AN ASSESSMENT OF THE RISK MAPPING SYSTEM FOR THE USE OF MANAGING LOBLOLLY PINE DECLINE SITES WITHIN RED-COCKADED WOODPECKER HABITAT

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Roger Dale Menard
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ABSTRACT

A decline of loblolly pine (*Pinus taeda* L.), characterized by expanding areas of declining and dead trees, has become prevalent at Fort Benning, Georgia. A 3 year study was conducted to determine the kinds of fungi, insects, and site disturbances associated with this problem. The insects *Dendroctonus terebrans, Hylastes salebrosus, Hylastes tenuis, Pachylobius picivorus* and *Hylobius pales* were significantly more abundant in symptomatic than in asymptomatic loblolly pine plots. These root and lower stem-infesting insects consistently carried the fungi *Leptographium terebrantis, L. procerum,* and *L. serpens.* Root sampling revealed high levels of root damage and mortality, staining and infection with *Leptographium* species. This below-ground damage and mortality preceded the expression of above-ground symptoms, such as short chlorotic needles, sparse crowns, and reduced radial growth. A sequence of interactions among this complex of organisms and abiotic factors is proposed as the cause of 'loblolly pine decline.' This study confirms the findings for loblolly pine decline at other geographic locations and validates the Loblolly Pine Decline Risk Map as described by Eckhardt (2003).

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Forest Decline

"Decline" is a general term applied by forest pathologists to a reduction in tree vigor associated with a complex of symptoms involving reduced and thinning crowns, leaf discolorations and chlorosis, leaf size reduction, leaf loss, and reduction in stem radial growth that may lead to the death of the whole tree (Manion, 1991; Manion and Lachance, 1992). Symptoms of decline start very slowly and increase in severity over time, ranging from 3 to 30 years, and usually occur at the landscape level involving a single species (Skelly, 1993).

Reports of forest declines can be traced as far back as 1739 to oak decline in northern Germany (Edmond *et al.*, 2000) and more recently in 2007 with loblolly pine decline in the southeastern United States (Eckhardt *et al*., 2007). Forest decline appears to be on the increase and is presently thought to be a major threat in temperate ecosystems (Manion and Lachance, 1992). Although this may be true in the general definition of decline, it is usually a more specific "forest species decline" (Skelly, 1993), because all species within a forest ecosystem are not affected simultaneously. Decline diseases result from the interaction of abiotic and biotic factors to produce gradual decline and tree death. Predisposing factors that reduce tree vigor include site conditions, genetic potential, and soil conditions. Inciting factors that produce gradual decline are insects, drought, and anthropogenic activities. Factors that usually contribute to mortality include root disease fungi, wood and bark-boring insects, nematodes, viruses, and phytoplasmas. The complex of organisms associated with decline is usually opportunistic, competing as saprophytes or parasites, contributing to the occurrence of decline (Manion, 1991). Decline diseases are found in many hardwood species, such as birch (Betulaceae *Butula* L.), ash (Oleacea

Fraxinus Tourn. ex L.), maple (Sapindaceae *Acer* L.), oak (Fagaceae *Quercus* L.), and sweetgum (Altingiaceae *Liquidambar* L.). Decline complexes are also associated with many conifer species, including pole blight of western white pine (*Pinus monticola* Dougl.), decline of red pine (*Pinus resinosa* Aiton), decline of ponderosa pine (*Pinus ponderosa* Laws.), and littleleaf disease of shortleaf (*Pinus echinata* Mill.) and loblolly (*Pinus taeda* L.) pines. Pine decline has become a serious problem in the southeastern United States where the dominant forest type in the pre-settlement era was longleaf pine (*Pinus palustris* Mill.) (Hepting, 1971).

1.2 Loblolly Pine Decline

Loblolly pine decline is a syndrome associated with loblolly pine in the southeastern United States that it is reported to occur from eastern Mississippi to central Alabama, and Georgia to the Carolinas. This decline is similar in symptomology to other pine diseases, such as littleleaf disease of short leaf pine (Campbell and Copeland, 1954), and has approximately the same geographic range as loblolly decline. The cause of littleleaf disease is usually attributed to a combination of soils that have poor drainage and to the presence of *Phytophthora cinnamomi* Rands (Campbell and Copeland, 1954; Roth, 1954; Oak and Tainter, 1988).

Loblolly pine decline complex is characterized by lateral root deterioration prior to crown symptoms, loss of fine roots before mortality, and heavy cone crops. The declining crowns occur within the 40 to 50 year age class when trees express decline symptoms and die prematurely. There was no evidence of insect activity, foliage disease, or heart rot disease to account for the mortality. Observations of crown symptoms were reported in 1959 on the Talladega National Forest, Alabama (Brown and McDowell, 1968). Loblolly pine decline occurs on sites with abiotic or biotic stress factors that may cause changes in the host chemical profile that are attractive to root feeding insects that vector the pathogenic *Leptographium* fungi species. The stress conditions at these sites favor an increase in root-feeding insect populations

and associated vector activity (Otrosina *et al*., 1997; Eckhardt *et al*., 2007). *Leptographium* species are vectored by at least 16 different species of Coleoptera (Eckhardt *et al*., 2007). Although necessary for the decline to develop, these insect vectors, by themselves, do not account for tree mortality. The primary predisposing factor for initiation of decline apparently relates to site topography parameters found in association with the presence of decline. Loblolly pine decline is generally associated with well-drained convex site features located on moderate to steep slopes with a southerly aspect, and trees in a state of low vigor. A non-decline site tends to have relatively flat to concave site features with a northerly aspect and is associated with trees in a high state of vigor (Eckhardt, 2003).

1.3 Mapping Decline

Spatial occurrences of the abiotic factors in loblolly pine decline follow a pattern in the landscape that relate to aspects generally facing southerly directions and slopes greater than 5 %. Recent research has made it possible to define a relatively thorough understanding of factors leading to general pine decline. Spatial analysis of information available from Geographical Information Systems (GIS) databases, and their relationship to new biological data established from the research into pine decline, resulted in the development of loblolly pine decline mapping technology (Eckhardt, 2003). The complex relationships of these topographic features were found in combination to produce varied levels of decline. Combinations of more influential features, such as steep slope (> 20%) and south/southwest aspect, produce the most severe decline symptoms across all age classes studied. The actual decline severity was relative to a range of slopes (> 5% and <20%) and aspects (south/southwest and southeast) associated with the occurrence of decline. The level of decline was also affected by combinations of landforms. Declines of other species have similar topographic relationships. Sugar maple (*Acer saccharum* Marshall) decline of the northeast occurred at higher elevations on S, SW, W, and

NW aspects. The severity of decline increased in areas of higher elevation (Drohan *et al*., 2002, Horsley *et al*., 2000). Fir (*Pinaceae Abies* Mill.) decline in the Vosges mountains of France is associated with elevation, aspect, and slope (Thomas *et al*., 2002). The severity of Chelean cedar (*Austrocedrus chilensis* (D. Don) Florin et Boutelje) decline was associated with high precipitation, moderate slope, and low elevation (Baccala *et al*., 1998). These relationships helped to identify sites predisposed to pine decline, for which GIS spatially identified the sites and allowed creation of the Loblolly Pine Decline Risk Map (LPDRM) (Eckhardt, 2003).

1.4 Study Area

Fort Benning Military Reservation (FBMR) is located in the mid-western portion of Georgia's Muscogee and Chattahoochee counties that are mid-state on the Alabama border. The predominant land base is Upper Coastal Plain with some Piedmont transition zone along the Fall Line. The original Reservation began with the acquisition of approximately 39,659 hectares during 1919-1921. An additional 34,398 hectares was acquired in 1941-1942. Seventy-five percent of the initial forest types of shortleaf and longleaf pine was cleared and the land heavily farmed prior to these acquisitions. Commercial forest management began in 1950 with the hiring of the first Army forester. Management during the 1950's to 1980 emphasized the use of dormant season prescribed burning and reforestation of open areas with loblolly and slash pine. From 1980to 1990, the remaining overgrown clear-cut areas were reclaimed by planting loblolly pine. An increase in southern pine beetle (SPB) activity and littleleaf disease became evident during this period (Coder, 1997).

In the late 1980's, management emphasis shifted to red-cockaded woodpecker (RCW) habitat restoration with growing season prescribed burning, aggressive regeneration of longleaf pine and thinning of overstocked loblolly pine stands. From 1990 to the present, the emphasis on longleaf pine restoration has continued with protection of existing longleaf stands, replanting of

longleaf, thinning to promote natural longleaf regeneration, and increased prescribed burning into growing seasons. It was during this time period that FBMR resource managers began to observe visual signs of senescence and symptoms of decline in the loblolly stands. The ramifications of premature pine die-off generated concern about the RCW habitat. Approximately 70% of the RCW cavity trees are currently found in loblolly pines, and much of their foraging area is also in loblolly pine stands. In 2003, the Fort Benning Conservation Branch requested that Forest Health Protection (FHP) complete an evaluation of their upland loblolly sites to project the impact of forest health condition on their RCW habitat management (U.S. Fish and Wildlife Service, 2002).

The presence of loblolly pine decline within RCW habitat at FBMR created a need to identify the scale, magnitude, and location of decline. The prior development of a LPDRM in nearby Alabama by Eckhardt (2003) provided an opportunity to address the FBMR loblolly pine management needs. The locations in Alabama and Georgia were believed to have similar forest ecosystems, and it was proposed that the LPDRM may be a useful approach to the loblolly pine decline management needs at FBMR. To accomplish this, a LPDRM was created for the FBMR using same methodology as Eckhardt (2003). The primary focus of this research was to assess the accuracy of the LPDRM and determine its efficacy in managing the loblolly pine decline sites with RCW habitat on FBMR.

CHAPTER 2

MATERIALS AND METHODS

2.1 Map Creation

Assessment of mapping accuracy in different physiographic regions was determined using procedures established in Eckhardt (2003), which are described below. A Loblolly Pine Decline Risk was created according to Eckhardt (2003) for FBMR located in Georgia.

