SURFACE SOIL ROOT DISTRIBUTION AND POSSIBLE INTERACTION WITH SITE FACTORS IN A YOUNG LONGLEAF PINE STAND

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Abstract—Interaction between soil bulk density and low soil water content may create root growth-limiting soil strengths. In a Louisiana longleaf pine (*Pinus palustris* Mill.) stand, soil strength at the zero- to 20.0-cm depth was assessed in response to no fire or biennial fires in May. At the 5.0- to 20.0-cm depth, one-half of the measurements were characterized by root growth-limiting soil strengths regardless of fire history. Where soil strengths were root growth limiting, pine fine root biomass was about 24 percent lower than where soil strengths were not root growth limiting. Correlation between soil strength and pine fine root biomass was only observed where samples were collected distal to the longleaf pine trees, where soil strengths were high, and where biennial fire was applied. Further research is needed to determine whether repeated fire interacts with the relationship between soil strength and longleaf pine root growth on the west Gulf Coastal Plain.

INTRODUCTION

Soils in the western range of longleaf pine (*Pinus palustris* Mill.) are frequently characterized as poorly drained and fine textured (Peet 2006). High bulk densities are likely when soil texture is dominated by silt and clay (Fisher and Binkley 2000). Recently on the Kisatchie National Forest in central Louisiana, bulk densities of typical silt loam soils averaged 1.4, 1.5 to 1.6, and 1.6 to 1.7 g/cm^3 for the A, B1, and B2 horizons, respectively (Patterson and others 2004, Sword Sayer 2007). Bulk densities >1.6 g/cm^3 are known to restrict pine root elongation (Kelting and others 1999, Pritchett 1979). These root growth-limiting bulk densities are countered by root elongation along interped spaces and in macropores created by old roots and soil fauna (Van Lear and others 2000). Fortunately, these attributes also introduce spatial variation into bulk density measurements so that extreme values are not constant over large areas.

During periods of sparse precipitation, low soil water content (SWC) interacts with bulk density to increase soil strength. Soil strength is the force required to advance through soil (Bennie 1996), and values >2000 kilopascals (kPa) are known to inhibit root elongation (da Silva and others 1994, Taylor and others 1966). When low precipitation evolves into drought, the negative effects of soil properties on pine root elongation are potentially far reaching on the west Gulf Coastal Plain. In effect, the land base with root-restricting soil characteristics is widened to include not only areas with high bulk densities but also areas that develop root growth-limiting soil strengths as the soil dries. Once again, in this situation, conduits produced by interped spaces, old root channels, and soil fauna allow root foraging for water and mineral nutrients.

Efforts to restore longleaf pine ecosystems have been successful, in part, by the renewed use of fire as a management tool (Brockway and Lewis 1997). In some situations, repeated prescribed fire reduces understory woody vegetation but increases the growth of herbaceous plants and grasses (Haywood and others 2001). It is hypothesized that by manipulating understory vegetation, repeated fire also changes the amount and distribution of soil macropores that serve as conduits for pine root elongation. This, in turn, could affect soil strength, its spatial variability, and the relationship between soil strength and pine root elongation. As an initial step toward understanding the relationship between soil strength and longleaf pine root growth, the present study was conducted to survey soil strength, longleaf pine fine root biomass (FRB), and their relationship where competing vegetation was not controlled and where biennial prescribed fire was applied in May.

MATERIALS AND MEHODS

Study Site

The study is located on the Kisatchie National Forest in central Louisiana at latitude 31°0'42.45" N, longitude 92°37'8.54" W. The soil is a Beauregard silt loam and Malbis fine sandy loam complex. A mixed pine-hardwood forest originally occupying the site was clearcut harvested in the mid-1980s, repeatedly burned, sheared and windrowed in 1991, and rotary-mowed in 1992 (Haywood 2002).

