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IMPACT OF COGONGRASS (IMPERATA CYLINDRICA) ON POPULATIONS OF ROOT-FEEDING BARK BEETLE SPECIES ASSOCIATED WITH LOBLOLLY PINE DECLINE

by
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ABSTRACT
The non-native, invasive grass, *Imperata cylindrica* (L.) Beauv, commonly known as cogongrass, is an increasing threat to the diversity of native plant and wildlife species of the southeastern United States. Another issue facing landowners of southeastern forests is loblolly pine decline. The factors associated with loblolly pine decline include a complex of abiotic and biotic stressors that cause economically significant premature mortality in pine forests. A suite of root-feeding bark beetles, which vector pathogenic ophiostomatoid fungi, are attracted to stressed pines. *Imperata cylindrica* could be inducing additional stresses, leading to higher infestations of root-feeding bark beetles and contributing to loblolly pine decline. To determine the effects of cogongrass on root-feeding bark beetles, 20 plots were established in a loblolly pine plantation located in southeastern Mississippi (10 with *I. cylindrica*/10 without *I. cylindrica*). Insect traps on each plot were checked bi-weekly for 24 months to observe insect populations over time. Insect collections indicated that *Hylastes salebrosus* is the most abundant species and had consistently higher populations in *I. cylindrica* plots, but were not significantly different between plots with and without cogongrass. *Dendroctonus terebrans* had higher populations in *I. cylindrica* plots. *Hylastes porculus* and *Hylobius pales* had similar trends but plots with and without were not different. *Pachylobius picivorus* had significantly higher populations in plots without *I. cylindrica*. *Hylastes tenuis* had a similar trend to *P. picivorus* but cogongrass had no effect on populations. Based on these trapping studies it appears that cogongrass does not increase insect populations associated with loblolly pine decline.

INTRODUCTION
Loblolly pine decline (LPD) is a stress-induced decline complex that involves root-feeding bark beetle and weevil species that vector root-inhabiting ophiostomatoid fungal species (Eckhardt et al., 2007). Eckhardt et al. (2004) found that these root-inhabiting fungi and their insect vectors correlated with the symptomology of LPD across multiple physiographic regions in central Alabama. Eckhardt and Menard (2008) found that increased slope and south to southwest facing aspect were predisposing stress factors associated with symptomology of LPD. Sandy loam or sandy clay loam soils were also found to be associated with increased susceptibility to LPD but tree age, topography, and organic matter content had a higher association to LPD than soil type (Eckhardt *et al.*, 2007). Some abiotic factors associated with LPD include environmental stressors such as drought and wind damage as well as mechanical damage from management activities such as thinning operations or prescribed burning.

The non-native, invasive grass *Imperata cylindrica* (L.) Beauv. , more commonly known as cogongrass, is becoming an increasing threat to the diversity of native plant and wildlife species of the southeastern United States. Cogongrass is estimated to infest between 500,000 and 1,000,000 acres in Florida, Alabama, and Mississippi (Faircloth et al., 2005). Due to rapid expansion through rhizomatous reproduction and fire adapted physiology, *I. cylindrica* is becoming an important threat to pine plantations of the southeastern United States (Daneshgar et al., 2008). Studies have found that *I. cylindrica* drastically reduced loblolly pine (*Pinus taeda* L.) and longleaf pine (*Pinus palustris* Mill.) regeneration in infested sites. Daneshgar et al. (2008) found that *I. cylindrica* competition resulted in only 26% survivability of loblolly pine regeneration as compared to 52% survivability in native vegetation competition. Seedlings growing in *I. cylindrica* competing vegetation had significantly smaller root collar diameters after the first growing season. Lippincott (2000) found that fire induced mortality in juvenile longleaf pine was higher in *I. cylindrica* invaded sites as compared to sites containing native vegetation.

Due to the high invasiveness of *I. cylindrica*, many studies such as the ones previously mentioned have documented the impact(s) that this weed species places upon plant species throughout the world. Since its introduction to the southeastern United States and subsequent spread into forested areas, research has evaluated the impact *I. cylindrica* has on the regeneration of southern pine species, but few have looked at its impact that *I. cylindrica* is having to on established, more mature pine. There are even fewer studies looking at the impact of *I. cylindrica* on populations of insects, more specifically, bark beetle populations. *Imperata cylindrica* could be causing additional stresses to loblolly pine roots and consequently increasing root-feeding bark beetle populations to infested sites. This study was instigated to test the hypothesis that *Imperata cylindrica* is increasing the population of root-feeding bark beetle species associated with LPD.

