Forest Science and Technology
Vol. 9, No. 3, September 2013, 137–146

Factors influencing loblolly pine stand health in Fort Benning, Georgia, USA

Soung Ryoul Ryu[a]*, G. Geoff Wang[b] and Joan L. Walker[c]

[a]*Department of Renewable Resources, University of Alberta, Edmonton, Alberta T6G 2H1, Canada;* [b]*Schoool of Agricultural, Forest and Environmental Science, Clemson University, 261 Lehotsky Hall, Clemson, South Carolina 29631, USA;* [c]*USDA Forest Service, Southern Research Station, Clemson University, 233 Lehotsky Hall, Clemson, South Carolina 29634, USA*

(*Received 3 September 2012; Accepted 3 December 2012*)

Loblolly pine (LBP; *Pinus taeda* L.) stands provides two-thirds of the existing federally protected red-cockaded woodpecker (RCW; *Picoides borealis*) habitat in Fort Benning, Georgia, USA. However, LBP in this area is suspected to face a forest decline issue, which may risk the sustainability of the RCW population. Land managers are attempting to convert LBP stands to longleaf pine (*Pinus palustris* Mill.), which once dominated the landscape, however the transition has to be gradual so current RCW habitat is maintained until longleaf pine stands sufficiently support RCW populations. It is critical to identify environmental factors influencing LBP health and convert LBP stands under poor environment to longleaf pine first. We installed 90 plots ($30 \times 30\,m^2$) in mature (>38 years) loblolly pine forests and measured aspect, slope, soil texture, soil (pH, organic matter, cation exchange capacity, and exchangeable phosphorus, potassium, magnesium, and calcium) and foliar (nitrogen and phosphorus) nutrient, diameter at breast height, light exposure, and crown vigor class (CVC; 1 = good, 2 = fair, and 3 = poor). Stand age, site index, and burning and thinning history were retrieved from existing inventory data. Our results show that site index was the main factor in determining LBP health. Site index showed significant correlation with percentage of LBP in CVC1 ($p = 0.04$) and CVC3 ($p = 0.07$). Percentage of LBP in CVC3 tended to decrease as soil texture became finer. Poorer site index and coarser soil likely resulted in water stress during periods of drought leading to higher %CVC3 LBP. Based on these results, conversion to longleaf pine should start from LBP stands on coarser soil (or lower site index) at Fort Benning.

Keywords: crown vigor; water stress; nutrient; site index; soil texture

Introduction

Loblolly pine (LBP; *Pinus taeda* L.) is the most widely planted pine species in the southeastern USA because of its relatively fast growth, wide geographical habitat range, and high commercial value (Schultz 1997). However, several studies reported decline of LBP trees in the southeastern USA over the last 50 years (Sheffield et al. 1985; Sheffield and Cost 1987; Hess et al. 1999), generating a significant stir in the regional community due to its ecological and economic importance (Zeide 1992). Especially, Sheffield et al. (1985) and Sheffield and Cost (1987) analyzed the forest inventory and analysis database and reported that the growth of four main pine species (i.e. loblolly, shortleaf, longleaf, and slash pines) continuously decreased by 30–50% from 1956 to 1982 in the Piedmont Mountains and Coastal Plain regions of South Carolina and Georgia. Bechtold et al. (1991) and Ruark et al. (1991) also confirmed the results of Sheffield et al. (1985) using a different statistical approach to analyze the same data. However, these studies did not find any biological or physical factors (e.g. aging of stands, stand density, hardwood competition, drought, and prescribed fire) satisfactorily explaining the cause of productivity decline. More recently, several studies reported premature LBP mortality on well-drained sites in central Alabama after the tress showed symptoms of short chlorotic needles, sparse crowns, fine-root deterioration, and reduced radial growth and argued that it was associated with *Leptographium* spp. (Hess et al. 1999; Eckhardt et al. 2007; Eckhardt and Menard 2008).

The LBP decline raised a concern to the land managers at Fort Benning, Georgia, USA, because the majority of LBP stands were located on well-drained nutrient-poor sandy soils. Unexpected LBP mortality could complicate the forest management goals of Fort Benning, which were to support existing red-cockaded woodpecker (RCW; *Picoides borealis*), to facilitate military training, and to sustainably produce timber. LBP forests are the primary habitat for the federally protected endangered RCW in the southeastern United States (Schultz 1997). Over 200 active RCW clusters are currently in LBP stands at Fort Benning for foraging and nesting (USAIC 2006). Therefore, LBP stands at Fort Benning are intensely managed to meet the RCW habitat requirements: below basal area of $18.4\,m^2\,h^{-1}$ or an average spacing of at least 7.6 m between pines with frequent (three-year mean interval) surface burns (USDI Fish and Wildlife Service 2003). Furthermore, land managers at Fort Benning have tried to restore longleaf pine forests, which was the historic vegetation type and original RCW habitat (USDI Fish and Wildlife Service 2003), by clearcutting the existing upland LBP stands and planting longleaf pine seedlings.

*Corresponding author. Email: soung.ryu@ualberta.ca

ISSN 2158-0103 print/ISSN 2158-0715 online

http://dx.doi.org/10.1080/21580103.2013.801175
http://www.tandfonline.com

However, this conversion process has to be done gradually, so RCW can have enough mature (>40 years) LBP stands to use for foraging and nesting during the conversion process. It is critical to understand the future LBP mortality pattern to develop a management plan satisfying all management objectives.

Tree mortality is a vital process in forest dynamics (Das et al. 2008) and tree vigor is often closely related to the tree mortality, since trees with low vigor are more susceptible to environmental stresses (Manion 1991; Pederson 1998). Therefore, various methods have been developed to assess tree health in the field, and these methods use crown transparency (Eichhorn et al. 2004), needle size or shape (Kozlov and Niemela 1999), crown morphology (Roloff 1987), crown ratio (Burkhart et al. 2001), and foliar and sapwood nutrient analysis (Stefan et al. 1997). These measures mainly rely on the crown condition, because photosynthesis is the energy source and trees allocate energy to the canopy development as a priority (Ryu et al. 2006). However, it is often difficult to clearly assess the tree vigor using one measure, because tree vigor is controlled by complex interactions between various physiological and morphological factors. Therefore, USDA Forest Service (1999) developed a canopy assessment system (named 'crown vigor class' (CVC)) that can be used to readily evaluate tree health in the field based on canopy conditions, and it was found to be well related to tree growth for many species (e.g. Manion 1991; Kramer 1996; Dobbertin 2005) including loblolly pine (Anderson and Belanger 1987). The CVC considers live crown ratio, crown dieback, and crown density to classify trees into good (CVC1), fair (CVC2), and poor (CVC3) vigor conditions (USDA Forest Service 1999).

The main objective of the study is to understand the current health condition of LBP stands and to identify factors negatively influencing the health of LBP. Considering that LBP mortality was observed in well-drained sites, we hypothesized that water stress was the main cause of LBP mortality, and management practices (e.g. prescribed burning history) influenced loblolly pine health. We expect to find a measure readily and easily usable for land managers to develop a long-term management plan in Fort Benning.

