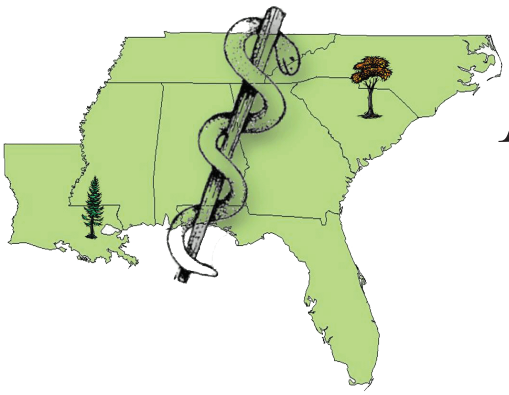

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THINNING AND HARVESTING EFFECTS ON ROOT-FEEDING BARK BEETLE POPULATION DYNAMICS IN *PINUS TAEDA* L. PLANTATIONS IN CENTRAL ALABAMA AND GEORGIA

by
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ABSTRACT
Root-feeding beetles, particularly *Hylastes* spp., *Hylobius pales* Herbst and *Pachylobius picivorus* Germar, are known to be vectors of *Grosmannia* spp. and *Leptographium* spp. which contribute to Southern Pine Decline (SPD) in the southeastern United States. This study examined population changes of root-feeding beetle in response to either mechanical thinning or harvesting in *P. taeda* stands in central Alabama and Georgia. Plots were established on five loblolly pine stands that were either thinned, harvested or control stands. Three different insect traps were used during the two-and- half-year study. All root-feeding bark beetles collected in the traps were identified. The most abundant root-feeding bark beetles were *Hylastes salebrosus* Eichhoff, *H. porculus* Erichson and *H. tenuis* Eichhoff. The number of *H. salebrosus* and *H. porculus* captured had peaks either in spring or fall, while the population of *H. tenuis* captured was erratic throughout the collection periods. Population of the *Hylastes* spp. significantly increased after thinning treatments at all five sites. Although *Hylastes* spp. decreased in response to harvesting in some plots, their populations recovered and were stable over the studies duration.

INTRODUCTION
Bark beetles, such as the southern pine beetle (*Dendroctonus frontalis* Zimmerman), mountain pine beetle (*Dendroctonus ponderosae* Hopkins), and the European spruce bark beetle (*Ips typographus* Linnaeus) are major conifer pests in North America and Europe. Most bark beetles attack weakened or dying trees, but *D. ponerosae* and *D. frontalis* can attack and kill healthy hosts (Amman and Baker 1972, Hofstetter et al. 2006, Wermelinger 2004). Bark beetle species that result in significant economic losses to forest landowners tend to be studied more thoroughly. However, there are many forest pests that are poorly understood. For example, the root-feeding *Hylastes* spp. are bark beetles reported to typically attack weakened pines and vector ophiostomatoid fungi, such as *Grosmannia alacris* T.A. Doung, Z.W. de Beer & M.J. Wingf.. sp. nov., *Leptographium procerum* (Kendr.) Wingf. and *Leptographium terebrantis* Barras

& Perry which contribute to southern pine decline (Klepzig et al. 1991, Jacobs and Wingfield 2001, Eckhardt and Menard 2005, Eckhardt et al. 2007).

In order to prevent bark beetle infestations and mitigate pest problems, silviculture treatments such as thinning, prescribed burning, and partial cutting are recommended to reduce insect populations (Ferrell 1996, Fettig et al. 2007). Most research exploring the relationship between management practices and insect infestations have only considered the impact on a few important insect species such as *Dendroctonus* and *Ips*. For example, numerous studies suggest that thinning and partial cutting will reduce tree competition and accelerate growth rate of ponderosa pines, which reduced stand susceptibility to *D. ponderosae* attack compared to untreated stands in the western United States (Sartwell 1971, Schmid and Mata 2005, Fettig et al. 2007, Kolb et al. 2007). In the southeastern United States, thinning is also a management strategy to control *D. frontalis* outbreaks by maintaining pine basal area to 34 m^2/ha (Larsson et al. 1983, Mitchell et al. 1983). However, stand management practices can also increase beetle populations. Campbell et al. (2008) reported that species richness of Scolytinae (Coleoptera: Curculionidae) in longleaf pine (*Pinus palustris* Mill.) stands on the Coastal Plain of Alabama was higher following a thin plus burn when compared to untreated controls. Harvesting a forest stand is an effective method to create animal habitat and browsing areas. However, stand disturbance can have negative impacts such as soil erosion, poor quality re-growth, increased risk of pests, loss of biodiversity and economic sustainability. For example, species richness and diversity of carabid beetles (Coleoptera: Carabidae) was greater on recently clear-cut plots in a boreal mixed-wood ecosystem than in mature or undisturbed plots (Duchesne et al. 1999). Because bark beetle population responses' to common silvicultural disturbances is controversial, forest stand treatment consequences should be well understood prior to forest management implementation.

Southern pine forests were historically dominated by longleaf pine (*P. palustris*), a tree species which is tolerant to fire and resistant to bark beetles. However, forest stand composition and densities of southern pine forests have changed primarily to loblolly pine (*P. taeda*), which is faster growing and more vulnerable to bark beetles (Baker 1972; Thatcher et al. 1980). In recent years, forest stands have begun to show decline symptoms from age 25, especially at sites with steeper slope and south/ southwest aspects (Eckhardt and Menard 2008). Once thought to be only associated with loblolly pine, other southern pine species have shown similar symptoms (Zanzot 2010, Matusick 2010). Through this association, loblolly pine decline is now refered as Southern Pine Decline (SPD). Management history is considered as an inciting factor in the occurrence of SPD (Menard et al. 2006, Menard 2007) because stand disturbance may be either directly responsible such as causing physical injury and stress, or indirectly resulting in the attraction of, or increasing the susceptibility to insects such as root-feeding bark beetles and weevils (*Hylastes* spp., *Hb. pales* and *P. picivorus).* In this case, forest managers need a better understanding of the short- and long-term impacts of forestry practices on pine ecosystems.

Understanding the response of root-feeding bark beetles to forest management is just as important as the main stem beetles *D. frontalis* and *D. ponderosae* that cause significant tree mortality throughout the United States. An awareness of the biological relationships that predispose loblolly pine stands to stress and potential root-feeding beetle outbreaks are essential to develop preventative stand management options. These studies will examine the effects of

standard pine management practices on the population levels of bark beetles that are known to carry root pathogens in an attempt to understand their role in SPD.

METHODS AND MATERIALS

Study Site and Plot Measurements

Five study sites (SS, RAY, WEY, WV and F&W) were established on property managed or owned by members of the Forest Health Cooperative in either central Alabama or Georgia (Fig. 2.1). SS sites located in Tallapoosa County, AL with an area of 106 ha. RAY sites were established in Stewart County, GA with an area of 16 ha. WEY sites were chosen from loblolly pine plantations in Perry County, AL with an area of 71 ha. WV sites are in Pickens County, AL with an area of 39 ha. FW sites located in Cusseta County, GA with area of 19 ha. Within each of the study sites, 9 monitoring plots were established per US Forest Service, Forest Health Monitoring (FHM) guidelines (Dunn 1999) in January 2009. Plots were evenly divided among the three treatments: 1) thinned, 2) harvested, and 3) control (no stand activity). Within each treatment, four subplots were established with three subplots located 36.6 m away from a center subplot at a bearing of 120, 240, and 360 degree (Dunn 1999) (Fig. 2.2). Latitude and longitude coordinates of center subplots were measured by using a GPS unit (Garmin GPSMAP 76Cx, Garmin International Inc., Olathe, KS). Plot conditions, including pine and hardwood basal area, slope inclination, slope aspect, and convexity of each plot were recorded from the center subplot before treatments occurred.

The treatment timeline for each plot is presented in Table 2.1. The thinning method used in these studies was row thinning, which removes trees by row. Because of poor road conditions and access problems, plot 2 at study site WEY was not thinned. Plot 7 and plot 8 in SS study site were not harvested as planned.

Weather data was obtained from the National Climatic Data Center (http://www7.ncdc.noaa.gov/IPS/coop/coop.html). Data from the Bankhead L&D weather station (AL), Alexander city weather station (AL), Marion Junction 2 NE weather station (AL), Columbus #2 weather station (GA), and Cuthbert weather station (GA) were used. The average bi-weekly maximum and minimum was calculated from daily record.

Insect Trapping

To monitor bark beetle population dynamics in the plots over time, three types of insect traps (pitfall trap, panel trap, and flight intercept trap) were placed in every center subplot. Panel traps (APTIV Company, Portland, Oregon) (Fig. 2.3A) are made of black corrugated plastic, and designed to capture flying beetles. The panel traps were installed 2 m above the ground with a plastic cup attached to the bottom that contained a 2:1 mixture of water and antifreeze to preserve captured insects. Pitfall traps (Fig. 2.3B) consisted of a 20-cm length of a 10-cm-diameter polyvinyl chloride plastic pipe with eight holes spaced equally around the circumference (Klepzig et al. 1991). Both ends of the pipe were capped with removable lids, and two holes were drilled in the bottom lid for drainage. The traps were buried into the soil/litter layer so that the entrance holes were slightly above the ground line. The interior of each trap was coated with a thin layer of liquid Teflon™ (Northern Products Woonsockets, RI) to prevent the escape of insects captured between each collection period. Each pitfall trap was baited with two 3 cm long

by 1 cm diameter loblolly pine twigs placed in the base of interior trap. Flight intercept traps (Fig. 2.3C) were made from plastic 3785 ml containers fitted with a 120 ml collection cup attached at the bottom. The trap was 1 m off the ground. Each container was cut open on three sides to expose the bait/attractants, with the fourth side attached to a metal pole. Like that of the pitfall trap, two 3 cm long by 1 cm diameter loblolly pine twigs were placed in the collection cup. In addition to the pine twigs, two 8 ml glass vials, filled with southern pine turpentine (W.M. Barr & Co., Inc., Memphis, Tennessee) and 95% ethanol (1: 1) were installed in every trap as an insect attractant. Both vials and panel trap cups were refilled every two weeks during insect collections.

Insect collection traps were monitored and sampled every 2 wk from March 2009 to September 2011. The traps were set in each of the plots and insects were collected one year prior to treatments to determine pre-treatment populations within each stand. During the thinning and harvesting periods, the insect traps were removed from the plots and then reinstalled upon completion. Captured insects were placed in sterile polyethylene cups transported back to the Forest Health Dynamics Laboratory at Auburn University (Auburn, AL, USA) for sorting and identification.

Tree Measurements

All loblolly pine with DBH greater than 10 cm within a 7.3 m radius on each subplot were tagged and rated for tree health based on Forest Health Monitoring (FHM) procedures (Dunn 1999). Since crown condition is an indication of tree health, the live crown ratio (a percentage of the live crown length by the actual tree length), crown light exposure (the amount of crown quarters equal to or greater than 35% of live crown ratio and crown top receiving direct light; 0 - 5), live crown position (superstory; overstory; understoyry; open story), live crown density (the amount of crown branches, foliage, and reproductive structures that block light visibility through the crown) as well as crown dieback (a percentage of the dieback area by the live crown area) and live foliage transparency (the amount of light visible through the live foliated portion of the crown) were measured and recorded for each tree.

In addition to crown condition, tree height and radial growth increment were collected from six trees randomly selected at center subplot. Increment cores were collected and returned to the Forest Health Dynamics Laboratory where 5-year and 10-year growth values were obtained using a digital (Mitutoyo Corporation, Maplewood, NJ) electronic ruler.

Stump Sampling

To assess insect gallery formation, brood levels and fungal populations and viability in roots on harvested trees, two lateral roots, greater than 2 cm dia, were collected from three stumps in harvested center plots. Roots were sampled every 3 months for one year post-treatment from September 2010 to October 2010 (stump samples in SS9 were collected in September 2011). Root sections from each stump were severed from the root system, labeled by site and treatment and then transported back to the laboratory for measurements. After peeling root bark, *Hylastes* spp. feeding galleries, larvae, pupae, and adult of each species observed were record.

DATA ANALYSIS

Insects captured were identified and recorded by species bi-weekly over two and a half years. Bi-weekly totals of *H. salebrosus*, *H. porculus*, and *H. tenuis* of pre-treatment (plots before thinning and harvesting, and plots for the first year control treatment were considered as pre-treatment plots) data were pooled by plot per site. In order to determine what variables had effects on root-feeding *Hylastes* spp., dummy variables of stand age class, live crown ratio class, live crown density class, crown sunlight exposure class, and season were created in SAS 9.2. Effects of those dummy variables on population of *Hylastes* spp. were analyzed using analysis of variance (ANOVA). Means of *Hylastes* spp. captured by plot weekly from pre-treatment data were analyzed using Tukey's Studentized Range test (PROC GLM; SAS 9.2) to compare means among classes. Four seasons were defined according to average temperature during the pre-treatment year, captures of *Hylastes* spp. were also compared among four season. In addition, Pearson Correlation Coefficients were used to determine the relationships among *Hylastes* spp. and *D. terebrans* and *Ips grandicollis*. The response of *Hylastes* spp. to the thinning and harvesting treatments were compared using ANOVA. Bi-weekly totals of *H. salebrosus*, *H. porculus*, and *H. tenuis* of both pre- and post-treatment data were pooled by treatment in each study site. Significant was determined using Tukey's Multiple Comparisons Procedure (PROC GLM; SAS 9.2). All tests were analysized at the significant level of 0.05. Bi-weekly insect data from pre-treatment plots were pooled as well as data from post-treatment plots, the number were used to calculate diversity index (Shannon-Weaver Index; $H' = -\sum_{i=1}^{R} p_i \log p_i$) in Excel 2010.

RESULTS

Description of Study Area

The plot conditions and crown rating parameters for all study plots are presented in Tables 2.1 and 2.2. The youngest plot was planted in 1998 and the oldest plot was 1959. Plots were distributed across percent slopes from 0% to 28% with variable aspects. Elevation ranged from 94 to 265 m above sea level. Pine basal area ranged from 4 to 16 m^2ha^{-1} (Table 2.2). Pre-treatment data of crown conditions (Table 2.3) showed that loblolly pine at SS plot 9 appeared to be more vigorous than other plots (Avg. DBH=9.7 in, Crown ratio=50, Crown density=40, Foliage transparency=30).

Relationship of *Hylastes* spp. and Stand Age and Crown Parameters

There was no correlation between the number of *Hylastes* spp. collected during the study and live foliage transparency within the stand (ANOVA; $F_{H.\ salebrosus} = 0.26$, $P_{H.\ salebrosus} = 0.7678$; $F_{H.\ porculus} = 0.26$, $P_{H.\ porculus} = 0.7709$; $F_{H.\ tenuis} = 0.36$, $P_{H.\ tenuis} = 0.6975$; df = 6, 28; Table 2.4). Even though there were no significant age effects on population of *H. salebrosus* (ANOVA; $F_{H.\ salebrosus} = 2.83$, $P_{H.\ salebrosus} = 0.0504$, df = 3, 41), *P. taeda* stands in the 30-40 and >40 year age classes attracted more *H. salebrosus* than age classes of 10-19 and 20-29 years (Tukey's Studentized Range (HSD) test; Table 2.5). Stands in the >40 year age class had significantly higher numbers of *H. porculus* than all other stand ages examined. Stand age had no effect on the number of *H. tenuis* collected (ANOVA; $F_{H.\ tenuis} = 0.52$, $P_{H.\ tenuis} = 0.6677$, df = 3, 41; Table 2.5).