MATERIALS AND METHODS

The research site was located on The Westervelt Co. land east of Leakesville, Greene County, Mississippi (N 31.147755, W -88.458567). Twenty plots were established by visually assessing *I. cylindrica* presence and density with 10 plots established in areas containing heavy infestation of *I. cylindrica* (Figure 2.1) and the remaining ten plots were established in areas containing no *I. cylindrica* (Figure 2.2). Plots without *I. cylindrica* competition mainly consisted of an open understory containing sparse patches of native grasses and scattered woody plants with a few patches *Rubus* spp. being dense. Some species found in the understory of these plots included American beautyberry (*Callicarpa americana* L.), blackberry (*Rubus* spp.), green briar (*Smilax rotundifolia* L.), yaupon (*Ilex vomitoria* Aiton) and winged sumac (*Rhus copallinum* L.). Plot boundaries were marked by placing metal poles at each corner of a square with each side being 15.24 m (50 ft.) in length. Center plot was determined by placing a metal pole half the distance diagonally across the plot. A metal tag was attached to each center pole denoting the plot identification. CO plots were labeled as C1- C10 while control plots were labeled NC1- NC10. The location (Table 2.1) and elevation of each center pole was mapped using a handheld geographical positioning system device (Garmin GPSMAP 76Cx, Garmin International Inc., Olathe, KS). Each tree within each plot was assigned a number and a metal tag with this number was attached to the tree at breast height (137 cm from ground level).

Traps for monitoring bark beetles were installed on each plot to trap and collect bark and ambrosia beetles as well as weevils. The traps used included one panel trap (Figure 2.3) placed one meter north of plot center and one pitfall trap (Figure 2.4) placed one meter south of plot center. The contents of each trap were collected on a bi-weekly basis for two years starting March 2010. Bait for each trap was replenished at the time of each collection.

Panel traps (APTIV Company, Portland, Oregon) are made of black, corrugated plastic panels with a top hood, bottom collecting funnel, collection cup, and a hanging lure opening. Panel traps were suspended from a metal pole approximately two meters from ground level. Two 8-ml glass vials, one filled with turpentine the other filled with 95% ethanol, were used as attractant for the bark beetle and weevil species. A 3-to-1 water to commercial anti-freeze (ethylene glycol) mix was placed in the collection cup to preserve captured insects. During a collection, the contents of the collection cup were poured through a strainer and emptied into a sterile 120 ml polyethylene specimen cup for transporting back to the lab. Collection cups were replaced, refilled with 3-to-1 water to antifreeze mix, and the bait vials refilled after each collection. Pitfall traps were made up of a 20 cm section of 10 cm diameter polyvinyl chloride (PVC) drain pipe with eight equally spaced holes drilled along the circumference (Klepzig et al., 1991). Both ends were capped with a removable PVC end cap. Two drain holes were drilled into the bottom of one end to allow excess moisture to drain. Traps were buried so that the eight holes were positioned just above ground level. Each pitfall trap was baited with an 8 ml vial of turpentine and an 8 ml vial of 95% ethanol. Two 3 cm long by 1 cm in diameter loblolly pine twigs were also placed into each pitfall trap. A coating of liquid Teflon™ (Northern Products Woonsockets, RI) was applied to the inside of each pitfall trap to ensure captured insects remain inside the trap. Captured insects were transferred to a sterile 120 ml polyethylene specimen cup for transporting back to the lab. At the time of collection, bait vials were refilled, two cut loblolly twigs were replaced, and another coat of liquid Teflon applied to the trap. All collected insects were brought back to the Forest Health Dynamics Laboratory (Auburn University, Auburn, AL) to be identified and enumerated by species. Approximately 10% of each species collected in the pitfall traps were further non-destructively rolled across CSMA (cycloheximide-streptomycin-malt extract agar) and MEA (2% malt extract agar) media to check for vectoring of fungi. Plates were incubated under florescent lights (460 μmol m_{-2} s_{-1}) at 25°C and inspected for fungal growth. Ophiostomatoid-like fungal growth was subcultured to sterile CSMA plates via transferring of hyphal tips. This process was repeated till pure hyphal growth was observed and then subcultured to MEA plates. Hyphal growth was then transferred to MEA slants for identification of the fungal species.