In 1992, 15 treatment plots [22 by 22 m (0.048 ha)] were established and assigned 1 of 3 vegetation management treatments (no plant control, herbicide application, or mulching after planting) (Haywood 2002). In February 1993 and January 1994, one-half of each plot was planted at 1.8 by 1.8 m with container-grown longleaf pine seedlings from a Mississippi source. By age 3 to 4 years, seedlings were overtopped by competing vegetation in spite of the vegetation management treatments (Haywood 2002). Competing vegetation was manually and chemically eradicated in 1997 and 1998, respectively.

In 1998, analyses of variance indicated that tree growth was significantly affected by vegetation management treatment but not by block, age, or their interaction with vegetation management treatment (Haywood 2002). The study was subsequently reconfigured with each of the original vegetation management treatments as one of three blocks, and random assignment of one of five treatments to each plot per block.

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The new study utilized a randomized complete block design with three blocks. Blocks were delineated by the former vegetation management treatments. New treatments were one of five management activities: (1) control (C)—no vegetation management after 1998, (2) herbicide—biennial application as needed beginning in 1999 at age 5 to 6 years of triclopyr herbicide to competing woody vegetation as a direct foliar spray in May, (3) prescribed fire in March—biennial burning in March, (4) prescribed fire in May (MB)—biennial burning in May, and (5) prescribed fire in July—biennial burning in July. Fires were applied as strip headfires in 1999, 2001, 2003, and 2005.

Before application of the prescribed fire scheduled for March 2007 and at age 13 to 14 years, a wildfire burned the entire study area on March 22, 2007. Based on a postfire survey, the fire burned intensely over the entire study area consuming nearly all living foliage and small woody stems within 1 m of the ground, and longleaf pine crown scorch was over 50 percent.[2] In each of the C and MB plots, 4 subplots were delineated, i.e., 2 treatments, 3 blocks, and 4 subplots per plot for a total of 24 subplots. Subplots contained four adjacent trees in two interior rows of two trees each, so that the dimension of the subplots was 1.8 by 1.8 m. Subplots contained four live trees with some live, unscorched crown, and avoided areas where the majority of the trees were missing or where stump holes and animal burrows were found.

Root Measurements

Root distribution was evaluated with 12 soil cores that were nearby, i.e., proximal, and 12 soil cores that were distant from, i.e., distal, the 4 corner trees of each subplot. The six proximal soil cores were collected from around the two trees in each subplot having the most similar diameters at breast height. Proximal core locations were equidistant around the circumference, and 30 to 45 cm from the base of each of these two trees. On the interior of each subplot, distal soil cores were collected at 12 locations >45 cm from the base of the 4 corner trees. All soil coring for root biomass was done in November 2007.

Proximal and distal soil cores were 20 cm deep and were extracted with a tractor-mounted hydraulic probe (5.1 cm diameter). Cores were partitioned into six depth intervals—i.e., zero to 2.5 cm, 2.5 to 5.0 cm, 5.0 to 7.5 cm, 7.5 to 10.0 cm, 10.0 to 15.0 cm, and 15.0 to 20.0 cm—in the field with a box cutter knife. Soil samples in each subplot were pooled by proximity, i.e., proximal and distal samples, and depth so that 48 soil samples were collected per plot.

Root biomass was removed from soil samples by wet sieving (1 mm^2 mesh). Pine roots were distinguished from nonpine roots based on diameter, color, plasticity, and the appearance of lateral roots and ectomycorrhizae. Using digital calipers, fine plus small pine roots, zero ≤2 mm in diameter, i.e., fine roots, were separated from root samples, ovendried to equilibrium at 70 °C, ground in a Wiley mill (1 mm^2 mesh), and combusted (450 °C, 8 hours) to obtain ash-free dry weights. Fine pine root biomass was expressed as mg/cm^3.