Methods and materials

Study area

Fort Benning is located on the southern edge of the fall line, which borders the Piedmont and Coastal Plain physiographic provinces. The study landscape is composed of two major physiographic subsections, the Sand Hills and the Upper Loam Hills (McNabb and Avers 1994). The Sand Hills are part of the Lower Coastal Plains and Flatwoods section and cover approximately the northeast two-thirds of the installation (Figure 1). The Upper Loam Hills are part of the Middle Coastal Plains and are more mesic, with higher organic matter content than soils of the Sand Hills. The predominantly rolling terrain is highest (225 m above sea level) in the east and lowest (58 m above sea level) in the southwest along the Chattahoochee River. The climate is characterized by hot and humid summers and mild winters (National Data Center, Asheville, NC). Mean annual precipitation was 1240 mm, evenly distributed throughout a year (Columbus, GA, Airport weather station). In the last 10 years (1997–2006), March had the highest mean precipitation (135 mm) followed by June (119 mm) and July (114 mm), while October had the least precipitation (50 mm). The Department of Defense acquired Fort Benning in 1918, which is currently 72,800 ha. Prior to Fort Benning's establishment as a military installation, the landscape was heavily farmed, primarily for cotton, resulting in widespread erosion and depletion of organic matter in the soil (USAIC 2006).

Data collection and analysis

Stand selection

Our sampling design aimed to catch a wide range of spatial variation, stand age, and stand health condition. We first located all mature (>35 years old) LBP stands based on the stand map derived from Fort Benning's forest inventory, and then overlaid each LBP stand with 2003 aerial photographs (50 cm resolution) to inspect the species composition (e.g. hardwood cover) and size (minimum 40 m × 40 m) of the stands. Afterward, we visited each candidate stand to visually confirm whether the stands were dominated by LBP. Among the stands satisfying these criteria, we selected study plots systematically using the management compartments (land unit for army training purposes). When a compartment had more than two qualifying stands, we selected two stands representing the healthiest and unhealthiest condition through visual inspection (29 compartments). Among these compartments, four compartments (D17, E7, O7, and S3) had highly heterogeneous (e.g. age structure) LBP stands, so we selected one more LBP stand for each of these compartments. Twenty-eight compartments had only one suitable LBP stand. The selected LBP stands were secondary growth forests or plantations.

We installed one $30 \times 30\,m^2$ plot per selected stand (total of 90 plots; 36 in 2006 and 54 in 2007). Field survey and data collection were conducted over two growing seasons during July–September 2006 and June–August 2007, respectively.

Data collection

We measured the diameter at breast height (dbh; 1.3 m height) and recorded the species of each tree >5 cm dbh in each plot. For LBP trees, we also evaluated CVC, where the CVC was determined mainly by live crown ratio (%), crown dieback (% crown), and crown density (%; relative to the nearby highest crown density) following the USDA Forest Service Health Monitoring protocol (USDA Forest Service 1999). CVC assigns each tree a "grade" to describe canopy health (1 = good, 2 = fair, and 3 = poor) and was used as an indicator of tree health (CVC1 = live crown ratio >35%, crown dieback <5%, and crown density >80%; CVC3 = live crown ratio

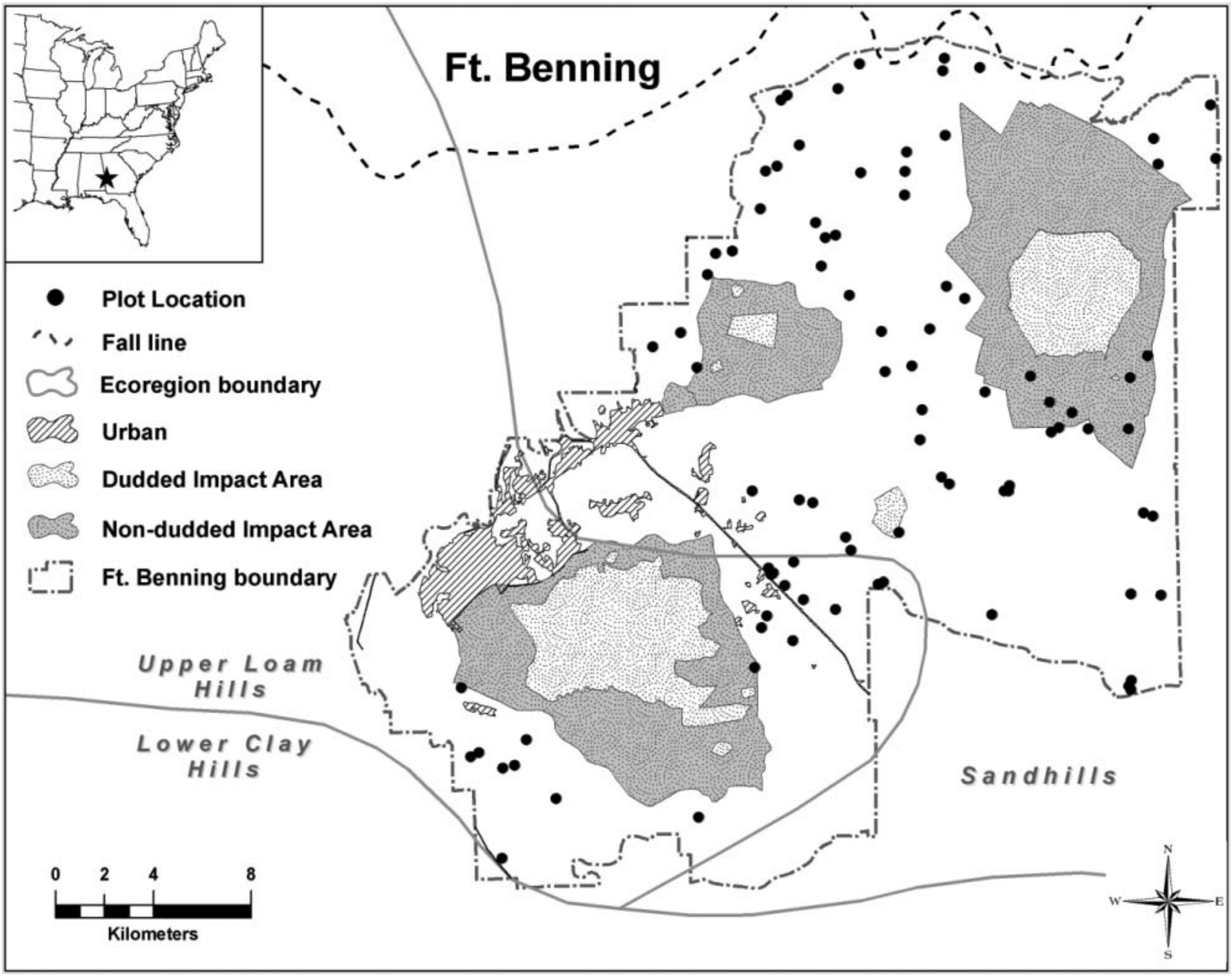

Figure 1. Geographic location of Fort Benning, GA (inset), and the locations of study plots (total 89 plots) in the base.

