MANAGEMENT OF LONGLEAF PINE ECOSYSTEMS: CAN SOIL MAP UNITS IMPROVE EVALUATIONS OF SOIL CHANGE?

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Abstract—Adjoining soil map units that vary in slope were evaluated to assess if soil properties differed sufficiently to impact analyses of soil change under longleaf pine (*Pinus palustris*) management. A Piedmont site, an Upper Coastal Plain site, and two Middle Coastal Plain sites in Georgia were sampled. All sites were dominated by an overstory of longleaf pine. A total of 24 profiles were collected to a depth of 200 cm with each site containing two or three map units and two or three profiles within each map unit. Use of visible/near-infrared (VNIR) spectroscopy was also incorporated as a rapid, field-based approach for analyzing soil properties (i.e., clay, carbon [C], and pH_{CaCl2}) that can aid in quantifying soil variability across topographic gradients or dynamic soil properties (DSP) over time. Results indicate that soil map unit phases capturing steepness of slope were not a valuable stratification variable in analyzing DSP under longleaf pine at these sites. Few significant differences were observed with slope steepness at any depth (0–200 cm) for percent clay, percent C, or pH_{CaCl2}. Values ranged broadly across the sites and among depths. Percent clay ranged from <1 to >70 percent, percent C ranged from 0.01 to 3.78 percent, and pH_{CaCl2} ranged from 3.42 to 6.17. Visible/near-infrared calibrations for percent clay demonstrated predictive value (i.e., R^2 = 0.72-0.96) while those for C (i.e., R^2 = 0.55-0.73) and pH_{CaCl2} (i.e., R^2 = 0.20-0.62) indicated some utility for field classification or monitoring of DSP under longleaf pine ecosystems.

INTRODUCTION

Restoration of the longleaf pine (LLP; *Pinus palustris*) ecosystem throughout its historical range has become an important goal for the U.S. Department of Agriculture (USDA), Forest Service and Natural Resources Conservation Service (NRCS). For example, the NRCS participated in the USDA Farm Service Agency's Conservation Reserve Program's Longleaf Pine Initiative (LLPI) that started planting marginal agricultural lands to LLP in 2006. In 2010, the NRCS extended the LLPI to foster regeneration and restoration of LLP on private lands. To do this, the NRCS typically regenerates LLP through planting of seedlings; restoration is most often through the reintroduction of prescribed fire (Platt and others 1988). The NRCS also promotes forest stand improvement through thinning or hardwood removal, restoration and management of rare habitats, and tree/shrub establishment (USDA NRCS 2011).

The NRCS has developed a range of state-and-transition models for the restoration and regeneration of LLP that identify expected shifts in ecological site conditions with a change in management (i.e., agricultural abandonment or introduction of fire). The state-and-transition models are designed for specific physiographic settings and ecological site descriptions that are predominantly defined by plant communities but also by soil properties (Caudle and others 2013). Across the Southeast, soil moisture and percent silt have been identified as critical attributes distinguishing plant community composition and productivity of LLP ecosystems (Peet 2006). For example, in the Middle Coastal Plain of Georgia, both soil moisture and topographic relief class (steeply sloping [>8 percent], undulating [>3–8 percent], or nearly level [1–3 percent]) were found to influence overstory species diversity (Kirkman and others 2004). Similarly, and also in the Middle Coastal Plain of Georgia, landscape position affected soil attributes with greater soil carbon (C) content in bottomlands compared to uplands despite similar LLP management (Silveira and others 2009). These above gradient studies made inferences about LLP ecosystems at the level of soil suborders (e.g., Aquult). In contrast to these broad soil comparisons, studies that have investigated changes in soil properties under LLP with changes in management often limit investigation to a single or a few soil series. A study in southern Georgia, for example, investigated

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changes in soil attributes under LLP after agricultural abandonment and reported working only on two closely related series of Wagram and Norfolk (Markewitz and others 2002). Another study at the Savannah River Site in South Carolina investigating fire frequency and land use history impacts on soil under LLP focused on Blanton and Fuquay series (Bizzari and others 2015).

Within this framework of state transitions for a particular ecological site, there is an interest in understanding how soil characteristics may vary with landscape position (and thus impact LLP communities) and how changing management will change dynamic soil properties (DSP). When studying DSP such as pH or organic C (i.e., properties that are expected to change on human timescales of decades to centuries), it is recommended that studies focus on specific soil map units, specifically the series (Tugel and others 2008). However, this recommendation does not address the fact that a soil series is only one component of a map unit. Differences in slope, historical erosion, or other features indicated by the map unit may be as important as the soil series itself for determining vegetation-soil relationships (USDA NRCS 1993). As such, when studying DSP under LLP one might keep the soil series consistent while sampling across different map unit phases with varying slope, which can impact both LLP communities and soil attributes.

Presently, there is little research concerning how soil map units relating to slope steepness within a soil series might impact inferences about LLP community classification or about DSP under LLP regeneration or restoration. In this study, we analyzed how adjoining map units varying in slope steepness differed in several DSP. We also incorporated the use of visible/near-infrared (VNIR) spectroscopy as a rapid, field-based approach for analyzing soil properties of interest (i.e., clay, C, and pH_{CaCl2}) that may help evaluate soil variability across slopes or over time. Based on previous research on landscape position, we hypothesized that slope steepness across map units would differ in soil properties affecting soil moisture (i.e., clay) and that pH_{CaCl2} and C would be higher in map units with the lowest slopes.

METHODS

Study Sites

This study within Georgia used two sites located within the Piedmont and Upper Coastal Plain and two on the Middle Coastal Plain (fig. 1). The Piedmont site was located on the Hitchiti Experimental Forest (Oconee National Forest) near Juliette in Jones County, while the Upper Coastal Plain site was on private property in Hancock County. The Middle Coastal Plain sites were located within the Ohoopee Dunes Natural Area near Swainsboro (Emanuel County) and the Jones Center at Ichauway near Newton (Baker County). All sites