Pine basal area was determined using a twenty factor prism. Diameter at breast height (approximately 137 cm from soil surface) was measured on each tree with a diameter of 11.43 cm or greater within each plot using a logger's tape and recorded to the nearest 0.25 cm. Percent slope was measured using an electronic clinometer (HEC, Haglof Sweden, Inc.) by targeting an object at equal height of my eye at the point of greatest slope along the aspect of the plot. Elevation was determined by GPS (Garmin GPSmap 76S) at the center of each plot. Forest Health Monitoring (FHM) crown/damage measurements were taken on each pine tree within each plot. These measurements include crown light exposure, live crown ratio, crown density, and foliar transparency. Crown light exposure equals the total number of 1/4 crown areas plus tree top (5 parts in total) receiving full light with a minimum of 35% live crown ratio. Crown dieback is the percentage of live crown dead: the code 0 =no dieback through 100 =total dead crown. Live crown ratio is the percent of live crown length divided by the actual tree length. Crown density is the amount of crown branches, foliage, and reproductive structures that blocks light visibility through the crown (includes missing spaces and dead foliage of live crown ratio). The code 00 =no crown, 05 =1-5%, through 99 =96-100%. Foliage transparency is the percentage of skylight visible through the live, normally foliated portion of the crown. The code 0 = no skylight visible through 99 = complete visibility of skylight, the lower the percentage the less light visible through the crown. Tree increment cores were taken from the same six study trees per plot to determine tree age, five year annual growth, and ten year annual growth. Increment cores were removed from each tree at breast height (approximately 137 cm from the ground) using increment borers. The number of annual rings was counted from the pith of the core to the inside of the bark to determine age. Five year annual growth was determined by measuring the length of the most recent five annual rings with a metric ruler beginning from the early-wood of fifth annual ring from the bark to the end of the late-wood of the most recent annual ring. Ten year annual growth was determined using same procedure as for the five year annual growth except measuring the most recent ten annual rings. Five and ten year annual growth was measured and recorded to the nearest tenth of a centimeter. Soil bulk density and soil gravimetric moisture content were calculated from three 60 cm soil cores taken at each plot. Soil strength was measured using a Rimik CP20 recording cone penetrometer by recording 3 insertions per soil sample site (9 total for each plot). Coarse and fine root weights were determined by excavating two 0.25 m^2 squares of soil to a depth of 23 cm per plot. One square was excavated at the drip line and one halfway between the drip line and the trunk of the tree. Excavated soil was placed in a wheel barrow and the pine roots were separated from other roots found within that soil. Pine roots were separated by coarse and fine roots, washed, dried in an oven for 48 hours at 70°C. Once dried, roots were weighed and the weight recorded to the nearest tenth of a gram. Fine roots were classified as any pine root ≤2mm in diameter, roots greater than 2 mm in diameter were classified as coarse roots. Rhizome density was determined by weighing the amount of rhizomes present in the same pits where pine roots were sampled. Rhizomes were washed, oven dried for 48 hours at 70°C, then weighed to the nearest tenth of a gram. Thatch cover was determined by graphing each plot on paper and drawing the areas that didn't contain *I. cylindrica* on the graphing paper. The area that wasn't drawn out was then determined by subtracting the drawn out area from the total square area of the plot.

Analysis of the differences between root-feeding bark beetle populations from CO plots and NCO plots for each bark beetle species were completed using PROC GLM with Tukey's Studentized Range (HSD) Test in Statistical Analysis Software (SAS Institute, 9.2., Cary, NC). Using the distribution chart produced by SAS, individual outliers were observed and removed from the data to observe the effects that one observation had on the significance and to determine if or how it could impact this study. All p-values in this study reported with no outliers removed.

