MANAGEMENT DEPENDENT SOIL PROPERTIES OF CULTIVATED VERSUS NON-CULTIVATED SOUTHEASTERN COASTAL PLAIN ECOSYSTEMS

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THESIS ABSTRACT

MANAGEMENT DEPENDENT SOIL PROPERTIES OF CULTIVATED VERSUS NON-CULTIVATED SOUTHEASTERN COASTAL PLAIN ECOSYSTEMS

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Management dependent properties describe dynamic soil quality. Comparisons of disturbed to reference sites are not extensive in the southeastern (SE) U.S. due to scarcity of undisturbed land. Objectives of this study were to evaluate land use effects on dynamic soil properties of SE soils, and investigate carbon stocks and soil quality of mature longleaf pine (*Pinus palustris* Miller) – wiregrass (*Aristida stricta* Michx.) habitat relative to more intensively cultivated Coastal Plain ecosystems. Sites in Thomas County, GA, representing well-drained, upland soils, were selected in each of three management systems for comparison of near surface soil properties. Land management included mature, multi-aged longleaf pine (LL) forest, slash pine (*Pinus elliottii* Engelm.) plantation (PP), and conventional row crop (RC) systems.

Concentrations of microbial biomass C (0–5 cm) in LL were 69 %> RC, while TOC was 138 % higher in LL relative to RC. Anthropogenic inputs were evident in RC (0–30 cm) based on higher TON (31 % > PP), exchangeable Ca (102 %> LL) and K (433 %> LL), extractable P (1700 %> LL), and base saturation (142 %> LL). Cultivation increased bulk density (ρ_b) (P=0.029) compared to LL. Soil strength (SS) (0–50 cm) in PP was 106 % > LL (P= 0.061). The highest soil infiltration rate (IR) was in LL (42.5 cm hr $^{-1}$) (P= 0.038), which was 1015 % higher than PP. Saturated hydraulic conductivity (Ksat) was lowest in PP (5.7 cm hr $^{-1}$). Multivariate analysis indicated 79% of data variability was largely explained by exchangeable bases, C pools, and hydraulic properties, indicating the utility of these properties for a minimum data set of soil quality in similar agroecosystems of the SE U.S. Euclidean clustering of raw data indicated near-surface soil properties were more similar owing to soil management than soil map unit.

Soil properties most sensitive to management included particulate organic matter fractions of C and N, potentially mineralizeable N, extractable P and Al, pH, exchangeable bases, IR, ρ_b, and plant available water. Measurement of these near-surface properties is suggested for evaluating soil change in similar upland soils of the SE U.S.

Longleaf ecosystems had better soil quality as indicated by lower ρ_b and SS, and higher C stocks, IR, Ksat, and plant available water. Longleaf sequestered 13 and 64 % more total organic C than planted pine and row crop sites respectively, indicating the potential of longleaf ecosystems for storing C. In the SE U.S., more intensive cultivation increased soil nutrients and compaction, and reduced water infiltration, C stocks, and inherent variability of soil properties relative to uncultivated longleaf – wiregrass ecosystems.

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I. LITERATURE REVIEW

Introduction

Soils around the world have been affected by human activity (Granatstein and Bezdicek, 1992). The world population is projected to increase from the current 6.4 billion to over 8.9 billion by 2050 (FAO, 2005). Increasing demands resulting from a growing population put stress on our soil resources. Demand for food, textiles and timber parallel the population, consuming arable land in the process. Land use decisions will be made for these demands, and soils will undoubtedly be altered to accommodate contemporary needs. By assessing changes in properties of soils under different management, an interpretation of soil quality can be made (Norfleet et al., 2003). Management decisions can then be made that enhance and sustain the non-renewable nature of our soil resource.