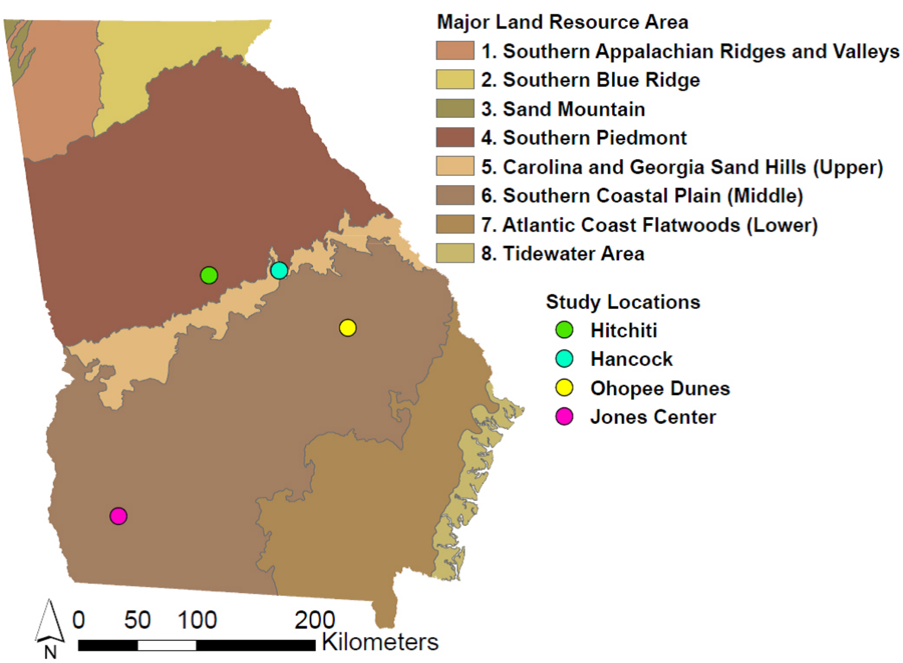

Figure 1—Site locations in the Piedmont (Hitchiti Experimental Forest), Upper Coastal Plain (private property in Hancock County), and Middle Coastal Plain (Ohoopee Dunes Natural Area and Jones Center) in Georgia. Georgia map indicates physiographic regions and sites.

were dominated by an overstory of LLP, although the Piedmont and Upper Coastal Plain sites were planted 8 and 16 years ago while the Middle Coastal Plain sites were more mature (many trees >40 years old), naturally regenerated stands. The Hitchiti and Hancock County sites are both cutover sites converted from loblolly pine stands (*Pinus taeda*) to LLP. The Ohoopee Dunes site is managed by the Georgia Department of Natural Resources as a conservation area with some use of prescribed fire, while the Jones Center site has been minimally harvested and is managed with prescribed fire on a 2-year return interval.

Hitchiti soils consist of the Vance series, which is a fine, mixed, semiactive, thermic Typic Hapludult. The soil map units within this site are VaB2 and VaC2 with a slope of 2–6 or 6–10 percent, respectively, and these units are eroded (fig. 2A). The Hancock County site is dominated by the Bonifay soil series (fig. 2B), which is a loamy, siliceous, subactive, thermic Grossarenic Plinthic Paleudult. The soil map units within this site are BnB and BnD, indicating slopes of 0–6 or 6–12 percent, respectively. The Ohoopee Dunes (fig. 2C) site also consists of the Bonifay soil series but with different soil map unit notation, which can occur between counties. The soil map units of interest are BoB, BoC, and BoD, with slopes of 0–5, 5–8, and 8–12 percent, respectively. Lastly, the Jones Center (fig. 2D) site comprises the Troup soil series, which is a loamy, kaolinitic, thermic Grossarenic Kandiudult. The soil map units of interest are TwB and TwC indicating slopes of 0–5 and 5–8 percent, respectively. These soil series descriptions are based on USDA NRCS Soil Survey Division (https://soilseries.sc.egov.usda.gov).