<35%, crown dieback >50%, and crown density <20%; and all other trees were classified as CVC2). We also measured crown light exposure (0 is the lowest light exposure and 5 is full exposure; a point is given to a quarter of crown exposed to direct sunlight and top of the tree exposed to direct sunlight) and crown position in the canopy (dominant/co-dominant and suppressed). Additionally, any visible symptoms of poor health or damage (e.g. fusiform rust, physical scar, stem canker, and excessive cone production) were also noted. The coordinates of each plot's center were recorded using a global positioning system, and slope and aspect of each plot were measured using a clinometer and compass.

With the exception of one plot, which was disturbed by logging, soil samples were collected for soil chemical analysis during the dormant season (February 2007 for 2006 plots and March 2008 for 2007 plots). We collected five samples (the plot center and the points midway between the center and each corner) per plot using a 2.5 cm diameter Oakfield soil corer (0–20 cm depth), and samples were composited for analysis. Soil samples were air-dried as soon as possible and later sent to Spectrum Analytic Inc. (Ohio, USA) to analyze soil pH (water), organic matter (%), exchangeable phosphorus (P), potassium, magnesium, and calcium (ppm; extracted by Mehlich-3), and cation exchange capacity (CEC) (cmol kg^{-1}). Soil texture of each plot was analyzed using the hydrometer method (Milford 1997) and classified following the USDA soil classification system.

Foliage samples were collected to evaluate the nitrogen (N) and P status of each plot. We randomly selected five super-dominant or dominant LBP trees per plot. Three samples from each tree were collected using a shotgun during the growing season before needles changed color to yellow. The three samples were taken from below the top quarter of a crown and above the top third of a crown and composited for each tree for further analysis. Fully grown current year needles were manually sampled. The foliage samples were immediately stored in a cooler after collection and frozen as soon as possible. Only fully grown needles were later manually sorted and dried for 48 hours between 65 and 70 °C. The foliar N and P were analyzed at the Clemson University Agricultural Service Laboratory (SC, USA). The sampling period was August for 2006 plots and July for 2007 plots. We sampled 20 plots in 2006 and 50 plots in 2007, but failed to sample the other 20 plots, because accessibility to the plots could not be gained before natural senescence occurred. We averaged the foliar N and P of trees in a plot to be related to other characteristics at plot level.

Using Fort Benning's forestry field survey data, stand age and site index (SI) were estimated, and previous management history including years since the last burn and thin, and number of burns since 1985 was determined. Moreover, stand density index (SDI) (Equation (1)) was calculated to standardize the tree competition (Reineke 1933), where TPH and DBHq stand for number of trees per hectare and quadratic mean diameter (cm), respectively.

$$SDI = TPH\left(\frac{DBHq}{25}\right)^{1.6}. \quad (1)$$

Statistical analysis

To quantify stand health, we calculated %CVC1 and %CVC3 as the percentage of LBP trees (both live and dead) classified as crown vigor class 1 and 3, respectively. High %CVC1 and high %CVC3 indicate healthy and poor LBP stand, respectively. We compared the plot characteristics of the healthiest (top 10%; nine plots of highest %CVC1) and the poorest (bottom 10%; nine plots of highest %CVC3) stands using *t*-test.

We conducted a Spearman correlation test among crown health metrics (%CVC1 and %CVC3) and stand characteristics (stand age (year), site index (m at age 50), slope (degree), stem density (SD; live stems only; number of stems ha^{-1}), basal area (BA; $m^2 ha^{-1}$), nutrient condition (soil pH, organic matter (%), exchangeable soil P, K, Mg, and Ca (ppm), CEC (cmol kg^{-1}), foliar N and foliar P), and management history (time since last thinning (years), time since burning (years), and number of burns since 1985)), because data did not satisfy normality assumptions. The Kruskal–Wallis test was employed to test the effects of soil texture on the %CVC1 and %CVC3 due to the non-normality data distributions. Effects of fusiform rust, stem canker, physical damage, and abundant cone presence on the CVC of individual trees were tested using Chi-square and Kendall's Tau-b due to their non-parametric data characteristics. We tested if there was an effect of CVC classes on dbh at individual tree level using ANOVA followed by post-hoc Tukey tests. We also compared the light exposure among different CVC trees using Kruskal–Wallis tests and evaluated the relationship between them using Kendall's Tau-b test. All statistical analyses were performed using SAS (SAS version 9.1, SAS institute, Inc., Cary, NC, USA) and significant differences were based on an alpha of 0.05 unless stated otherwise.

Results

Characteristics of studied plots

Selected plots covered a wide range of ages (38–98 years), SI (19.5–36.3 m at age 50), slope (0–10 degree), SDI (108.8–541.0), SD (55.6–577.8 stems ha^{-1}), LBP SD (55.6–566.7 stems ha^{-1}), and BA (8.1–28.4 $m^2 ha^{-1}$) (Table 1). The sampled stands were mostly mature (mean age of 62.1) with an open canopy (mean SD of 195.8 stems ha^{-1} and loblolly pine BA of 13.7 $m^2 ha^{-1}$) as result of RCW habitat management guidelines, which requires the BA of each stand to be between 9 and 14 $m^2 ha^{-1}$ (USDI Fish and Wildlife Service 2003). The study plots had been rigorously managed, burned every three years and thinned regularly with a mean of 8.5 years since last thinning. More than half of our plots (60 plots) had more than 50% of LBP trees classified in CVC1, 21 plots had LBP classified in CVC3, and only 11 and 3 plots had more than 10% and 20% VC3, respectively. Overall mean %Dead was 8.2% and mean %Dead of plots with CVC3 LBP presence was 8.9%, which was not significantly different. Mean %Dead of plots with >10% and >20% CVC3 were 7.9 and 4.5, respectively.

When we compared the top 10% stands and the bottom 10% stands, we found significant ($p < 0.10$) differences in

Table 1. Summary on the characteristics of loblolly pine study plots in Fort Benning, Georgia.

		Mean (SE)	Sample Size	Min	Max	Top 10%	Bottom 10%
Age (yr)		62.1 (1.7)	86	38.0	98.0	59.0 (5.0)	61.3 (6.0)
Site Index		26.5 (0.4)	86	19.5	36.3	28.0 (1.6)	24.8 (1.2)
Slope (degree)		3.4 (0.3)	89	0.0	10.0	2.6 (2.6)*	4.4 (0.8)*
SDI		280.6 (8.6)	90	108.8	541.0	262.1 (19.2)*	341.9 (38.4)*
SD		195.8 (10.9)	90	55.6	577.8	155.6 (14.4)*	248.1 (48.1)*
Basal Area		15.2 (0.5)	90	8.1	28.4	13.5 (0.9)	17.4 (1.9)
Time since last thinning (yr)		8.5 (0.8)	87	0.0	30.0	9.0 (3.0)	12.3 (3.9)
Time since last burn (yr)		1.1 (0.1)	87	0.0	3.0	0.9 (0.3)	0.9 (0.4)
Numbers of burns since 1985		6.7 (0.2)	87	2.0	12.0	6.7 (0.8)	7.4 (0.5)
	Live SD	153.4 (8.3)	89	55.6	566.7	128.4 (11.5)*	209.9 (39.4)*
Loblolly Pine	Live Basal Area	13.7 (0.4)	89	4.5	25.8	13.2 (0.9)	16.1 (1.7)
	%CVC1	54.1 (2.6)	89	0.0	100.0	91.7 (1.3)***	37.4 (8.0)***
	%CVC2	34.8 (2.4)	89	0.0	100.0	6.2 (1.7)***	36.0 (7.7)***
	%CVC3	2.9 (0.7)	89	0.0	31.0	0.0 (0.0)**	19.1 (2.4)**
	%Dead	8.2 (0.9)	89	0.0	33.3	2.1 (1.5)**	7.5 (1.9)**