The FBMR provided the topographic and geographical data from their geo-spatial database. Topographic data were derived from the 10m Digital Elevation Model (DEM), which are based on contours obtained from the United States Geological Service 7.5 minute (1:24,000) topographic quadrangles. Slope and aspect were derived from multiple DEM coverages of the FBMR area. The shape file coverage for FBMR was used to delineate reservation boundaries, stands, compartments, roads, and streams for the pine decline risk map assessment. All data gathered were georeferenced and projected in Universal Transverse Mercator 83 (UTM83) and thus constitute a geographic database of FBMR, Georgia (Fig 2.1).

ArcView 3.2 (ESRI, 1996), along with the Spatial Analyst extension (ESRI, 1996), was used to combine and analyze the different maps created by a series of ArcView 3.2 functions containing multiple steps that create, merge, and intersect parameters of loblolly pine decline. The resulting product spatially presents the topological parameters in a multicolored polygon map (green = minimal, yellow = low, magenta = moderate, and red = high) to classify the level of loblolly pine decline. The reclassified data from the aspect and slope maps have polygons that contain combinations of unique topology parameters associated to decline and represent the occurrence of some level of loblolly pine decline as described by Eckhardt (2003).

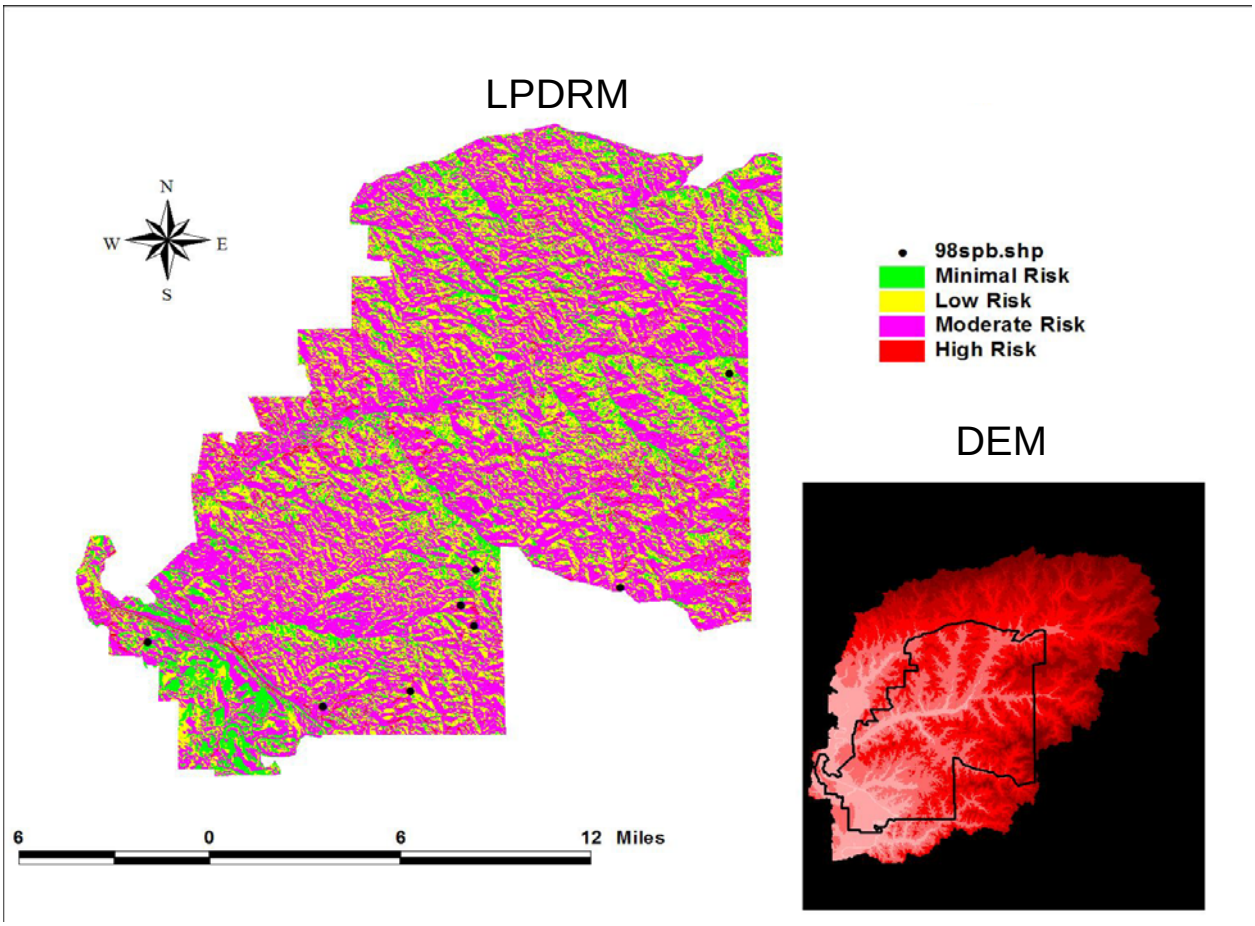

Figure 2.1. Digital Elevation Model (DEM) lower right used to convert decline parameters to the color reclassification scheme, of the Loblolly Pine Decline Risk Map (LPDRM) center with preliminary plot locations.

1) Aspect was derived using DEMs for FBMR and ArcView Spatial Analyst. The aspect theme created was reclassified based on biological parameters statistically associated to a measured range of aspect degree orientations where green (minimal risk) equaled 337.5° to 67.5°, yellow (low risk) equaled 67.6° to 112.5° and 292.6° to 337.4°, magenta (moderate risk) equaled 247.6° to 292.5°, and red (high risk) equals 112.6° to 247.5°. The reclassified aspect theme was converted to a shape file using the 'Theme' function, and legend parameters were changed to the color classification scheme for commensurate risk level. As a result, an aspect map for FBMR was created, reclassified, converted, and legend edited to be ready for intersection with the slope map.

2) Slope was derived using a DEM for FBMR and ArcView Spatial Analyst. The slope theme created was reclassified based on biological parameters statistically associated with measured range of percent slope where green (minimal risk) equaled 0 to 5%, yellow (low risk) equaled 6 to 10%, magenta (moderate risk) equaled 11 to 15%, and red (high risk) equaled >15%. The reclassified slope theme was converted to a shape file using the 'Theme' function, and legend parameters were changed to the color classification for commensurate risk level. The slope map for FBMR was then created, reclassified, converted, and legend edited to be ready for intersection with the aspect map.

3) Aspect and slope were each queried to select their similar relative risk categories, i.e. minimal aspect and minimal slope, using a 'Theme' properties query function. The aspect and slope query for minimal risk was intersected using the 'View' function in the 'Geoprocessing Wizard.' The intersected theme for minimal risk could then be merged with the remaining risk intersections when the processes were completed for remaining risk categories (16 total intersections).

4) Aspect and Slope intersections were merged together using the 'View' function in the 'Geoprocessing Wizard' by selecting the intersected aspect and slope themes to be merged into one risk map theme. The final LPDRM was legend edited to the commensurate color ranking to complete the process.

2.2 Plot Descriptions

The plot sites were located using a Global Positioning System (GPS) within the mid-western portion of Georgia's Muscogee and Chattahoochee counties (Fig 2.2) and two physiographic regions of Georgia: the Upper Coastal Plain and the Piedmont. Sites were predominately loblolly pine with a mix of competing species of pine, including shortleaf and longleaf, as well as hardwood species such as dogwood (*Cornus florida* L.), red maple (*Acer*

rubrum L.), water oak (*Quercu nigra* L.), southern red oak (*Quercus falcate* Michx.), and black jack oak (*Quercus marilandica* Muench.). Surface soil type varied from sandy through loam to clay. Topography was generally lower to moderate relief upland ridges with moderate drainages to flat alluvial plains. Research plots were established in 2003 and monitored through 2005.

2.3 Study Design

Thirty-six 0.07 ha plots were located using GPS and established using Forest Health Monitoring (FHM) protocols (Dunn, 1999). The location of the plots was determined using LPDRM to designate a site as either symptomatic (decline) or asymptomatic (healthy) (Fig. 2.3). There were 15 asymptomatic and 21 symptomatic plots established. The symptom categories were divided into four loblolly pine age/size classes: seedlings/saplings < 10 year age class (< 10.0 cm diameter), pulpwood 10 to 19 year age class [> 10.0 cm but < 29.75 cm diameter at breast height (DBH)], 20 to 40 year age class (>29.75 cm DBH), and greater than 40 year age class (>29.75 cm DBH). Pine decline study plots consisted of a 0.02 ha central permanent plot and three 0.02 ha subplots (Table 2.1). The subplots were marked off 120m from the central plot at bearings of 120, 240, and 360 degrees (Fig. 2.4) (Dunn, 1999). At each location, a root health assessment was performed on three dominant or co-dominant pines nearest to the center plot location. Root sampling was done with the modified two-root excavation method (Otrosina *et al.*, 1997). Tree species, diameter at breast height (DBH), age, and 5 and 10 year radial growth increments were recorded from each of the root-sampled trees. Root-feeding insects were sampled 2003 to 2004 on subplots of 32 center plots using pitfall traps (three subplots per plot, 96 total pitfall traps) from March to May for 2003. There were 31 plots sampled for insects the second year, 2004 (one plot destroyed in 2004). Insects were collected on a biweekly basis and transported to the laboratory for identification and isolation of associated fungi. Special emphasis was placed on those fungi felt to be possible pathogens.