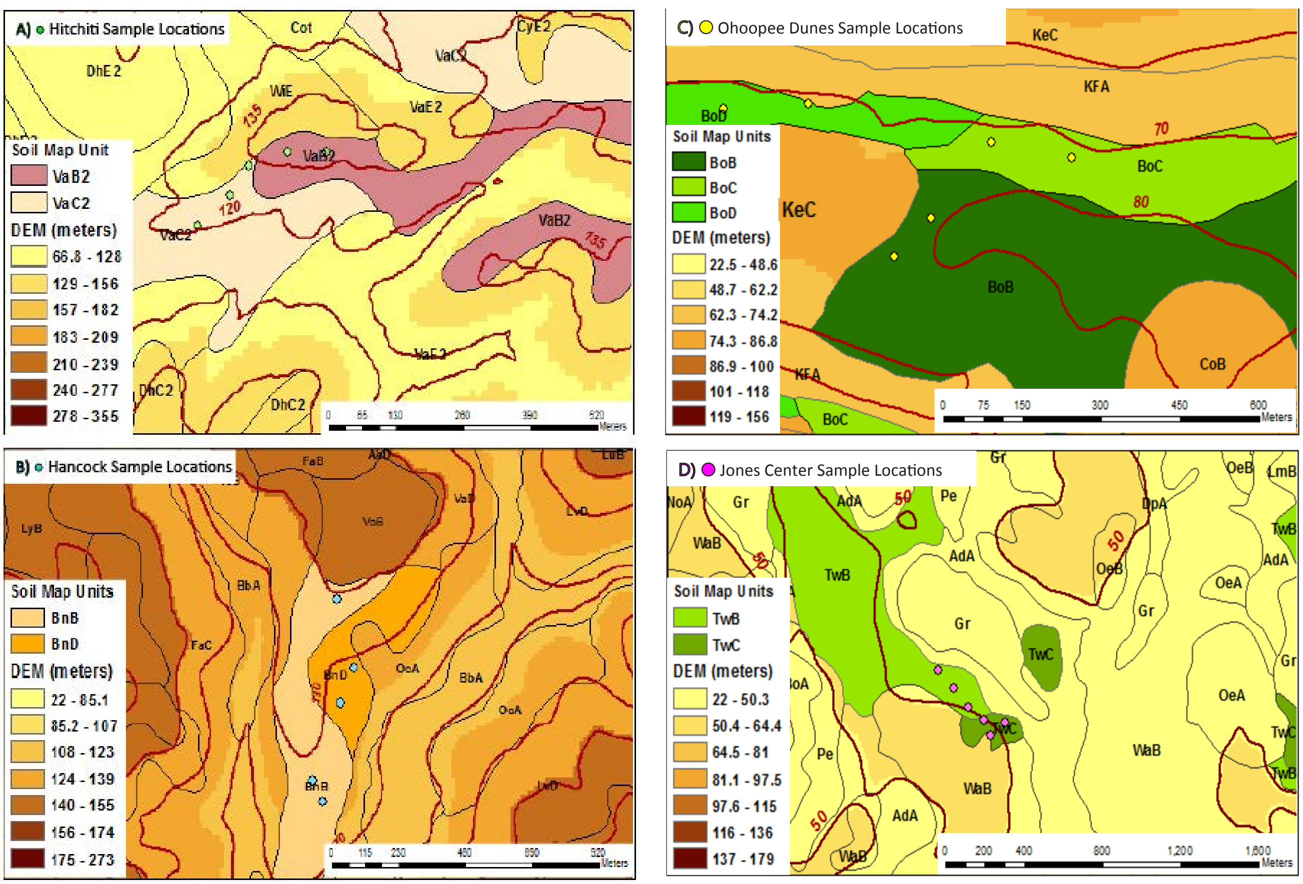

Figure 2—Site maps for A) Hitchiti Experimental Forest, B) private property in Hancock County, C) Ohoopee Dunes Natural Area and D) Jones Center. Maps include soil series, unit phases, sampling locations, and elevation contours (red lines at 10 or 15 (Hitchiti only) m contours) from digital elevation model (DEM). Points in each location indicate the slope gradient across the map units that was sampled for soil and stand attributes.

Soil Sampling and Analyses

In each soil map unit, two or three sampling locations were randomly selected. These random selections in the map units were not always consistent with the slope designation, but the locations were maintained and these few discrepancies are described below. Mineral soils were sampled in two ways. For two upper depths (0–2 and 9–11 cm) used to improve VNIR calibration, a soil punch with 2-cm diameter was used and three to five cores per sampling location were composited. In addition, 20-cm increment samples (i.e., 0–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, and 180–200 cm) were collected with a 6-cm-diameter soil auger. Sampling location VaC2-3 was an exception with a lithic contact at 120 cm.

A VNIR field spectrometer (Analytical Spectral Devices [ASD], Inc., Boulder, CO) with Indico® Pro software was used to scan soil samples in the field. The VNIR scanned from 350 to 2500 nm in 1-nm increments using a contact probe with a 2-cm-diameter window. The scans were completed by first performing a baseline scan using a Spectralon® white blank (Labsphere, North Sutton, NH). The lens of the contact probe was pressed firmly against the surface of the soil within its sample bag so that no light from the lens was visible. Soil within the sample bag was mixed, and the refreshed surface was scanned again. Each spectrum was averaged from a compilation of 50 readings during each scan. This was performed three times per sample, and the three scans were then averaged. Between each sample, the contact probe was cleaned. A baseline scan was performed after every 10 samples.

Samples were air-dried and passed through a 2-mm sieve. An oven-dry (105 °C) moisture correction factor was determined for each air-dried sample. Soils were analyzed for percent clay using the hydrometer method (Gee and Or 2002), C using a Flash 2000 Series CN soil analyzer (CE Elantech, Inc., Lakewood, NJ), and pH_{CaCl2} using a 1:1 ratio of soil and 0.01 M $CaCl_2$ following Thomas (1996).

Stand Attributes

In each plot, all individual trees within a radius of 10 m from the plot center and with a diameter at breast height (d.b.h.) >4 cm were identified and d.b.h. measured to determine basal area. Stem density was calculated within a diameter of 10 m by counting all stems with a height >1 m. Ground cover was determined for a 10-m transect in both the eastward and westward direction from plot center. Ground cover directly below each meter along the transects was classified as green/living, bare soil, or forest floor, and a percentage was calculated for each category. Lastly, three dominant tree heights were measured within the plot. Descriptive data are in table 1.

Statistical Analyses

Soil map units were sorted into flat, medium, and steep categories comprising 0–6, >6–8, and >8–12 percent slope, respectively. Results were analyzed by depth as a randomized block design with some blocks being incomplete (i.e., not all slope categories) and no medium slope in the Piedmont. Soil chemical and physical comparisons were made between region (Piedmont/Upper Coastal Plain and Middle Coastal Plain) and map unit slope (flat, medium, steep) with site (Ohoopee Dunes, Jones Center, Hitchiti Experimental Forest, Hancock County) as the blocking factor that is nested within a region. Data were compared using a mixed effects analysis of variance (ANOVA) across both regions and slope categories, although region x slope interactions only include flat and steep slope categories. Pairwise comparisons were tested for significant difference at $p < 0.05$ using Tukey's Honestly Significant Difference (HSD). If region was not significant, slope data were pooled across region to test among flat, medium, and steep slopes.

Visible/near-infrared raw reflectance spectra were preprocessed using Savitzky-Golay (SG), continuum removal (CR), or wavelets transformations (WT). Spectra and percent clay, percent C, or pH_{CaCl2} were randomly separated into 20-percent test and 80-percent training datasets. To avoid splitting up soil profiles within these sets, the Kennard-Stone algorithm was used (Kennard and Stone 1969). Partial least square regression (PLSR) after data reduction with principle components analysis or support vector machine (SVM) was used to perform the calibration (Thissen and others 2004). Coefficients of determination (R^2) and the root mean square error (RMSE) were used to compare results. The best calibration was determined for all data, Piedmont/Upper Coastal Plain samples, and Middle Coastal Plain samples. Data were analyzed using R version 3.2.3 using packages Prospctr (Stevens and Ramirez-Lopez 2013) and Soil.spec (Sila and others 2014) and ArcMap version 10.3. For more detail see Stockton (2016).

RESULTS

Soil Profile Attributes

Measured soil attributes across the sites ranged broadly (fig. 3). Percent clay, for example, ranged from <1 percent to >70 percent. Between the regions, clay content was statistically greater in the Piedmont/Upper Coastal Plain versus the Middle Coastal Plain by an absolute amount of ~15 percentage points within 40–60 cm and by ~13 percentage points within 80–100 cm ($p = 0.008$ and 0.03, respectively, fig. 4a). Other depths were not statistically different between the regions. In these depths, after pooling data, among slope steepness, percent clay was ~20 percentage points lower ($p = 0.045$) on an absolute basis when comparing steep slope to flat and medium slopes in 180–200 cm

Table 1—Stand characteristics and soil map unit slope for sites in Georgia, taken at each location in 2015/2016