In an effort to evaluate sustainability of management systems, it is necessary to employ a comparative assessment (Larson and Pierce, 1994) to a natural ecosystem or undisturbed area (Sarrantonio et al., 1996). This approach compares characteristics of alternative systems at a given time with respect to desired attributes. Differences in measured parameters are assessed to determine the relative sustainability of the management systems in question (Larson and Pierce, 1994). In addition to differentiating between soils, a comparative assessment can be utilized to make connections between soil properties. One such property suggested by Karlen et al. (1990) is soil tilth, defined as “the physical condition of a soil described by its bulk density, porosity, structure, roughness, and aggregate characteristics as related to water, nutrient, heat and air transport; stimulation of microbial and micro fauna populations and processes; and impedance to seedling emergence and root penetration.” Based upon this definition, soil tilth can be viewed as a subset of properties important to overall soil quality. Native soils are often thought to have high soil quality because of lack of anthropogenic disturbance. Natural limits of some soil properties can also be estimated from undisturbed ecosystems (Sarrantonio et al., 1996). However, today’s management practices are capable of improving soil conditions after extensive cultivation. Karlen et al. (1992) suggested practices of conservation tillage, cover crops, and crop rotations had the highest potential for improving soil quality in cultivation systems. Correctly documenting the history of a given soil is necessary before drawing conclusions about a soil’s quality (Bezdicek et al., 1996).

Soil properties are functionally related to one another (Jenny, 1941). Therefore, grouping many soil characteristics into one category can lead to a better understanding of soil condition. It should be noted that “soil is an exceedingly complex system possessing of a great number of properties” (Jenny, 1941). These soil properties vary spatially and temporally depending upon the magnitude of the five soil forming factors (Soil Survey Division Staff, 1993). For comparison of management dependent properties, Sarrantonio et al. (1996) suggest three designs: 1) comparisons of side-by-side management on similar soils, 2) a single location over time, or 3) a desired site compared to neighboring farms or nearby undisturbed areas inhabited by natural ecosystems. “There is no absolute standard of soil health against which to judge an individual soil’s status” (Sarrantonio et al., 1996); therefore, a comparison of soils is merely relative due to the lack of a widely accepted set of data with quantified ranges of various soil properties.

Methods of soil sampling, handling and transport are important considerations for accurately measuring soil properties. Composite sampling, which creates a representative sample of the area of interest, can be utilized for most chemical and biological measurements. This sampling method can significantly reduce the amount of analyses required for interpretation (Dick, et al., 1996). To fully understand soil quality, a representative pedon must be sampled in horizontal (spatial) and vertical (depth) directions. The actual number of samples collected depends on the type of measurement as well as the desired parameters (Arshad, et al., 1996). Topography and vegetation can be used to estimate spatial boundaries of soil properties (Soil Survey Division Staff, 1993). In experimental design, utilizing natural boundaries for blocking improves comparison among treatments (Mead et al., 2003).

Longleaf Ecosystems

The southeastern U.S. has a large area of soils classified as Ultisols that are extensively used for agriculture and forestry production (Shaw, 2002; Boul et al., 2003). Prior to European settlement, longleaf pine (*Pinus palustris* Miller) forest in the southern states covered an estimated 30 million hectares with an additional 7 million hectares in mixed stands (Frost, 1993). Forested land in much of the southern U.S. was converted for agricultural use around the turn of the twentieth century (Hamdar, 1993). Decimation of the longleaf ecosystem by logging and turpentining began in the mid 1800s, and today only 3 percent of the original acreage remains (Frost, 1993). This means that a large portion of southeastern Ultisols once supported mature forests prior to being cleared for agricultural practices. A soil's maturity is based upon horizon differentiation (Jenny, 1941), and Ultisols are pedogenically well developed (Shaw, 2002; Soil Survey Staff, 2006). Investigating well-developed soils for management dependent properties may provide better understanding of management effects than newly-formed soils.

Management Dependent Properties and Soil Quality

Soil quality has recently been addressed as a result of expanding populations throughout the world. Several properties are recognized as indicators of the overall sustainability of the soil resource. These indicators include physical, chemical and biological soil properties, as well as appearance and general interpretation of the soil tilth and productivity (Karlen et al., 1992). Dynamic soil properties are those that change on a human time scale of decades or centuries (Smeck and Olson, 2007) in response to use and management (Carter, 2002). Thus, management dependent soil properties are sensitive to shifts in land management practices. Land use and management can have an impact on the overall state of dynamic soil properties. In general, increasing soil disturbance by tillage, compaction, etc. negatively affect the soil's ability to function. However, "Soil quality and soil productivity are not necessarily synonymous" (Fauci and Dick, 1994).