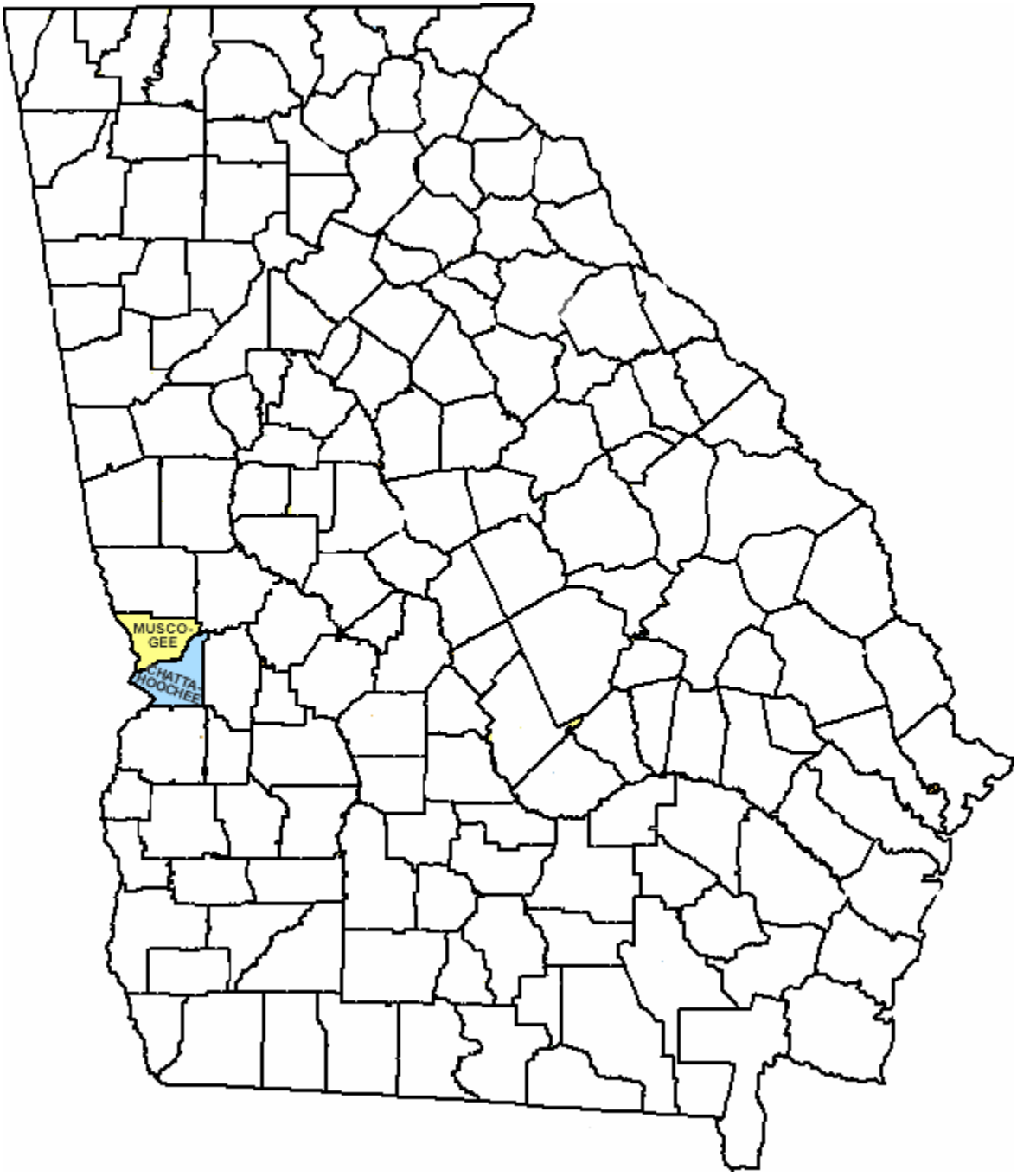

Figure 2.2. A Georgia county map showing the counties of Muscogee and Chattahoochee where Fort Benning Military Installation is located.

Data collections on study plots involving forestry mensurations, resin sampling, and crown conditions were conducted by Forest Service personnel trained and certified in the respective forestry practices and completed on a blind treatment basis.

2.4 Root Sampling

Roots were collected from the 36 research plots during the summers (May, June, and July) of 2004 and 2005, with 18 plots sampled the first summer and 18 the second. The two-root excavation method (modified from Otrosina *et al.*, 1997) was used in which three dominant/co-dominant trees nearest to the plot center were selected for sampling. Two primary lateral roots extending away from the tree base were excavated with hand tools from the root collar out to the approximate crown drip line for each selected tree. Root depth was also recorded at this time. Roots were visually examined for primary root damage and fine root presence or absence, damage, and/or death before removal from soil. Primary roots were defined as the major lateral roots extending from the base of the tree to the drip line. All secondary and feeder roots were categorized as fine roots. Roots that were shriveled and dried were tallied as dead. Trees with primary roots but no secondary root growth were tallied as having their fine roots absent. Root wedge samples were cut from primary roots at 16 cm intervals, beginning at 16 cm from the root collar. Also, random samples of 2 to 8 cm fine root samples were collected between primary root sample intervals. All root samples were placed in plastic bags and kept chilled in ice chests for transport to the laboratory. Roots were stored in the laboratory at 4°C until they could be processed (about 2 to 3 days). The roots were cut into pieces, rinsed in tap water, surface disinfected in a mixture of commercial bleach, ethanol and dH_2O (10:10:80 v/v/v) for one min, rinsed in tap water for 3 min, and blotted dry with sterile Kimwipes. The root samples were incubated in culture dishes containing two media types (4 pieces per plate, 20 plates/ sample/media) on MEA (2% malt extract agar) and CSMA (MEA containing 800mg/l of

Figure 2.3. Examples of loblolly pines exhibiting symptomatic (Decline) and asymptomatic (Healthy) conditions.

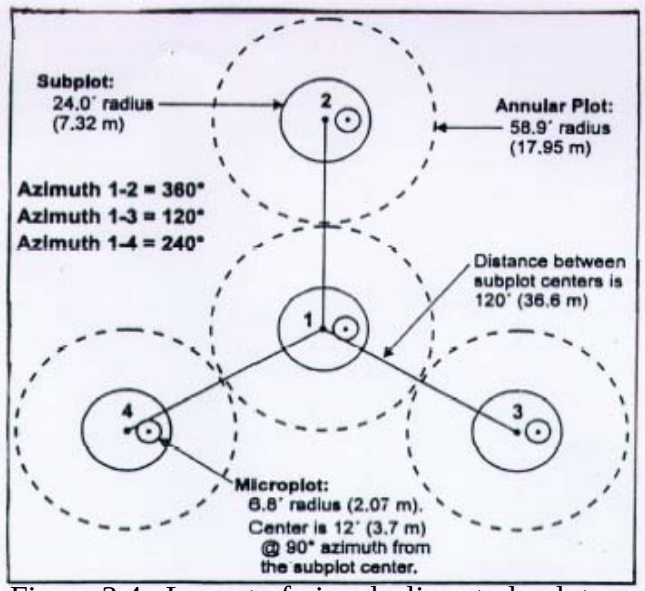

Figure 2.4. Layout of pine decline study plots using Forest Health Monitoring protocols established in Dunn (1999).

Table 2.1. Fort Benning loblolly pine decline plot symptom classes D = decline (symptomatic) and H = healthy (asymptomatic) and plot number identifications, Global Positioning System locations, and stand age categories.

PLOT ID	LATITUDE	LONGITUDE	AGE CATEGORY
D25	32.34220505	-84.80924972	<10
D26	32.3187089	-84.82315966	<10
D27	32.29040623	-84.82568094	<10
D28	32.39846706	-84.88276907	<10
D32	32.40911007	-84.80527469	<10
D29	32.33699083	-84.81278487	<10
H30	32.28182316	-84.82206532	<10
H31	32.39389658	-84.84760531	<10
H36	32.33561754	-84.82941457	<10
D9	32.34737635	-84.82796618	10-19
D10	32.29431152	-84.82331523	10-19
D11	32.3203826	-84.81631466	10-19
D12	32.30252981	-84.80400869	10-19
D15	32.30246544	-84.80526933	10-19
H13	32.49955416	-84.77557727	10-19
H14	32.34516621	-84.82392677	10-19
H16	32.3107481	-84.82407697	10-19
H33	32.39614964	-84.67189916	10-19
H35	32.35010147	-84.81238254	10-19
D18	32.32300043	-84.69167241	20-40
D19	32.51013279	-84.64518436	20-40
D20	32.50978947	-84.65324172	20-40
D22	32.40125656	-84.82672163	20-40
D24	32.28914022	-84.83678528	20-40
D21	32.32145548	-84.81739291	20-40
H23	32.51204252	-84.76686009	20-40
H37	32.52955198	-84.81859454	20-40
H38	32.43033171	-84.78867718	20-40
D1	32.45543718	-84.80148205	>40
D2	32.34465122	-84.67975804	>40
D3	32.52519608	-84.75726315	>40
D4	32.44475126	-84.87541982	>40
H6	32.34538078	-84.6818448	>40
H7	32.29770184	-84.81538662	>40
H8	32.50878096	-84.63932642	>40
H5	32.46567249	-84.85079178	>40

Cycloheximide and 200 mg/l of streptomycin sulfate) (Hicks *et al*., 1980).Culture dishes were incubated at 25°C under fluorescent lighting (460 µmol m^{-2} s^{-1}) for 2 weeks and then examined for fungal growth. *Leptographium*-like fungi were subcultured by transferring hyphal tips and/or spore heads of each isolate to sterile plates of MEA. Subcultured isolates were placed on MEA agar slants and were stored at 4°C for subsequent identification to species. Logistic Regression methods using PROCLOGIST (SAS Institute Inc., 2001) were used to analyze the incidence of staining fungi, root damage type, and root health in symptomatic versus asymptomatic plots.

2.5 Soil Sampling

Soil samples were collected from all root sampled plots in 2004 and 2005. A soil auger was used to collect soil near the lateral roots of three dominant or co-dominate loblolly pine trees closest to the plot center using a collection pattern that followed Lewis *et al.* (1987). The soil samples collected near each root were placed in individual plastic bags, kept on ice, transported to the laboratory and stored at 4°C for no more than 3 days. Each soil sample was thoroughly mixed, and a representative 10 g subsample was taken. The subsample was suspended in 40 ml of sterile 0.5% water agar, after sifting through a #12 sieve to remove root fragments. One ml aliquots were spotted onto each of 10 CSMA and MEA plates (adapted from Johnson and Curl, 1972). Plates were incubated at 25°C under fluorescent lighting (460 µmol m^{-2} s^{-1}) for 2 weeks and then examined for fungal growth. Ophiostomatoid fungi were processed as described in root sampling.