Soil Strength Measurements

Pairs of soil strength and SWC measurements were taken six times in June through September 2008. Soil strength was measured with a CP40II cone penetrometer equipped with a 130-mm^2 tip (Agridry Rimik Pty Ltd., Queensland, Australia). At each of the six measurement times, a soil strength profile was generated at one location around the circumference of each of the two measurement trees per subplot. Soil strength profiles were the average of five inserts within a 20-cm radius, 25 to 30 cm from the base of the stem, and at least 20 cm away from where soil cores were extracted for root samples. The soil strength data for each insert was recorded at 1-cm intervals to a 20-cm depth, and averaged by depth interval and measurement tree. For each measurement tree and time, the soil strength of each of the six depths where roots were sampled was calculated as the average of the appropriate 1-cm interval data—i.e., zero to 2.5 cm: depth intervals 1, 2, and 3 cm; 2.5 to 5.0 cm: depth intervals 3, 4, and 5 cm; 5.0 to 7.5 cm: depth intervals 6, 7, and 8 cm; 7.5 to 10.0 cm: depth intervals 8, 9, and 10 cm; 10.0 to 15.0 cm: depth intervals 11, 12, 13, 14, and 15 cm; 15.0 to 20.0 cm: depth intervals 16, 17, 18, 19, and 20 cm.

Air pockets, plinthite, charcoal, and abrupt changes in resistance caused by semi-impenetrable soil layers led to outliers in the raw data which were eliminated in three ways. First, for each set of raw soil strength data, "0" values were changed to missing data. Second, for each set of raw soil strength data per 1-cm interval and measurement time, i.e., 240 observations, data outside two standard deviations of the mean were changed to missing data. Third, for each of the six soil layers and measurement times, mean soil strength outside two standard deviations of the mean was changed to missing data. These three actions deleted approximately 4 percent of the raw soil strength data that was paired with SWC data.

At each measurement interval, one soil core (25 cm long, 6.5 cm diameter) was extracted from the 20-cm radius where five soil strength inserts were performed. This was done manually with a metal coring device (Veihmeyer 1929). Cores were partitioned into six depth increments using a box cutter knife, i.e., zero to 2.5, 2.5 to 5.0, 5.0 to 7.5, 7.5 to 10.0, 10.0 to 15.0, 15.0 to 20.0 cm. Mineral soil from each depth increment was put into preweighed tins. Capped tins containing wet soil were weighed, uncapped and dried at 105 °C for 24 hours, and reweighed. Gravimetric SWC was calculated which represented SWC when soil strength measurements were taken. Again, artifacts, e.g., large decomposing roots and old root channels, caused outliers in the SWC data. Data quality was refined by excluding data outside two standard deviations

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of the mean for each depth and measurement time. This action affected approximately 5 percent of the raw SWC data.

With the refined soil strength and SWC data, a linear regression equation describing the relationship between soil strength and SWC was developed for the 6 depths in each of the 24 subplots. Each equation was based on 6 data points from each of the 2 measurement trees per subplot, i.e., 12 observations. For regression equations with coefficients of determination, i.e., R^2, that were significant at the alpha-level of 0.05, the soil strength at 16 percent SWC, i.e., SS_{16}, was predicted. The 95-percent prediction interval for SS_{16} was determined, i.e., SS_{16} PI (Neter and Wasserman 1974), and SS_{16} PI were scaled by equation 1 so that the variation associated with SS_{16} could be compared across the range of predicted SS_{16} values.

$$SS_{16}\ PI_{scaled} = (SS_{16}\ PI/2)/SS_{16} \qquad (1)$$

Statistical Analyses

The soil strength profile of each subplot was visually assessed, and subplots were partitioned into two groups: those with the majority of SS_{16} ≤2000 kPa, i.e., low SS_{16} subplots, and those with the majority of SS_{16} >2000 kPa, i.e., high SS_{16} subplots. For the low and high SS_{16} subplots and C and MB treatments, the mean and standard deviation of SS_{16}, SS_{16} PI_{scaled}, and proximal and distal FRB were calculated for each of the six depth intervals.

Because all SS_{16} values at the 2.5- to 5.0-cm depth and 20 percent of the SS_{16} values at the 15.0- to 20.0-cm depth were <2000 kPa on the high SS_{16} subplots, regressions between SS_{16} and FRB excluded data from the 2.5- to 5.0- and 15.0- to 20.0-cm depths. Simple linear relationships between SS_{16} and either distal or proximal FRB at the 5.0- to 15.0-cm depth were evaluated by ordinary least squares regression for the low and high SS_{16} subplots on the C and MB plots. Residuals were assessed for normality by the Shapiro-Wilk statistic (SAS Institute Inc. 2000), and as a result, FRB was transformed to natural logarithm values to insure that residuals were normally distributed. The F statistics associated with R^2 values were considered significant at an alpha-level of 0.05.