Several definitions of soil quality have been suggested. Karlen et al. (1992) defined soil quality as "the ability of the soil to serve as a natural medium for the growth of plants that sustain human and animal life." A review by Doran and Parkin (1994) concluded that soil quality is the capacity of a soil to function. This interpretation holds true at present and will continue to be important for further definitions. The term soil quality can be linked to sustainability by interrelations of management dependent properties and production stability (Larson and Pierce, 1994). Good management of soil resources is the way to maintain a sustainable agricultural system.

The portion of the soil solum most affected by land use and management is the surface (Blank and Fosberg, 1989; Liebig et al., 2004; Wood et al., 1991; Wood and Edwards, 1992), and the amount of residue returned to the soil can strongly influence soil properties being evaluated for changes due to management (Liebig et al., 2004). Fertilizers, lime, and irrigation water are often applied directly to the soil surface (Kelly et al., 2007; Ritchey et al., 2004; Schneider and Howell, 1999). Tillage effects include inversion and mixing and are generally targeted toward the surface layers of a given soil as these horizons are very important for plant growth. Root growth generally decreases with increasing depth (Jackson et al., 1996; Jackson et al., 1997). Depending on land-use, management practices will affect the soils ability to function.

Overall soil quality can be assessed by examining soil degradation processes such as erosion, compaction, acidification, salinization, sodification, water-logging, and other chemical and biological parameters (Arshad and Coen 1992). Other contributing factors to soil quality include climate, landform and human management decisions (Arshad and Coen 1992). In order to interpret the soil condition, a given soil can be compared to another, compared against a uniform set of criteria pre-determined for soils in a similar management or geographic area, or be assessed over time (Larson and Pierce, 1994; Sarrantonio et al., 1996). Establishment of pre-determined criteria requires quantifiable variables. Such variables include soil depth, water holding capacity, bulk density (ρ_b), hydraulic conductivity, nutrient availability, organic matter (OM), pH and electrical conductivity (Arshad and Coen 1992).

Arshad and Coen (1992) suggest four categories of soil quality: 1) soil attributes (physical, chemical and biological properties) 2) land (vegetation, terrain, geology, drainage and runoff) 3) mankind (land-use, management practices, ownership, cost of inputs, marketability and farm policy, and 4) climate (rainfall, temperature and storms). Of these, only some soil attributes and certain points under mankind can be easily changed by human interaction. Dynamic soil properties can only change within limits set by their genetic properties (Norfleet et al., 2003); therefore, the land use and management are critical to maintaining a sustainable soil environment. The nature of the soil can change in a very short time with human intervention or failure to intervene (Norfleet et al., 2003).

Chemical Soil Properties

"Soil chemical tests are probably the most consistent and repeatable" compared to physical and biological measurements (Granatstein and Bezdicek, 1992); therefore, chemical measurements of soil can be of great importance for differentiation by land use. Numerous chemical analyses are available for characterizing soil; however, some are more intensive than others. Karlen et al. (1992) point out that the efficiency of nutrient cycling, including mineralization, immobilization and leaching, are potential indicators of soil quality.

Many studies indicate that management affects extractable nutrients. Research has shown that exchangeable bases can be higher (Fesha, 2004; McCracken et al., 1989) or lower (Anderson and Browning, 1949; Malo, et al., 2005) in cultivated soils relative to uncultivated soils. Fertilizer input to cultivated sites can elevate levels of most nutrients, especially macronutrients. Mitchell and Tu (2006) found that fertilization with poultry litter increased levels of Ca, Mg, K, P, Cu, Zn, and B in the soil surface relative to untreated plots. Levels of exchangeable bases have reportedly increased (Knoepp et al., 2004; Sherman et al., 2005) and decreased (Brye, 2006) in response to burning. More extractable Fe was found in surface horizons of cultivated soils than in virgin soils in a South Dakota study conducted by Blank and Fosberg (1989). Extractable P of soils under loblolly pine management was exceptionally high when compared to levels present in mixed hardwood and pine forest in Alabama (Fesha, 2004). Brye (2006) found that prescribed burning significantly decreased extractable P; however, Binkley et al. (1992) found no evidence of increased P cycling with fire in South Carolina pine stands. Nair et al. (2007) found that silvopastoral practices in Florida reduced levels of P in lower depths of the soil profile relative to grassland ecosystems.