SD indicates stem density (number of stems ha^{-1}). The unit of site index and basal area are m at age 50 and $m^2 ha^{-1}$, respectively. Data are presented as mean values (one standard error; SE). CVC indicates crown vigor class, where 1, 2, and 3 are healthy, intermediate, and poor, respectively, and percentages are calculated only among loblolly pine trees. *, **, and *** within a row indicate a significant difference ($p < 0.10$, 0.05, and 0.01, respectively) between healthier (top 10%) and poorer canopy condition (bottom 10%) stands.

slope, SDI, and SD (both total and loblolly trees) between the two groups (Table 1). The BA of the bottom 10% stands (17.4 $m^2 ha^{-1}$) slightly exceeded the RCW habitat guideline (Table 1). %CVC1 was significantly ($p < 0.01$) higher in the top 10% stands and %CVC2, %CVC3, and %Dead were significantly ($p < 0.05$) higher in the bottom 10% stands. The poorest stands had 63% higher SD than the healthiest stands, but BA was only 22% larger in the poorest stands, suggesting that loblolly pines had smaller dbh in the bottom 10% than the top 10% stands.

Soil pH ranged between 4.4 and 5.8 (Figure 2b). Mean organic matter content was 1.0% (median 0.9%) with

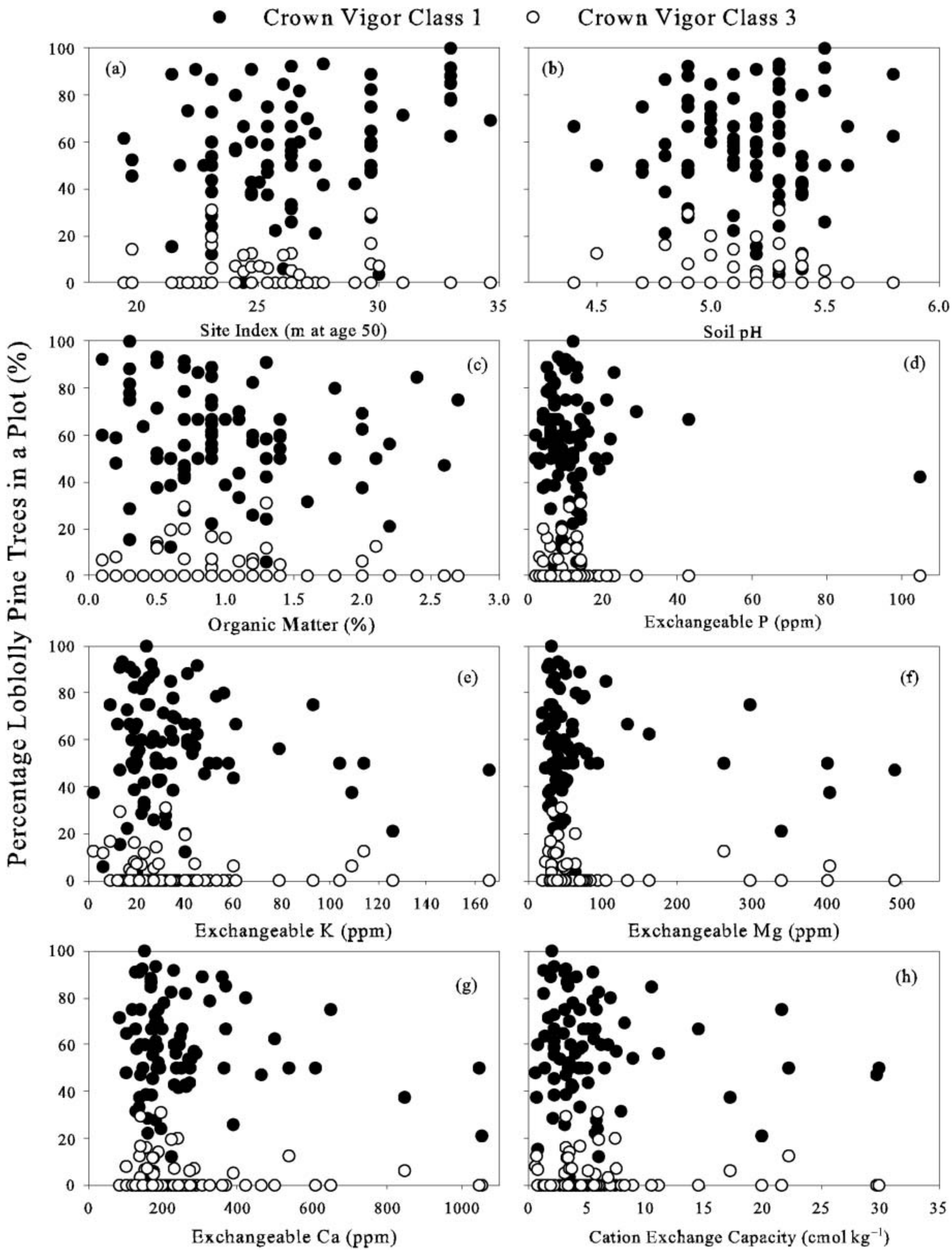

Figure 2. The relationship between loblolly pine trees classified as Crown Vigor Class 1 (%; closed circle) and Crown Vigor Class 3 (%; empty circle) with (a) site index, (b) soil pH, (c) organic matter, (d) exchangeable phosphorus (*P*), (e) exchangeable potassium (K), (f) exchangeable magnesium (Mg), (g) exchangeable calcium (Ca), and (h) cation exchange capacity.

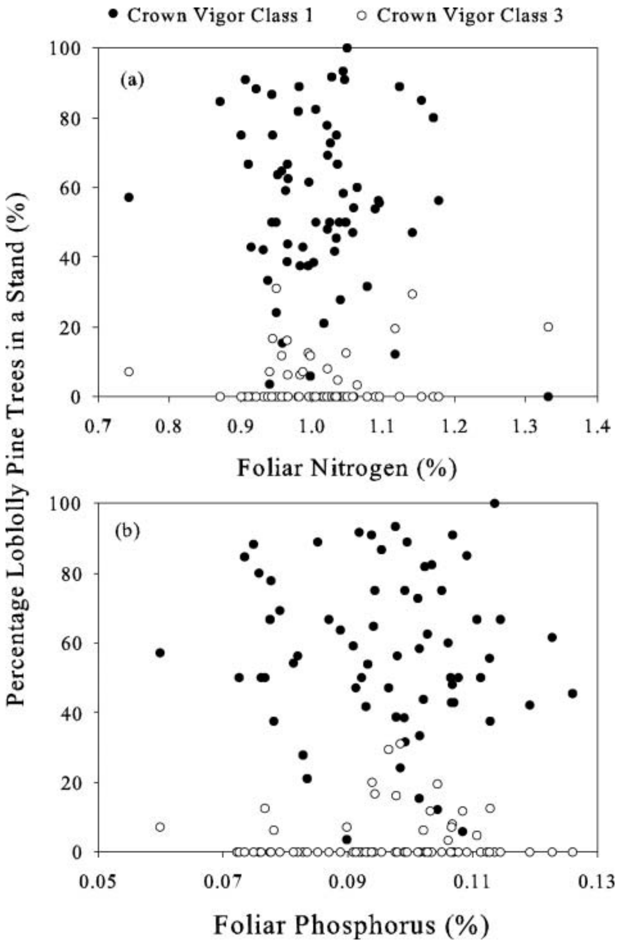

Figure 3. The relationship between loblolly pine trees classified as Crown Vigor Class 1 (%; closed circle) and Crown Vigor Class 3 (%; empty circle) with (a) foliar nitrogen and (b) foliar phosphorus concentration.