2.6 Insect Activity

Pitfall traps (adapted from Klepzig *et al.*, 1991) were used to capture root-feeding insects on the subplots of 32 center plots (three subplots per plot, 96 total pitfall traps) from March to May for the 2003 trap year period and 31 plots for the 2004 trap year period (one plot destroyed

2004) to allow for the best chance of bracketing the emergence period of most bark beetles (Drooz, 1985). Insects were collected on a biweekly basis and transported to the laboratory for identification and isolation of associated fungi with special emphasis was placed on those felt to be possible pathogens. Traps were made of 20 cm sections of 10 cm diameter polyvinyl chloride (PVC) drain pipe with eight entrance holes equally spaced around the pipe circumference at one end (Fig. 2.5). The interior of each trap contained a catch cup and was coated with a thin layer of liquid Teflon^{TM} (Northern Products, Woonsocket, RI) to prevent the escape of the captured insects. Both ends were capped with removable plastic lids, and two holes were drilled in the bottom lid for drainage. A plastic skirt cut from a 15 cm diameter plastic funnel was placed over the PVC sections and pushed even with entrance holes to prevent water from entering the trap. The traps were then buried, leaving the bottom of the skirt even with ground level. Each trap was baited with two 8 ml glass vials, one containing 95% ethanol and one containing steam distilled southern pine turpentine (Hercules), and two cut pine stems approximately 5 cm long by 2 cm diameter. Trapped insects were collected biweekly and placed in sterile polyethylene specimen cups and refrigerated at 4°C for no more than 3 days. These insects were identified and rolled non-destructively across MEA and CSMA. Plates were incubated at 25°C under fluorescent lighting (460 µmol m^{-2} s^{-1}) for 2 weeks and examined for fungal growth. Ophiostomatoid fungi were processed as in root sampling.

Data were analyzed using generalized linear procedure models with repeated measures analysis in Proc GLM (SAS Institute, Inc. 2001). The model was Y = m + treatment, where *m* is the mean, and treatment was the treatment effect. When significant treatment differences were indicated, means were separated by Fisher's Protected LSD test ($P = 0.05$).

Figure 2.5. Pitfall trap viewed disassembled (left) and assembled (right) used to catch root feeding insects.

2.7 Plot Characterization

2.7.1 Plot Measurements

Measurements taken on all center and subplots included tree species composition (pines and hardwoods), tree diameter at breast height (DBH, approximately 137 cm above ground), basal area (tree count using 10 factor prism .10 acre plot) for the loblolly pines, and total trees present (Dunn, 1999). Additional measurements of sampled trees included age and growth increment (5 and 10 yr) (Dunn, 1999). Other site data collected were aspect of slope, percent slope, elevation, topographic position, land form, percent soil moisture, and soil pH. These data provided a measure of site conditions, stand density, and influence of external stresses. Plot measurements were analyzed using ANOVA.

2.7.2 Crown Ratings

Live crown ratio (comparison of crown length with total tree height), crown light (a measure of light impacting the crown from all sides and the top exposure), crown position (superstory, overstory, midstory, or understory), crown density (percent of crown outlined with living branches and foliage), crown dieback (the ratio of recent fine twig dieback to total live

crown), and foliage transparency (percent sunlight transmitted through the living crown) are FHM crown/ damage indicators that were recorded for all loblolly pines with DBH 12.7 cm or greater to describe relative tree health (USDA, 2001). Trees with high scores for live crown ratio, density and diameter and low scores for dieback and foliage transparency have increased potential for carbon fixation, nutrient storage and increased potential for survival and reproduction (USDA, 2001). Crown evaluations quantitatively assessed current tree conditions and provided an integrated measure of site conditions, stand density and influence of external stresses. Crown rating data were analyzed using ANOVA.

2.7.3 Resin Sampling (Tree Vigor)

One hundred ninety eight trees were sampled (33/decline/age class) on the south side of each tree by punching a hole approximately 137 cm above ground with a 1.9 cm diameter arch punch (No. 149 Osbourne). A plastic resin sampler (Missoula Technology Development Center, Montana) was screwed in place over the punch hole with two wood screws (Fig 2.6). A pre-weighed polyethylene terephthalate (PET) Corning 15 ml centrifuge tube was screwed into the resin sampler and left for 24 hours. Centrifuge tubes with resin were then collected, capped, and put on ice for transport to laboratory. Resin weights were determined. Results of the resin sampling were compared using ANOVA.

2.7.4 Insect Damage

Damage caused by insects was determined by direct observation at the time of root sampling on every pine on all center and sub-plots. Infestation and damage caused by *Hylastes salebrosus* Eichoff, *Hylastes tenuis* Eichoff, *Hylobius pales* Herbst., and *Pachylobius picivorus* (Germar) (all Coleoptera : Curculionidae) were estimated by sweeping soil away from the root collar and lateral roots, and looking for entrance/exit holes and pitch formation on the bark

(Fig. 2.7). Damage was also assessed in the laboratory by peeling the bark from the roots and looking for the presence of insect galleries.

Figure 2.6. Resin sampler disassembled (left) and assembled (right) with polyethylene terephthalate centrifuge tube.

Figure 2.7. Insect feeding damage to a lateral root and the resin response caused by *Hylastes salebrosus* Eichoff (Coleoptera: Curculionidae).

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Results

3.1.1 LPDRM Assessment

3.1.1.1 Topology

Plots in this study were selected in 2003 using the LPDRM. The plots were georeferenced from LPDRM and located in the field using a global positioning system (GPS). The field data were collected 2003 to 2005, compared to LPDRM, and measured for the ranges of percent slope and aspect direction known to be associated with loblolly pine decline biology (Eckhardt, 2003). Plots had elevation ranges from 98 m to 175 m and a 139 m mean, and aspect ranges from 5° to 360° and a 234° mean, with a slope range from 1% to 12 % and a 6% mean. The assessment of the LPDRM for the 36 plots indicated accurate identification for 13 of 15 (86%) asymptomatic and 21 of 21 (100%) symptomatic plots (Fig. 3.1). Slope greater than 5% was the only topographic factor that was statistically significant ($F_{1, 36}$=10.1, p=0.0031) by treatment. At slope greater than 5%, decline incidence increased (Fig 3.2). No other site topography factors had statistical significance when compared to treatment and when alone, appear to have only minor effects. Although the LPDRM was still highly accurate at identifying sites by symptom category and was used effectively to do so, other biological parameters associated with symptom categories were used to verify this as well (e.g. radial growth, crown condition, resin weight, root condition, and insect activity).

3.1.1.2 Growth Variables

Tree ages ranged from 6 to 84 years in the study plots. The range of DBH measurements for loblolly trees sampled for growth and vigor was 10.4 to 53.3 cm.

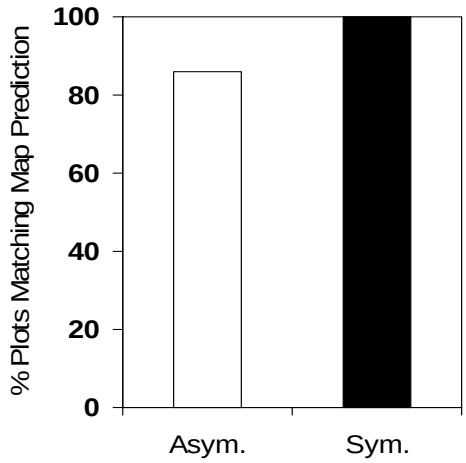

Figure 3.1. The percent predictive accuracy of the Loblolly Pine Decline Risk Map by symptom category.

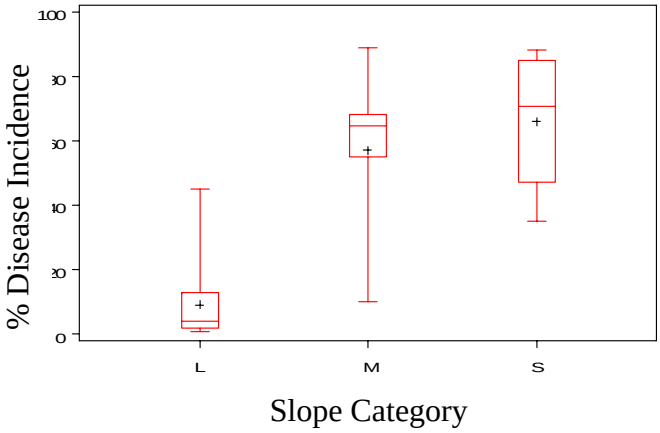

Figure 3.2. Effect of slope on Loblolly Pine Decline disease incidence (L = 6 to 10%, M = 11 to 15%, S = >15%).

Higher mean DBH was to be shown significant in symptomatic trees when correlated to radial growth ($F_{1, 49}$=5.42, p=0.0241) in the10 to 19 year age category. The 5 year radial growth ranged from 4.5 to 31.4 mm, and 10 year radial growth was 9.8 to 58.45 mm. Asymptomatic plots had trees with increased radial growth in 5 and 10 year measurements (Fig 3.3). The increased 5 and 10 year radial growth was statistically significant in asymptomatic plots compared to symptomatic for the tree age categories 10 to 19, 20 to 40, and 40+ (Table 3.1). The range of height for trees on the study plots was 16 to 88 feet. There was no significant difference in the mean DBH and tree height measurements when overall means for symptomatic vs. asymptomatic trees was compared by age category. A response trend indicating reduced DBH and tree height means for symptomatic plots began in the 30 to 39 year age category and continued through 40+ year age (Table 3.2).