Soil pH is a readily available measurement for a quick estimation of soil condition. However, pH cannot be interpreted without additional knowledge of farming activities and environmental conditions (Peryea and Burrows, 1999). Both pH and electrical conductivity have been recognized as good indicators of soil quality because they change relatively quickly in response to management practices (Smith and Doran, 1996). Research by Blank and Fosberg (1989) reported the surface pH of virgin soils to be slightly lower than for cultivated soils. Manipulation of the soil solution for farming commonly involves the addition of lime to increase the availability of nutrients and ameliorate Al toxicity. More intensely cultivated sites tend to have higher soil pH than uncultivated sites (Fesha, 2004; McCracken et al., 1989). Sherman et al. (2005) reported fire-induced changes in pH were temporary (<1 yr) after first-time prescribed burning; however, pH can be maintained with regular burning (Brye, 2006).

Many nutrients important to plants are cations, and soil cation exchange sites are necessary to hold these nutrients for release into the soil solution for plant uptake (Barker and Collins, 2003). Thus, the ability of a soil to supply nutrients to plants is commonly determined by calculation of cation exchange capacity (CEC) (Liu et al., 2001). Cations such as Ca, Mg and K (base cations) and acidic cations (H and Al) are commonly exchangeable (Borge, 1997). Research indicates CEC is influenced by soil OM (Hussain et al., 1999) and ash from prescribed burning (Sherman et al., 2005). The CEC of organic matter (OM) is strongly pH-dependent (Bohn et al., 1985). If sufficient variable charge (pH-dependent) exists, the measured CEC of soils extracted with solutions having a higher pH than field conditions will be notably higher than if extracted by solutions at lower pH (Borge, 1997). To have a more consistent measurement, Ca, Mg, K, Al and Na ions can be summed (NH_4OAc extractable) to calculate the effective CEC (ECEC) (Liu et al., 2001).

Management can influence cation exchange capacity. This is commonly the case in Ultisols because of their low base saturation (Boul et al., 2003; Brady and Weil, 2002; Shaw, 2002). Research indicates that forested areas have higher CEC values than cultivated areas (Abbasi and Zafar, 2007; Balesdent et al., 1998; Fesha, 2004). More extractable Al was found in woodland (mixed oak/pine) soils than hayland or row cropping situations in a study conducted by Fesha (2004) in Alabama. Soils under managed loblolly pine plantations have shown low ECEC compared to mixed forest systems (hardwood/pine), hayland and row cropping systems (Fesha, 2004).

Carbon and Nitrogen Pools

Carbon (C) and Nitrogen (N) are important elements for soil formation and development. In particular, the biological soil forming factor is heavily dependent on C and N cycling and availability. "Nitrogen, because of its high demand in the plant and variability within the soil, is the most intensively managed plant nutrient in crop production." (Schlemmer et al., 2005). A healthy, productive soil is very important to maintaining a carbon dioxide balance between soil and atmosphere (Pasztor and Kristoferson, 1990). Carbon has been connected to global climate change (Skinner, 2007) which may cause shifts in ecological patterns (Walther et al., 2002). Tillage systems used in crop production can have more of an effect on soil organic C and N than crop rotation (Wood and Edwards, 1992).

Numerous studies show that no till operations increase soil OM when compared to conventional systems (Cambardella and Elliot, 1992; Rhoton et al., 2002; Wood and Edwards, 1992). This can be explained by rapid oxidation of OM and potential erosion problems due the absence of vegetation (Pasztor and Kristoferson, 1990). Keeping the soil covered with vegetation in intensively managed systems allows more surface soil organic carbon (SOC) to persist than in less intensive systems (Wood et al., 1990). Organic C has been found in higher amounts in uncultivated soils when compared to adjacent cultivated soils (Ashagrie et al., 2007; Blank and Fosberg, 1989; Bronson et al., 2004; Malo et al., 2005). Cultivation of soils can reduce OM levels compared to less disturbed conditions; however, the opposite is true for improved cropping systems that sometimes elevate OM fractions relative to cultivation (Tan et al., 2007). A study conducted on a Typic Kanhapludult in central Alabama found that SOC levels in surface horizons under monocultures of pine were lower than systems with multiple species (Wood et al., 1992). Additions of OM from multiple plant species contributes to the availability of necessary elements and compounds for the promotion of microbial activity (Wood and Edwards, 1992).