There was a significant correlation between live crown ratio and the population of *H. salebrosus* (ANOVA; $F_{H.\ salebrosus} = 7.47$, $P_{H.\ salebrosus} = 0.0025$, df = 6, 28). Stands that contained >35% live

crown ratio had significantly more *H. salebrosus* captured than the other live crown ratio classes. Live crown ratio did not have a significant effect on the population of *H. porculus* and *H. tenuis* (ANOVA; $F_{H.porculus} = 2.39$, $P_{H.\ porculus} = 0.1102$; $F_{H.tenuis} = 0.27$, $P_{H.\ tenuis} = 0.7678$; df = 6, 28). However, live crown ratio lower than 30% had fewer *H. porculus* than live crown ratio >30%. Although there was no significant difference of *H. porculus* and *H. tenuis* captured among the live crown ratio classes examined, the mean numbers of *H. porculus* and *H. tenuis* were higher in stands with higher live crown ratios (Table 2.6). Loblolly pine stands with higher live crown density had more *H. porculus* captured than lower live crown density class (Table 2.7). There were no significant differences among live crown light class and populations of *Hylastes* spp.

Insect Activity

A total of 46,865 beetles and weevils comprising 25 different insect species in 15 genera were captured from March 2009 to September 2011 (Fig. 2.4, 2.5). The most frequently captured insects were four species of scolytine bark beetles (*H. porculus*, *H. salebrosus*, *H. tenuis*, and *Ips grandicollis*), two species of molytine weevils (*Hb. pales* and *Pb. picivorus*) and four scolytine ambrosia beetles (*Gnathotrichus materiarius* Fitch, *Xyleborus pubescens* Zimmerman, *Xyleborinus saxesenii* Ratzeburg, *Xylosandrus crassiusculus* Motschulsky). Of all the insects collected, 48% were the root-feeding *Hylastes* spp. Other scolytines and curculionidae captured included *Dendroctonus terebrans* Oliver (n=799), *D. frontalis* (n=9), *I. avulsus* Eichhoff (n=195), *I. calligraphus* Germar (n=50), *Xylosandrus compactus* Eichhoff (n=212), *Monarthrum mali* Fitch (n=230), *M. fasciatum* Say (n=387), *Xyleborus atratus* Ecihhoff (n=230), *Xylosandrus germanus* Blandford (n=136), *Pissodes nemorensis* Germar (n=292), *Orthotomicus caelatus* Eichhoff (n=252), *Cnestus mutilatus* Blandford (formerly *Xylosandrus mutilatus*) Blandford (n=1518), *Xyleborus ferrugineus* Fabricius (n=134), *Trypodendron scabricollis* LeConte (n=221), *Pityborus comatus* Zimmerman (n=289), and *Dryoxylon onoharaensum* Murayama (n=196).

Population trends of Hylastes *spp. and Seasonal Effects on Populations* - During the two and a half year collection period, *H. salebrosus* was the most frequently captured insect (Fig. 2.4). Even though numbers of *Hylastes* spp. captures were different among sites (Table 2.8), the *Hylastes* spp. (Fig. 2.6) in SS site was representative of the insect populations captured at the other 4 study sites in Alabama and Georgia when looking at overall insect population trends. Season had a significant effect on the *Hylastes* spp. activity (ANOVA, $F_{H.\ salebrosus} = 10.68$, $P < 0.0001$; $F_{H.porculus} = 8.49$, $P < 0.0001$; $F_{H.tenuis} = 7.63$, $P < 0.0001$; df = 3, 133). Both *H. salebrosus* and *H. porculus* peaked in spring, while only *H. porculus* had an additional peak in the fall. Unlike *H. salebrosus* and *H. porculus*, *H. tenuis* population fluctuated frequently over the growing season (Tukey's Studentized Range (HSD) test; Table 2.10). Fewer *Hylastes* spp. were captured during the winter and several collections of *H. salebrosus* and *H. tenuis* dropped to zero corresponding to a period of low temperature (Table 2.9).

Correlations among Hylastes *spp.,* D. terebrans *and* I. grandicollis - Populations of *H. salebrosus*, *H. porculus* and *H. tenuis* were correlated to each other. ($r_{H.\ salebrosus\sim H.\ porculus} = 0.9177$, $P < 0.0001$; $r_{H.\ salebrosus\sim H.\ tenuis} = 0.6689$, $P < 0.0001$; $r_{H.\ porculus\sim H.\ tenuiss} = 0.96504$, $P < 0.0001$; Pearson correlation and Scatter plot matrix; Fig. 2.7). Additionally, plots with higher captures of *D. terebrans* had higher populations of *Hylastes* spp. (Table 2.11).

Hylastes *spp. Response to Thinning Treatment* - The interaction effects of treatment and time on *Hylastes* spp. populations were significant (Table 2.12). Two-year insect collection data indicates a significant increase in captures of *H. salebrosus* and *H. porculus* after thinning treatments when compared to insect captures in the control plots (Tukey's Multiple Comparison; Fig. 2.8 & 2.9; Fig. 2.10 & 2.11; Fig. 2.12 & 2.13; Table 2.13). In addition, both *H. salebrosus* and *H. porculus* were active the first winter season after thinning. More *H. tenuis* were captured in thinned plots in WEY, RAY, and SS sites than captures in control plots. The second year collections of *H. tenuis* in control plots in WV and SS sites were less than the first year (P_{WV}=0.0217, P_{SS}=0.0174; a=0.05).

Insect Diversity Response to Thinning Treatment - Captures of most bark beetle and weevil species increased after thinning treatment (Table 2.14). Although some species were trapped after thinning treatment compared to pre-thinning captures, the Shannon-Weaver index of bark beetle and weevils decreased in all study sites (Table 2.16). However, the diversity change of ambrosia beetle is not consistent. In RAY and WEY site, ambrosia beetle diversity decreased after thinning while it increased in SS and WV site post-thinning treatment (Table 2.15 & 2.16).

Hylastes *spp. Response to Harvesting Treatment* - Unlike the thinning treatment, harvesting seemed to have no effect on *Hylastes* populations. Only *H. porculus* in WV and SS sites and *H. tenuis* in SS site decreased after harvesting treatment (Fig.2.17A & 2.19; Fig.2.22; Table 2.15). Populations of *H. porculus* and *H. tenuis* captured in control plots at SS site were reduced compared to year one data (Fig.2.19 & 2.22; Table 2.15). Significantly fewer *H. salebrosus* at the WV site and *H. porculus* in WV and F&W were captured when post-harvested numbers were compared to pre-harvesting captures. However, *H. salebrosus* captured in WV site returned to levels in the second year after harvesting. The population of *H. tenuis* did not respond to the harvesting treatment, but the number of *H. tenuis* caught in F&W site decreased in the second year after harvesting. More *H. tenuis* were captured in WEY site after harvesting, but the population dropped in the second year after harvesting.

Insect Diversity Response to Harvesting Treatment - Captures of insect species respond different among study sites after harvesting treatment (Table 2.20 & 2.21). The diversity of bark beetle and weevils decreased in RAY and F&W sites compared to the diversity change in SS, WEY, and WV sites. However, the diversity of ambrosia beetles decreased in RAY, F&W, WEY, and WV sites except the captures in SS site (Table 2.22).

Stump Observations - The most commonly collected insect from loblolly pine root sections was *H. tenuis* followed by *H. salebrosus, Hb. pales, Pb. picivorus, O. caelatus,* and termites (species not identified). Galleries of *H. tenuis* and tunnels of regeneration weevils were frequently found on root samples (Fig. 2.23). Xylem and phloem tissues collected from root sections were discolored and *L. procerum* and *L. terebrantis* was recovered from those tissues (Table 2.17).

DISCUSSION

This study is the first report of population responses of pathogen-vectoring root- feeding beetles (*H. salebrosus, H. porculus* and *H. tenuis*) to a thinning treatment in loblolly pine stands. Summer and winter thinning may significantly increase populations of *Hylastes* spp. which have

been shown to vector *Leptographium* spp. involved with Southern Pine Decline by releasing plant volatile compunds. Generally, thinning is recommended as a bark beetle management strategy because it maintains higher vigor of remaining trees, removes trees which are susceptible to diseases and pests, and decrease infestation rates of remaining trees. Thinning also can keep residual trees alive and increase light around the entire crown (Werner 2002). In recent years, row thinning operations have become preferred in pine plantations because it is a quick and economical method. However, a row-thinning considers little about the crown conditions of either the removed or residual trees. Thinning may cause either visible damage to residual trees or invisible damage to root systems. In these current trials, the more recent thinning damaged some of the remaining trees. For example, large branches were broken, and the bark of remaining trees was damaged. Wounded trees exposed xylem tissue and the cut stumps released plant volatiles such as turpentine and alpha-pinene (USDA guidelines 2011) that attract root-feeding *Hylastes* spp. High populations of *Hylastes* spp. in thinned stands may cause higher infestation of ophiostomatoid fungi in root systems and could further predispose the remaining trees to other secondary pests such as *Dendroctonus* spp. and *Ips* spp. In order to reduce losses, a landowner could treat damaged trees and remaining stumps with preventative chemicals to decrease host volatiles release, and minimize logging damage to residual trees during thinning. Feduccia and Mann (1976) found in a previous study that spraying injured trees with preventative chemicals immediately after thinning in *P. taeda* stands prevented *D. terebrans* from attacking damaged trees. In addition, if a pine stand contains a significant level of diseased trees, a landowner may decide to perform a light row thinning as fifth row thinning instead of third row thinning because only 40% of remaining trees are impacted compared with third row thining, or perform thinning treatment during fall season because trees are more susceptible to be damaged in spring and summer when they are growing. In a high risk stands, to avoid SPD infestation, a landower should either plant resistant species or plant loblolly pine in wider space.

Previous studies reported that *H. salebrosus* and *H. porculus* were usually captured in panel traps while *H. tenuis* was often traped in pitfall traps (Thompson 2011). Therefore, *H. salebrosus* and *H. porculus* may establish their colonies in the root systems and in the upper stumps of cut trees. Following harvesting, temperature of the air near the ground and within upper soil horizons may be increased, and the humidity near the surface may be decreased (Nyland 2002), thus higher air temperature would dry remaining stumps and roots close to soil surface. Because of habitat removal, lack of food sourses and temperature limitations, it is hypothesized that harvesting would reduce populations of *Hylastes* spp.when compared to control treatments. In the present study, however, the harvesting treatment did not affect captures of *H. salebrosus* and *H. tenuis*, although fewer *H. porculus* were trapped in some harvested sites. *Hylastes porculus* is reported to have a more northern range (Wood 1982), so its activity would be expected to be reduced in higher temperatures. However, *H. tenuis* galleries and different stage of *H. tenuis* were observed very often one year after harvesting in root samples, which may explain why the populations of *H. tenuis* were more stable in response to harvesting comparing to *H. salebrosus* and *H. porculus*. The number of *Hylastes* spp. in harvested stands returned to pre-treatment capture levels in the second year following harvesting. Since the harvesting effects on insect populations are inconsistent, it is difficult to summarize conclusions on how harvesting affected root-feeding bark beetles. However, there were no reports of these *Hylastes* spp. attacking pine seedlings in the United States as reported in New Zealand with *H. ater* (Reay et al. 2012). Hence, it will not be an issue if landowners replant pine seedlines in those harvested plots.

Seasonal data prior to stand treatment (Table 2.3; Fig. 2.6) indicates that root- feeding *Hylastes* beetles are active throughout most of the year which is in agreement with the previous work (Zanzot et al. 2010, Thompson 2011). Thus it is necessary to monitor insect population peaks using the year-round sampling method as insect activity does not always overlap the traditional spring trapping period for southern pine beetle (Thatcher et al. 1980, Gardner 2011). Numbers of *H. salebrosus* captured were greater than the other two *Hylastes* spp., which is unlike previous work (Zanzot 2009) showing *H. tenuis* as the dominant species in longleaf pine stands. However, *H. porculus* and *H. salebrosus* were dominant species in other studies (Bauman 2003, Eckhardt et al. 2007, Sullivan et al. 2003).

Hylastes spp. are less active in summer and winter than in spring and fall (Table 2.3), however, captures of *H. porculus* were less than *H. salebrosus* and *H. tenuis* in summer while greater in winter. Although little is known about the biology and physiology of *Hylastes* spp., it is possible that both the maximum and minimum temperature threshold of *H. porculus* is lower than other two species because *H. porculus* is a northern species (Wood 1982). During the survey period, most of the *H. salebrosus* and *H. porculus* were consistently collected from panel and flight intercept trap, while *H. tenuis* was captured frequently from pitfall trap. Numbers of *Hylastes* spp. captured is positively correlated with captures of *D. terebrans* which also showed spring and fall peaks in this study. Therefore, *D. terebrans* might be a good indicator of *Leptographium* root infection (Fatzinger 1985).

Hylastes spp. are vectors of ophiostomatoid fungi which contribute to SPD. In this study, more *Hylastes* spp. captured in older stands (Zanzot et al. 2010) provided additional evidence that loblolly pines at age class 40-50 years were more apt to show decline symptoms than younger trees. Futher research on isolating blue-stain fungi from root-feeding *Hylastes* spp. should be considered in those stands in order to better prove loblolly pines are more prone to infest SPD disease although previous studies (Eckhardt et al. 2007, Zanzot et al. 2010) reported that ophiostomatoid fungi were recovered from exoskeletons of *H. salebrosus* and *H. tenuis*.

Crown conditions such as live crown ratio, live crown density, and crown light were associated with higher captures of *Hylastes* spp. However, live foliage transparency had no correlation with collections of *Hylastes* spp., which is in contrast with the study conducted by Menard (2007) and Thompson (2011). Higher percentage of live crown ratio, crown density and foliage exposure to light generally indicates vigorous loblolly pines (Schomaker et al. 2007). Thus, crown variables may not be a good indicator to estimate initial populations of root-feeding bark beetle species as no symptoms are present until significant root damage occurs.

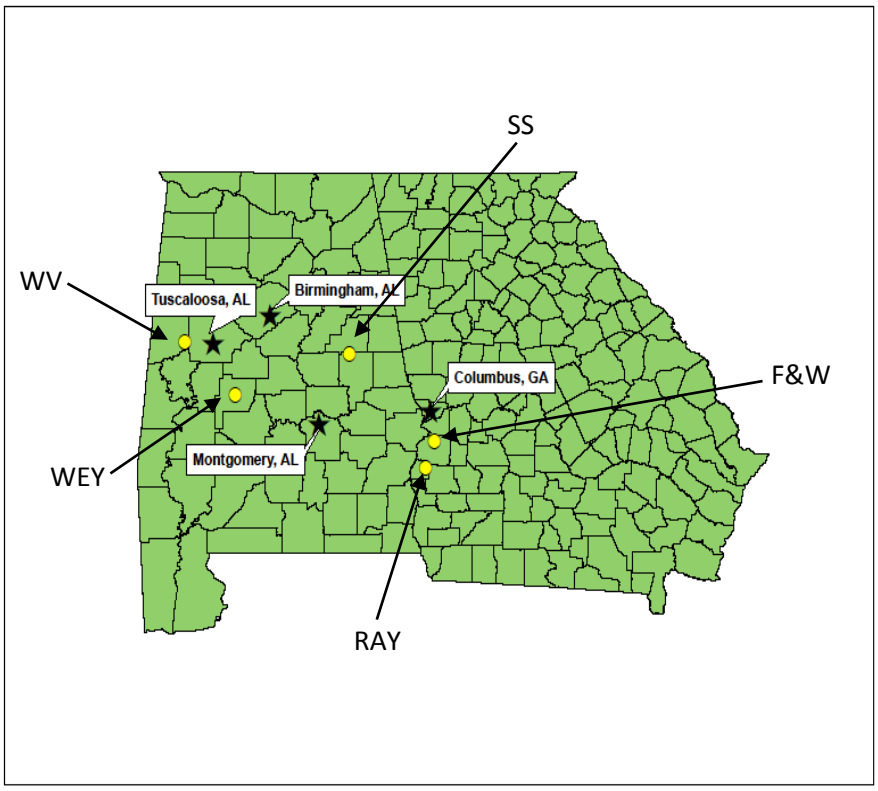

Fig. 2.1. Study locations in Alabama and Georgia.