RESULTS

Population comparisons between treatment and control plots

Twenty-three species of bark and ambrosia beetles as well as three species of weevils were identified and populations recorded from panel and pitfall traps (Table 2.2). Of these 26 species, four species of root- and lower bole-feeding bark beetles, as well as two root-feeding weevil species, were considered study species due to their relevance to LPD. These six species include *Hylastes salebrosus*, *Hylastes porculus*, *Hylastes tenuis*, *Dendroctonus terebrans*, *Hylobius pales* (weevil), and *Pachylobius picivorus* (weevil). *Hylastes salebrosus* was found to be the most abundant species collected in this study with >16,000 captures, approximately 51% of the total insects captured (Table 2.1). *Hylastes salebrosus, H. porculus, D. terebrans,* and *Hs. pales* had consistently higher populations in plots containing cogongrass throughout the collection period but no significance difference was found for these species (Table 2.3). *Pachylobius picivorus* and *H. tenuis* had opposite trends and populations of *P. picivorus* were found to be significantly higher in control plots (*P*=0.0299, *F*=5.56) (Table 2.3).

Even though panel trap captures greatly exceeded pitfall captures, analysis of population comparisons among CO and NCO plots for just pitfalls showed a different trend than panel traps. All species except *D. terebrans* had higher populations in the NCO plots with *P. picivorus* being the only one that had a significant difference (*P*=0.0153, *F*=7.27) (Table 2.4).

Population comparisons to field data

Populations of bark beetles were compared to tree vigor covariables to assess if any interactions exist. Covariables include basal area of pine, diameter at breast height (DBH) of pine, five- and ten-year annual growth of measured pine, coarse and fine root weight, elevation, slope, soil moisture levels, soil bulk density, soil strength, crown density, crown ratio, foliar transparency, and crown light. Cogongrass plots were also analyzed with covariables *I.cylindrica* rhizome density and thatch cover area. Populations of *D. terebrans* was found to be significantly higher in plots with larger DBH (*P*=0.0077, *F*=8.98). Lower populations of *P. picivorus* (*P*=0.0397, *F*=4.92) were correlated with plots of higher mean DBH (Table 2.5). Higher populations of *D. terebrans* (P=0.0118, F=7.86) and *H. salebrosus* (*P*=0.0078, *F*=8.95) was found to be correlated with plots at higher elevation (range 37 to 87.5 m) (Table 2.6). Lower populations of *P.picivorus* were also found to be correlated with plots of higher levels of percent moisture of total sample weight (*P*=0.0314, *F*=5.45) and gravimetric water content (*P*=0.0409, *F*=4.85) (Table 2.7). Populations of *H. porculus* (*P*=0.0485, *F*=0.0311) and *H. salebrosus* (*P*=0.0311, *F*=6.81) were negatively correlated with increased *I. cylindrica* thatch cover area while *P. picivorus* populations were positively correlated with increased thatch cover area (*P*=0.0120, *F*=10.45) (Figure 2.8). Lower *P. picivorus* populations were found to be correlated with higher crown density percentages (*P*=3.93, *F*=4.94) (Table 2.9).
Significance tested at *P*<0.05

DISCUSSION

Hylastes salebrosus was the most abundant species captured throughout the entire collection period and is consistent with other studies that captured root-feeding bark beetle species associated with LPD (Eckhardt et al., 2007). Temporal trends found in this study for each bark beetle species were also similar to other population studies for these species. The six insect species combined were approximately 68% of the total insect population. Populations of *D. terebrans, H. porculus, H. salebrosus,* and *Hy. pales* all showed consistently higher numbers in cogongrass plots than non-cogongrass plots. However, the lack of significance indicates that the presence of *I. cylindrica* in forest plots is not affecting populations of these species. In addition, *Pachylobius picivorus* and *H. tenuis* had fewer numbers in cogongrass plots than in non-cogongrass plots. The lack of significant bark beetle population differences between CO and

NCO plots occurred throughout the study period. Therefore, it appears that the presence of cogongrass in forest plots does not result in stand stress such that insects associated with LPD are increased by *I. cylindrica*.

Pitfall insect trap collections showed that except for *D. terebrans,* insect captures were higher in NCO plots than CO plots, even though there were higher mean captures for most of these species in the panel traps in the CO plots. These trends may suggest that the *I. cylindrica* thatch cover is having an effect on the attractiveness of the baited pitfall trap by dampening the effects of the ethanol and turpentine used as attractants. This could possibly infer that *I. cylindrica* thatch is having a "trapping" or "suppressing" effect on the chemicals released by the pine roots themselves therefore reducing the attraction of the root-feeding bark beetle species to roots under heavy infestation of *I.cylindrica.*

Symptoms of LPD have been found to include fine root deterioration, short chlorotic needles, sparse crowns, and reduced radial growth (Eckhardt et al., 2007). Populations of root-feeding bark beetle species were found to be correlated with plots exhibiting these symptoms (Eckhardt et al., 2007). Tree vigor measurements were made to assess whether *I. cylindrica* is having negative effects on loblolly pine and subsequently increasing the populations of root-feeding bark beetle species. Insect populations were analyzed to assess if correlation exist between the tree vigor measurements and increased bark beetle populations.