Region Site	Map unit	Replicate	Map unit slope	Soil series	Basal area	Mean tree height	Stem density	Ground cover FF	Ground cover GR	Ground cover BS
					m^2/ha	*m*	*stems/ha*	- - - -*percent* - - - -		
Middle Coastal Plain										
Ohoopee	BoD	1	Steep	Bonifay	2.88	21.20	509	90	0	10
Dunes	BoD	2	Steep	Bonifay	20.20	13.13	764	90	10	0
	BoC	1	Medium	Bonifay	16.50	18.97	891	65	35	0
	BoC	2	Medium	Bonifay	8.58	19.34	637	90	10	0
	BoB	1	Flat	Bonifay	18.30	15.03	1,401	85	15	0
	BoB	2	Flat	Bonifay	1.45	11.93	637	90	10	0
Jones	TwC	1	Medium	Troup	1.50	11.00	2,165	0	10	90
Center	TwC	2	Medium	Troup	0.07	2.80	762	0	25	75
	TwC	3	Medium	Troup	0.08	3.40	382	30	10	60
	TwB	1	Flat	Troup	0.23	4.43	3,183	40	10	50
	TwB	2	Flat	Troup	0.00	23.20	509	40	10	50
	TwB	3	Flat	Troup	0.02	2.11	1,655	35	5	60
Piedmont/Upper Coastal Plain										
Hitchiti	VaC2	1	Steep	Vance	0.04	12.30	4,329	20	80	0
	VaC2	2	Steep	Vance	0.03	3.60	5,474	40	60	0
	VaC2	3	Steep	Vance	0.04	3.08	3,310	10	85	5
	VaB2	1	Flat	Vance	0.02	3.67	6,366	40	60	0
	VaB2	2	Flat	Vance	0.08	4.60	2,674	55	45	0
Hancock	BnB	1	Flat	Bonifay	7.83	10.50	N/A	25	70	5
County	BnB	2	Flat	Bonifay	28.70	5.91	N/A	40	30	30
	BnB	3	Flat	Bonifay	26.40	4.57	N/A	20	55	25
	BnD	1	Steep	Bonifay	16.00	25.30	N/A	25	70	5
	BnD	2	Steep	Bonifay	17.20	3.60	N/A	60	30	10

FF = forest floor, GR = green/living vegetation, BS = bare soil, N/A = Not available.

(fig. 4b) and ~13 percentage points lower in 160–180 cm. Other depths were not statistically different for percent clay among steepness.

Within specific sites, map unit profiles did not vary consistently for clay. At the Hitchiti, for example, VaB2 (replicate 1 and 2) had clay concentrations between 40 and 60 percent, and VaC2 (replicate 1 and 2) had 30 to 40 percent clay, which is consistent with a Bt horizon for a Vance soil series. However, VaC2-3 only contained 10 percent clay at the Bt horizon depth (fig. 3). For the Hancock County site, percent clay was generally low (1–5 percent) in the upper 40 cm but increased to a peak of 70 percent clay within the 120–160 cm depth, but variance with slope steepness was inconsistent at this site (fig. 3). Within the Ohoopee Dunes, percent clay generally increased with depth for all map units, with the exception of BoD-1 and BoD-2, which had very little clay present (fig. 3). Within the Jones Center site, percent clay increased relatively consistently with depth and ranged from 0–30 percent (fig. 3).

Percent soil C was significantly different between the regions in 0–2-, 9–11-, and 40–60-cm depths (p = 0.02, 0.04, and 0.02, respectively; fig. 4c). Percent soil C within 9–11 cm was 47 percent lower on a relative basis in the Piedmont/Upper Coastal Plain than the Middle Coastal Plain. Differences by slope steepness were only significant in 9–11 cm (p = 0.0004). Within the Coastal Plain, medium slope (1.7 percent carbon) was higher than the flat slope (0.65 percent carbon) and the steep slope (0.20 percent carbon; fig. 4d). The flat slopes (0.70 percent) and steep slopes (0.45 percent) in the Piedmont were not significantly different than flat or