RESULTS

Evaluation of relationships between soil strength and FRB was done using SS_{16} that was predicted with equations exhibiting a significant R^2. The R^2 value of these equations was significant for 5 of the 6 depths and for the majority of the 24 subplots (table 1).

There were 12 low SS_{16} subplots, i.e., 5 C and 7 MB subplots, and 12 high SS_{16} subplots, i.e., 7 C and 5 MB subplots. For the low and high SS_{16} subplots, mean SS_{16} was higher at the 5.0- to 15.0-cm depth than at the 2.5- to 5.0- or 15.0- to 20.0-cm depths (fig. 1A). Across the 2.5- to 20.0-cm depth, SS_{16} averaged 31 percent less on the low SS_{16} subplots compared to the high SS_{16} subplots. Within the low and high SS_{16} subplots, mean SS_{16} at each depth was similar between the C and MB treatments. For the low and high SS_{16} subplots, mean SS_{16} PI_{scaled} at each depth was similar between the C and MB treatments (fig. 1B). At the 10.0- to 15.0-cm and 15.0- to 20.0-cm depths, there was a trend for mean SS_{16} PI_{scaled} to be larger on the low SS_{16} subplots compared to the high SS_{16} subplots.

Values of FRB were greatest in the zero- to 5.0-cm depth and decreased with depth to 20.0 cm (figs. 2A and 2B). Across the C and MB treatments and the distal and proximal locations 17, 27, 12, 33, 36, and 17 percent more FRB was observed on the low SS_{16} subplots than the high SS_{16} subplots for the six depth intervals, respectively.

Among the four linear regressions between SS_{16} and proximal FRB, none were significant (figs. 3A and 3B). Where subplot SS_{16} was low, the two linear regressions between SS_{16} and distal FRB were not significant (fig. 3C). Where subplot SS_{16} was high, linear regression between SS_{16} and distal FRB was significant for the MB treatment (R^2 = 0.3261, P = 0.0262) but not significant for the C treatment (fig. 3D).

Table 1—For the control (C) and May burn (MB) treatments and at each of 6 soil depth intervals, number of subplots out of 12 subplots with significant linear regressions that predicted soil strength at 16 percent soil water content, and number of these subplots that had a coefficient of determination (R^2) >0.50

	Soil depth (cm)					
Treatment	0 to 2.5	2.5 to 5.0	5.0 to 7.5	7.5 to 10.0	10.0 to 15.0	15.0 to 20.0
	Number of subplots with a significant soil strength–soil water content regression					
C	6	10	11	10	10	9
MB	1	9	10	11	9	7
	Number of subplots with a significant regression with R^2 >0.50					
C	3	8	9	8	8	8
MB	0	5	9	9	5	6