Results shown in Table 2.5 illustrate that insect populations did not correlate with reduced tree vigor measurements. Lower populations of *P. picivorus* were found to be associated with plots with higher DBH and lower populations of *P. picivorus* were associated with increase in soil moisture. Although these were opposite trends than we anticipated, lower *Hy. pales* populations were found to be correlated with increase pine coarse root weight which was expected. Average DBH was found to be significantly higher in CO plots versus NCO plots (P=0.0306, F=5.51) which is mostly likely due to the fact that the majority of CO plots are located in an 18-year old stand while the majority of NCO plots are located in a 13-year old stand. This difference in age probably accounts for the significance in higher average DBH for CO plots.

Topographical effects have been found to correlate with stands containing declining loblolly pine (Eckhardt and Menard, 2008) in which increased slopes greater than 5% and SE/S/SW aspect were found to be pre-disposing factors to decline. There was no correlation between insect populations and increased slope (range 2-11%) but plots located at higher elevations (range 37-87.5 ft) correlated with increased populations of *D. terebrans* and *H. salebrosus*. CO plots were found to be located at significantly higher elevations than NCO plots (P=0.0006, F=16.94). The fact that CO plots were located at higher elevations and the fact that there were higher insect populations associated with those higher elevations did not support our hypothesis. Other factors, including soil moisture, composition, and nutrient content, can vary along an elevation gradient and maybe what is actually contributing to the increase in insect populations with response to elevation. We did observe a high concentration of pitch tubes in the larger diameter trees on plot C8, which are indicative of *D. terebrans* attacks.

Lower populations of *P. picivorus* being associated with plots with higher soil moisture levels are also not suggestive of our hypothesis because increased soil moisture is not typically associated with stress to loblolly pine except in cases where there is prolonged saturation (i.e. flooding). Albaugh et al. (2004) showed a growth increase in loblolly pine, although relatively small, in response to irrigation.

The thatch cover area and rhizome density of each of the CO plots was analyzed against each of the insect populations to see if higher populations were associated with increased density of *I. cylindrica*. We found the opposite effect occurred to *H. salebrosus* and *H. porculus* populations, which had lower populations associated with increase thatch cover area which supports the idea of cogongrass suppressing the effects of chemicals given off by the roots or being a physical barrier to the insects attracted to the roots. A surprising correlation between higher populations of *P. picivorus* and increased thatch cover was also observed. It was surprising to see this result because *P. picivorus* has shown to have trends toward lower populations with more healthy parameters (i.e. increased DBH and crown density) and lower populations with increase soil moisture. Having a significantly higher population in NCO plots also makes this result surprising. The variability in these results also lends to the idea that infestations of *I. cylindrica* are not increasing root-feeding bark beetle populations.

Forest Health Monitoring (FHM) crown/damage measurements were compared to beetle populations to see if there was a correlation between increased insect activity and reduced crown density, crown ratio, and light availability as well as high foliage transparency. Eckhardt et al. (2007) found trees with lower growth rates and high root mortality and staining were positively correlated to low crown density, high foliage transparency, and increased insect populations. Populations of *P. picivorus* were found to be lower in plots that had higher crown density. This result also suggests that the trees are not enduring additional stress from the *I. cylindrica* infestation. According to these results, it can be suggested that trees in CO plots are not being stressed more by the *I. cylindrica* than trees in NCO plots.

Overall, all study species except *P. picivorus* and *H. tenuis* had higher populations in plots containing *I. cylindrica* infestations. Pitfall trap collection showed an opposite trend in all species but *D. terebrans* which could suggest that *I. cylindrica* is influencing the attractiveness of the baited trap to the root-feeding bark beetle species. Population comparisons to tree vigor and plot measurements did not have suggestive trends that tree conditions in areas containing *I. cylindrica* were attracting higher populations of root-feeding bark beetle species. These insect populations should be reexamined in the future to see if prolonged infestations to cogongrass may eventually lead to the significantly higher populations of root-feeding bark beetle species due to increase age of the trees and compounding stresses to the trees.