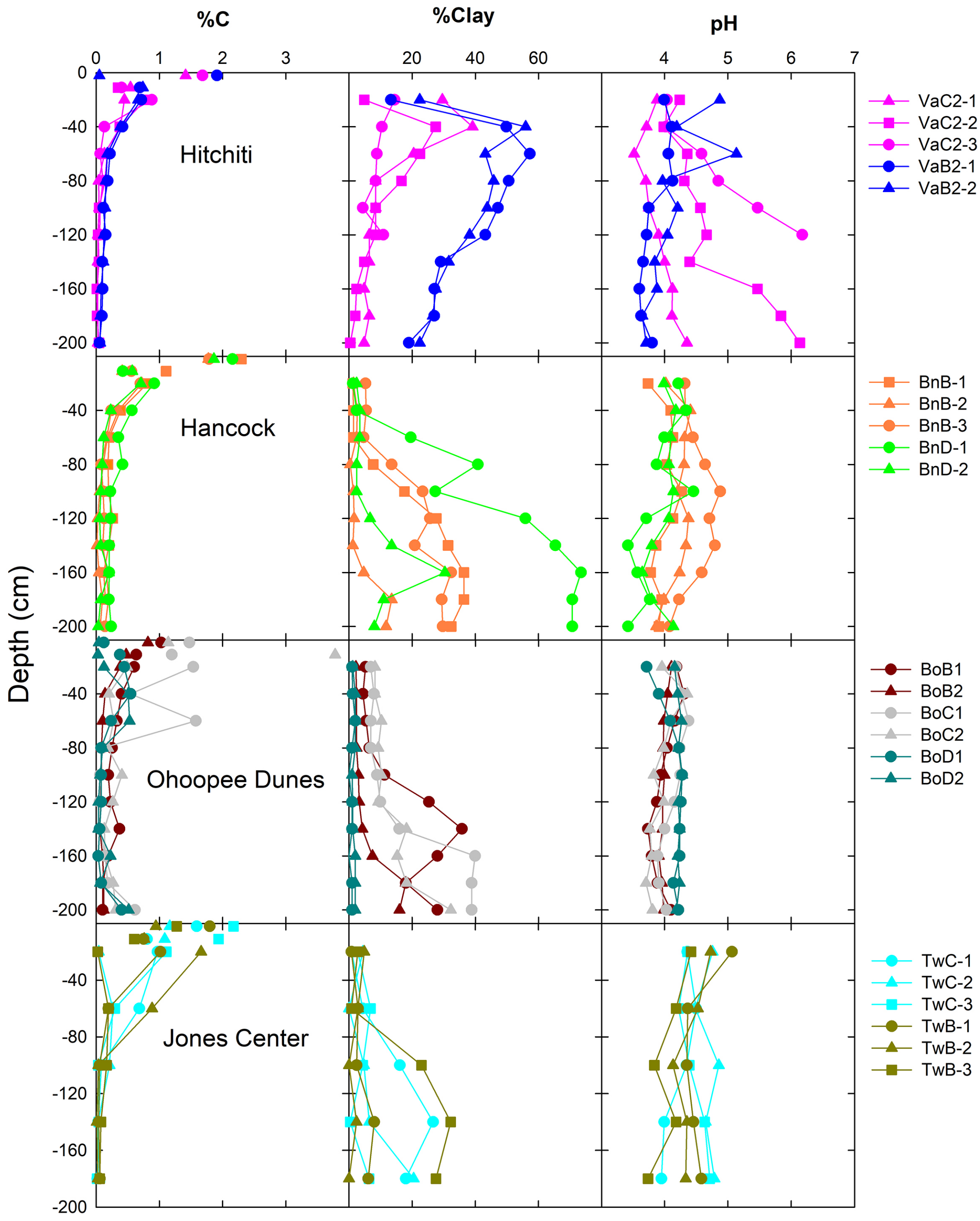

Figure 3—Soil profiles by site and soil series map unit. Within each graph, the same color indicates the same map unit, and different shapes indicate different soil profiles within that map unit category. For soil C, 0–2- and 9–11-cm data are included as well as the 0–20-cm data. Samples were collected 2015/2016.

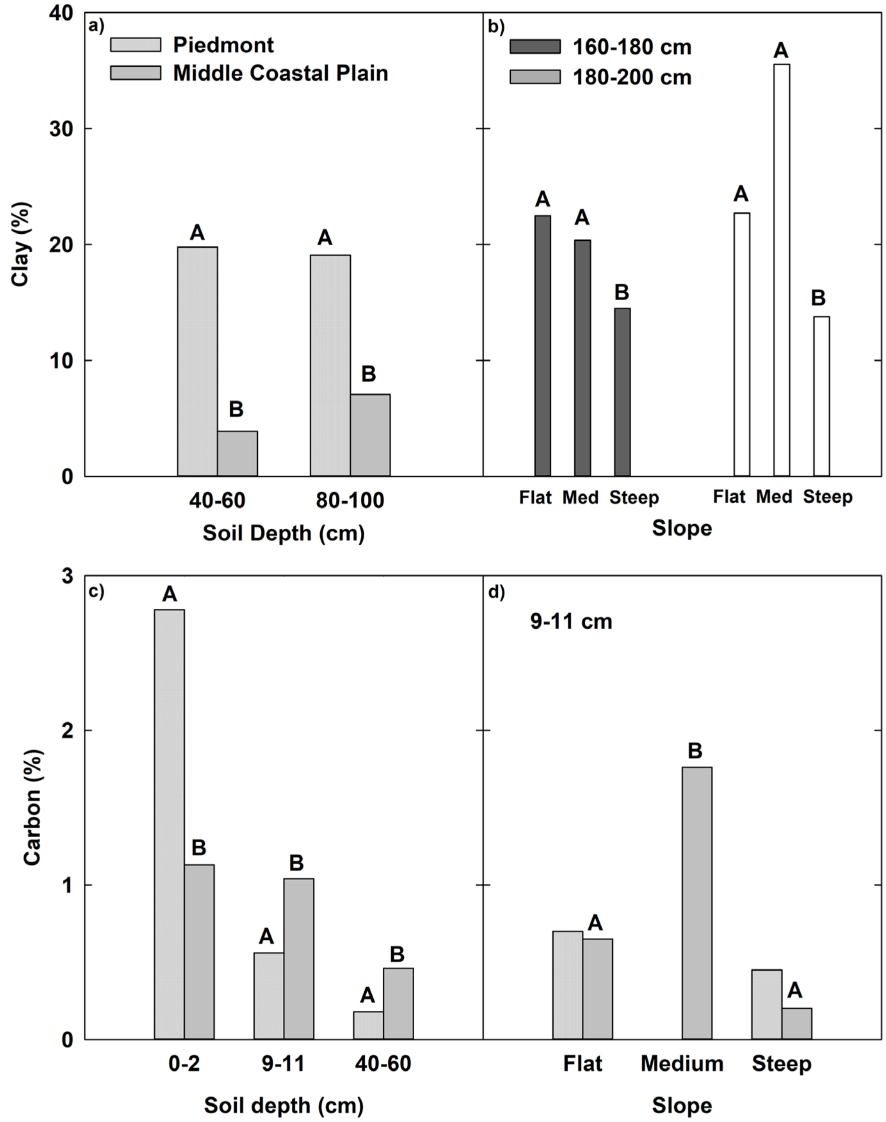

Figure 4—Percent clay averaged by depth and compared by region (a) or slope (b). Percent carbon averaged by depth or depth x region and compared by region (c) or slope within region (c). Capital letters indicate significant differences between regions (a and c) or between slopes (b and d).

steep slopes in the Coastal Plain (fig. 4d). In all the sites, percent C declined steadily with depth for each profile (fig. 3) except for the Ohoopee Dunes where percent C decreased with depth until 180 cm but increased slightly within 180–200 cm (fig. 3).

Finally, pH_{CaCl2} exhibited no significant differences for any depth across region or slope. At the Hitchiti, there was a distinct increase when comparing VaC2 to VaB2, with VaC2 pH increasing with depth, but pH remained fairly consistent with depth for all map units for all other sites (fig. 3).

VNIR Analysis

Field-based VNIR calibrations and validations focused on percent clay, percent soil C, and pH_{CaCl2} for both soil map unit classification and DSP measurement. The analysis investigated calibrations over all the data as well as by region. For all percent clay data, the best model used WT and SVM algorithm for prediction (R^2 = 0.72 for predicted versus observed; table 2 and fig. 5). For Piedmont/Upper Coastal Plain or Middle Coastal Plain data separately, PLSR with CR provided the best models (R^2 = 0.96 and 0.91, respectively; table 2). The combined data analyses for percent clay also resulted in higher RMSE than either Piedmont/Upper Coastal Plain or the Middle Coastal Plain separately (table 2). For all percent C data, PLSR with WT provide the best predictions (R^2 = 0.55). The same PLSR with WT approach was also best for the Piedmont/Upper Coastal Plain (R^2 = 0.67) and Middle Coastal Plain (R^2 = 0.73). The RMSE, however, did not vary substantially (table 2). Finally, for all pH_{CaCl2} data, PLSR with WT yielded the best model (R^2 = 0.20), which was improved for Piedmont/Upper