3.1.1.3 Crown Condition

Crown ratings were taken in 2004 and 2005 with a total of 1207 trees rated. Crown condition analysis of plot trees consisted of five variables (crown light, crown position, crown

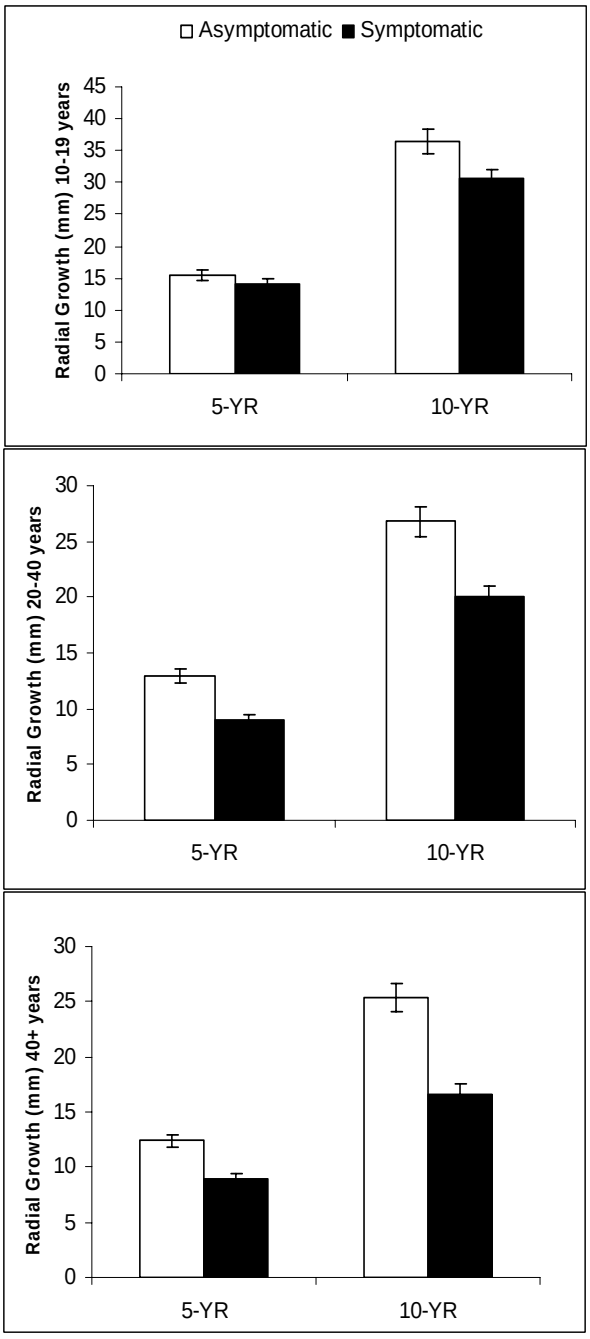

Figure 3.3. Mean radial growth by age and symptom category observed for 2003 to 2005 for Fort Benning Military Reservation study plots asymptomatic (N=30) and symptomatic (N=20) for loblolly pine decline.

Table 3.1. Mean (standard deviation) radial growth (mm) in asymptomatic and symptomatic loblolly pine decline plots of three age categories.

	10 to 19		20 to 40		40 +	
	5-yr	**10-yr**	**5-yr**	**10-yr**	**5-yr**	**10-yr**
Asym.	15.4 a (5.1)	36.4 a (10.7)	12.9 a (5.3)	26.7 a (10.9)	12.3 a (5.2)	25.4 a (14.6)
Sym.	14.1 a (4.7)	30.5 b (8.0)	9.1 b (2.9)	19.9 b (6.3)	8.9 b (2.2)	16.6 b (4.5)

[1]Within a column, values followed by the same letter are not significantly different at the p=0.05.

Table 3.2. Mean observed diameter at breast height & height by age and symptom category in loblolly pine decline plots for 2003 to 2005 (P=pooled data, A=asymptomatic, S=symptomatic).

Age Category	**DBH (cm)**			**Height (m)**		
	P	**A**	**S**	**P**	**A**	**S**
15 to 19	13.49	13.10	13.79	10.20	9.63	11.16
20 to 24	18.97	17.53	26.54	13.69	14.30	16.00
25 to 29	20.77	19.08	22.02	16.04	15.99	16.10
30 to 39	25.83	27.84	24.87	18.86	19.20	18.69
40+	31.34	32.77	29.87	20.61	21.08	20.18

density, crown ratio, and foliar transparency) correlated by age category against symptom category. Three crown conditions (crown density, crown ratio, and foliar transparency) were found to be statistically significant when compared to symptom category (Table 3.3). The variables for crown condition show some variation in symptom category correlations. The age category for pulpwood (10 to 19) had foliage transparency reported as significant ($F_{1, 437}$ =14.27, p=0.0002) and in age category 20-40 crown ratio ($F_{1, 451}$=9.52, p=0.0002) was significant for symptomatic categories (Table 3.3). This may be a result of crown rating tree locations, as not all crown rated trees were on the center plot where the plot is risk rated.

3.1.1.4 Resin Analysis

Resin sampling of 198 trees (99 asymptomatic and 99 symptomatic) was completed in 2005. Mean resin weights were 10.8 g for asymptomatic and 6.1 g for symptomatic sampled trees. Resin weights on asymptomatic plots were statistically significant when compared to symptomatic plots and by age 10 to 19 years ($F_{1, 65}$=19.59, p<.0001), 20 to 40 years ($F_{1, 65}$=26.33, p<.0001), and 40+ years ($F_{1, 65}$=23.28, p<.0001) (Table 3.4).

Table 3.3. Mean (standard deviation) crown condition (percentage) in asymptomatic and symptomatic plots of three age categories for loblolly pine decline study.

	10 to 19 years		20 to 40 years		40+ years	
Crown Condition Percentage	**Asym.**	**Sym.**	**Asym.**	**Sym.**	**Asym.**	**Sym.**
Crown Ratio	42.3a (10.3)	40.9a (9.9)	36.1b (12.8)	39.6a (11.4)	47.8a (13.4)	43.9b (13.4)
Crown Density	47.3a (5.1)	35.2b (7.2)	47.1a (5.8)	35.2b (7.1)	48.4a (7.9)	39.1b (9.1)
Foliar Transparency	26.5b (5.8)	28.4a (4.9)	26.8a (4.9)	29.3b (4.9)	28.6a (5.4)	28.5a (5.0)

[1]Within a row and within each age category, values followed by the same letter are not significantly different at the *p*=0.05.

Table 3.4. Mean (standard deviation) resin weight (grams) in asymptomatic and symptomatic plots of three age categories for loblolly pine decline study.

	Resin Weight (g)	
Age Category	**Asymptomatic**	**Symptomatic**
10 to 19 years	6.44a (1.1)	4.5b (2.2)
20 to 40 years	10.3a (3.9)	6.3b (2.0)
40+ years	10.6a (4.0)	6.8b (2.0)

[1]Within a row, values followed by the same letter are not significantly different at the *p*=0.05.

3.1.1.5 Root Condition/Isolations and Soil Isolations

Roots and soil were sampled over a 2 year period. *Leptographium* species were isolated from the primary and fine root samples from 23 of the 36 plots and from the soil in 5 of the 36 plots (Table 3.5). *Leptographium* species. isolated from the primary root samples were *L.*

terebrantis Barras & Perry, *L. procerum* (Kendr.) Wingfield, *L. serpens* (Goid.) Wingfield, and an unidentified *Ophiostoma* sp. Only *L. procerum* was isolated from the fine roots. The overall proportion of *Leptographium* species isolated from all infected roots was higher from roots of trees on symptomatic plots (91%) than those from asymptomatic plots (0.08%). In addition, only *L. procerum* was isolated from the soil samples and was generally more common in soil from symptomatic (80%) vs. asymptomatic (20%) plots. Root system deterioration was significantly higher in symptomatic than in asymptomatic trees. Symptomatic trees consistently had more dead and fewer fine roots present, more physical damage from insects and fire, more staining of the primary roots (Table 3.6), and a higher percentage of *Leptographium* species per root system (Table 3.5).

Phytophthora cinnamomi was not isolated from any of the root or soil samples. *Heterobasidium annosum* (Fr.) Bref. was not found in any of the root samples, nor were any fruiting bodies of the fungus found on trees or stumps. However, some small *H. annosum* fruiting bodies were found on old stumps at other locations on the installation, but there was no evidence of root infection of trees in the sample plots.

3.1.1.6 Insect Variables

The total number of root feeding insects (*Hylastes* spp.) and reproduction weevils (*Hylobius pales* and *Pachylobius picivourus*) captured in pitfall traps increased annually during the 3 years of trapping (1117 in 2003, 1253 in 2004 and 2423 in 2005). The mean pest insect abundance for all plots and years increased from 82.78 to 127.33. Mean insect numbers were significantly higher on symptomatic plots than asymptomatic plots for study years 2003 ($F_{1, 30}$=4.22, p=0.0495) and 2004 ($F_{1, 30}$=4.33, p=0.0468) (Fig 3.4). Insect abundance increased when plots had a history of disturbance (burning, thinning, or feral hog rooting) and when multiple disturbances occurred (Fig. 3.5). Insect abundance by age category was statistically significant

Table 3.5. Isolation of pathogenic fungi from roots, soil, and insects by plot [D=decline (symptomatic) and H=healthy (asymptomatic)]. Neither *P. cinnamomi* nor *H. annosum* were isolated from any of these sites. [(-) No insects trapped at these locations].