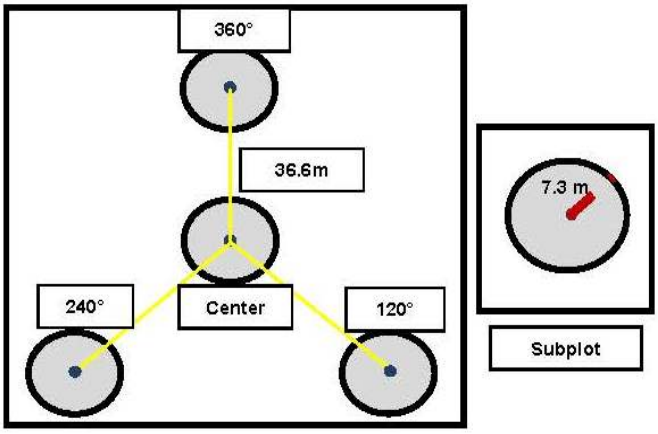

Fig. 2.2. Subplot layout at each treatment site.

Fig. 2.3. (A) Panel trap (B) pitfall trap and (C) flight intercept trap placed at the center subplot to capture ground and flying insects.

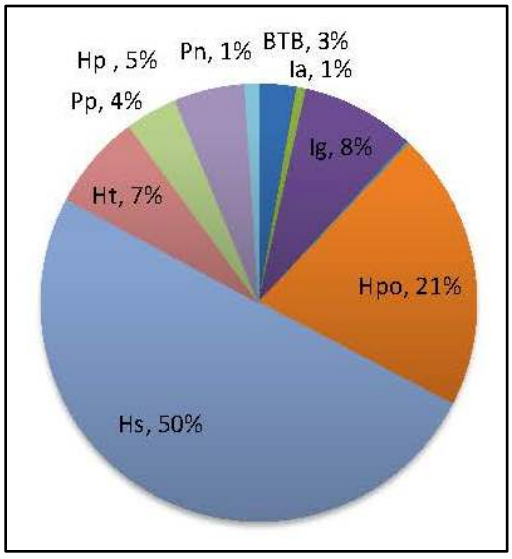

Fig. 2.4. Percentage of bark beetles and weevils captured in loblolly pine stands using pitfall, panel, and flight intercept traps, from 13 March 2009 to 29 September 2011 in Alabama and Georgia (BTB-*D. terebrans*; SPB-*D. frontalis*; Ia-*I. avulses*; Ig-*I. grandicollis*; Ic-*I. calligraphus*; Hpo-*H. porculus*; Hs-*H. salebrosus*; Ht-*H.tenuis*; Pp-*Pb. picivorus*; Hp-*Hb. pales*; Pn-*Pissodes nemorensis*; Oc-*O. caelatus*)

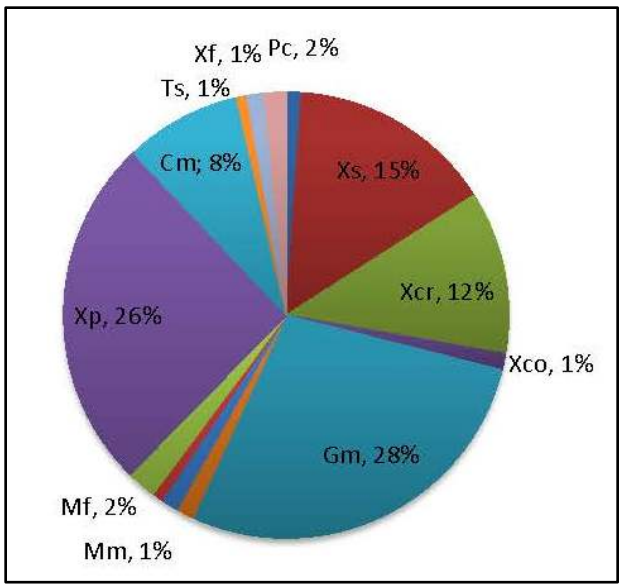

Fig. 2.5. Percentage of ambrosia beetles captured in loblolly pine stands using pitfall, panel and flight intercept traps, from 13 March 2009 to 29 September 2011 in Alabama and Georgia (Do- *Dryoxylon onoharaensum*; Xs- *Xyleborinus saxesenii*; Xcr- *Xylosandrus crassiusculus*; Xco- *Xylosandrus compactus*; Gm- *G.s materiarius*; Mm- *M. mali*; Xa- *Xyleborus atratus*; Xg- *Xylosandrus germanus*; Mf- *M. fasciatum*; Xp- *Xyleborus pubescens*; Cm- *C. mutilatus*; Xf- *Xyleborus ferrugineus*; Ts- *T. scabricollis*; Pc- *Pityborus comatus*).

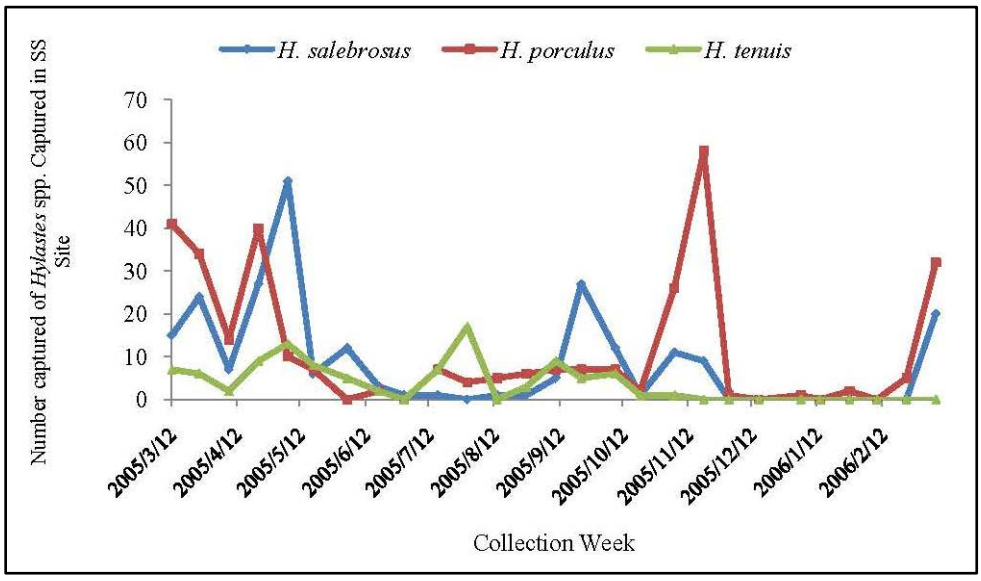

Fig. 2.6. Biweekly Captures of *Hylastes* spp. in baited pitfall, panel, and flight intercept traps on SS Site, from 13 March 2009 to 10 March 2010.

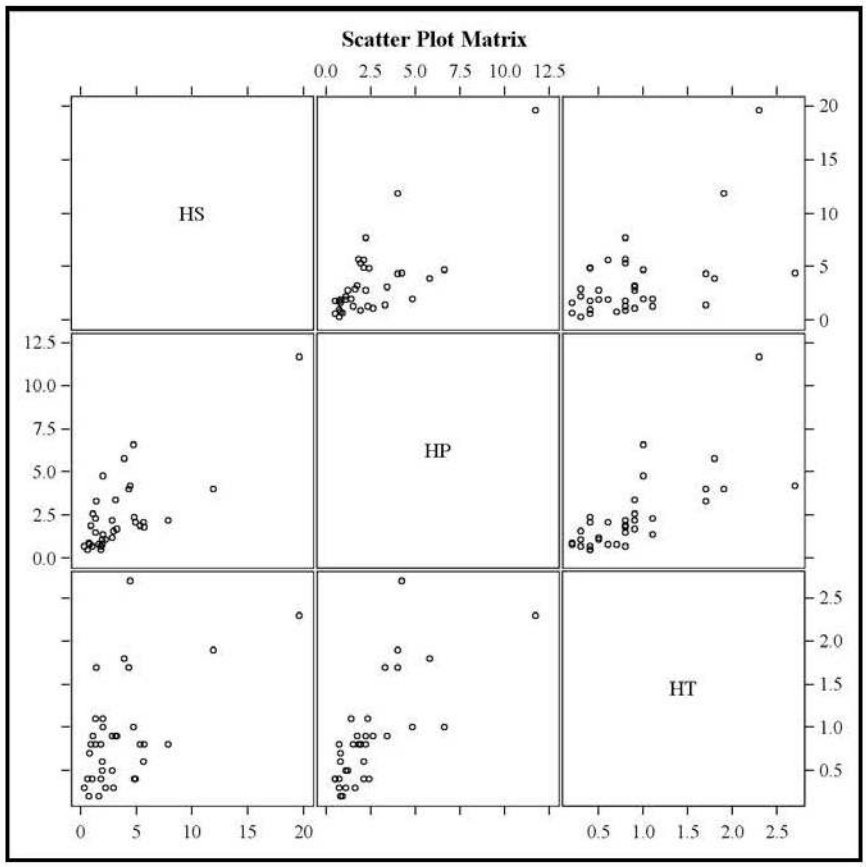

Fig. 2.7. Scatter Plot Matrix showed the correlations among *Hylastes* spp. captured from 13 March 2009 to 10 March 2010.

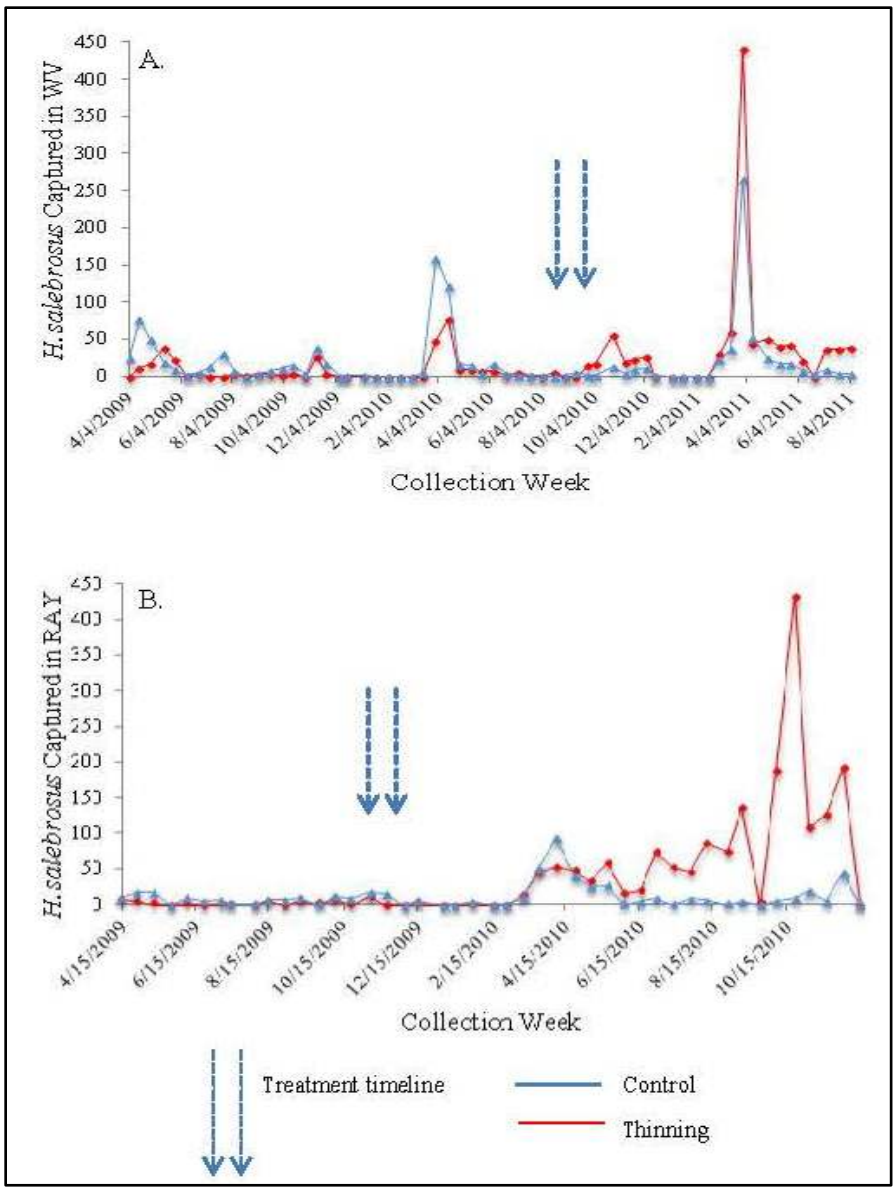

Fig. 2.8. Bi-weekly captured *Hylastes salebrosus* in thinning treatment plots and control plots, showing both pre- and post-treatment data. (A) *H. salebrosus* captured in WV site from April 2009 to August 2011. (B) *H. salebrosus* captured in RAY site from April 2009 to December 2010.

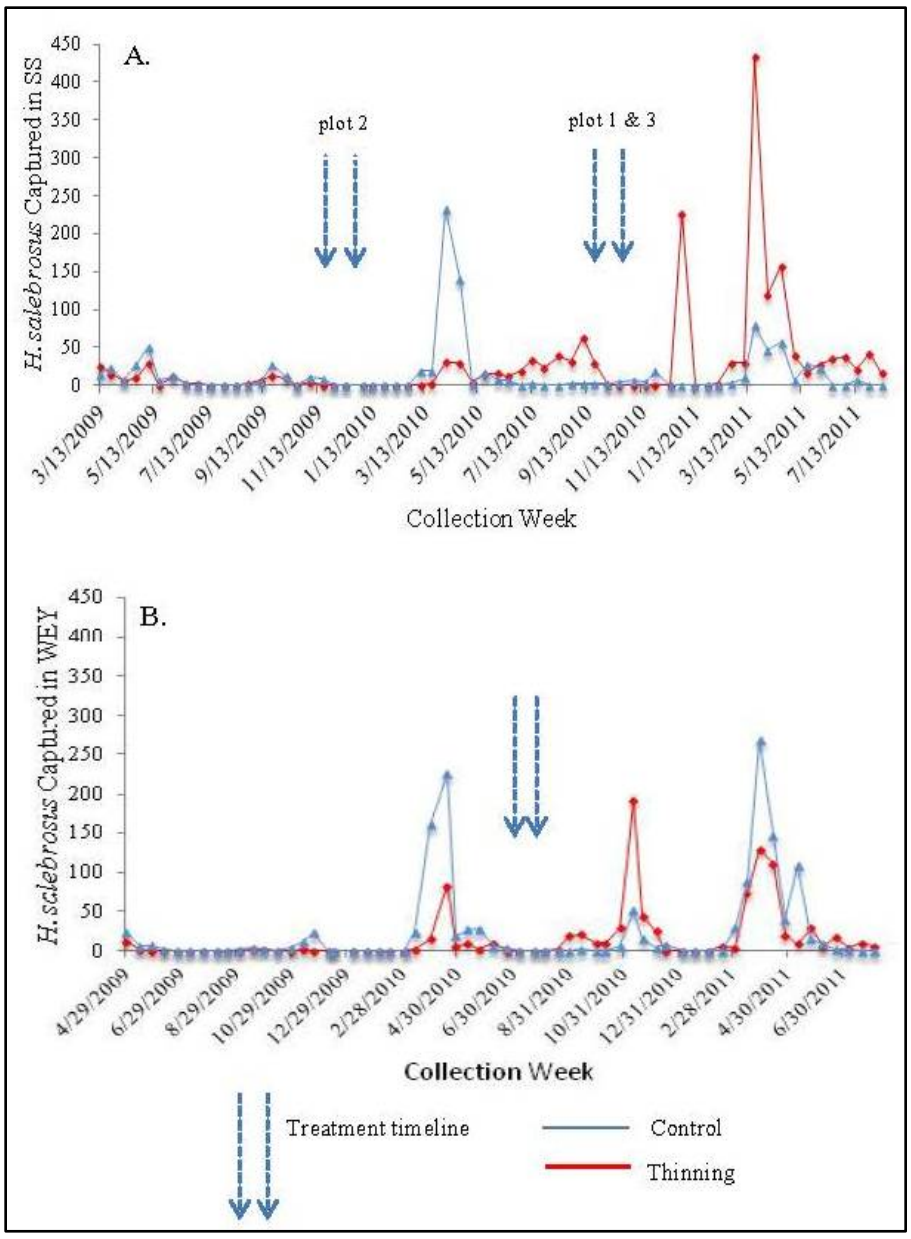

Fig. 2.9. Bi-weekly captured *Hylastes salebrosus* in thinning treatment plots and control plots, showing both pre- and post-treatment data. (A) *H. salebrosus* captured in SS site from March 2009 to August 2011. (B) *H. salebrosus* captured in WEY site from April 2009 to August 2011.