Table 2—Best prediction models for soil attributes from visible/near-infrared spectra

Soil attribute	Data	Method	Transformation	N comp.	Validation R^2	Validation RMSE	Cross-validation R^2	Cross-validation RMSE
Clay (%)	All	SVM	WT	8	0.72	0.9719	0.93	1.0281
	P/UCP	PLSR	CR	8	0.96	0.5398	0.96	0.5631
	MCP	PLSR	CR	8	0.91	0.4586	0.94	0.4615
C (%)	All	PLSR	WT	5	0.55	0.8840	0.80	0.9492
	P/UCP	PLSR	WT	11	0.67	0.8906	0.93	0.8985
	MCP	PLSR	WT	3	0.73	0.9996	0.86	1.0217
pH_{CaCl2}	All	PLSR	WT	16	0.20	4.0296	0.82	4.2045
	P/UCP	PLSR	SG	9	0.62	4.1822	0.95	4.1822
	MCP	PLSR	CR	10	0.54	3.3460	0.91	3.3460

All = all data, P/UCP = Piedmont Upper Coastal Plain, MCP = Middle Coastal Plain.
PLSR = partial least square regression, SVM = support vector machine.
CR = continuum removal, SG = Savitzky-Golay, WT = wavelets.
N comp. = number of principle components.
n_{All} = 221, $n_{Piedmont/Upper\ Coastal\ Plain}$ = 116, $n_{CoastalPlain}$= 105.

Coastal Plain using PLSR and SG (R^2 = 0.62) or for Middle Coastal Plain using PLSR and CR (R^2 = 0.54). All pH_{CaCl2} data and Piedmont/Upper Coastal Plain had similar RMSE while Middle Coastal Plain RMSE declined (table 2).

DISCUSSION

When considering sharply delineated polygons of soil map units, it is well recognized that such classifications are not 100 percent pure and will contain inclusions of other soil series or other soil phases (i.e., slopes) (Burrough and others 1997, Odgers and others 2014). Similarly, soil does not usually change abruptly at the polygon boundaries (Greve and Greve 2004). In our study, both issues of inclusions and boundary delineations were evident. At the Hitchiti site, for example, the profiles collected farthest down the hillslope (VaC2-3 and VaC2-2) had an increase in pH_{CaCl2} at depth unlike the other profile in the same map unit (VAC2-1) or the other two profiles in the adjacent map unit phase of the same soil series (VaB2-1 and VaB2-2). This may have been due, in part, to surrounding mafic soils as represented by the Davidson soil series (fine, kaolinitic, thermic Rhodic Kandiudults; DhE2 and DhC2 in fig. 2A). The Rhodic designation indicates a darker color in the Davidson from the mafic rock but may also cause the soil to become more basic with depth compared to the more acidic felsic soils located at the top of the hillslope that have a slightly declining pH with depth (Raulund-Rasmussen and others 1998). These types of inclusions might well impact community composition, as observed by Kirkman and others (2004) at a slightly larger scale but cannot be identified in the absence of finer scale map units (Ogders and others 2014).

Another map unit inconsistency was identified within the Ohoopee Dunes. Despite locating profiles BoD-1 and BoD-2 within the map unit boundary (fig. 2C), the percent clay is well below the other four profiles in the adjacent Bonifay map units (BoC and BoB in fig. 3). In fact, these low clay profiles are not Bonifay as they do not possess an argillic horizon that would be defined by a 4 percent absolute increase in clay with depth (USDA NRCS 1999). Thus, regardless of their location near the middle of the BoD map unit, these profiles display characteristics of the Kershaw soil series (KeC), which is present next to the BoD map unit. This BoD map unit was identified as having 8-12 percent slope, but field observations clearly indicated inclusions of some slopes <8 percent. When using map units for investigations of slope steepness or DSP, it is evident that units must be ground-truthed such that geographical delineations of mapping units are consistent with physiographic realities in the field. This caution is stated in the NRCS Soil Change Guide (Tugel and others 2008) but is often ignored in modeling efforts that may, for example, be interested in estimating soil C sequestration with LLP regeneration across the region.

The two examples above demonstrate some of the potential utility in developing VNIR for field use. In the first example, an ability to measure pH in the field might help identify changes in underlying bedrock, which may alter soil fertility (e.g., phosphorus availability) and thus LLP regeneration or restoration objectives. The VNIR calibrations for pH across all data were poor (R^2 = 0.20), but separating the data into Piedmont/Upper Coastal Plain and Middle Coastal Plain regions yielded improved results (R^2 = 0.62 and 0.54, respectively; table 2). Although these validation results are below what is