Plot ID Symptom/Number	***Leptographium* Species**						***P.c.* %**	***H.a.* %**
	Roots		**Soil**		**Insects**			
	Yes	**No**	**Yes**	**No**	**Yes**	**No**		
D24	X			X	X		0	0
H7		X		X	X		0	0
D10	X			X	X		0	0
D27	X			X	X		0	0
H30		X		X	X		0	0
D12	X		X		X		0	0
D9	X		X		X		0	0
H14		X		X	X		0	0
H35		X		X	-	-	0	0
D25	X			X	X		0	0
D29	X			X	X		0	0
H6	X			X	X		0	0
D2	X		X		X		0	0
D18	X			X	X		0	0
D22	X			X	X		0	0
D32	X			X	X		0	0
H8		X		X	X		0	0
D19	X			X	X		0	0
D20	X			X	X		0	0
H33	X		X		-	-	0	0
H37		X		X	-	-	0	0
H38		X		X	-	-	0	0
D1	X			X	X		0	0
H5		X		X	X		0	0
D3	X			X	X		0	0
H23		X		X	X		0	0
H13		X		X	X		0	0
H31		X		X	X		0	0
D28	X			X	X		0	0
H36		X		X	-	-	0	0
D21	X			X	X		0	0
H16		X		X	X		0	0
D11	X			X	X		0	0
D26	X			X	X		0	0
D15	X			X	X		0	0
D4	X		X		X		0	0

Table 3.6. Condition comparison of primary and fine roots on asymptomatic and symptomatic loblolly pine decline plots.

	Asymptomatic	Symptomatic	P-value [1]
Fine Roots	**- % of roots -**		
Present (Alive)	85	13	0.0025
Present (Dead)	5	39	0.0018
Absent	2	43	0.1071
Primary Roots			
Damage (Insect)	10	72	<0.0001
Damage (Fire)	10	81	<0.0001
Dead	2	55	0.0001
Stained	12	98	<0.0001

[1] P-values are the logistic regression comparisons for asymptomatic (N=15) vs. symptomatic (N=21) sites in each category.

($F_{3, 123}$ =10.52, p<0.0001) with higher abundance in precommerical (< 10 years) and 40+ years (Fig 3.6). Insect abundance of different root feeders was similar; symptomatic plots had greater numbers than asymptomatic plots, and insects were more abundant in older tree age categories (Fig. 3.7).

Leptographium species were isolated from the surface of three species of root-feeding bark beetles [*Dendroctonus terebrans* Olivier (Coleoptera: Curculionidae), *H. salebrosus*, and *H. tenuis*], and two species of root-feeding weevils (*H. pales* and *P. picivorus*). Eight other bark beetles and fungus-feeding insects [Coleoptera: Scolytidae: *Ips avulses* (Eichhoff), *Ips grandicollis* (Eichhoff), *Xyleborinus saxeseini* (Ratzeburg), *Xylosandrus compactus* (Eichhoff), *Xylosandrus crassiusculus* (Motschulsky), *Gnathotrichus materiarius* (Fitch), and *Monarthrum mali* (Fitch); and Coleoptera: Nitidulidae: *Colopterus unicolor* (Say)] were trapped from the 32 plots.

3.2 Discussion

This study in Georgia confirms the findings for declining loblolly pine described by Eckhardt *et al*. (2007), and Hess *et al*. (2005) for sites in Alabama. It was found in this study

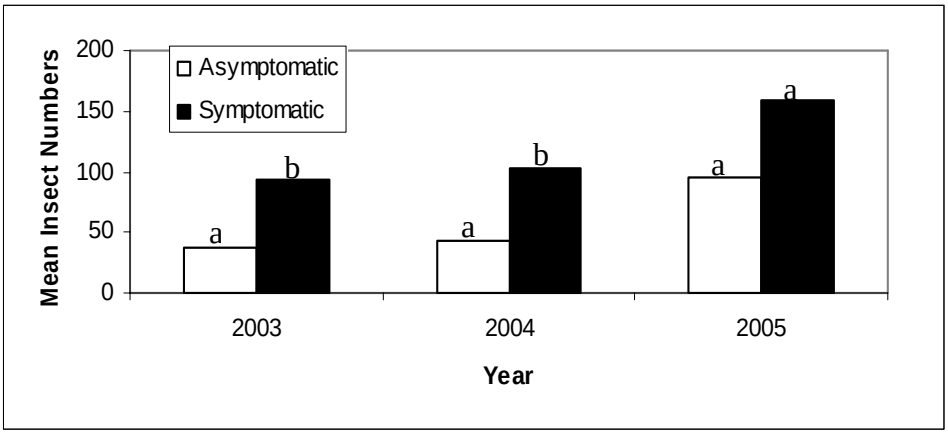

Figure 3.4. Mean insect abundance by plot treatment for all trap years on Fort Benning Military Reservation. Bars with the same letter at each treatment are not significantly different (P> 0.05).

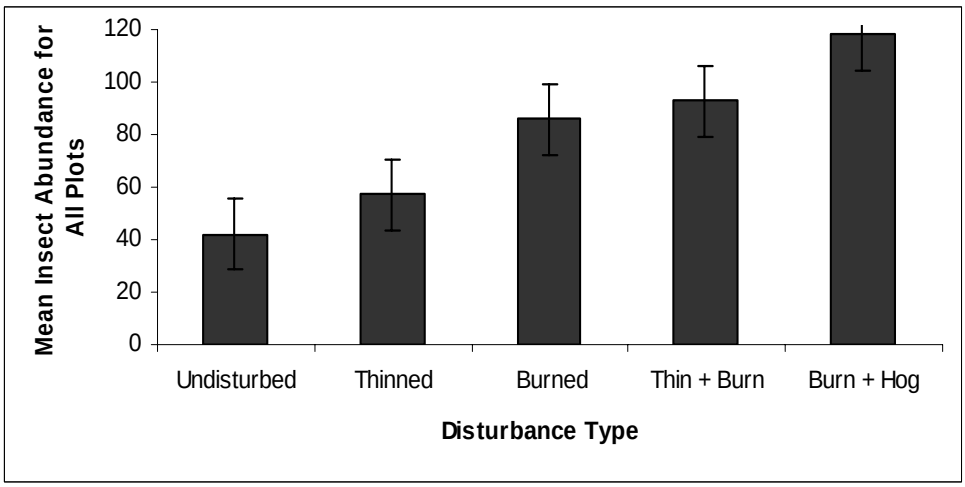

Figure 3.5. Mean abundance of insects captured at Fort Benning Military Reservation for all plots, all years, and segregated by the type of disturbance on plots.

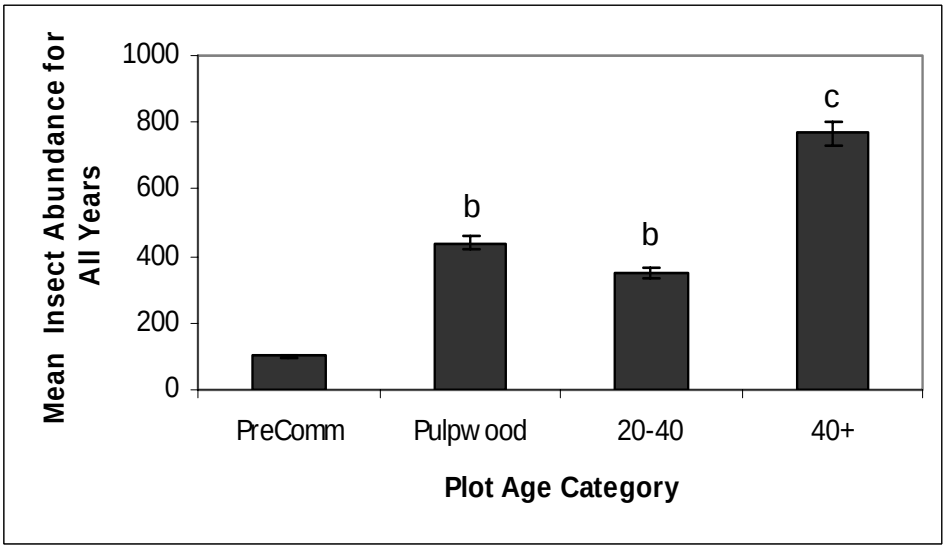

Figure 3.6. Mean insect abundance per plot for all trapping years (2003 to 2005) segregated by age category (PreComm <10 years, Pulpwood 10 to 19 years) of the plots on Fort Benning Military Reservation. Bars with same letter for each age category are not significantly different ($p > 0.05$).

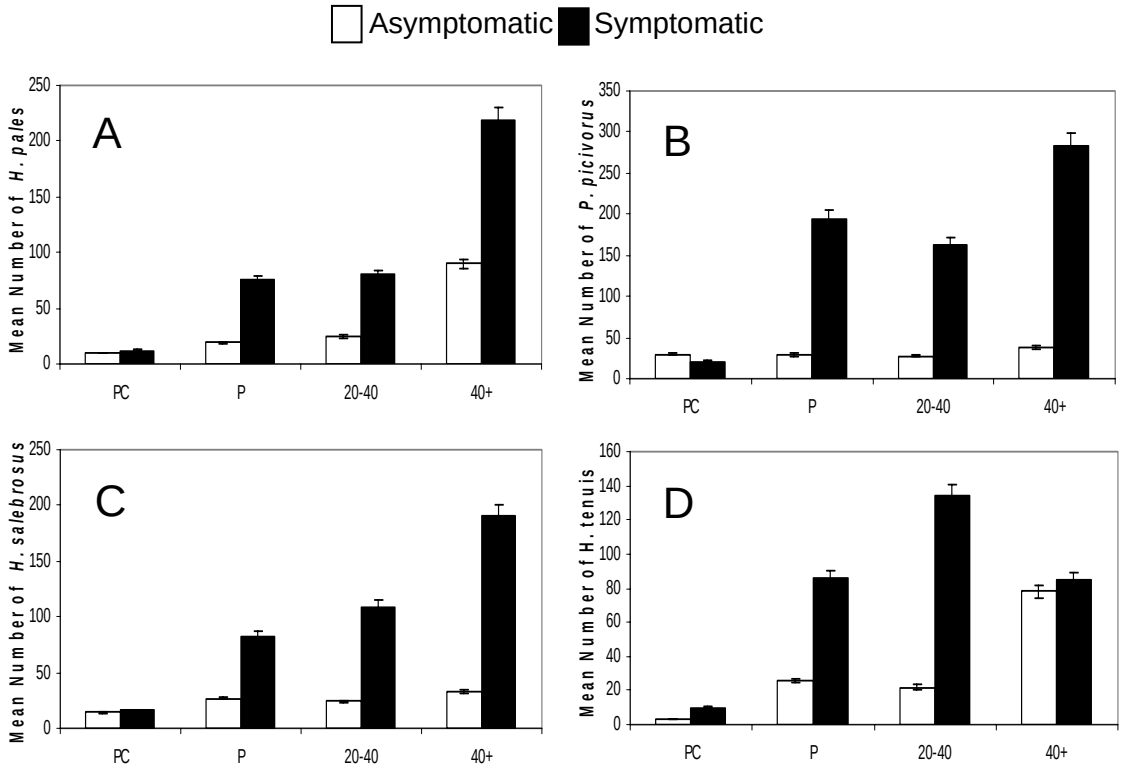

Figure 3.7. Abundance of root feeding bark beetles and weevils in different tree age categories and symptom treatments captured on plots at Fort Benning Military Reservation.. (A) *H. pales*, (B) *H. picivorus*, (C) *H. salebrosus*, and (D) *H. tenuis*. PreComm (<10 years), Pulpwood (10 to 19 years).

that loblolly pine decline is characterized by the occurrence of deteriorated root systems, short chlorotic needles, sparse crowns, and reduced radial stem growth that may be followed by death of the affected trees.