Nitrogen availability is partially attributed to soil water content and leaching potential (Schmidt et al. 2002). Wood et al. (1992) suggest that soil organic N loss via NO_3 leaching may result from the control of competing vegetation. Schmidt et al. (2002) suggest that sandy-textured soils are prone to N losses via leaching below the root zone which can reduce yield potential. Average N loss in the upper six inches of cultivated plots (<100 yrs) has been shown to be nearly 30% when compared to virgin prairie soils (Anderson and Browning, 1949). Wood et al. (1992) found that organic N levels of surface soils (0-5 cm) to be considerably lower in monocultures (pine only communities) relative to more diverse plant communities. This suggests cultivation can negatively affect N levels of natural systems.

Nitrogen management can potentially be improved in fields that show variability of available N (Schmidt et al. 2002). Research by Wood et al. (1990) shows elevated rates of C and N mineralization under more intensive cropping systems after just 3.5 yrs. Research by Follett and Schimel (1989) suggests that soils with reduced tillage are capable of retaining more added N in the organic form as opposed to mineralized N.

Slope position can influence the levels of C and N in a given environment (Wood et al., 1990; Wood et al., 1991). Mixed stands of hardwood, pine and herbaceous vegetation had higher levels of potential C and N mineralization relative to monocultures in a study by Wood et al. (1992). Some research has indicated a relationship between mineralizeable N and soil P (Hue and Adams, 1983; Piatek and Allen, 1999).

The use of prescribed burning is a common practice in pine stands of the southeastern U.S. (Binkley et al., 1992; Lewis, 1974). Fire maintains the open structure of longleaf pine forest and is important in promoting natural regeneration of the dominant tree (Boyer, 1993; Chapman, 1932). Increased nutrient cycling (Biswell, 1989) and microbial activity (Scifres and Hamiltion, 1993) often result from fire exposure. Nutrient concentrations of plant matter ash are generally elevated relative to unburned materials (Raison et al., 1985; Scifres and Hamiltion, 1993). A large portion of N and S are lost through volatilization (Binkley et al., 1992; Christensen, 1993); however, N decomposition from the atmosphere, increased N-fixing plants, and increased N availability from microbial communities help replenish N lost in gaseous forms due to burning (Scifres and Hamiltion, 1993). Severe fires can significantly reduce total organic carbon (TOC) in mineral soils (Brais et al., 2000); however, prescribed fires are generally of low intensity (Carter and Foster, 2004). Sherman et al. (2005) (Maryland Coastal Plain) found prescribed burning increased OM. Other researchers (Alexis et al., 2007) (Florida Coastal Plain) found that burning decreased C and N. A 30-yr prescribed burning study on pine forest of the South Carolina Coastal Plain did not show significant fire effects on soil C or N levels (Binkley et al., 1992).

Particulate organic matter (POM) is mainly composed of plant matter. It is comparable to the light fraction of OM, and is often more sensitive to cultivation and land use change than other fractions (Balesdent et al., 1998; Cambardella and Elliot, 1992; Chan, 2001). Increased crop residue can increase levels of POM (Liebig et al., 2004). Lower Coastal Plain soils tend to have more C and N in the lighter fractions of soil OM (i.e., POM) than finer Piedmont soils (Echeverría et al., 2004). Levels of POM are dependant upon management as well as climate. Uncultivated soils tend to have more POM relative to cultivated soils (Bronson et al., 2004; Cambardella and Elliot, 1992). The type of vegetation overlying the soil greatly influences the quantity and quality of the debris reaching the soil. Gupta et al. (1994) found that POM levels were influenced by the C/N ratio of the retained residue. POM has been identified in relatively high amounts for woodland (mixed hardwood/pine) and hayland depending on geographic location and soil type (Fesha, 2004). In a study conducted in North Dakota, POM was most sensitive measurement out of 13 for an assessment of soil quality (Liebig et al., 2004).