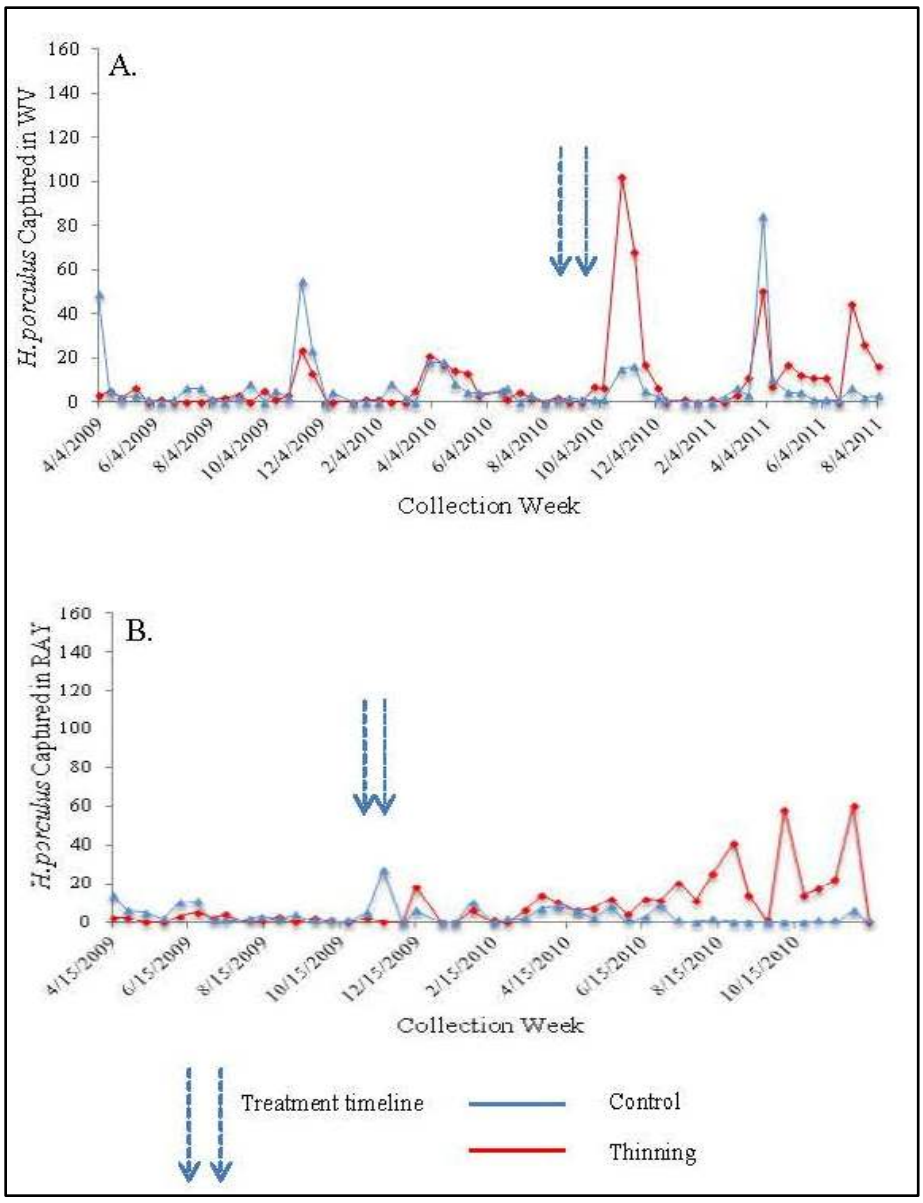

Fig. 2.10. Bi-weekly captured *Hylastes porculus* in thinning treatment plots and control plots, showing both pre- and post-treatment data. (A) *H. porculus* captured in WV site from April 2009 to August 2011. (B) *H. porculus* captured in RAY site from April 2009 to December 2010.

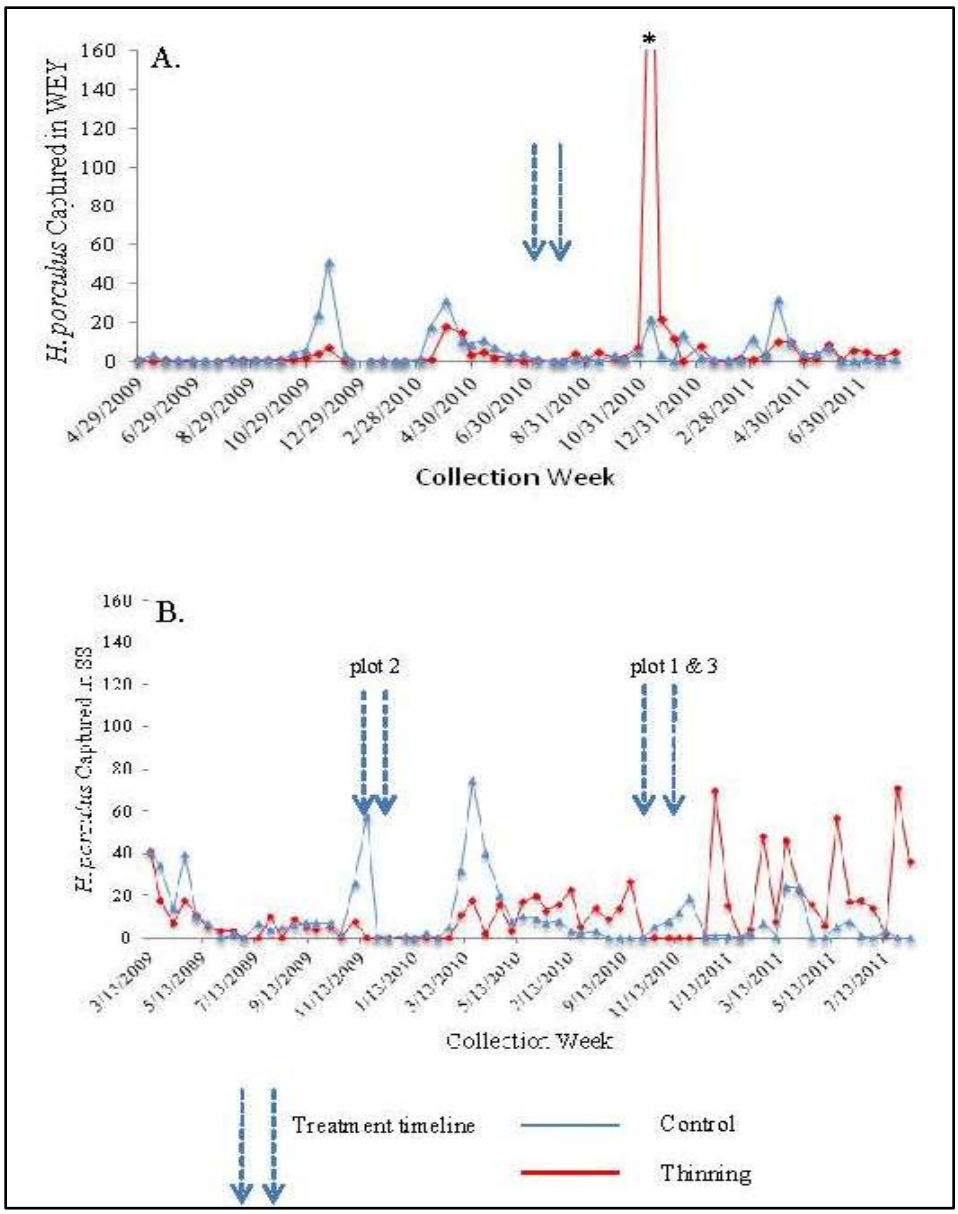

Fig. 2.11. Bi-weekly captured *Hylastes porculus* in thinning treatment plots and control plots, showing both pre- and post-treatment data. (A) *H. porculus* captured in WEY site from April 2009 to August 2011, and * indicated that 254 *H. porculus* were captured. (B) *H. porculus* captured in SS site from March 2009 to August 2011.

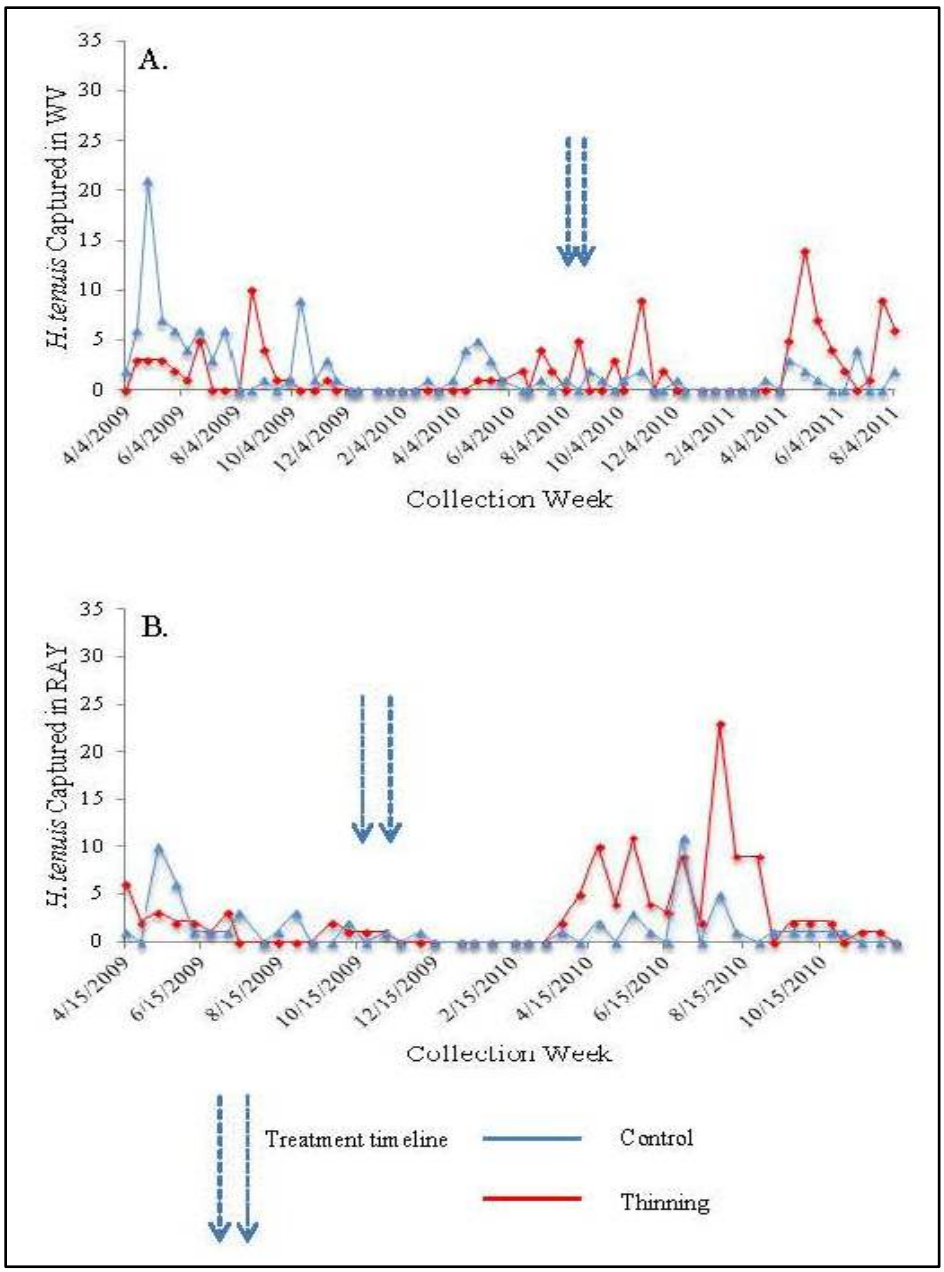

Fig. 2.12. Bi-weekly captured *Hylastes tenuis* in thinning treatment plots and control plots, showing both pre- and post-treatment data. (A) *H. tenuis* captured in WV site from April 2009 to August 2011. (B) *H. tenuis* captured in RAY site from April 2009 to December 2010.

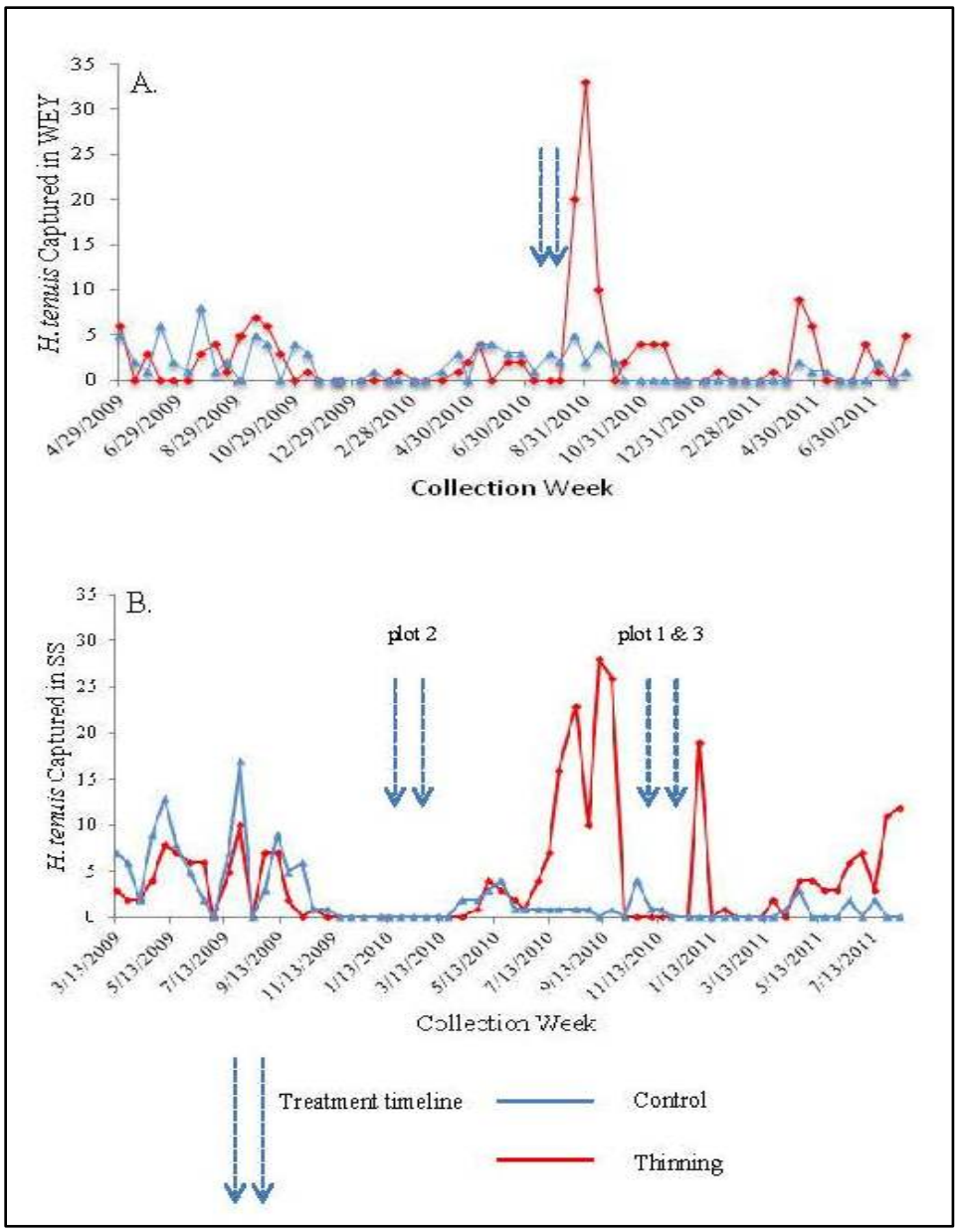

Fig. 2.13. Bi-weekly captured *Hylastes tenuis* in thinning treatment plots and control plots, showing both pre- and post-treatment data. (A) *H. tenuis* captured in WEY site from April 2009 to August 2011. (B) *H. tenuis* captured in SS site from March 2009 to August 2011.