Figure 2.1. *Imperata cylindrica* infested plot.

Figure 2.2. Plot containing no infestation of *Imperata cylindrica*.

Figure 2.3. Panel trap

Figure 2.4. Pitfall trap

Table 2.1. Plot locations in Greene County, Mississippi

Plot	Location	
C1	N 31.14768	W 88.48222
C2	N 31.14788	W 88.48177
C3	N 31.14896	W 88.48191
C4	N 31.14804	W 88.47518
C5	N 31.14785	W 88.48038
C6	N 31.14884	W 88.48322
C7	N 31.14684	W 88.47682
C8	N 31.14850	W 88.47382
C9	N 31.14952	W 88.47441
C10	N 31.14819	W 88.47145
NC1	N 31.15198	W 88.48292
NC2	N 31.15067	W 88.48293
NC3	N 31.14714	W 88.47630
NC4	N 31.14825	W 88.48052
NC5	N 31.15009	W 88.48226
NC6	N 31.14842	W 88.48200
NC7	N 31.14861	W 88.48422
NC8	N 31.14839	W 88.48536
NC9	N 31.14896	W 88.48483
NC10	N 31.14935	W 88.48349

Table 2.2. Total insect captures by species

Species	Number Caught
Hylastes salebrosus	16404
Hylastes porculus	1653
Hylastes tenuis	1462
Dentroctonus terebrans	1218
Pachylobius picivorus	624
Hylobius pales	507
Xyleborinus saxesenii	1635
Xylosandrus crassiusculus	2695
Gnathotrichus materiarius	540
Xyleborus pubescens	3288
Dentroctonus frontalis	0
Ips grandicollis	1087
Other*	1201

*Includes: *Ips avulsus, Ips calligraphus, Hylastes opacus, Xylosandrus compactus, Monarthrum mali, Pissodes nemorensis, Monarthrum fasciatum, Xyleborus ferrugineus, Pityoborus comatus, Trypodendron scabricollis, Dryoxylon onoharaensum, Xyleborus atratus, Xylosandrus germanus,* and *Orthotomicus caelatus*

Table 2.3. Mean population comparison between CO plots and NCO plots by study species for panel and pitfall traps combined.

Species	CO	NCO	*P*-value
Dendroctonus terebrans	64	46	0.1009[1]
Hylastes porculus	102	91	0.5907 [2]
Hylastes salebrosus	1036	878	0.3505
Hylastes tenuis	91	105	0.4312 [3]
Pachylobius picivorus	32	68	0.0299[†]
Hylobius pales	29	22	0.4797[4]

*Significantly higher population in CO plots

[†]Significantly higher population in NCO plots

[1] Significance determined after removal of outliers C8 and NC2 population data (*P*-0.0124, *F*- 7.92)

[2] C9 and NC2 were outliers but removal of those plots was not significant

[3] C9, C10, and C7 were outliers but removal of those plots was not significant

[4] C8 found to be an outlier but removal of that plot was not significant

Significance tested at P<0.05

Table 2.4. Tukey comparisons of average pitfall populations between CO and NCO plots

Species	CO Plot Mean	NCO Plot Mean	*P*-value
Dendroctonus terebrans	3	2	0.2905
Hylastes porculus	11	17	0.4320
Hylastes salebrosus	121	153	0.5852
Hylastes tenuis	20	30	0.2475
Pachylobius picivorus	9	21	0.0153[†]
Hylobius pales	4	6	0.1002

[†]Significantly higher population in NCO plots. Significance tested at *P*<0.05

Table 2.5. P-values of correlations between insect species populations and tree vigor measurements

Species (Range of Data)	Basal Area (4.4-10.5m2)	DBH (16.5-25 cm)	5-year Annual Growth (18-30mm)	10-year Annual Growth (35-61mm)	Pine Coarse Root Wt. (8.5-120g)	Pine Fine Root Wt. (11.5-42g)
Dendroctonus terebrans	0.3745	0.0077*[1]	0.9897	0.4717	0.1085	0.4794
Hylastes porculus	0.3440	0.3369	0.8349	0.3993	0.4312	0.9748
Hylastes salebrosus	0.8037	0.1475	0.6284	0.5144	0.0813	0.7300
Hylastes tenuis	0.4579	0.9495	0.3068	0.3736	0.9998	0.8360
Pachylobius picivorus	0.3780	0.0397†	0.0592[3]	0.0893[4]	0.8681	0.3158
Hylobius pales	0.1782	0.4188[2]	0.7004	0.5681	0.0346†	0.7434