The abiotic factors that predispose trees to decline may be the result of changes in the pine physiology that provides an environment favorable to predisposing biotic factors (Hodges *et al.,* 1979). Decline symptoms appeared to be more pronounced in areas that had steeper slopes and a south facing aspect. These microsite conditions are primarily associated with minor changes in topography that create distinctive environmental conditions and appear to be the essential elements correlating to the biology of decline. Microsite differences are often strongly correlated with whether the site is symptomatic or not, the presence of an association of root-feeding insects and *Leptographium* fungi, and loblolly pine vigor. The topography of microsites was correlated with abiotic conditions (positive or negative) to which loblolly pine responded physiologically with changes in growth parameters, vigor, insect abundance, isolation rates of *Leptographium* species, and root condition of the trees. Physiographic factors exert a general influence on stand quality, but microsite variation in percent slope, aspect, and moisture are critical components in the distribution of either symptomatic or asymptomatic trees within a given stand. These findings are similar to results reported by Shoulders and Walker (1979) and Zahner (1958). Slope percentage may have an effect on soil moisture where a gentle slope of less than 5% is optimal. A slope of 1 to 2% is optimal for tree growth and vigor; and a slope in excess of 5% causes a reduction in tree growth and vigor (Lorio and Hodges 1968, 1971; Lorio *et al*., 1972). The data reported here support these findings (Fig. 3.2) and are the essential elements to the validation of LPDRM accuracy. The strong association with a vigor condition led to an accurate identification of microsite locations for selecting plots within the proper symptom treatment. Aspect appears to affect the soil temperature (Marshall and Holmes, 1988)

and soil water balance in high latitude regions (Hanna *et al.*, 1982), and was correlated with loblolly pine decline (Eckhardt *et al.,* 2007). The effects of slope and aspect may combine to create microclimates within microsites. Adverse (symptomatic) microclimates act as a predisposing disturbance that alone or in combination with other inciting disturbances (Appendix A) reduce tree vigor. Accurate delineation of microsites using the LPDRM provided by this study can provide managers with the opportunity to mitigate some inciting disturbances and lower the risk of decline.

The accurate delineation of microsites and their predisposing effect on loblolly pine and commensurate vigor response provided the study with a biological association (growth parameters) for assessing the LPDRM. Evidence for pine growth decline in the southeastern U.S. has been reported by the United States Department of Agriculture, Forest Service, Forest Inventory Analysis (FIA) to have occurred over the last decade (Bechtold *et al.,* 1991, Gadbury *et al.,* 2004), although no casual factors where identified. Other studies investigating southern pine decline complexes have also reported reduction in growth parameters that can be associated with abiotic and biotic stress factors (Hess *et al.,* 1999; Otrosina *et al*., 1999, 2002; Eckhardt *et al.,* 2007; Zanzot and Eckhardt, *unpublished*). These studies suggest that southern pines exhibiting reduced growth parameters are associated with a reduced vigor condition. The past decade has experienced extremely high southern pine beetle activity that can be associated with pines of reduced vigor (Hicks *et al.,* 1980; Blanche *et al.,* 1983; Schultz, 1997). This suggests that there may be predisposing ecological conditions that reduce the health and vigor of pines across the southeastern United States. This study may have provided some elucidation of possible factors affecting reduced growth and vigor of pines. The reduced growth reported in this study was consistently associated with predisposing physiographic factors associated with varied tree vigor. Symptomatic plots that exhibited lower stem growth values (Fig 3.3) appeared

to be similar to other southeastern U.S. sites that had reduced growth. Reduced growth and vigor were physiological conditions that were used in this study to assess the presence of an abiotic site stress brought on by microsite factors. Poor crown conditions and lower resin production were significant factors in association with loblolly pine decline. Trees with large, dense crowns, and high resin production were associated with asymptomatic sites. In contrast, trees with small, thin crowns, and low resin production were associated with symptomatic sites.

Resin flow is the primary defense of pines against insect attack and fungal invasion (Bridges, 1987; Hodges and Lorio, 1975). Relative vigor can be associated with the amount of resin production by loblolly pine. Trees that produced more resin for a given measured time period had greater vigor at asymptomatic microsite locations. The trees on symptomatic plots showed lower resin production when compared with trees on asymptomatic plots (Fig. 3.4). The above ground symptoms of reduced radial growth, increased foliar transparency, decreased crown density, and reduced resin production (low vigor), were displayed by trees in the symptomatic plots but not in the asymptomatic plots. Trees in symptomatic plots also had deteriorated root systems. These results are consistent with results from studies of other pines associated with *Leptographium* species (Leaphart and Gill, 1959; Wagener and Mielke, 1961).

The decline of loblolly pine at FBMR appears to have resulted from the debilitation of root systems infected with *Leptographium* species associated with root-feeding insects attracted by the weakened condition of potential host trees influenced by stress or onsite disturbances. This finding is consistent with the findings in similar pine decline studies (Eckhardt *et al.*, 2007; Hess *et al.*, 2005; Klepzig *et al.*, 1991). *Leptographium* species and root-feeding insects were consistently associated with declining trees, and the damage apparent in the root systems was typically higher in symptomatic trees (Table. 3.6). This is consistent with observations made for

other pines with *Leptographium* species activity in their roots (Klepzig *et al.*, 1991; Eckhardt *et al.*, 2004).

Total pest insect numbers showed a > 2-fold increase over the 3-year study. The average daily catch per trap of 30 for southern pine beetle is considered epizootic, and in 2005 an average of 43 root-feeding beetles were collected per day per trap. This association indicates that root-feeding beetles may be at abnormally high populations (epizootic) and spreading infection by *Leptographium* fungi. These insects were found to be a significant contributing factor in the occurrence of loblolly pine decline on symptomatic plots. The overall average number of insects and the average number of insects associated with some type of plot disturbance (i.e. thinning, burning, and feral hog rooting) were higher in all symptomatic plots compared to the asymptomatic plots. The same pattern occurred when counts made from non-disturbed plots were compared to single disturbance plots. Multiple disturbance plots had consistently higher average insect catches than single disturbance plots (Fig. 3.7). These data indicate that higher numbers of root-feeding insects are significantly associated with a disturbance and further suggest that any increase in the number of disturbances to which a site is subjected favors further increases in the population of root-feeding insects. The association of root-feeding insects and *Leptographium* species on disturbed sites and the occurrence of loblolly decline suggest that disturbance mitigation may be a management option.

Five insect species (*H. picivorus, H. pales, H. salebrosus, H. tenuis,* and *D. terebrans*) occurred in higher numbers in symptomatic than in asymptomatic plots. This corresponds to the increased levels of associated beetle activity within stands having an elevated incidence of *Leptographium* species reported for declining loblolly pine in Alabama (Eckhardt *et al.*, 2007), for stands showing red pine decline in Wisconsin (Klepzig *et al.*, 1991), and for stands exhibiting black stain root disease caused by *L. wageneri* (Hansen, 1978; Harrington *et al.*, 1985). These

root-feeding insects were consistently associated with *L. terebrantis, L. procerum,* and *L. serpens* and may be serving as vectors of these, as well as similar, fungi in other disease complexes (Klepzig *et al.*, 1991; Rane and Tattar, 1987). Insect damage alone was not found to seriously affect the trees, but the resulting colonization by the introduced *Leptographium* species was extensive. All of the pestiferous insects (five root-feeding bark beetle and weevil species) and other bark beetles and fungus-feeding insects have had *Leptographium* fungi isolated from them. Conidia are produced in sticky drops on the heads of condiophores growing from fungal hypae within beetle galleries. New infections are initiated when contaminated beetles (from broods developing in diseased roots) are attracted to disturbed or stressed stands, dig through the soil in search of suitable roots for breeding and feeding, and bore into roots of living trees. The weakening and killing of root systems can provide enough susceptible hosts (brood substrate) to maintain high bark beetle populations over time. *Leptographium* isolates from root samples were collected on plots with high populations of root-feeding bark beetles and weevils that are aggressive in their feeding habits, thus creating new wound courts and opportunities for fungal invasion. At high population levels, the aggressive feeding activity of these bark beetles and weevils appears to have a major role in the occurrence of *Leptographium* species within areas of decline, as demonstrated by high insect numbers trapped with consistent *Leptographium* isolations from these insects (Eckhardt *et al.,* 2007). The insect numbers trapped were also significantly correlated with the degree of decline and root disease (Eckhardt *et al.,* 2007). The high pestiferous insect population and their association with *Leptographium* species were correlated with *Leptographium* pine root disease (Eckhardt *et al.,* 2007). This study confirms the similar findings for loblolly pine decline reported by Eckhardt *et al.* (2007) and Hess *et al.* (2005) and thus validated the potential of the LPDRM system as a useful tool for identifying and managing this disease.