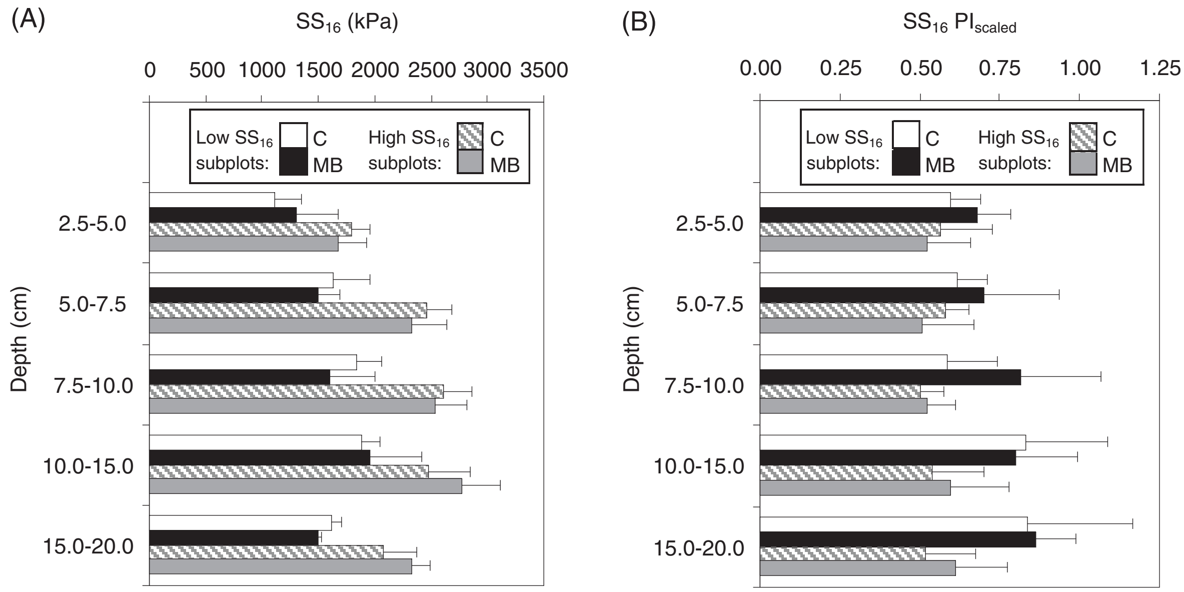

Figure 1—(A) Mean predicted values of soil strength at 16 percent soil water content (SS_{16}) and (B) scaled prediction intervals of SS_{16} in the 2.5- to 20.0-cm depth for subplots with low and high SS_{16} and in response to no vegetation management (C) or biennial fire in May (MB). Values of SS_{16} for the zero- to 2.5-cm depth were excluded because the majority of predictive equations at this depth interval were not significant. Bars represent the standard deviation of the mean.

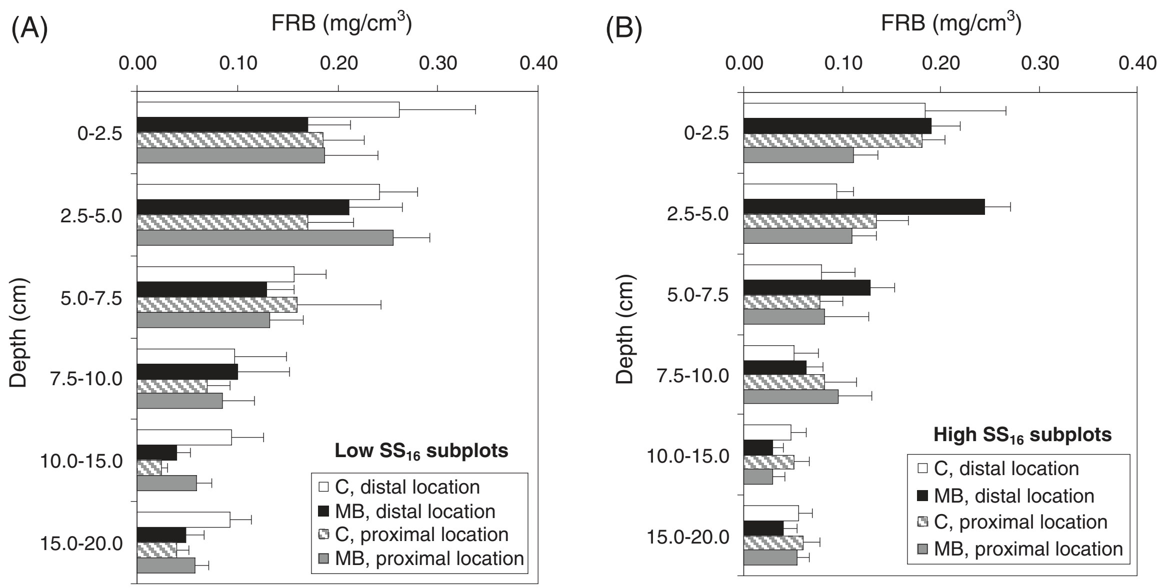

Figure 2—Mean pine fine root biomass (FRB) in the zero- to 20.0-cm depth for subplots with (A) low SS_{16} and (B) high SS_{16}. Sampling was done at locations that were distal or proximal to the measurement trees and in response to no vegetation management (C) or biennial fire in May (MB). Bars represent the standard deviation of the mean.