* significantly higher population with increase in the corresponding vigor measurement
† significantly lower population with increase in the corresponding vigor measurement
[1] *P*-value after removal of C8 as outlier (0.2765, *F*= 6.04)
[2] *P*-value after removal of C8 and C7 as outliers (0.0089, F=0.8.87)
[3] *P*-value after removal of NC5 as outlier (0.0138, *F*=7.54)
[4] *P*-value after removal of NC5 as outlier (0.0110, *F*= 8.13)

Table 2.6. *P*-values of correlations between insect species populations and topography measurements

Species (Range of Data)	Elevation (37-88m)	Slope (2-11%)
Dendroctonus terebrans	0.0118*	0.4193
Hylastes porculus	0.4166	0.8708
Hylastes salebrosus	0.0078*	0.5841
Hylastes tenuis	0.6580	0.1387
Pachylobius picivorus	0.0074†	0.9995
Hylobius pales	0.2645	0.0856

*significantly higher population with increase in the corresponding topography measuremen
† significantly lower population with increase in the corresponding topography measurement
[1]*P*-value after removal of C8 data (0.0869, *F*=7.86)
Significance tested at *P*<0.05

Table 2.7. *P*-values of correlations between insect species populations and soil moisture measurements

	Bulk Density	% Moisture of Section	% Moisture of Total Sample Wt.	Gravimetric Water Content	Soil strength
Species (Range of Data)	**(1.36-1.65g/cm^3)**	**(11-24%)**	**(14-28%)**	**(20-35g)**	**(1.7-2.7mPa)**
Dendroctonus terebrans	0.3977	0.2397	0.4560	0.4028	0.6549
Hylastes porculus	0.2842	0.4753	0.2926	0.2337	0.4068
Hylastes salebrosus	0.0930	0.5805	0.3912	0.2580	0.8577
Hylastes tenuis	0.9627	0.1262	0.0757	0.1235	0.1643
Pachylobius picivorus	0.3260	0.0807	0.0409†	0.0314†	0.7772
Hylobius pales	0.7187	0.0804	0.2735	0.2735	0.1579

* significantly higher population with increase in the corresponding vigor measurement
† significantly lower population with increase in the corresponding vigor measurement
Significance tested at $P<0.05$

Table 2.8. *P*-values of correlations between insect species populations and *Imperata cylindrica* data

	Rhizome Density	Thatch cover
Species (Range of Data)	**(50-180g)**	**(149-223m^2)**
Dendroctonus terebrans	0.5832	0.9935
Hylastes porculus	0.4617	0.0485†
Hylastes salebrosus	0.6212	0.0311†
Hylastes tenuis	0.3975	0.3674
Pachylobius picivorus	0.5634	0.0120*
Hylobius pales	0.2261	0.6139

* significantly higher population with increase in the corresponding vigor measurement
† significantly lower population with increase in the corresponding vigor measurement
Significance tested at $P<0.05$

Table 2.9. *P*-values of correlations of insect species populations and crown data

Insect species	(Range of Data)	Crown Density (27-33%)	Crown Ratio (38-51%)	Foliar Transparency (24-24%)	Crown Light (1.5- 4)
Dendroctonus terebrans		0.1807	0.3058	0.8847	0.8034
Hylastes porculus		0.8020	0.4560	0.5792	0.6481
Hylastes salebrosus		0.9508	0.7684	0.3213	0.6780
Hylastes tenuis		0.5753	0.4249	0.9613	0.9772
Pachylobius picivorus		0.0393[†1]	0.5426	0.8020	0.7627
Hylobius pales		0.9135	0.9419[2]	0.7414	0.5100

[†] significantly lower population with increasing crown measurement

[1] *P*-value after removal of NC5 data (0.1465, *F*-2.32)

[2] *P*-value after removal of C8 data (0.0271, F=5.85)

Significance tested at $P<0.05$