW	Clearcut	1.0
		TOTAL	111.0



STAND		ACRES	STAND		ACRES
1	Field	4.7	17(19)	ShP	4.0
2(5)	Cove	17.5	18	ShP	2.3
3(4)	Hdwd.-Pine	20.7	20	Cove	6.3
6	ShP-Hdwd.	5.6	21	ShP	5.9
7(8)	ShP	14.4	22	ShP	17.1
9	Loblolly	1.0	23	ShP	4.9
10(11)	ShP	3.7	24	ShP	7.9
12	ShP-Hdwd.	7.0	25	Hdwd.	2.3
13	LoP Saps	7.9	26	ShP	2.1
14	ShP	4.1	27	Loblolly	1.8
15	Shp-LoP	3.8	28	Shp-Hdwd Saps	6.7
16	Upland Hdwd.	4.0			
				TOTAL	155.7 Acres

Appendix B

Total Numbers of Southern Pine Beetles Trapped in Each Treatment Unit (May-October 2001)

REP	TRT	GRID POINT	Weeks 1-3	Weeks 4-6	Weeks 7-9	Weeks 10-12	Weeks 13-15	Weeks 16-18
1	Burn	6	0	0	0	0	0	0
1	Burn	14	0	0	0	0	0	0
1	Burn	19	0	0	0	0	0	0
1	Burn	32	0	0	0	0	0	0
1	Burn	36	0	0	0	0	0	0
1	Thin A	1	0	0	0	0	0	6
1	Thin A	6	0	0	0	0	0	0
1	Thin A	19	0	0	0	0	14	0
1	Thin A	32	0	0	0	0	0	9
1	Thin A	35	0	0	0	0	0	2
1	Thin B	6	0	0	0	0	0	0
1	Thin B	8	0	0	0	0	0	0
1	Thin B	17	4	0	0	0	0	0
1	Thin B	28	0	0	0	0	0	0
1	Thin B	32	0	0	1	0	0	0
1	Control	5	0	0	0	0	0	0
1	Control	10	0	0	0	1	4	0
1	Control	22	22	13	30	5	12	0
1	Control	32	1	4	0	0	0	0
1	Control	40	3	6	0	0	0	0
2	Burn	6	0	0	0	0	0	1
2	Burn	15	0	0	0	0	0	0
2	Burn	24	0	0	0	0	0	0
2	Burn	34	0	0	0	0	3	1
2	Burn	39	0	0	0	0	0	0
2	Thin A	10	0	0	0	0	0	0
2	Thin A	14	0	0	0	0	0	1
2	Thin A	23	0	0	0	0	0	0
2	Thin A	29	0	0	0	0	0	0
2	Thin A	36	0	0	0	0	0	0
2	Thin B	6	0	0	0	0	0	1
2	Thin B	16	0	0	0	0	0	0
2	Thin B	27	0	0	0	0	0	0
2	Thin B	30	0	0	0	0	0	0
2	Thin B	37	0	0	0	0	0	1
2	Control	4	0	0	0	0	0	0
2	Control	10	0	0	0	0	0	0
2	Control	17	0	0	0	0	0	2

2	Control	33	0	0	0	0	0	0
2	Control	35	0	0	0	0	0	0
3	Burn	4	0	0	0	0	0	0
3	Burn	10	0	0	0	0	0	3
3	Burn	19	0	0	0	0	0	0
3	Burn	31	6	4	0	0	0	0
3	Burn	37	0	0	0	0	0	2
3	Thin A	7	0	0	0	0	0	7
3	Thin A	17	0	0	0	0	0	3
3	Thin A	23	0	0	0	0	0	0
3	Thin A	35	0	0	0	0	0	0
3	Thin A	40	0	0	0	0	0	2
3	Thin B	4	0	0	0	0	0	16
3	Thin B	14	0	0	0	5	3	0
3	Thin B	19	0	0	6	0	0	4
3	Thin B	29	1	0	0	0	0	2
3	Thin B	34	0	0	0	0	0	0
3	Control	6	0	2	0	0	0	0
3	Control	14	0	0	0	0	0	0
3	Control	23	0	0	0	0	0	0
3	Control	27	0	0	0	0	0	0
3	Control	39	0	0	0	0	0	1