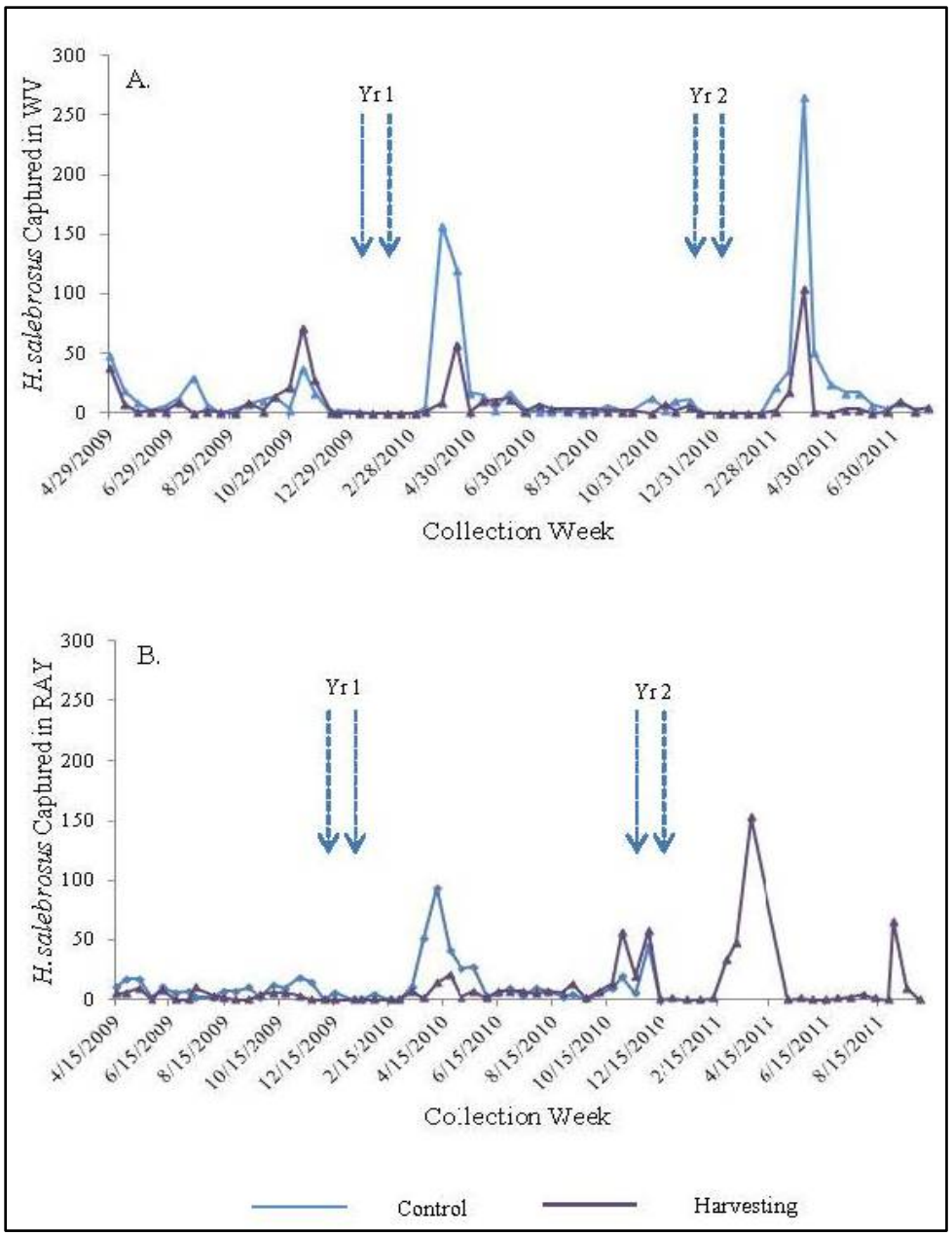

Fig. 2.14. Bi-weekly captured *Hylastes salebrosus* in harvesting and control plots, showing both pre- and post-treatment data. (A) *H. salebrosus* captured in WV site from April 2009 to August 2011. (B) *H. salebrosus* captured in RAY site from April 2009 to September 2011.

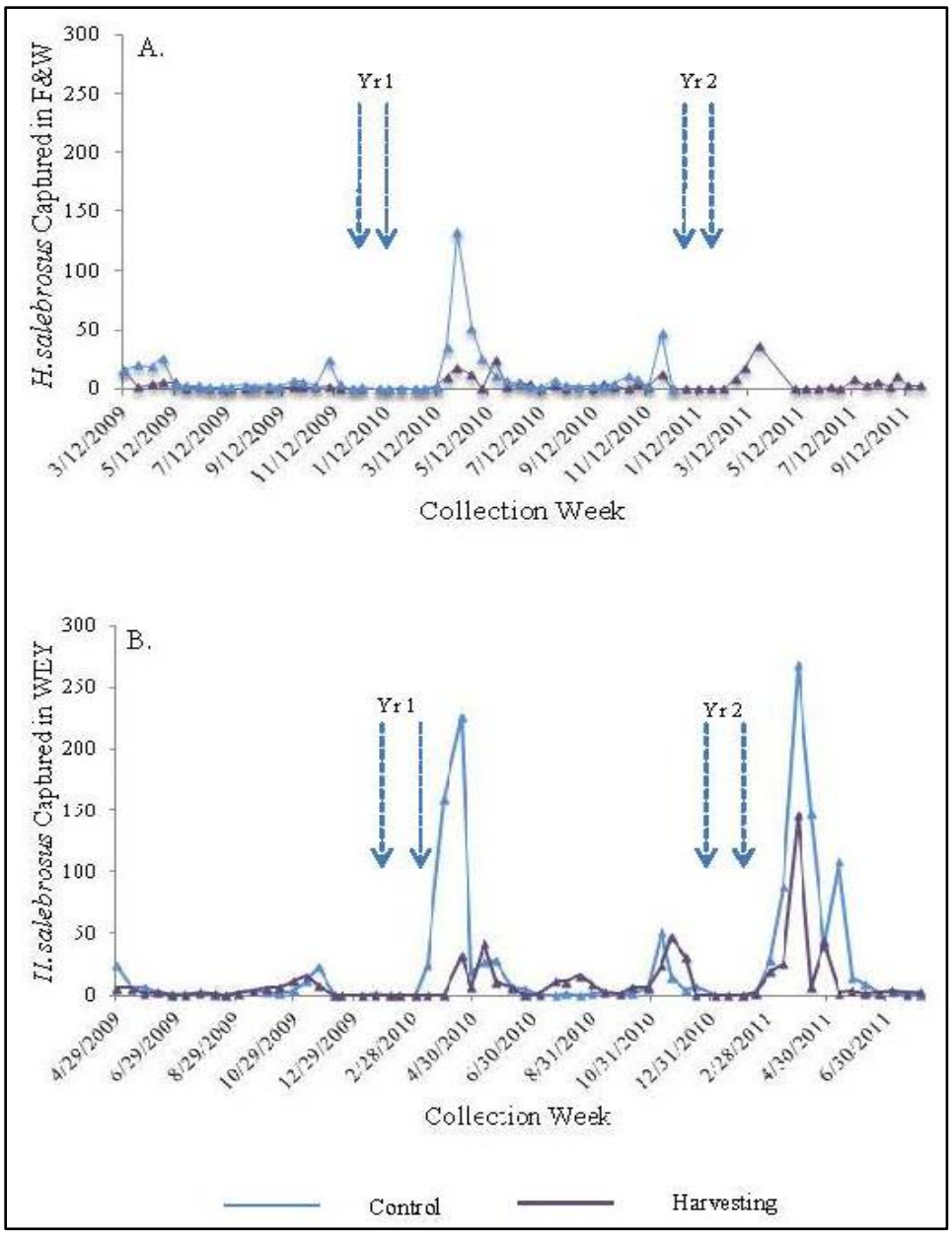

Fig. 2.15. Bi-weekly captured *Hylastes salebrosus* in harvesting and control plots, showing both pre- and post-treatment data. (A) *H. salebrosus* captured in F&W site from March 2009 to September 2011. (B) *H. salebrosus* captured in WEY site from April 2009 to August 2011.

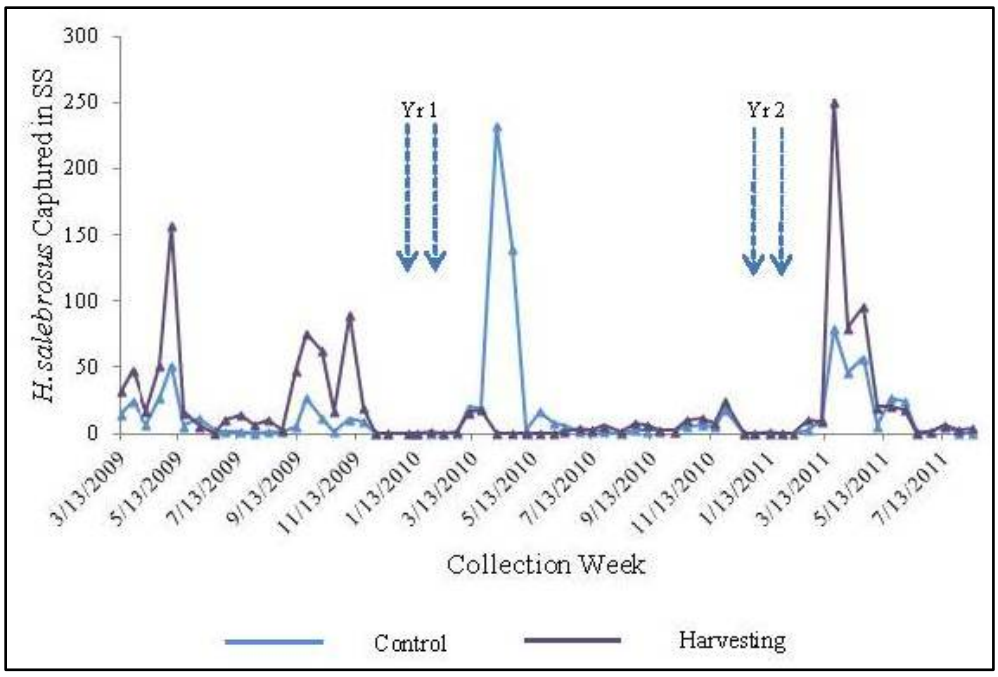

Fig. 2.16. Bi-weekly captured *Hylastes salebrosus* in harvesting and control plots in SS site from March 2009 to August 2011, showing both pre- and post-treatment data.

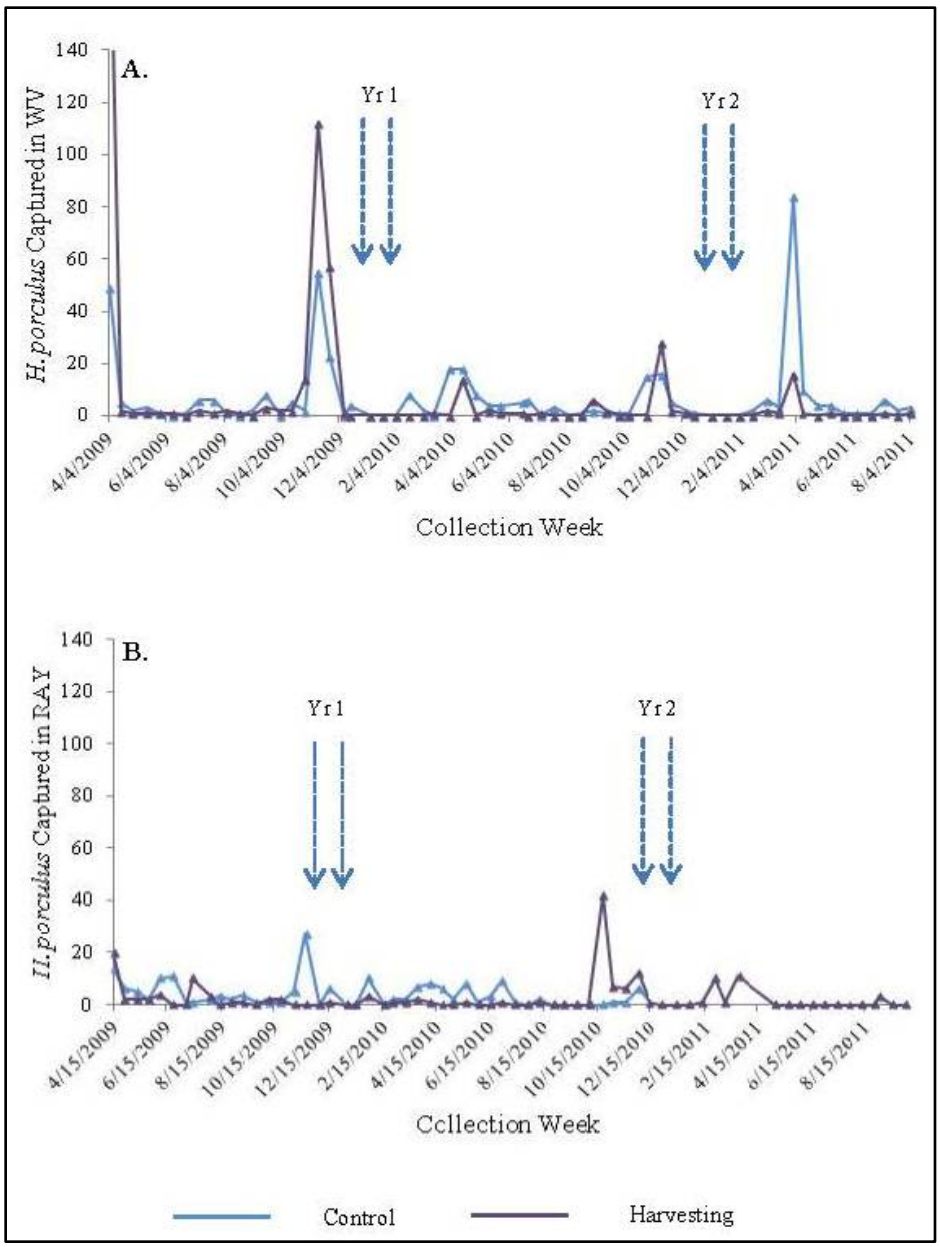

Fig. 2.17. Bi-weekly captured *Hylastes porculus* in harvesting and control plots, showing both pre- and post-treatment data. (A) *H. porculus* captured in WV site from April 2009 to August 2011. (B) *H. porculus* captured in RAY site from April 2009 to September 2011.