CHAPTER 4

SUMMARY AND CONCLUSIONS

4.1 Summary

The purpose for this study was to create a Loblolly Pine Decline Risk Map for Fort Benning Military Reservation, Georgia and to identify study plot locations for accuracy assessment based on map model predictions and assess map model accuracy by using the abiotic and biotic factors as described by Eckhardt (2003).

Map creation based on parameters of previous work by Eckhardt (2003) was a straight forward project. It was originally completed with 30 m digital elevation models, but resolution was too coarse for accurate microsite locations to be used for assessment. The final version used 10 m digital elevation models, which have been sufficiently accurate for mapping and biological assessments.

Assessment of the Loblolly Pine Decline Risk Map was accomplished by an analysis of factors previously found to be significant in the biology of loblolly pine decline (Eckhardt, 2003). These factors involved both abiotic and biotic parameters that had interacting and influencing relationships in loblolly pine decline. The reproducibility of trends from the previous study confirmed the validity of this assessment protocol.

The LPDRM validation has confirmed the previous studies findings that loblolly pine decline etiology has a spatial context that is correlated to specific biological elements. The elements can now be located at a landscape level and managed through proactive mitigation.

4.2 Conclusions

Based on this work, the described decline of loblolly pine has shown the Loblolly Pine Decline Risk Map to be an effective tool for mapping the potential occurrence of pine decline

across large landscapes. Predisposing factors, related to site topography and inciting disturbance factors resulting in host stress, are primary contributors to the occurrence of pine decline. Affected areas are predominantly upland sites that were planted with loblolly pine after a history of previous agriculture. In their current condition, these sites are not well suited for the long-term red-cockaded woodpecker habitat management goal of Fort Benning Military Reservation.

Symptoms and signs of damaging agents observed in declining trees included fine root deterioration, and lateral root staining and damage that result in less radial growth than in healthy trees. (These symptoms are similar to the symptoms of littleleaf disease; however, the associated pathogen *P. cinnamomi* was not present and site conditions are not appropriate for that disease.) Among the factors observed as contributing to the decline of loblolly pine were root-feeding insect damage on the primary roots and the infection with *Leptographium* fungi. Insect damage alone was not sufficient to seriously affect the trees; root colonization by *Leptographium* fungi was extensive, although its significance is as yet to be fully elaborated. A significant level of *Leptographium* infection was dependent upon the number of root-feeding insects and the related wound courts created by their feeding activity, which introduce the fungi to the roots.

All of the insect species in this study appear to respond similarly to environmental factors relating to loblolly pine stress. Five insect species (*D. terebrans, P. picivorus, H. pales, H. salebrosus* and *H. tenuis*) occurred in higher numbers in symptomatic than in asymptomatic plots. These insects were also consistently associated with *L. terebrantis, L. procerum,* and *L. serpens,* and were serving as vectors of these fungi. *Leptographium* species are vectored primarily by *Hylastes* species, although root-feeding weevils are also important. This elevated population can reach numbers at which both healthy and stressed trees are attacked. Therefore, at high insect populations, predisposition as a result of root disease may appear to be less

significant, but this is not necessarily true since disease could be the factor responsible for the beetle epidemic originally (Cobb, 1988).

A very important question to be considered is - what factors affect insect populations and behavior? The spatial occurrence of the abiotic factors follow a pattern in the landscape that relate to aspects generally facing southerly directions and slopes greater than 5 percent. These microsites are where the highest amount of pestiferous insect activity, root disease, and decline symptomology occurred (Eckhardt, 2003). Stress within these sites can be increased with the addition of a disturbance i.e. drought, storm damage, fire, or anthropogenic activity. The additional stress can be related to increasing insect activity, root disease, and decline symptomology. The level to which these disturbances change pine decline severity vary depending upon: (1) type of disturbance; (2) simultaneous occurrence of multiple disturbances; (3) severity of predisposing abiotic stress (slope and aspect); (4) epizootic insect populations; and (5) host age and vigor. Sites with predisposing abiotic-topography-stress that have anthropogenic sources, i.e. stand thinning and/or prescribed fire, have sharply spiking pestiferous insect populations that remain high for up to 3 years after the event (Eckhardt, 2003). These sites also have higher *Leptographium* species isolation rates from the insects and roots, more evidence of diseased roots, and more crown symptomology associated with decline (Eckhardt *et al.,* 2007). On sites that had a favorable aspect and slope, e.g., a northerly to east facing aspect and a slope of 5 % or less had significantly lower pestiferous insect numbers trapped, with lower incidence of *Leptographium* infection in the roots, and no evidence of root disease. This is an important factor since pine decline is not evident on these microsite locations, suggesting that mitigation of inciting factors can reduce or prevent pine decline (Appendix B).

The higher incidence of loblolly pine decline symptoms (lower resin production, radial growth reduction, poor crown condition, and corresponding deteriorated root conditions) resulted

in low vigor trees within symptomatic plots. The low vigor trees of symptomatic plots had increased insect numbers, more insect feeding on roots, and higher fungal infection in roots. The Loblolly Pine Decline Risk Map can be used by researchers and land managers to identify sites that have these biological associations to loblolly pine decline. The assessment of the Loblolly Pine Decline Risk Map predictive accuracy was successfully accomplished using these significant biological parameters. The conclusion is that the Loblolly Pine Decline Risk Map is accurate and is an effective method of identifying the occurrences of loblolly pine decline disease. Further research is needed to understand the population dynamics and biology of the root feeding insects and their association with *Leptographium* fungi in the complex of loblolly pine decline disease.

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APPENDIX A: TREE STRESSORS

Inciting Disturbances

1. Anthropogenic
   a. Silvicultural (any mgmt)
   b. Recreational (ie. off-road vehicles)
   c. Training (ie. Military)

2. Natural
   a. Weather (ie, drought, flood, storm)

3. Biotic
   a. Stand density
   b. Stand species composition
   c. Understory vegetation density
   d. Vector population[2]

Predisposing Disturbances

1. Abiotic[1]
   a. Slope
   b. Aspect
   c. Convexity
   d. Elevation

These disturbances may cause damage to the tree at three levels.

1. Root
   a. Compaction - caused by logging equipment, training equipment, off-road vehicles, etc.
   b. Wounding - caused by equipment, training, natural (wind throw), hogs, fire, etc.
   c. Exposure - caused by erosion, various types of equipment, training, etc. This type of damage exposes roots to fire, insect attack and other types of wounding damage listed above.

2. Bole
   a. Wounding - caused by logging equipment, training equipment, felling of hazard trees, lightning strike, fire, breaks/cracks from storm damage, etc.

3. Crown
   a. Foliage - loss from burning, insect defoliation, disease, etc.
   b. Branches & upper bole - storm damage (wind/ice), fire, lightning, etc.

[1] Abiotic (topographical features) are listed in order of significance.
[2] This is predicated on other disturbances. These insects are drawn to stress chemicals being volitalized by the tree. There populations will increase with disturbances (Eckhardt, 2003).

APPENDIX B: MANAGEMENT OPTIONS

1. Manage current stands, recognizing that decline of loblolly pine is affecting the ability of the forest to sustain RCW habitat.
   - Continue utilizing the LPDRM to determine condition class of existing loblolly stands and their projected life expectancy to allow appropriate planning for current and future pine stocking.
   - Assess the loblolly component within the habitat (nesting, foraging, and recruitment) of RCW using the LPDRM provided to Fort Benning.
   - Compare U.S. Fish and Wildlife Service RCW habitat guidelines to the decline risk assessment projections to establish loblolly pine management goals that fall within the guidelines for RCW habitat management.
   - Identify loblolly sites within RCW habitat that are at risk and modify management to reduce immediate losses and allow time for new regeneration to replace existing high-risk stands.
   - Use the decline risk assessment to project the probable sustainability of the loblolly pine component of existing RCW habitat to facilitate guideline implementation for RCW habitat sustainability.
   - Prioritize restoration to longleaf pine on high-risk, unsustainable loblolly sites to provide for future habitat needs of the RCW.
2. Longleaf pine is the preferred management species for the upland pine sites on the FBMR. Restoration of the longleaf pine ecosystem on these sites will provide for long-term RCW habitat needs, will reduce SPB risk, and will allow the Army Base to manage for the desired future condition of a healthy forest.

3. Tree Condition
    - Keep trees healthy and vigorous
    - Adjust rotation ages on stressor sites
    - Plant pines more suitable to the stressor sites (no off-site pine)
4. Disturbance Awareness
    - Minimize site disturbance
    - Minimize tree injury
    - Whenever possible, avoid overlapping disturbances
5. Insect Population Control
    - Favor winter cutting (when ground is dry; wet soil [in other seasons] promotes compaction)
    - Remove slash promptly to avoid population buildup in slash
    - Remove stumps where feasible to reduce potential insect habitat
    - Plant more resistant species in mixed stands (longleaf, slash, hardwood)
    - Perform appropriate site preparation to favor desirable, healthy and vigorous trees

VITA

Roger Menard was born in Killeen, Texas, on July 8, 1950. His father was in the Army during most of his secondary school years requiring relocation every 3 to 5 years. He enlisted in the Army in1969 and served for 3 years. After serving time in the Army, he worked in the forest industry, owned a private business, and pursued academic study until receiving a bachelor's degree. He received a General Studies III Emphasis in Science from Northwestern State University, Natchitoches, Louisiana in 1995, and continued working in the forest industry until 1998. He began working, for the US Forest Service in 1998, and in 2003, while still work for the Forest Service, began a master's degree program at Louisiana State University, Baton Rouge, Louisiana, with an emphasis in forest pathology under Dr. Jones and now under Dr. Holcomb. He is a member of the Society of American Foresters and the American Phytopathological Society. He is now a candidate for the degree of Master of Science in plant health, which will be granted in August 2007.