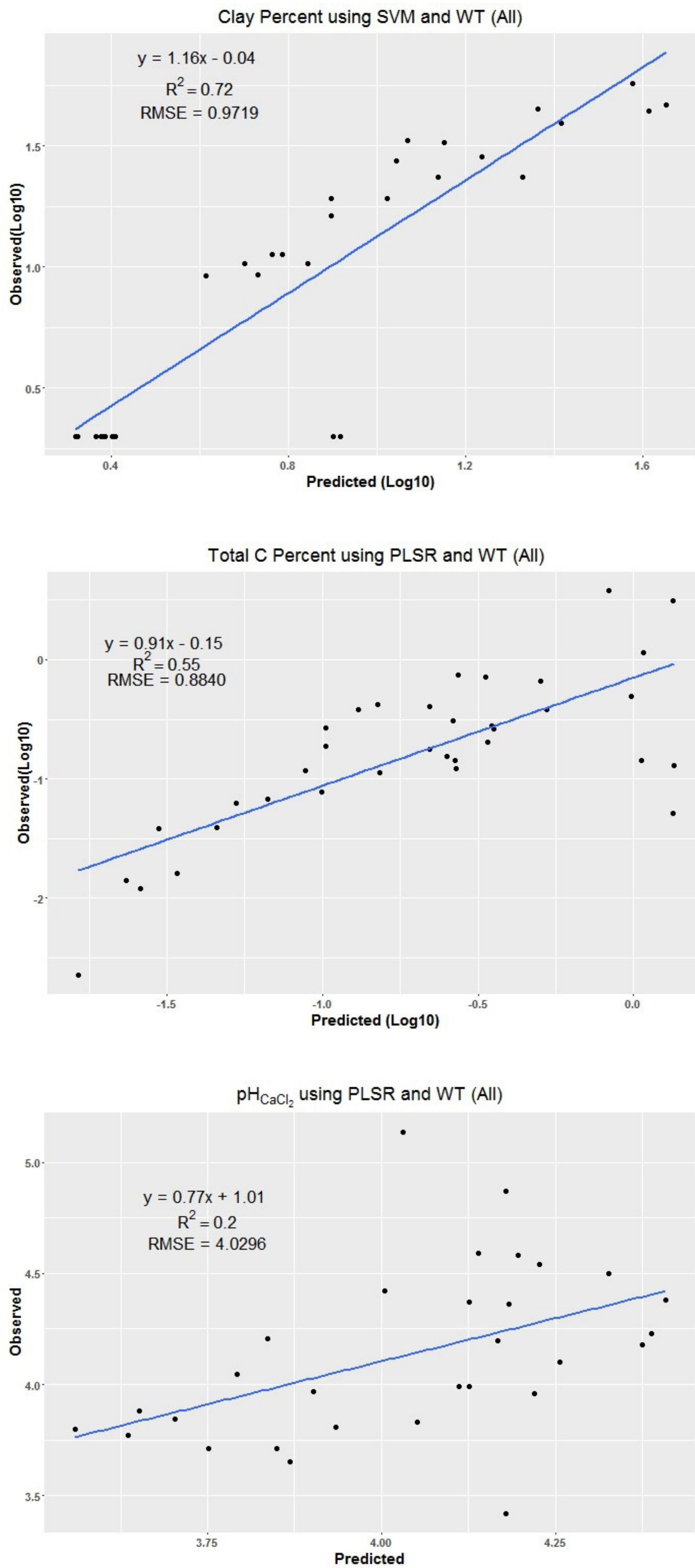

Figure 5—Best validation models across all sites for percent clay, percent C, and pHCaCl2 using support vector machine or partial least square regression (PLSR) after wavelets transformations (WT).

desired for a predictive model (i.e., $R^2 > 0.8$), they still might detect a pH change from 4 to 6 as observed in the Hitchiti site.

We focused on soil variance across soil map unit phases of slope steepness within a soil series as it might relate to understanding changes in DSP during LLP regeneration or restoration. For example, the ability to measure pH as a DSP under LLP regeneration or restoration should prove beneficial. Declines in surface soil (0–10 or 0–15 cm) pH have been observed under LLP regeneration on post-agricultural land compared to reference LLP (Bizzari and others 2015, Markewitz and others 2002), although in both cited cases pH decreases ranged from 4.8 to 4.0 or 4.7 to 4.5. To identify such changes in pH, VNIR prediction models will need to improve.

In the second example above, the ability to measure percent clay in the field might also prove useful. Of the three soil characteristics measured, VNIR predicted percent clay best with validations of R^2 = 0.72, 0.96, and 0.91 for all data, Piedmont/Upper Coastal Plain, and Middle Coastal Plain datasets, respectively. Previous VNIR models for clay measurement have also been successful (Waiser and others 2007). The VNIR could be used to classify soils within the field. For example, VNIR may enable a user to determine if and where the argillic horizon starts within a profile, which might help distinguish between an Arenic or Grossarenic designation. Similarly, distinguishing between sandy series such as Kershaw (≤5 percent silt + clay) and Lakeland (>5 percent silt + clay) might be possible in the field. This information could aid with soil mapping and thus regeneration or restoration management decisions.

The final VNIR calibration was for percent C. Prediction models with the PLSR and WT approach performed best with R^2 for validations of 0.55, 0.67, and 0.73 for all data, Piedmont/Upper Coastal Plain, and Middle Coastal Plain, respectively (table 2 and fig. 5). Being able to accurately estimate soil C within the field will help determine how LLP regeneration or restoration may be altering C concentrations or contents, which plays a fundamental role in soil fertility. Also, knowing the amount of C being stored during LLP regeneration or restoration has taken on a particular interest relative to atmospheric carbon dioxide (CO_2) concentration and fire management (Lavoie and others 2014, Butnor and others 2017).

Previous studies within LLP have clearly demonstrated changes in soil C with regeneration, fire, and landscape position. For example, in the Middle Coastal Plain of South Carolina, soil on post-agricultural lands regenerating with LLP had 0–15-cm soil C values of 0.9 percent compared to reference LLP of 1.35 percent (Bizzari and others 2015). In the Middle Coastal Plain of Georgia, similar results were observed for 0–10-cm soil (mean ± 1SE) in regenerating stands (0.6 ± 0.6 percent C) relative to reference stands (2.19 ± 0.19 percent C) (Markewitz and others 2002). In this same Georgia location, LLP in the absence of fire had 2.57 percent C while regularly burned reference stands had 1.7 percent C (Boring and others 2018). Finally, relative to 0–20-cm upland soils (1.29 ± 0.6 percent C), bottomland soils were threefold higher (4.79 ± 5.61 percent C) (Silviera and others 2009). The VNIR calibrations should be able to detect these size differences.

Relative to our primary interest in map units and slope steepness, surface soil C (0–2, 9–11, or 0–20 cm) did not vary consistently with slope (fig. 4). In the 0–2-cm layer, soil C increased with slope steepness but not significantly. Only in 9–11 cm was slope significant, with the medium steepness in the Coastal Plain showing the highest soil C, which is not consistent with our original hypothesis. Whether variance in these map units with slope steepness can inform changes in DSP during LLP regeneration or reforestation depends on the variance in the units (or strata) compared to the overall landscape variance. When measuring 186 samples in an upland-to-bottomland gradient study previously noted above, the coefficient of variation (CV) for soil C was 144 percent over all samples and 50 and 118 percent in the upland and bottomland, respectively (Silviera and others 2009). In our study, CV of percent C for all soil samples in 0–2-, 9–11-, and 0–20-cm depths was 127, 92, and 58 percent, respectively (n = 22 per depth increment). Pooled across regions, the slope classes of flat (n = 10), medium (n = 5), and steep (n = 7) had CV for soil C of 49, 28, and 150 percent within 0–2 cm, respectively. In 9–11 cm, CV was 29, 68, and 46 percent, respectively. Finally, in the 0–20-cm sample, CV was 58, 70, and 47 percent, respectively. Only the 9–11-cm depth had smaller CV within all slope classes than the overall sample CV suggesting slope class was a useful stratum within this depth. Within the sample size constraints of our study, soil map unit phases did not greatly improve our ability to determine soil property change (i.e., DSPs) under LLP regeneration or restoration. There was too much variance within soil map unit phases for inclusion of slope to improve statistical tests of change over time.