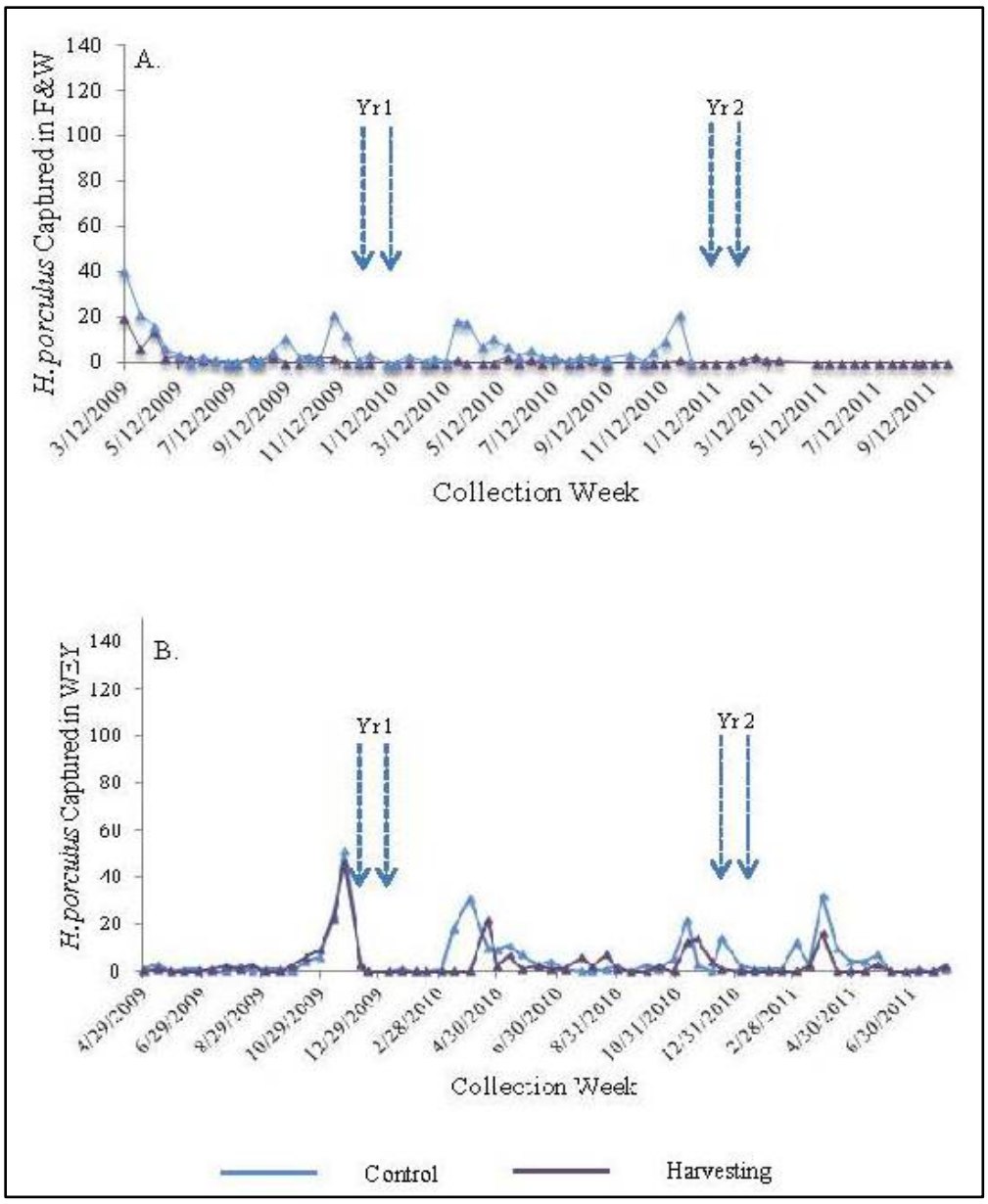

Fig. 2.18. Bi-weekly captured *Hylastes porculus* in harvesting and control plots, showing both pre- and post-treatment data. (A) *H. porculus* captured in F&W site from March 2009 to September 2011. (B) *H. porculus* captured in WEY site from April 2009 to August 2011.

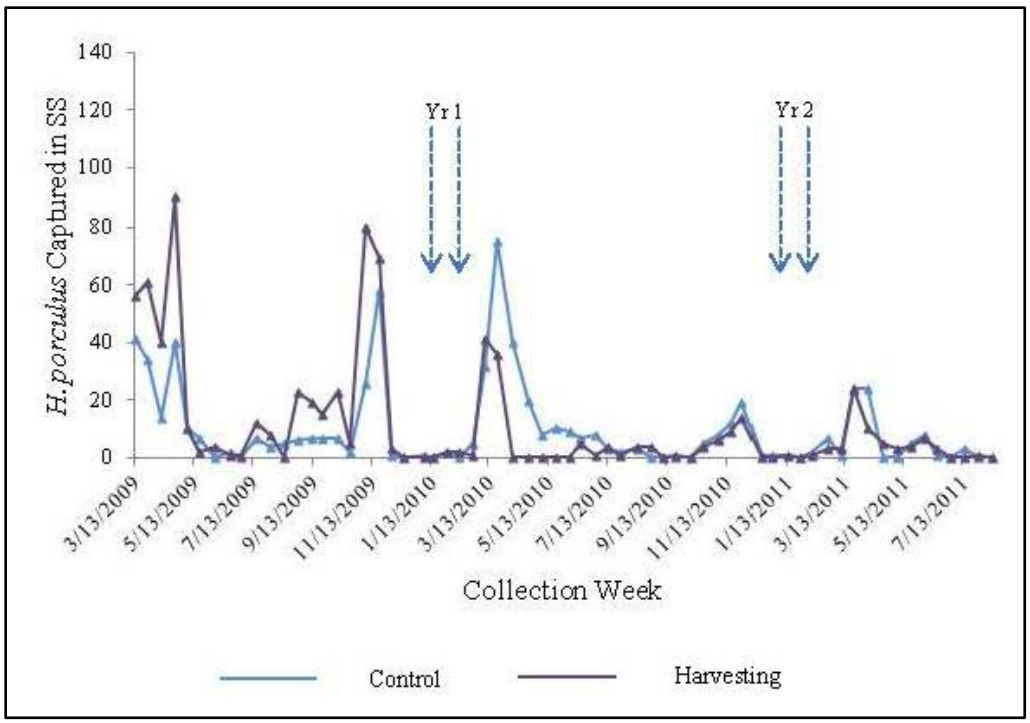

Fig. 2.19. Bi-weekly captured *Hylastes porculus* in harvesting and control plots in SS site from March 2009 to August 2011, showing both pre- and post-treatment data.

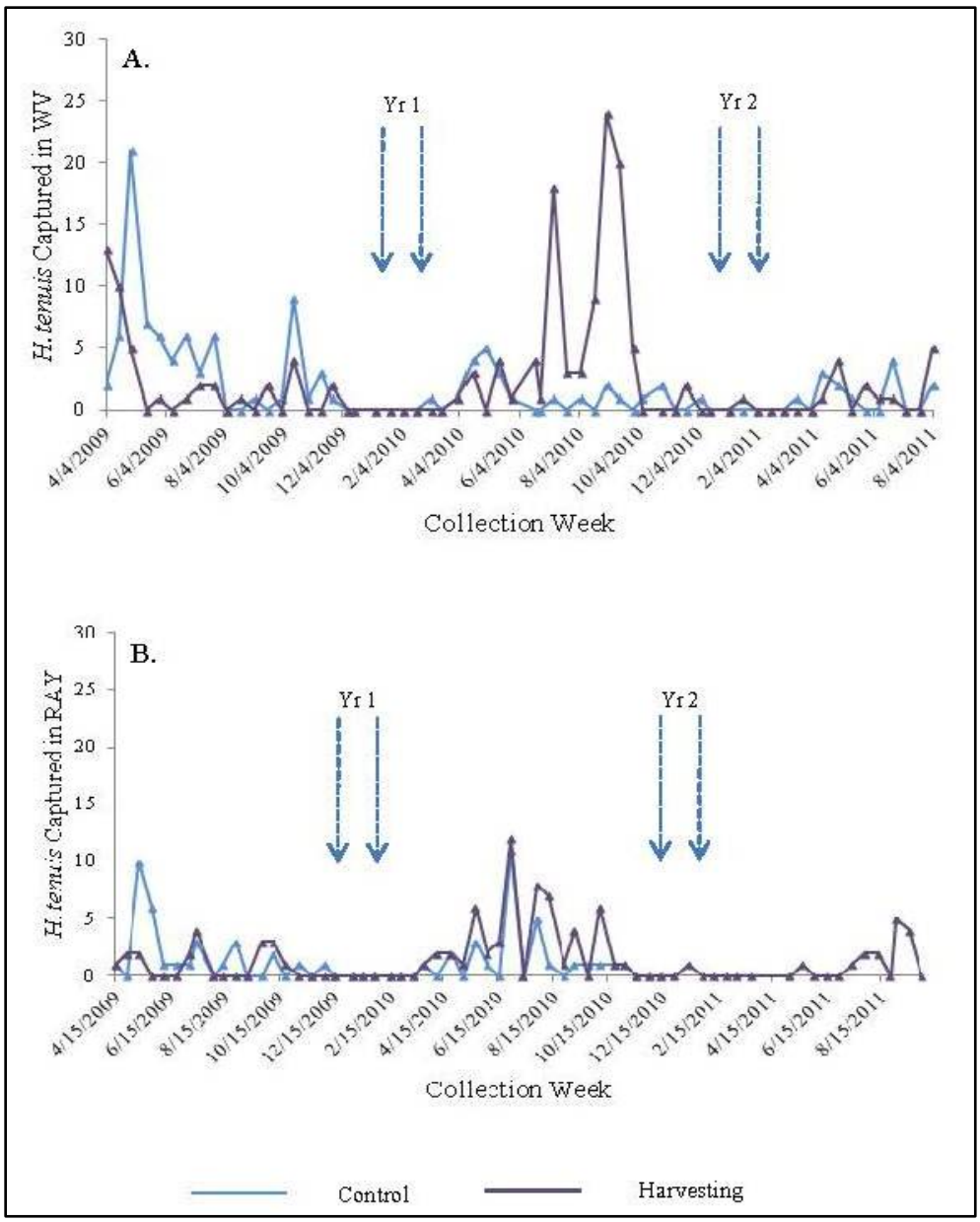

Fig. 2.20. Bi-weekly captured *Hylastes tenuis* in harvesting and control plots, showing both pre- and post-treatment data. (A) *H. tenuis* captured in WV site from April 2009 to August 2011. (B) *H. tenuis* captured in RAY site from April 2009 to September 2011.

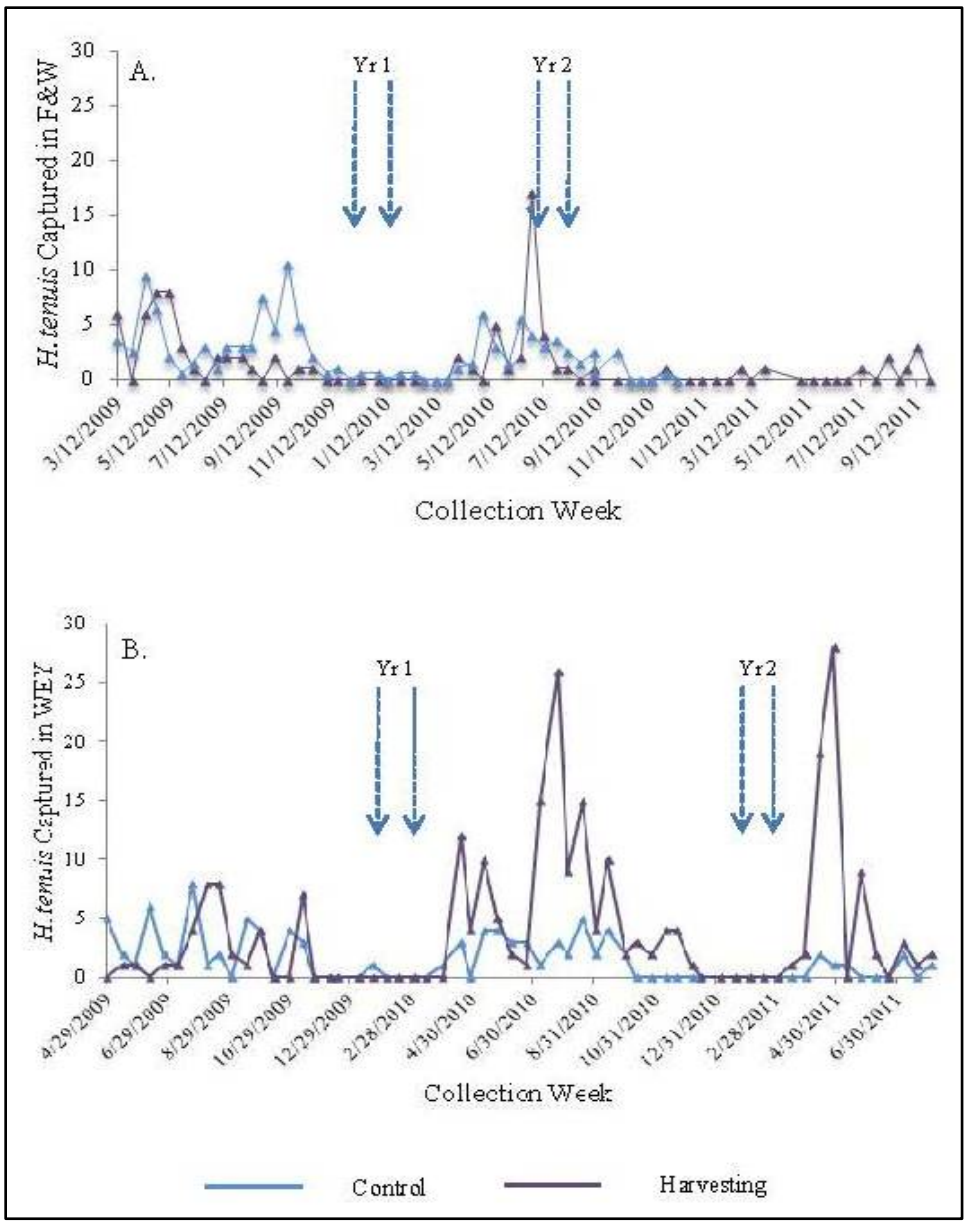

Fig. 2.21. Bi-weekly captured *Hylastes tenuis* in harvesting and control plots, showing both pre- and post-treatment data. (A) *H. tenuis* captured in F&W site from March 2009 to September 2011. (B) *H. tenuis* captured in WEY site from April 2009 to August 2011.