standard deviation of 0.6%; ranging between 0.1% and 2.7% (Figure 2c). Mean (standard deviation) values of exchangeable P, K, Mg, and Ca were 11.5 (±11.7), 35.7 (±26.9), 67.8 (±85.9), and 250.2 (±174.7) ppm, respectively (Figure 2defg). Mean CEC was 5.4 cmol kg^{-1}; median and standard deviation were 3.7 and 5.6 cmol kg^{-1}, respectively (Figure 2h). Among 89 plots, 32, 42, 11, 3, and 1 plots were classified as sand, loamy sand, sandy loam, sandy clay loam, and clay loam, respectively. Mean foliar N content was 1.01% with standard deviation of 0.08% (Figure 3a). Foliar N content ranged between 0.74% and 1.33% (Figure 3a). Mean foliar P content was 0.10% with standard deviation of 0.01% (Figure 3b). Foliar P content ranged between 0.06% and 0.13% (Figure 3b).

Factors related to crown health

Slope showed no significant relationship (Figure 4c) with either %CVC1 ($r = -0.04$, $p = 0.74$) or %CVC3 ($r = 0.13$, $p = 0.21$). The highest %CVC3 was observed at slope 8 degree, but it was not significantly different from %CVC3 at other slopes (Figure 4c). Moreover, we did not observe any noticeable influence of aspect on %CVC1 and %CVC3 (Figure 4a, b). As expected, %CVC1 was negatively and significantly ($r = -0.39$, $p < 0.001$) correlated with %CVC3.

SI correlated positively and significantly (Figure 2a) with %CVC1 ($r = 0.22$, $p = 0.04$) and negatively with %CVC3 ($r = -0.19$, $p = 0.07$). We did not find any significant correlation between crown health condition metrics (%CVC1 and %CVC3) and foliar and soil nutrient condition (Figures 2 and 3). Soil texture did not have any significant effect on %CVC1 and %CVC3 (Figure 5). However, %CVC3 tended to decrease as soil texture became finer; mean %CVC3 was 4.0%, 2.6%, 1.7%, 0.0%, and 0.0% for sand, loamy sand, sandy loam, sandy clay loam, and clay loam (Figure 5b).

We found a significant negative relationship between %CVC1 and time since the last thinning ($r = -0.25$, $p = 0.02$; Figure 6a), but time since last thinning showed no relationship with %CVC3. Neither of the burn measures (time since last burn and number of burns since 1985) showed significant relationships with %CVC1 and %CVC3 (Figure 6bc). We did not observe any pattern of %Dead associated with burning activity. Mean %Dead values were 8.6%, 7.4%, 9.7%, and 7.0% for 0, 1, 2, and 3 years since last burn, respectively, and 0.0%, 10.5%, 0.0%, 7.8%, 9.6%, 7.6%, 8.4%, 2.4%, 8.3%, 12.5%, and 0.0% for 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12 number of burns since 1985, respectively.

Soil texture of the bottom 10% stands was sand (44.4%), loamy sand (44.4), and sandy loam (11.2%), while sand, loamy sand, and sandy loam composed 36.0%, 47.2%, and 12.4%, respectively, of total plots (89 plots). The bottom 10% experienced the last thinning 2–30 years before and no trend was observed. Moreover, the bottom 10% experienced prescribed burning 6–10 times since 1985 with mean of 7.3 times, which was not significantly different from the overall mean, 6.7 times.

Individual tree condition

We surveyed 1246 LBP trees and observed 210 and 38 trees with fusiform rust and stem canker, respectively, while 37 trees suffered with both symptoms. Fusiform rust presence did not have significance effect on CVC class (chi-square $p = 0.63$, Kendall's Tau-b $= 0.02$ and $p = 0.44$). However, stem canker presence showed significant effect on CVC class (chi-square $p = 0.05$, Kendall's Tau-b $= 0.07$ and $p = 0.02$); 36.1%, 58.35, and 5.6% trees fell in CVC1, 2, and 3, respectively, compared to 56.25, 39.85, and 4.0% without stem canker, respectively. We also observed that 226 LBP trees were physically damaged (e.g. by fire and logging), but did not find significant effect on CVC (chi-square $p = 0.23$, Kendall's Tau-b $= -0.04$ and $p = 0.10$). There were 139 LBP trees with very abundant cones (2, 130, and 7 trees were super-dominant, dominant/co-dominant, and intermediate/overtopped trees), but the presence of many cones did not show significant effect on CVC (chi-square $p = 0.53$, Kendall's Tau-b $= -0.03$ and $p = 0.28$). There was a significant difference in dbh between CVCs ($p < 0.01$), with mean dbh