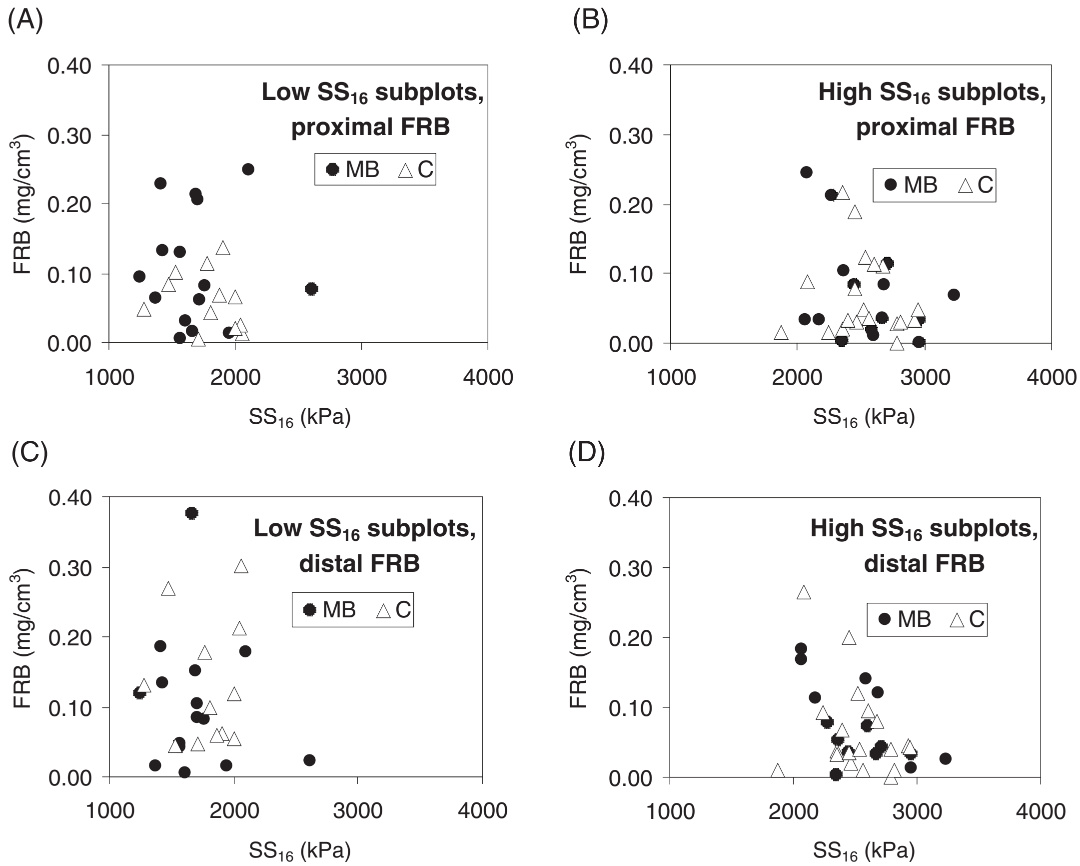

Figure 3—Scatter plots describing the relationship between soil strength at 16 percent soil water content (SS_{16}) and pine fine root biomass (FRB) across the 5.0- to 15.0-cm soil depth and in response to no vegetation management (C) or biennial fire in May (MB) for proximal FRB on the (A) low SS_{16} subplots and the (B) high SS_{16} subplots, and for distal FRB on the (C) low SS_{16} subplots and the (D) high SS_{16} subplots.