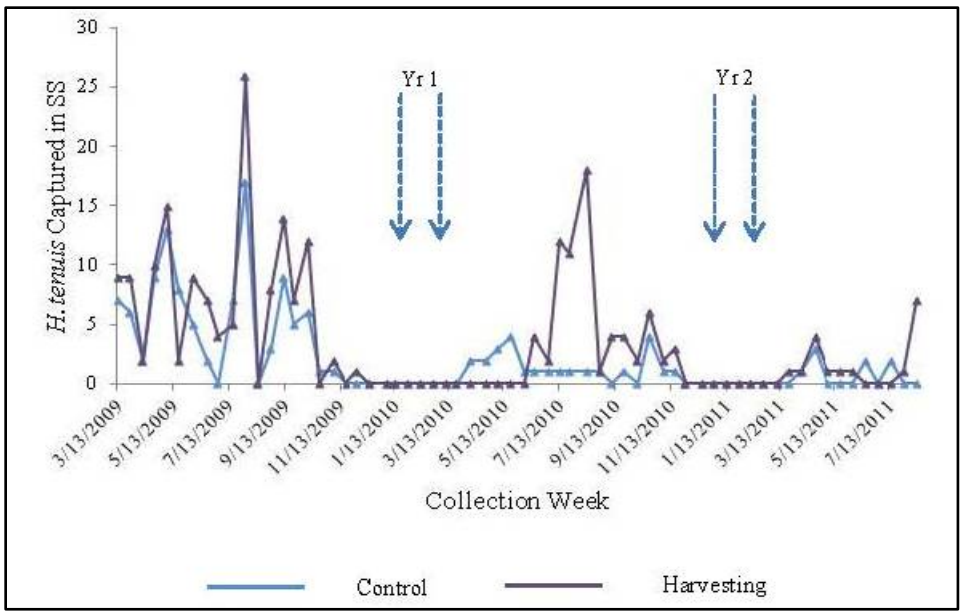

Fig. 2.22. Bi-weekly captured *Hylastes tenuis* in harvesting and control plots in SS site from March 2009 to August 2011, showing both pre- and post-treatment data.

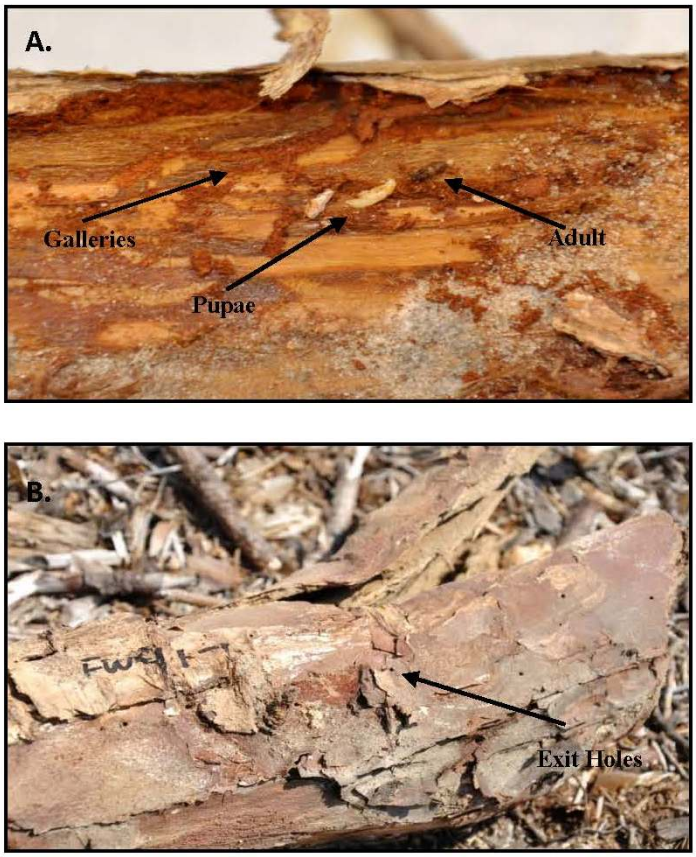

Fig. 2.23. (A) *P. taeda* root sections from stump sampling infested with *H. tenuis* root beetle, showing galleries, pupae and adult of *H. tenuis*. (B) Root section showing exit holes of *H. tenuis*.

Table 2.1 Treatment timeline in study sites.

Study Site	Thinning	Harvesting
SS	20 Nov 2009-24 Feb 2010 (Plot 2) 9 Oct 2010-17 Dec 2010 (Plot 1&3)	Feb 2010 (Plot 9)
RAY	19 Nov 2009-4 Dec 2009	19 Nov 2009-4 Dec 2009
F&W	NA	19 Nov 2009-29 Jan 2010
WV	21 Jul 2010-5 Aug 2010	9 Dec 2009- 22 Jan 2010
WEY	25 Jul 2010-10 Aug 2010 (Plot 1&3)	16 Dec 2009-28 Feb 2010

NA indicates no treatment during collection years.

Table 2.2 Plot locations and pre-treatment site characteristics in Alabama and Georgia.

Plot	Location	Age	PBA (m^2ha^{-1})	TBA (m^2ha^{-1})	Elev (m)	SL (%)	Asp	LF	TP
WV 1	N 33.217 W87.891	16	16	17	121	22	N/NW	v	Ss
WV 2	N 33.214 W87.893	16	17	18	100	18	W	v	Ss
WV 3	N 33.211 W 87.895	16	15	15	124	16	N	v	Ss
WV 4	N 33.2057 W 87.949	19	14	16	107	14	NW	v	Ss
WV 5	N 33.2058 W 87.948	18	15	17	106	8	NW	c	Ss
WV 6	N 33.206 W 87.949	18	11	11	101	26	E/NE	v	Rt
WV 7	N 33.181 W 87.928	51	4	4	102	5	NE	v	Rt
WV 8	N 33.1814 W 87.927	52	4	4	114	9	E/NE	v	Rt
WV 9	N 33.191 W 87.904	51	7	10	113	28	SW	v	Ss
SS 1	N 33.087 W 85.879	18	15	16	247	19	E	v	Ts
SS 2	N 33.090 W 85.884	18	16	16	210	4	NW	c	Ts
SS 3	N 33.085 W 85.880	18	13	13	254	19	NW	v	Ns
SS 4	N 32.913 W 85.709	26	10	10	253	3	SE	v	Ns
SS 5	N 32.9126 W 85.699	26	12	13	245	4	E	v	Ts
SS 6	N 32.9119 W 85.695	26	12	14	239	3	NW	f	Rt
SS 7	N 32.9110 W 85.714	26	7	8	265	2	SW	f	Ts
SS 8	N 32.913 W 85.715	26	11	13	258	5	NE	c	Ts
SS 9	N 32.916 W 85.713	26	10	10	265	1	NW	f	Ss
WEY 1	N 32.755 W 87.413	13	13	13	94	13	NW	v	Ts
WEY 2	N 32.750 W 87.4128	13	13	13	116	2	N	v	Rt
WEY 3	N 32.759 W 87.4121	13	14	15	93	13	W/SW	v	Rt
WEY 4	N 32.796 W 87.4357	28	9	10	121	30	SW	v	Ss
WEY 5	N 32.794 W 87.4353	28	7	10	127	6	W	v	Ss

(continued)

Plot	Location	Age	PBA (m^2ha^{-1})	TBA (m^2ha^{-1})	Elev (m)	SL (%)	Asp	LF	TP
WEY 6	N 32.743 W 87.401	13	13	14	131	3	N	v	Rt
WEY 7	N 32.655 W 87.280	30	7	8	106	6	W/SW	v	Rt
WEY 8	N 32.658 W 87.277	30	7	10	130	18	N/NW	v	Ss
WEY 9	N 32.661 W 87.276	30	9	10	131	10	N	v	Ss
FW 1	N32.1892 W 84.853	17	8	9	128	25	S/SW	v	Ss
FW 2	N 32.189 W 84.858	17	14	14	141	6	S/SW	v	Ss
FW 3	N 32.185 W 84.860	17	16	16	132	8	N/NW	v	Ss
FW 4	N 32.191 W 84.859	24	13	15	150	6	NW	v	Rt
FW 5	N 32.174 W 84.839	20	14	17	119	11	N/NE	v	Ts
FW 6	N 32.156 W 84.942	23	9	12	109	19	SE	v	Ss
FW 7	N 32.150 W 84.934	32	11	15	94	1	NA	f	Ss
FW 8	N 32.154 W 84.932	23	8	13	111	8	S/SE	v	Ss
FW 9	N 32.152 W 84.930	32	7	11	104	1	NA	f	Rt
Ray 1	N 32.002 W 84.977	16	10	10	146	14	N/NW	v	Ss
Ray 2	N 31.997 W 84.860	18	13	15	123	4	E/NE	v	Rt
Ray 3	N 31.992 W 84.904	16	20	20	180	0	NA	f	Rt
Ray 4	N 32.014 W 84.970	16	9	9	159	8	SW	c	Ss
Ray 5	N 32.009 W 84.969	16	9	9	163	6	S/SW	f	Ss
Ray 6	N 31.992 W 84.866	18	19	19	137	1	NA	f	Rt
Ray 7	N 31.890 W 84.956	22	13	14	111	2	NW	f	Rt
Ray 8	N 31.893 W 84.950	22	13	14	123	8	SE	v	Ss
Ray 9	N 32.003 W 84.981	16	11	12	126	10	E/NE	v	Ss

PBA = pine basal area; TBA = total basal area; Elev = elevation; SL = slope; Asp = aspect; LF = ; v= convex; c = concave; f = flat; TP = topographic position; NA = no aspect; Ss = side-slope; Rt = ridge-top; and Ts = toe-slope.

Table 2.3 Mean values of pre-treatment data for growth and crown rating parameters.

Plot	DBH (in)	CR (%)	CL	CP	CDen (%)	CDie (%)	FT (%)	5-yr Growth (cm)	10-yr Growth (cm)
WV1	7.9	35	1	2	30	0	30	1.53	4.23
WV2	6.6	30	1	2	25	0	35	1.68	4.25
WV3	8.2	35	2	2	35	0	25	1.8	4.0
WV4	6.8	35	1	2	30	0	25	1.42	2.9
WV5	7.5	35	2	2	35	0	25	1.32	3.33
WV6	6.3	40	3	2	35	0	30	1.73	3.75
WEY1	8.4	35	1	2	35	0	30	2.12	5.57
WEY2	7.3	40	1	2	35	0	30	1.93	5.12
WEY3	7.4	35	1	2	40	0	30	2.03	5.77
WEY4	9.4	35	2	2	30	0	30	1.3	2.82
WEY5	12.1	40	3	2	35	0	25	1.65	4.33
WEY6	6.9	45	2	2	35	0	25	2.1	5.42
FW1	8.3	30	1	2	35	0	25	1.23	3.47
FW2	6.2	35	1	2	30	0	25	1.53	3.6
FW3	5.6	30	1	2	30	0	25	1.33	3.23
FW4	6.3	30	1	2	35	0	25	1.04	3.12
FW5	6.9	30	2	2	30	0	35	0.9	2.82
FW6	6.5	30	2	2	30	0	45	1.06	3.67
Ray1	6.5	35	1	2	30	0	30	1.76	4.64
Ray2	6.7	25	1	2	30	0	25	1.4	3.73
Ray3	6.2	30	1	2	30	0	30	1.47	1.63
Ray4	5.6	30	1	2	25	0	35	1.32	4.44
Ray5	5.8	25	1	2	25	0	25	1.52	4.7
Ray6	7.0	25	1	2	35	0	35	1.28	3.3
Ray7	6.7	25	1	2	35	0	25	NA	NA
Ray8	5.9	30	1	2	35	0	25	NA	NA
SS1	7.0	30	1	2	35	0	25	1.3	3.84
SS2	8.3	35	1	2	40	0	30	1.44	4.5
SS3	6.9	35	1	2	30	0	30	1.88	4.58
SS4	8.4	35	1	2	35	0	35	1.6	2.75
SS5	10.0	30	1	2	40	0	30	NA	NA
SS6	9.3	30	1	2	45	0	45	1.8	3.5
SS7	10.2	35	2	2	35	0	25	2.3	4.8
SS8	9.1	35	2	2	35	0	25	1.67	3.86
SS9	9.7	50	1	2	40	0	30	NA	NA

CR = crown ratio; CL = crown light; CP = crown position; CDen = crown density; CDie = crown dieback; FT = foliage transparency; and NA = growth measurements didn't record during the experiment periods.

Table 2.4 Summary statistics for Tukey's Studentized Range (HSD) test for means of *Hylastes* spp. captured among live crown transparency class in central Alabama and Georgia, March 2009 to March 2010.

Insect Species	Live crown transparency class (%)		
	<= 25	30-35	>35
H. salebrosus	4.0 a	3.2 a	2.0a
H. porculus	2.7 a	2.6 a	2.3 a
H. tenuis	1.0 a	0.9 a	0.9 a

Mean values with different letters within a row indicate significant difference within the species.

Table 2.5 Summary statistics for Tukey's Studentized Range (HSD) test for means of *Hylastes* spp. captured among stand age class in central Alabama and Georgia, March 2009 to March 2010.

Insect Species	Age class (yr)			
	10-19	20-29	30-40	>40
H. salebrosus	3.0 ab	4.0 ab	1.2 a	8.2 b
H. porculus	1.7 b	3.6 b	1.5 b	7.3 a
H. tenuis	0.8 a	1.0 a	0.8 a	0.7 a

Mean values with different letters within a row indicate significant difference within the species.

Table 2.6 Summary statistics for Tukey's Studentized Range (HSD) test for means of *Hylastes* spp. captured among live crown ratio class on *Hylastes* spp. in central Alabama and Georgia, March 2009 to March 2010.

Insect Species	Live crown ratio class (%)		
	<30	30-35	>35
H. salebrosus	2.4 b	2.7 b	8.5 a
H. porculus	1.1 b	2.3 ab	4.0 a
H. tenuis	0.5 a	0.9 a	1.2 a

Mean values with different letters within a row indicate significant difference within the species.

Table 2.7 Summary statistics for Tukey's Studentized Range (HSD) test for means of *Hylastes* spp. captured among live crown density class in central Alabama and Georgia, March 2009 to March 2010.

Insect Species	Live crown density class (%)		
	<30	30-39	40-45
H. salebrosus	1.5 a	3.3 a	5.7 a
H. porculus	0.9 b	2.2 ab	4.7 a
H. tenuis	0.6 a	0.9 a	1.1 a

Mean values with different letters within a row indicate significant difference within the species.

Table 2.8 Mean ± SE captures of Hylastes spp. per collection among sites.

Site	H. salebrosus	H. porculus	H. tenuis
SS	13.4 ± 2.7	13.0 ± 2.2	3.9 ± 0.6
RAY	5.3 ± 0.7	3.2 ± 0.7	1.4 ± 0.3
FW	4.3 ± 1.0	4.9 ± 1.2	2.6 ± 0.4
WEY	9.7 ± 3.4	4.2 ± 1.0	1.9 ± 0.2
WV	16.0 ± 3.2	9.0 ± 2.7	2.0 ± 0.4

Table 2.9 Average air temperature among season during pre-treatment sampling year.

Season	Air Temperature (°C)		
	Minimum	Maximum	Average
Spring	-1.6-18.5	11.4-29.4	15.3
Summer	17.0-22.8	28.1-35	33.2
Fall	4.8-20.9	17.8-29.6	19.1
Winter	-6.9-5.5	4-17.6	6.1

Table 2.10 Summary statistics for Tukey's Studentized Range (HSD) test for seasonal effects on Hylastes spp. in central Alabama and Georgia, March 2009 to March 2010.

Insect Species	Means captured by season			
	Spring	Summer	Fall	Winter
H. salebrosus	29.3 a	10.6 b	8.7 b	0.9 b
H. porculus	13.1 a	4.8 b	10.0 a	1.6 b
H. tenuis	3.3 a	4.5 a	2.2 ab	0.4 b

Different letters within a row indicate significant difference within the species.

Table 2.11 Pearson correlation results between root-feeding *Hylastes* spp. (captured from March 2009 to March 2010), *D. terebrans* and *I. grandicollis*.

Insect species	*D. terebrans*		*I. grandicollis*	
	r	*P*	r	*P*
H. salebrosus	0.6628	<.0001	0.1493	0.3275
H. porculus	0.5580	<.0001	-0.0629	0.6817
H. tenuis	0.4763	0.0009	-0.0002	0.9991

$P < 0.05$ indicates correlations between variables are different.

Table 2.12 Interaction of treatment variable and time variable effects on *Hylastes* spp. by ANOVA.