Biological Soil Properties

Soil organisms are vital to decomposition and cycling of plant and animal materials in soils; however, the exact role of soil biological communities in maintaining soil quality is unclear (Turco et al., 1994). Levels of microbial biomass C and N correlate with the concept of soil quality. High levels suggest good quality whereas lower levels indicate poor soil conditions (Duxbury and Nkambule, 1994). Microbial biomass measurements can be used for comparison of microbial populations on a relative scale (Turco et al., 1994). Organic substrates that microbial communities rely on for growth can be temporarily elevated; therefore, the potential for reporting false levels is present (Duxbury and Nkambule, 1994). The size of the ecosystem (e.g., landscape position, soil depth zones) should be taken into consideration when considering microbial status of soil for quality interpretations (Turco et al., 1994).

In general, surface horizons show elevated levels of microbial biomass C relative to subsurface soils (Feng et al., 2003; Fesha, 2004). Gupta et al. (1994) reported lower levels of biomass C in plots where crop residues were burned compared to treatments that retained residues for extended periods. Surface soil layers are closer to the air/soil interface; therefore surface interactions can easily alter biological communities. Increased biological activity has been shown with increased soil disturbance by logging machinery (Lister et al., 2004). However, other researchers (Feng et al., 2003; Follett and Schimel, 1989) have found microbial respiration rates generally decrease with increased cultivation. Research by Wood et al. (1992) suggests that microbial activity, based on potential C mineralization, increases with the presence of herbaceous vegetation in plant communities of pine. Some research has found mixed forests of hardwood and pine had higher levels of microbial biomass C in surface soils (0-5 cm) compared to hayland and row crop management (Fesha, 2004).

Physical Soil Properties

Near-surface soil physical properties can be altered by human manipulation; however, many physical properties are determined by genetic soil properties. Research has indicated that physical properties are sensitive to tillage and other disturbances (Busscher et al., 2006; Hartemink, 1998; Xu et al., 2002). Soil particle size distribution is an inherent, relatively static physical soil property (likely one of the most stable) (Arshad et al., 1996; Carter, 2002). Unlike soil texture, other physical properties of soils are more susceptible to change by management and can indicate changes in soil condition (e.g., bulk density, infiltration rate) (Blanco-Canqui et al., 2005; Hartemink, 1998). However, a study conducted on the Coastal Plain of South Carolina showed that mixing of the soil surface by logging machinery did not affect the measured soil physical properties when compared to unlogged adjacent sites (Lister et al., 2004). Duffera et al. (2007) suggest soil physical properties could be used to describe field-scale variability if separated into two separate categories: 1) particle size distribution, soil water content, plant available water, cone index, and 2) bulk density (ρ_b), total porosity, and saturated hydraulic conductivity (K_{sat}).

A soil's bulk density is defined as "the mass of dry soil per unit bulk volume" (Soil Science Society of America, 2001). The ρ_b can change relatively rapidly, therefore ρ_b can be viewed as 'red flag' indicator of overall soil quality (Brady and Weil, 2002). Bulk density (ρ_b) is a dynamic property of the soil that varies with the physical condition of the soil structure, and it can be an indicator of soil compaction (Arshad et al., 1996). Compaction is important when considering root growth and water movement. Research by Rhoton et al. (2002) suggests that runoff variability in no-till treatments can be attributed to $\rho_{b.}$

Variability of surface soil ρ_b is often more pronounced relative to vertical differences. Blank and Fosberg (1989) and Sarrantonio et al. (1996) found ρ_b values of surface soils were lower in native, uncultivated soils than in cultivated sites. Research by Fesha (2004) conducted in a 40-50 yr. old mixed forest of mostly oak and pine showed that ρ_b of surface soils (0-5 cm) were lower (by ≥20%) when compared to adjacent conventional tillage (~12 yr.), no-tillage (~12 yr.) and hayland (~22 yr.) locations. In a study conducted by Bauer and Black (1981), the average ρ_b of cropland and grassland increased with increasing soil depth. Liebig et al. (2004) found ρ_b to be affected by soil tillage and crop sequence at 7.5-15 cm.