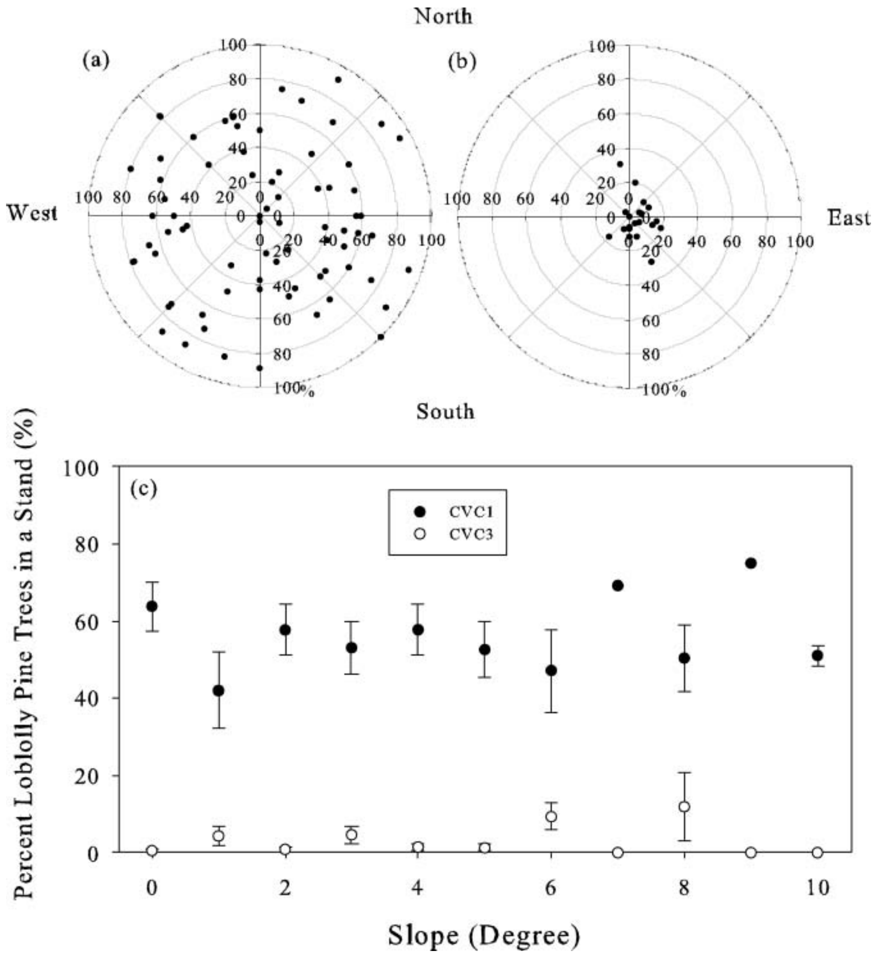

Figure 4. The loblolly pine trees classified as (a) Crown Vigor Class1 (%; CVC1) and (b) Crown Vigor Class3 (%; CVC3) distributions by plot aspect and (c) CVC1 and CVC3 distribution by slope. The dot and error bar indicate mean value and one standard error, respectively.

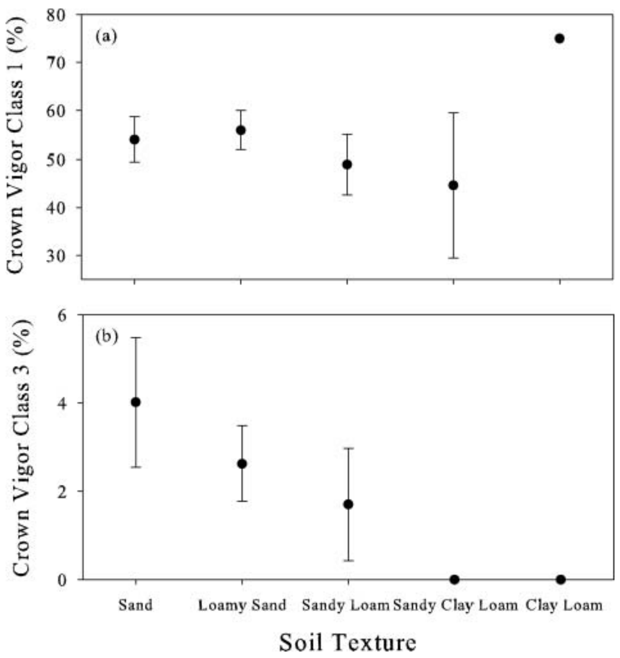

Figure 5. The distribution of loblolly pine trees classified as Crown Vigor Class1 (%) and Crown Vigor Class3 (%) by soil texture classes. The dot and error bar indicate mean value and one standard error.

of 35.3, 27.6, and 16.1 cm for CVC1, CVC2, and CVC3 (Figure 7a), respectively. We also found that healthier LBP trees were exposed to more light (Figure 7b; $p < 0.01$; Kendall's Tau-b = 0.11 and $p < 0.01$).

Discussion

SI was the only variable showing a significant relationship with %CVC1 and %CVC3 (Figure 2a), which indicated that tree health was limited by poor growth condition (e.g. nutrients and water). Generally, LBP demands more nutrients and water than other pine species (Baker and Langdon 1990); therefore nutrient and/or water deficiency could have stronger effects on LBP health than on other pine species. Our results showed a clear trend of higher unhealthy LBP (%CVC3) associated with coarser soil texture (Figure 5), as coarse soil texture has a small soil surface area and low electrical charges, resulting in low nutrient and water-holding capacity. However, we did not observe any significant influence of soil and foliar nutrient on crown health metrics (%CVC1 and %CVC3) in this study (Figures 2 and 3), which suggested that water stress could be the main causal factor determining LBP crown health. Although we did not find an impact of slope and

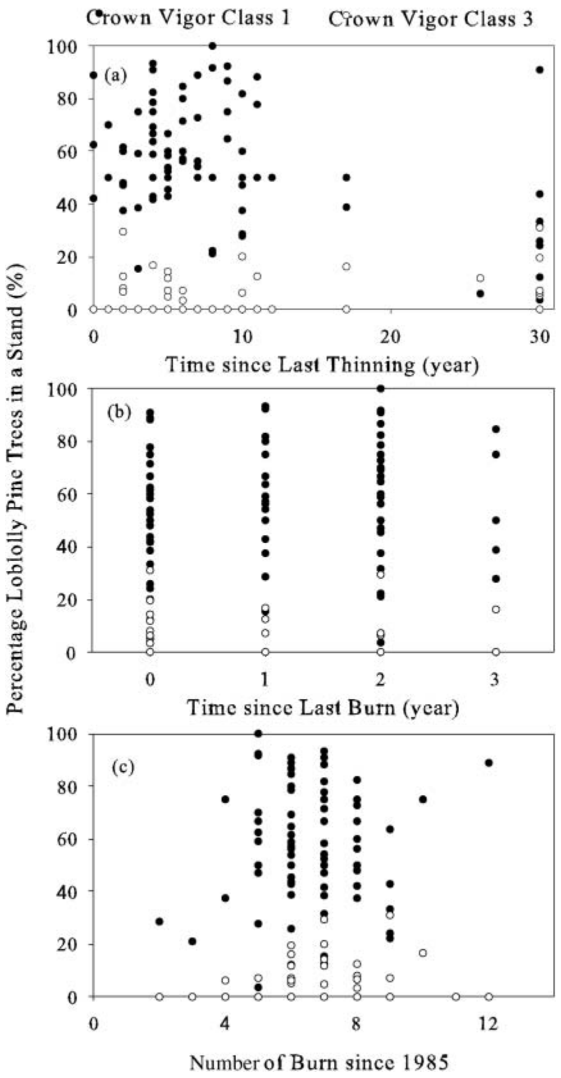

Figure 6. The relationship between loblolly pine trees classified as Crown Vigor Class 1 (%; closed circle) and Crown Vigor Class 3 (%; empty circle) with (a) time since last thinning, (b) time since last burn, and (c) numbers of burn since 1985.

aspect on LBP health, a study in central Alabama reported that higher slope and southern aspect increased LBP decline (Eckhardt and Menard 2008). Theoretically, greater slopes tend to increase lateral water flow and soil erosion, resulting in decreased soil water-holding capacity (Miller and Donahue 1995), and, similarly, south-facing stands receive more direct sunlight than other aspects, resulting in increased soil temperatures, greater evaporation, and reduced water availability. It was possible that the observed effects of slope and aspect implied the water stress, but it did not appear in this study because water stress already existed regardless of slope and aspect. Furthermore, prescribed burning has been implemented in Fort Benning since the 1980s, and the area of treatment for RCW habitat management has increased at the rate of 12,000 ha per year on an approximately three-year rotation (USAIC 2006). Although fire can be an effective management tool (e.g. for reducing understory hardwood), it is also known to reduce nutrient availability (Raison et al. 1985; Landsberg 1993) and water availability (Boyer and Miller 1994; Busse et al. 2000; DeBano 2000). In addition, prescribed burns under some circumstances can attract root beetles (e.g. *Hylastes* spp.) that carry pathogenic fungi (Sullivan et al. 2003), which have been associated with thinning and discolored pine crowns (Otrosina et al. 1999). Stem canker results also support the impact of water stress on tree health. Stem canker presence was found to significantly worsen crown health, and according to the study by MacFall et al. (1994) stem canker caused by fusiform rust reduces water flow in the xylem leading to water stress. Klos et al. (2009) also showed a decrease in pine growth with increasing drought severity.