Insect Species		Statistic results of treatment * time
H. salebrosus	WV	$F = 1.88$; $P = 0.1374$; df = 3, 120
	WEY	$F = 2.36$; $P = 0.0748$; df = 3, 116
	RAY	$F = 8.08$; $P < 0.0001$*; df = 3, 86
	SS	$F = 3.58$; $P = 0.0158$*; df = 3, 124
H. porculus	WV	$F = 3.22$; $P = 0.0251$*; df = 3, 120
	WEY	$F = 1.39$; $P = 0.2497$; df = 3, 124
	RAY	$F = 9.55$; $P < 0.0001$*; df = 3, 86
	SS	$F = 3.45$; $P = 0.0188$*; df = 3, 124
H. tenuis	WV	$F = 2.77$; $P = 0.0448$*; df = 3, 120
	WEY	$F = 3.42$; $P = 0.0197$*; df = 3, 124
	RAY	$F = 3.06$; $P = 0.0326$*; df = 3, 86
	SS	$F = 5.33$; $P = 0.0017$*; df = 3, 124

* Indicates significant difference at a = 0.05.

Table 2.13 Tukey's Multiple Comparison of pre-treatment data and post-treatment data.

Insect Species		*P*-values	
		Thinning Treatment	Control Treatment
H. salebrosus	WV	0.0199 * (+)	0.9484
	WEY	0.0299* (+)	0.2426
	RAY	<0.0001* (+)	0.6517
	SS	0.0051* (+)	0.3624
H. porculus	WV	0.0035 * (+)	0.9394
	WEY	0.0493* (+)	0.9098
	RAY	<0.0001* (+)	0.2296
	SS	0.0032* (+)	0.6074
H. tenuis	WV	0.0915	0.0217 * (-)
	WEY	0.0140* (+)	0.2111
	RAY	0.0022* (+)	0.6257
	SS	0.0421* (+)	0.0174 * (-)

* Indicates significant difference between pre- and post- treatment at a = 0.05;
+ Indicates increasing captures; - Indicates decreasing captures.

Table 2.14 Number of bark beetle and weevil species captured pre-thinning and post-thinning among study sites.

Study Sites	Insect Species	Pre-thinning Captures	Post-thinning Captures
RAY	*D. terebrans*	13	63
	D. frontalis	0	2
	I. avulses	5	18
	I. gradicollis	71	142
	I. calligraphus	0	0
	H. porculus	37	415
	H. salebrosus	69	1735
	H. tenuis	24	99
	Pb. picivorus	60	74
	Hb. pales	25	51
	P. nemorensis	4	23
	O. caelatus	0	50
SS	*D. terebrans*	7	26
	D. frontalis	0	0
	I. avulses	6	4
	I. gradicollis	25	76
	I. calligraphus	0	1
	H. porculus	147	268
	H. salebrosus	141	415
	H. tenuis	70	116
	Pb. picivorus	37	12
	Hb. pales	102	27
	P. nemorensis	22	11
	O. caelatus	6	7
WEY	*D. terebrans*	1	60
	D. frontalis	0	0
	I. avulses	0	8
	I. gradicollis	10	55
	I. calligraphus	0	0
	H. porculus	71	373
	H. salebrosus	156	780
	H. tenuis	51	104
	Pb. picivorus	20	13
	Hb. pales	25	36
	P. nemorensis	35	1
	O. caelatus	2	1
WV	*D. terebrans*	11	68
	D. frontalis	0	0
	I. avulses	8	11

(continued)

	I. gradicollis	110	29
	I. calligraphus	0	0
	H. porculus	155	322
	H. salebrosus	304	942
	H. tenuis	45	61
	Pb. picivorus	23	21
	Hb. pales	42	60
	P. nemorensis	30	5
	O. caelatus	5	5

Table 2.15 Number of ambrosia species captured pre-thinning and post-thinning among study sites.

Study Sites	Insect Species	Pre-thinning Captures	Post-thinning Captures
RAY	*D.onoharaensum*	5	10
	X. saxesenii	55	224
	X. crassiusculus	52	179
	X. compactus	3	2
	G. materiarius	94	134
	M. mali	6	8
	X. atratus	6	22
	X. germanus	2	6
	M. fasciatum	1	18
	X. pubescens	79	536
	C. mutilatus	41	33
	X. ferrugineus	0	7
	T. scabricollis	0	9
	P. comatus	9	33
SS	*D.onoharaensum*	2	6
	X. saxesenii	95	55
	X. crassiusculus	17	59
	X. compactus	3	5
	G. materiarius	181	165
	M. mali	16	14
	X. atratus	10	3
	X. germanus	3	6
	M. fasciatum	0	51
	X. pubescens	56	124
	C. mutilatus	27	40
	X. ferrugineus	0	11
	T. scabricollis	2	26
	P. comatus	6	29

(continued)

WEY	*D.onoharaensum*	3	0
	X. saxesenii	45	11
	X. crassiusculus	89	50
	X. compactus	10	0
	G. materiarius	126	33
	M. mali	8	0
	X. atratus	4	1
	X. germanus	6	3
	M. fasciatum	3	7
	X. pubescens	40	70
	C. mutilatus	77	25
	X. ferrugineus	2	6
	T. scabricollis	5	11
	P. comatus	27	1
WV	*D.onoharaensum*	3	2
	X. saxesenii	57	13
	X. crassiusculus	28	79
	X. compactus	21	1
	G. materiarius	396	67
	M. mali	10	1
	X. atratus	0	2
	X. germanus	6	3
	M. fasciatum	7	5
	X. pubescens	99	150
	C. mutilatus	38	33
	X. ferrugineus	6	2
	T. scabricollis	10	6
	P. comatus	2	2

Table 2.16 Shannon-Weaver Index for pre- and post-treatment captures among study sites.

Study Sites	Insect Category	Pre-thinning Index	Post-thinning Index
RAY	Bark beetles & Weevils	1.91	1.26
	Ambrosia beetles	1.89	1.70
SS	Bark beetles & Weevils	1.86	1.54
	Ambrosia beetles	1.67	2.13
WEY	Bark beetles & Weevils	1.65	1.30
	Ambrosia beetles	2.00	1.85
WV	Bark beetles & Weevils	1.70	1.23
	Ambrosia beetles	1.50	1.65

Table 2.17 Interaction of treatment variable and time variable effects on *Hylastes* spp. by ANOVA.

Insect Species		Treatment * Time interaction
H. salebrosus	WV	$F = 1.46$; $P = 0.2284$; df = 3, 117
	WEY	$F = 1.56$; $P = 0.2042$; df = 3, 107
	RAY	$F = 1.19$; $P = 0.3184$*; df = 3, 106
	SS	$F = 0.83$; $P = 0.4790$; df = 3, 121
	F&W	$F = 4.61$; $P = 0.0045$*; df = 3, 103
H. porculus	WV	$F = 3.10$; $P = 0.0293$*; df = 3, 117
	WEY	$F = 0.6$; $P = 0.6193$; df = 3, 107
	RAY	$F = 1.4$; $P = 0.2474$; df = 3, 106
	SS	$F = 8.07$; $P < 0.0001$*; df = 3, 121
	F&W	$F = 7.04$; $P = 0.0002$*; df = 3, 103
H. tenuis	WV	$F = 2.36$; $P = 0.0749$; df = 3, 117
	WEY	$F = 6.5$; $P = 0.0004$*; df = 3, 107
	RAY	$F = 0.55$; $P = 0.6487$; df = 3, 106
	SS	$F = 5.34$; $P = 0.0017$*; df = 3, 121
	F&W	$F = 8.50$; $P = 0.0001$*; df = 3, 103

*Indicates significant difference at a = 0.05.

Table 2.18 Tukey's Multiple Comparison of mean *Hylastes* spp. captured pre- and post-treatment.

Insect Species		*P-values*	
		Harvesting Treatment	**Control Treatment**
H. salebrosus	WV	0.0798	0.5172
	WEY	0.2966	0.1322
	RAY	0.4464	0.6496
	F&W	0.5449	0.0058* (+)
	SS	0.4661	0.3070
H. porculus	WV	0.0031* (-)	0.7878
	WEY	0.3281	0.8408
	RAY	0.8506	0.2269
	F&W	0.0606	0.9079
	SS	<0.0001* (-)	0.0188* (-)
H. tenuis	WV	0.6257	0.0191* (-)
	WEY	0.0122* (+)	0.6019
	RAY	0.4928	0.6242
	F&W	0.2081	0.0020* (+)
	SS	0.0220* (-)	0.0133* (-)

*Indicates significant response at a=0.05.

+Indicates increasing captures; -Indicates decreasing captures.

Table 2.19. Tukey's Multiple Comparison of mean *Hylastes* spp. captured pre-treatment with year one post-treatment data, and pre-treatment with year two post-treatment data in harvesting plots.

Insect Species		*P*-values	
		Yr1-Post	Yr2-Post
H. salebrosus	WV	0.0365* (-)	0.0903
	WEY	0.1967	0.1280
	RAY	0.3925	0.0780* (+)
	F&W	0.6508	0.5473
H. porculus	WV	0.0472*(-)	0.0478*(-)
	WEY	0.6584	0.1325
	RAY	0.8998	0.5130
	F&W	0.0093* (-)	0.0071* (-)
H. tenuis	WV	0.2304	0.4276
	WEY	0.0218* (+)	0.4230
	RAY	0.1509	0.2907
	F&W	0.4394	0.0279* (-)

* Indicates significant response at a=0.05.
+ Indicates increasing capture; - Indicates decreasing capture.

Table 2.20. Number of bark beetle and weevil species captured pre-harvest and post-harvest among study sites

Study Sites	Insect Species	Pre-harvest Captures	Post-harvest Captures
RAY	*D. terebrans*	12	8
	D. frontalis	0	0
	I. avulses	3	5
	I. gradicollis	58	77
	I. calligraphus	0	0
	H. porculus	47	12
	H. salebrosus	64	106
	H. tenuis	18	49
	Pb. picivorus	51	42
	Hb. pales	28	107
	P. nemorensis	9	14
	O. caelatus	2	20
FW	*D. terebrans*	3	9
	D. frontalis	0	0
	I. avulses	8	2
	I. gradicollis	45	74
	I. calligraphus	0	0
	H. porculus	62	8
	H. salebrosus	26	105
	H. tenuis	43	35
	Pb. picivorus	34	103
	Hb. pales	35	102
	P. nemorensis	5	12
	O. caelatus	1	17
SS	*D. terebrans*	20	47
	D. frontalis	0	0
	I. avulses	3	5
	I. gradicollis	19	41
	I. calligraphus	0	0
	H. porculus	604	116
	H. salebrosus	720	576
	H. tenuis	142	71
	Pb. picivorus	13	49
	Hb. pales	67	54
	P. nemorensis	12	0
	O. caelatus	3	10
WEY	*D. terebrans*	1	22
	D. frontalis	0	1
	I. avulses	0	6
	I. gradicollis	13	97
	I. calligraphus	0	0

	H. porculus	98	86
	H. salebrosus	82	268
	H. tenuis	39	138
	Pb. picivorus	5	43
	Hb. pales	13	58
	P. nemorensis	0	8
	O. caelatus	1	12
WV	*D. terebrans*	7	29
	D. frontalis	0	0
	I. avulses	0	3
	I. gradicollis	28	90
	I. calligraphus	0	1
	H. porculus	414	59
	H. salebrosus	467	145
	H. tenuis	43	99
	Pb. picivorus	9	95
	Hb. pales	21	120
	P. nemorensis	1	29
	O. caelatus	3	17

Table 2.21. Number of ambrosia species captured pre-harvest and post-harvest among study sites.

Study Sites	Insect Species	Pre-harvest Captures	Post-harvest Captures
RAY	*D.onoharaensum*	8	5
	X. saxesenii	48	144
	X. crassiusculus	67	23
	X. compactus	12	1
	G. materiarius	80	38
	M. mali	3	1
	X. atratus	9	16
	X. germanus	6	1
	M. fasciatum	0	0
	X. pubescens	88	310
	C. mutilatus	25	23
	X. ferrugineus	0	9
	T. scabricollis	0	6
	P. comatus	1	4
FW	*D.onoharaensum*	9	1
	X. saxesenii	61	200
	X. crassiusculus	52	53
	X. compactus	10	2
	G. materiarius	160	11
	M. mali	17	0
	X. atratus	7	3
	X. germanus	3	4
	M. fasciatum	1	4
	X. pubescens	26	129
	C. mutilatus	17	11
	X. ferrugineus	0	7
	T. scabricollis	0	15
	P. comatus	1	0
SS	*T. scabricollis*	53	2
	P. comatus	236	44
	X. crassiusculus	100	83
	X. compactus	5	2
	G. materiarius	690	95
	M. mali	40	0
	X. atratus	17	2
	X. germanus	6	3
	M. fasciatum	40	7
	X. pubescens	236	128
	C. mutilatus	77	99
	X. ferrugineus	0	2

	T. scabricollis	1	5
	P. comatus	9	3
WEY	*D.onoharaensum*	1	5
	X. saxesenii	49	88
	X. crassiusculus	29	72
	X. compactus	22	2
	G. materiarius	137	27
	M. mali	2	1
	X. atratus	1	12
	X. germanus	2	1
	M. fasciatum	1	1
	X. pubescens	68	343
	C. mutilatus	72	43
	X. ferrugineus	0	9
	T. scabricollis	0	2
	P. comatus	3	1
WV	*D.onoharaensum*	4	0
	X. saxesenii	98	236
	X. crassiusculus	17	35
	X. compactus	2	1
	G. materiarius	170	95
	M. mali	5	2
	X. atratus	4	3
	X. germanus	2	0
	M. fasciatum	1	63
	X. pubescens	224	489
	C. mutilatus	106	38
	X. ferrugineus	1	16
	T. scabricollis	0	9
	P. comatus	2	7

Table 2.22. Shannon-Weaver Index for pre- and post-treatment captures among study sites.

Study Sites	Insect Category	Pre-harvest Index	Post-harvest Index
RAY	Bark beetles & Weevils	1.97	1.93
	Ambrosia beetles	1.89	1.43
FW	Bark beetles & Weevils	1.96	1.87
	Ambrosia beetles	1.75	1.50
SS	Bark beetles & Weevils	1.28	1.42
	Ambrosia beetles	1.71	1.79
WEY	Bark beetles & Weevils	1.45	1.83
	Ambrosia beetles	1.74	1.44
WV	Bark beetles & Weevils	1.14	2.05
	Ambrosia beetles	1.58	1.51

Table 2.23. Characteristics of stump samples collected from center subplot in harvested plots.

Plot	Mean ± SSSS of root length (cm)	Mean ± SSSS of root diameter (cm)	Roots with galleries (%)	Range of numbers of exit holes	Roots with insects present (%)	Roots with stain fungus (%)
WV7	35.05± 2.81	6.22±1.26	50%	0-7	33%	17%
WV8	28.19±2.54	5.55±1.23	33%	0-7	17%	0
WV9	31.24±1.10	5.63±0.43	67%	2-11	33%	0
WEY7	42.32±4.01	4.47±0.58	33%	0-4	33%	17%
WEY8	32.82±1.39	4.48±0.60	50%	0-8	50%	50%
WEY9	34.24±3.05	5.04±0.33	83%	0-4	50%	50%
F&W7	27.05±1.65	4.06±1.78	50%	0-22	50%	0
F&W8	16.34±5.80	3.89±1.03	33%	0-23	17%	17%
F&W9	18.72±3.32	2.14±0.18	67%	0-28	33%	17%
Ray7	32.92±1.14	3.71±0.56	50%	0-5	33%	0
Ray8	32.41±3.34	3.56±0.66	17%	0-2	0	0
Ray9	32.26±2.88	6.31±1.00	50%	0-19	50%	17%
SS9	30.87±2.62	4.32±0.78	60%	0-10	33%	40%