Soil ρ_b and organic C tend to have an inverse relationship (Liebig et al., 2004; Mzuku et al., 2005; Rhoton et al., 2002). Thus, increasing organic C via methods of conservation tillage systems can potentially lower ρ_b in surface soils. In areas under timber harvesting, heavy machinery such as skidders can affect soil properties. Harvests of established loblolly pine (20-25 yrs) in South Carolina increased the ρ_b of soils compared to pre-harvest conditions, with the most significant increases in wet harvest situations (Xu et al., 2002).

Soil strength is very important for engineering use of the soil (Brady and Weil, 2002). Root growth has been shown to decrease with increasing soil strength (Botta et al., 2006; Busscher and Bauer, 2002), and crop yield is negatively correlated with soil strength (Abu-Hamdeh, 2003; Botta et al., 2006). Water content is a key factor in soil strength determination and interpretation (Brady and Weil, 2002; Busscher, 1990). The use of equations to correct measured cone index values for water content can help quantify differences in management practices (Busscher et al., 1997). A study conducted by Busscher et al. (2006) on Coastal Plain Ultisols showed that cone indices measured with a cone-tipped penetrometer were consistently lower in soils that had been treated with a deep till device (subsoiler or paratill) when compared to soils not receiving deep tillage. The same study showed that disking nearly eliminated the differences in soil strength among tillage systems. Botta et al. (2006) and Abu-Hamdeh (2003) found that deep tillage reduces soil compaction in Argentina and Jordan soils. Blanco-Canqui et al. (2005) found that cone indices were significantly higher in cultivated soils relative to pasture and forest soils in central Ohio.

A soil aggregate is "a group of primary soil particles that cohere to each other more strongly than to other surrounding particles" (Soil Science Society of America, 2001). Soil structure is influenced by the degree of aggregation. Stable aggregates can better withstand factors such as erosion and compaction and facilitate water movement. Levy and Miller (1997) indicated that clay content and clay type affect aggregate stability (AS). Arshad et al. (1996) suggest clay type in addition to OM, wetting and drying, freezing and thawing, electrolytes affecting colloidal dispersion, biological activity, and cropping systems affect AS. Aggregation binds particles with substances derived from root exudates and microbial activity (Soil Science Society of America, 2001). Water stable aggregates within soils under loblolly pine plantation management (~15 yr.) were found to be higher in Alabama Coastal Plain soils compared to those under tillage (Fesha, 2004). Cultivated soils generally have fewer aggregates than virgin prairie soils (Anderson and Browning, 1949). Soils under no-tillage corn and cotton had significantly higher AS than the same crops under conventional tillage in surface soils of Mississippi and Ohio (Rhoton et al., 2002). Ashagrie et al. (2007) found that 26 years of continuous cultivation reduced water stable aggregates relative to natural forest. Most of the differences were attributed to tillage, type of OM, and mycorrhizal hyphae. The same study found that most differences in management were found in macro-aggregates rather than micro-aggregates.

The degree to which a soil is disturbed can sometimes be inferred through soil structure. Lado et al. (2004) suggest that soil structure can be degraded by three mechanisms: 1) clay dispersion, 2) swelling and, 3) slaking. Slaking refers to breakdown of soil peds in the presence of water facilitated by trapped gases. Research by Lado et al. (2004) indicates that soils higher in OM are more resistant to slaking of aggregates (<6-mm) than soils with lower OM. Organic matter influences K_{sat} due to increased AS (better structure) (Lado et al., 2004). Similarly, the susceptibility of soils in humid areas to crust formation, decreased permeability, and runoff has also been linked to AS (Levy and Miller, 1997). Effective management should strive to increase the development of aggregates in soil to improve soil physical properties.

Another soil property related to soil aggregation is water dispersible clay (WDC). This soil property is important to erosion and is highly correlated with total clay (Brubaker et al., 1992; Igwe, 2005). The ratio of WDC to total clay has been reported as both positively (Igwe, 2005) and negatively correlated to SOC (Shaw et al., 2002; Rhoton et al., 2002). Shaw et al. (2002) found higher amounts of WDC resulting from increased mixing of soil from tillage. Conventional tillage systems have been shown to have increased water dispersible clay compared to hayland and woodland (Fesha, 2004). Rhoton et al. (2002) showed that no till management had lower WDC than similar soils under conventional tillage, and soils under no till management were more responsive to changes in SOM compared to similar soils under conventional tillage. The same study showed that WDC and aggregate stability were inversely related (Rhoton et al., 2002). Research by de Azevedo and Schulze (2007) suggested WDC was released from larger aggregates in the soil. They further suggested that land management indirectly affects WDC by altering the size fractionation of aggregates in a given soil.