Availability of base cations can decrease under high temperature and reduced precipitation condition (Tomlinson 1993). Severe drought in 1998–2001 could have caused nutrient stress to LBP forest as well (Figure 8); however, we did not find evidence of nutrient stress

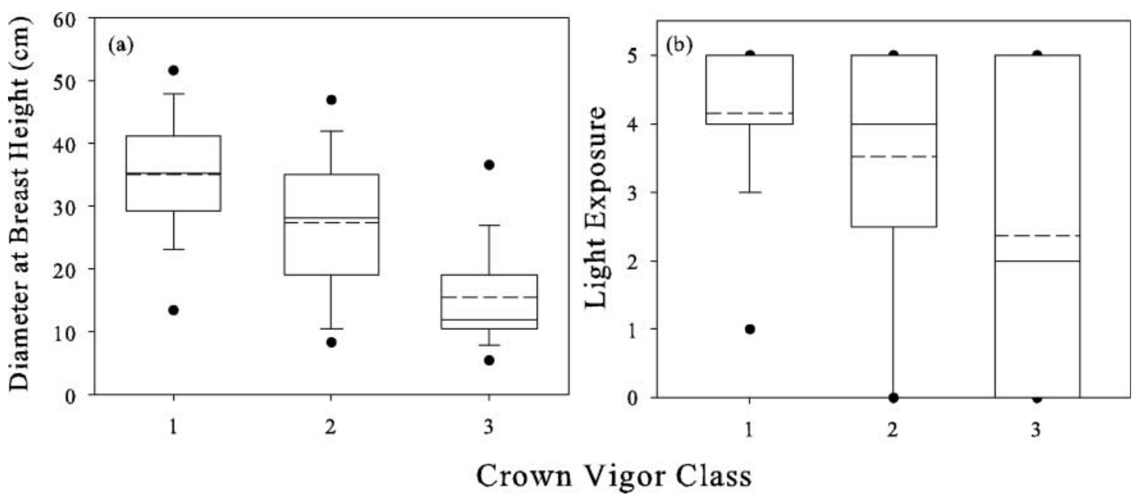

Figure 7. Box-whisker plot showing the range of (a) diameter at breast height and (b) light exposure (higher means more light exposure; range 0–5) of loblolly pine trees by crown vigor class. Solid bars of box-whisker plot represent 5%, 2%, 50%, 7%, and 95% values, and dashed bar is a mean.

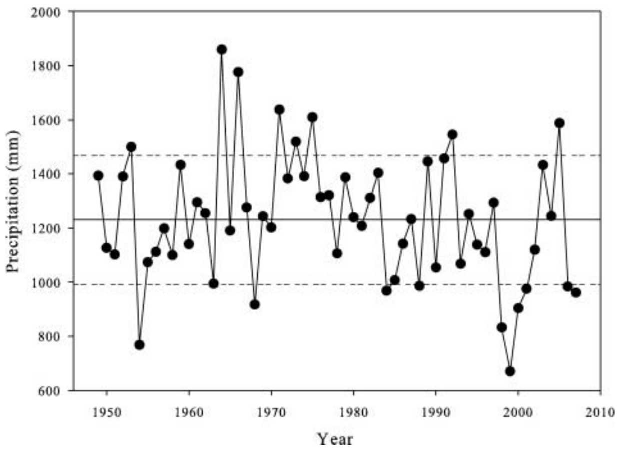

Figure 8. Historical (1949–2007) precipitation (mm) pattern of the region (data from Columbus airport approximately 10 km from the study landscape). The solid line indicates the mean annual precipitation throughout the period and dashed lines show one standard deviation from the mean value.

affecting LBP health. A possible explanation is that the LBP forest within our study area experienced nutrient stress during the drought period (1998–2001), but the stress was subsequently mitigated during favorable moisture conditions in 2002–2005. We observed that smaller trees tended to show poorer crown health (Figure 7), which could be due to mainly water and/or nutrient stress because it is harder for small trees to compete for nutrients and water (e.g. Binkley et al. 2002). The studied LBP stands were open, and light was not generally a limiting factor (e.g. 2–3 suppressed trees per 100 m^2).

We found only 4.0% of LBP in CVC3. Cao (1994) reported that annual LBP mortality could exceed 3% in thinned plots around age 30 in Louisiana. It was clear that LBP in our study plots were not experiencing major die-back of LBP stands. However, our results indicated that LBP stands in this area can have abnormally high LBP mortality under high-stress weather, which will likely happen considering that Fort Benning experienced severe drought during four consecutive years (1998–2001) (Figure 8) and we expect more abnormal weather under global climate change. Land managers may consider reducing the prescribed burn frequency or amending the soil physical property to decrease water stress. Furthermore, based on these results, conversion to longleaf pine should start from LBP stands on coarser soil (or lower SI) at Fort Benning.

Conclusions

Our results show that site index was the main factor in determining LBP health. Poorer site index and coarser soil likely resulted in water stress during periods of drought leading to higher %CVC3 LBP. Based on these results, conversion to longleaf pine should start from LBP stands on coarser soil (or lower SI) at Fort Benning. This approach will retain healthy and mature LBP stands for the RCW population to nest and forage, until longleaf pine stands become mature and large enough to support the RCW population. Additional studies are needed to understand how LBP CVC classes can be related to the annual mortality rate. It will help us understand the LBP mortality dynamics in the study area and develop better loblolly pine management guidance.

Acknowledgements

The study was supported by the Strategic Environmental Research and Development Program (SI-1474) and University of Alberta. We appreciate the help of Shawna Reid, Benjamin Knapp, Bryan Mudder, Robert N. Addington, Catherine Prior, Hunter Leary, Drew Pressley, and the Nature Conservancy on field survey and laboratory work. We especially thank Benjamin Knapp for constructive comments and editorial help in preparing this manuscript.

References

Anderson RL, Belanger RP. 1987. A crown rating method for assessing tree vigor of loblolly and shortleaf pines. Paper presented at: Biennial Southern Silvicultural Research Conference. Proceedings of the 4th Biennial Southern Silvicultural Research Conference; Atlanta, US.

Baker JB, Langdon OG. 1990. Silvics of North America: 1. Conifers. Loblolly pine (*Pinus taeda* L.). Washington: USDA Forest Service; p. 497–512.