DISCUSSION

The study site is representative of typical pine forests on the west Gulf Coastal Plain that seem relatively homogenous with regard to aboveground features such as slope and vegetation. The present results indicate that this appearance may be deceiving when belowground variables such as soil strength are considered. Overall, soil strength at 16 percent SWC averaged 1952±474 kPa which is representative of soil strengths for similar soils (Sword and Tiarks 2002). At this study area, one-half of the 24 subplots were characterized by values of SS_{16} at the 5.0- to 20.0-cm depth that were >2000 kPa. Soil strengths ≥2000 kPa are known to limit pine root elongation (Taylor and others 1966). Therefore, there was notable variation associated with soil strength, and in some locations, the volume of soil accessed by pine roots for water and mineral nutrients may have been considerably smaller than its potential.

The FRB in the zero- to 20-cm depth averaged 0.11 mg/cm^3 which is 63 percent less than that found at an adjacent study site (Sword Sayer and Kuehler 2010). This discrepancy may be attributed to the time of root sampling and the fact that in both studies, live, senescent, and dead but not visibly decomposing root biomass were combined. Higher values were obtained when sampling was done in September and October, while lower values were obtained when sampling was done in November. Silt loam soils in central Louisiana tend to be relatively dry in late summer and early fall. Often, as winter approaches, rainfall saturates the soil which reduces the supply of oxygen to roots (Sword and Tiarks 2002). Natural root mortality in response to dry soil conditions (Caldwell 1977) followed by wet soil conditions may have accelerated root decomposition leading to low FRB in November.

More FRB was found at the 0- to 20-cm depth on the low SS_{16} subplots compared to the high SS_{16} subplots. This suggests that pine root elongation in the upper portion of the soil profile was restricted by either soil strength or other variables that interfere with root growth, e.g., inadequate water or carbohydrate. Siegel-Issem and others (2005) have also found southern pine root growth limitations when soil bulk density and water content interact to increase soil strength. At this point, however, there is no evidence that tree growth suffered from less FRB in the zero- to 20.0-cm soil depth where SS_{16} was high. Rather, it is likely that tree growth was sustained by roots growing in portions of the soil where soil strength was not root growth limiting. If climate dictates other constraints to root growth such as inadequate plant-available water, however, the sum of all root growth limitations could reduce whole root system function and, therefore, tree growth.

Regardless of C or MB treatment, the high SS_{16} subplots produced less FRB in the 0- to 20-cm depth compared to the low SS_{16} subplots. Correlation between SS_{16} and FRB, however, was only significant on the MB plots when FRB was sampled in distal locations on the high SS_{16} subplots. This suggests that in addition to soil strength, pine root elongation was controlled by other site variables that differed between C and MB plots, proximal and distal locations, and low and high SS_{16} subplots. An obvious difference between burned and unburned stands is the production of understory woody vegetation (Haywood and others 2001). With repeated burning, understory woody vegetation is reduced, leading to less forest floor accumulation (Wells and others 1979) which has the potential to increase surface soil evaporation (Neary and others 1999, Wells and others 1979). Also, the uptake of water near the surface of the soil may be accelerated if repeated fire increases grass and herbaceous cover. Pine trees respond to this situation by increasing the uptake of deeper soil water (Fernández and others 2008). However, it is possible that low surface SWC indirectly inhibited pine root elongation on the high SS_{16} subplots of the MB plots by its inverse relationship with soil strength. Repeated fire may have also affected FRB by reducing resource foraging by pine and nonpine woody roots. Over time, this would lower soil perturbation which could increase soil strength and reduce its variability (Bennie 1996, Fisher and Binkley 2000). These speculations indicate that where soil strength is potentially root growth limiting, information on the composition and distribution of understory vegetation will benefit the evaluation of pine root responses to silvicultural treatments.

This preliminary survey of the relationship between soil strength and longleaf pine FRB suggests that soil strength has the potential to reduce pine root elongation on the west Gulf Coastal Plain. Furthermore, it appears as though repeated prescribed fire interacts with this relationship. These results set the stage for further research designed to evaluate the effect of nonpine woody vegetation on soil strength and its variation, and how pine root responses to soil strength are manifested by aboveground production.

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