CONCLUSIONS

We characterized 2-m profiles in adjoining map units to understand how well soil maps units, as delineated by polygons on soil maps, accurately capture variance over slope steepness and how soil variance across these units might impact our ability to quantify soil change. We also measured all soil with VNIR to assess how well this rapid field technique could measure soil attributes of interest both for field classification of soils and measurement of DSP over time. From these efforts, our study suggests that soil map unit phases capturing steepness of slope will not be a valuable stratification variable in analyzing DSP under LLP regeneration or restoration. Few significant differences were observed between slope classes at any depth (0–200 cm) for the measured variables (clay, C, or pH_{CaCl2}), and even in cases of observed differences there was not a clear monotonic pattern from flat to steep. Visible/near-infrared calibrations for percent clay demonstrated potential predictive value while those for C and pH_{CaCl2}, although not as strong, indicated some utility for field classification or monitoring of DSP.

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LITERATURE CITED

Bizzari, L.E.; Collins, C.D.; Brudvig, L.A.; Damschen, E.I. 2015. Historical agriculture and contemporary fire frequency alter soil properties in longleaf pine woodlands. Forest Ecology and Management. 349: 45–54.

Boring, L.R.; Hendricks, J.J.; Taylor, R.S.; Markewitz, D. 2017. Ecosystem processes and restoration. In: Kirkman, L.K.; Jack, S.B., eds. Ecological restoration and management of longleaf pine forests. Boca Raton, FL: CRC Press: 123-140.

Burrough, P.A.; van Gaans, P.F.; Hootsmans, R. 1997. Continuous classification in soil survey: spatial correlation, confusion and boundaries. Geoderma. 77(2): 115–135.

Butnor, J.R.; Samuelson, L.J.; Johnsen, K.H. [and others]. 2017. Vertical distribution and persistence of soil organic carbon in fire-adapted longleaf pine forests. Forest Ecology and Management. 390: 15-26.

Caudle, D.; Sanchez, H.; DiBenedetto, J. [and others]. 2013. Interagency ecological site handbook for rangelands. Washington, DC: U.S. Department of the Interior, Bureau of Land Management; U.S. Department of Agriculture, Forest Service; U.S. Department of Agriculture, Natural Resources Conservation Service. 109 p.

Gee, G.W.; Or, D. 2002. Particle-size analysis. In: Dane, J.H.; Topp, C.G., eds. Methods of soil analysis: Part 4: Physical methods. SSSA Book Series 5. Madison, WI: Soil Science Society of America: 255–293.

Greve, M.H.; Greve, M.B. 2004. Determining and representing width of soil boundaries using electrical conductivity and MultiGrid. Computers & Geosciences. 30(6): 569–578.

Kennard, R.W.; Stone, L.A. 1969. Computer aided design of experiments. Technometrics. 11(1): 137–148.

Kirkman, K.L.; Goebel, P.C.; Palik, B.J.; West, L.T. 2004. Predicting plant species diversity in a longleaf pine landscape. Ecoscience. 11(1): 80–93. doi: 10-1080/11956860.2004.11682815.

Lavoie, M.; Mack, M.C.; Hiers, J.K. [and others]. 2014. Effects of restoration techniques on soil carbon and nitrogen dynamics in Florida longleaf pine (*Pinus palustris*) sandhill forests. Forests. 5(3): 498–517. doi:10.3390/f5030498.

Markewitz, D.; Sartori, F.; Craft, C. 2002. Soil change and carbon storage in longleaf pine stands planted on marginal agricultural lands. Ecological Applications. 12(5): 1276–1285.

Odgers, N.P.; Sun, W.; McBratney, A.B. [and others]. 2014. Disaggregating and harmonising soil map units through resampled classification trees. Geoderma. 214: 91–100.

Peet, R.K. 2006. Ecological classification of longleaf pine woodlands. In: Jose, S.; Jokela, E.J.; Miller, D.L., eds. The longleaf pine ecosystem. New York: Springer: 51–93.

Platt, W.J.; Evans, G.W.; Rathbun, S.L. 1988. The population dynamics of a long-lived conifer (*Pinus palustris*). American Naturalist. 131(4): 491–525.

Raulund-Rasmussen, K.; Borggaard, O.K.; Hansen, H.C.B.; Olsson, M. 1998. Effect of natural organic soil solutes on weathering rates of soil minerals. European Journal of Soil Science. 49(3): 397–406.

Sila A.; Hengl, T.; Terhoeven-Urselmans, T. 2014. soil.spec: Soil spectroscopy tools and reference models. R package version 2.1.4.

Silveira, M.L.; Comerford, N.B.; Reddy, K.R. [and others]. 2009. Soil properties as indicators of disturbance in forest ecosystems of Georgia, USA. Ecological Indicators. 9(4): 740–747.

Stevens, A.; Ramirez-Lopez, L. 2013. An introduction to the prospectr package. R package version 0.1.3.

Stockton, J.C. 2016. Soil constituent patterns and predictions using VNIR calibrations and analyses of soil map units across slope steepness under longleaf pine ecosystems. M.S. thesis. Athens, GA: University of Georgia. 90 p.

Thissen, U.; Pepers, M.; Üstün, B. [and others]. 2004. Comparing support vector machines to PLS for spectral regression applications. Chemometrics and Intelligent Laboratory Systems. 73(2): 169-179.

Thomas, G.W. 1996. Soil pH and soil acidity. In: Sparks, D.L.; Page, A.L.; Helmke, P.A. [and others], eds. Methods of soil analysis: Part 3: Chemical methods. SSSA Book Series 5. Madison, WI: Soil Science Society of America: 475–490.

Tugel, A.J.; Wills, S.A.; Herrick, J.E. 2008. Soil change guide: procedures for soil survey and resource inventory, version 1.1. Lincoln, NE: U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center. 240 p.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 1993. Soil survey manual. Agriculture Handbook 18. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Science Division Staff. 315 p.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 1999. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. 2nd ed. Agriculture Handbook 436. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service, Soil Survey Staff. 886 p.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 2011. Longleaf pine initiative. http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/home/?cid=nrcsdev11_023913. [date last accessed: December 6, 2019].

Waiser, T.H.; Morgan, C.L.S.; Brown, D.J.; Hallmark, C.T. 2007. In situ characterization of soil clay content with visible near-infrared diffuse reflectance spectroscopy. Soil Science Society of America Journal. 71(2): 389–396.