Bechtold WA, Ruark GA, Lloyd FT. 1991. Changing stand structure and regional growth reductions in Georgia's natural pine stands. For Sci. 37(2):703–717.

Binkley D, Stape JL, Ryan MG, Barnard HR, Fownes J. 2002. Age-related decline in forest ecosystem growth: An individual-tree, stand-structure hypothesis. Ecosystems 5:58–67.

Boyer WD, Miller JH. 1994. Effect of burning and brush treatment on nutrient and soil physical properties in young longleaf pine stands. For Ecol Manage. 70:311–318.

Burkhart HE, Farrar KD, Amateis RL, Daniels RF. 2001. Simulation of individual tree growth and stand development in loblolly pine plantations on cutover, site-prepared areas. Blacksburg (Virginia): Virginia Tech. Publication No. FWS-1–87.

Busse MD, Simon SA, Riegel GM. 2000. Tree-growth and understory responses to low-severity prescribed burning in thinned *Pinus ponderosa* forest of central Oregon. For Sci. 46:258–268.

Cao Q. 1994. A tree survival equation and diameter growth model for loblolly pine based on the self-thinning rule. J Appl Ecol. 31:693–698.

Das A, Battles J, Van Mantgem PJ, Stephenson NL. 2008. Spatial elements of mortality risk in old-growth forests. Ecology 89(6):1744–1756.

DeBano LF. 2000. The role of fire and soil heating on water repellence in wildland environments: a review. J Hydrol. 231/232:195–206.

Dobbertin M. 2005. Tree growth as indicator of tree vitality and of tree reaction to environmental stress: a review. Eur J For Sci. 124:319–333.

Eckhardt LG, Menard RD. 2008. Topographic features associated with loblolly pine decline in central Alabama. For Ecol Manage. 255:1735–1739.

Eckhardt LG, Weber AM, Menard RD, Jones JP, and Hess NJ. 2007. Insect-fungal complex associated with loblolly pine decline in central Alabama. For Sci. 53: 84–92.

Eichhorn J, Szepesi A, Ferretti M, Durrant D, Roskams P. 2004. Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests. Hamburg: Federal Research Centre for

Forestry and Forest Products. Part II, Visual Assessment of Crown Condition.

Hess NJ, Otrosina WJ, Jones JP, Goddard AJ, Walkinshaw CH. 1999. Reassessment of loblolly pine decline on the Oakmulgee District, Talladega National Forest, Alabama. General Technical Report SRS-GTR-50. USDA Forest Service.

Klos RJ, Wang GG, Bauerle WL, Rieck JR. 2009. Drought impact on forest growth and mortality in the southeast USA: an analysis using Forest Health and Monitoring data. Ecol Appl. 19(3):699–708.

Kozlov MV, Niemela P. 1999. Difference in needle length - A new and objective indicator of pollution impact on Scots pine (*Pinus sylvestris*). Water Air Soil Poll. 116:365–370.

Kramer K. 1996. Phenology and growth of European trees in relation to climate change [Ph.D. dissertation]. Wageningen: Wageningen Agricultural University.

Landsberg JD. 1993. A review of prescribed fire and tree growth response in the genus Pinus. Paper presented at: International Conference on Fire and Forest Meteorology. Proceedings of the 12th Conference on Fire and Forest Meteorology; Georgia, USA.

MacFall JS, Spaine R, Doudrick R. Johnson GA. 1994. Alterations in growth and water-transport processes in fusiform rust galls of pine, determined by magnetic resonance microscopy. Phytopathology 84:288–293.

Manion PD. 1991. Tree Disease Concepts. Englewood Cliffs (NJ): Prentice Hall.

McNabb WH, Avers PE (compilers). 1994. Ecological subregions of the United States: section descriptions. WO-WSA-5. USDA Forest Service.

Milford MH. 1997. Introduction to Soils and Soil Science Laboratory Exercises. Dubuque (Iowa): Kendall/Hunt Publishing Company.

Miller RW, Donahue RL. 1995. Soils; In our environment. 7th ed. Englewood Cliffs (NJ): Prentice Hall.

Otrosina WJ, Bannwart D, Roncadori RW. 1999. Root-infecting fungi associated with a decline of longleaf pine in the southeastern United States. Plant Soil. 217:145–150.

Pederson BS. 1998. The role of stress in the mortality of Midwestern oaks as indicated by growth prior to death. Ecology 79(1):79–93.

Raison RJ, Khanna PK, Woods PV. 1985. Transfer of elements to the atmosphere during low-intensity prescribed fires in three Australian subalpine eucalypt forests. Can J For Res. 15:657–664.

Reineke LH. 1933. Perfecting a stand-density index for even-aged stands. J Agric Res. 46:627–638.

Roloff A. 1987. Morphology of crown development of *Fagus sylvatica* L. (beech) in consideration of new modifications. 1. Morphogenetic cycle, abnormalities specific to proleptic shoots and leaf fall. Flora 179:355–378.

Ruark GA, Thomas CE, Bechtold WA, May DM. 1991. Growth reductions in naturally regenerated southern pine stands in Alabama and Georgia. Southern J Appl For. 15(2):73–79.

Ryu SR, Chen J, Zheng D. Bresee MK, Crow TR. 2006. Simulating the effects of prescribed burning on fuel loading and timber production (EcoFL) in managed northern Wisconsin forests. Ecol Modell. 196:395–406.

Schultz RP. 1997. Loblolly pine: the ecology and culture of loblolly pine (*Pinus taeda* L.). Agriculture handbook 713. Washington, DC: USDA; p. 1–16.

Sheffield RM, Cost ND. 1987. Behind the decline. J For. 85:29–33.

Sheffield RM, Cost ND, Bechtold WA, McClure JP. 1985. Pine Growth reduction s in the Southeast. USDA. USDA For Ser Res Bull. SE-83.

Stefan K, Fürst A, Hacker R, Bartels U. 1997. Forest Foliar Condition in Europe. Results of the large-scale foliar chemistry surveys (survey 1995 and data from previous years). Vienna/Brussels/Geneva: Austrian Federal Forest Research Centre.

Sullivan BT, Fettig CJ, Otrosina WJ, Dalusky MJ, Berisford CW. 2003. Association between severity of prescribed burns and subsequent activity of conifer-infesting beetles in stands of longleaf pine. For Ecol Manage. 185(3):327–340.

Tomlinson GH. 1993. A possible mechanism relating increased soil temperature to forest decline. Water Air Soil Pollut. 66:365–380.

US Army Infantry Center (USAIC). 2006. Integrated Natural Resources Management Plan, Fort Benning Army Installation, Incremental Revision 2006. Fort Benning (GA): Directorate of Public Works, Environmental Division.

USDA Forest Service. 1999. Forest Health Monitoring 1998 field method's guide. Research Triangle Park (NC): National Forest Health Monitoring Program, USDA Forest Service.

USDI Fish and Wildlife Service. 2003. Recovery Plan for the Red-cockaded Woodpecker (*Picoides borealis*). 2nd revision. Atlanta (GA): US Fish and Wildlife Service; p. 296.

Zeide B. 1992. Has pine growth declined in the southeastern United States? Conserv Biol. 6(2):185–195.