"Soil physical tests should include *in situ* measurements, such as infiltration, that can reflect the soil condition in place without disturbance" (Granatstein and Bezdicek, 1992). The rate at which water enters the soil surface is the water infiltration rate (IR). Methods of IR measurement include ring (Bouwer, 1986) and sprinkle infiltrometers (Touma and Albergel, 1992). The Cornell Sprinkle Infiltrometer (Ogden et al., 1997) is a drop-forming rainfall simulator that uses coiled capillary drip tubes and a bubble tube to produce uniform rainfall rates to a desired area. Hydraulic head settings of the infiltrometer device can be used to approximate desired rainfall intensities (Ogden et al., 1997). To ensure that soils can be compared to one another, infiltration measurements should be made when soils have similar water content. Field capacity is the ideal moisture content level for measuring IR (Lowery et al., 1996). Variation in readings can be attributed to friction of coiled tubes (vs. theoretically straight), water quality, and non-uniformity of coils. Other factors affecting the IR measurement include water temperature and whether or not the simulator is level (Ogden et al., 1997).

Surface cover influences the infiltration of water (Brady and Weil, 2002). Soil organic carbon and water stable aggregates also influence IR. Compared to hayland and row cropping systems, woodland areas (loblolly pine ~15 yr. and mixed oak/pine forest~40-50 yr.) had higher IR in a study conducted by Fesha (2004). Hartemink (1998) found higher IR in natural grassland and inter-row sugar cane relative to between row measurements. The same study also noted decreased variation in measurements with increasing measurement time. Blanco-Canqui and Lal (2007) found that IR did not differ with increased application of wheat straw in uncropped no-till plots after 10 years. A study by Mallik et al. (1984) found that burning decreased IR significantly for 3 years when compared to adjacent unburned plots.

The movement of water through soils is of importance for determining land use capability, water and nutrient cycling processes, and pesticide movement. Hydraulic conductivity is an indicator of a soil's ability to transmit water through the porous system (Amoozegar, 1992). Darcy's law expresses the water flux in a one-dimensional soil system as

$$q_w = -K(dH/dz)$$

where q_w is the soil water flux (L/T), K is hydraulic conductivity (L/T), H is the hydraulic head (L), and z vertical distance (L) (Wagenet, 1986). For an accurate measurement of saturated hydraulic conductivity (K_{sat}) , *in situ* measurements are recommended with borehole permeameters (Lowery et al., 1996).

Blanco-Canqui and Lal (2007) found that mulching significantly increased K_{sat} for intact soil cores in surface soils (0– 3cm), but not for lower depths. The expected increase of *in situ* IR was not found in the same study. Results from studies in Alabama (Appalachian Plateau and Coastal Plain) showed that woodland areas had greater hydraulic conductivity than hayland and row cropping systems (Fesha, 2004). A study on northern Missouri Alfisols showed K_{sat} was higher in buffer areas (agroforestry and grassland) compared to row cropped sites (Seobi et al., 2005). Timber harvest can significantly reduce the hydraulic conductivity (initially unsaturated) of underlying soils, especially when soils are trafficked when wet (Xu et al., 2002).

Another indicator of soil quality is water retention or available water holding capacity. The composition of the soil dictates its ability to hold water, and increased water content can be attributed to increased levels of organic C, silt and clay (Mzuku et al., 2005). Management can affect levels of organic C, which can consequently affect the soil's ability to retain water. Soil water retention has been shown to be lower for conventional tillage operations than for woodland, hayland and no-till systems (Fesha, 2004). Seobi et al. (2005) found that surface soils of buffer strips (agroforestry and grassland) had higher water content relative to row crop sites at low pressures (0 to –0.4 kPa). The same study showed that row crop sites had higher water content compared to buffer areas at lower depths (30–40 cm) at higher pressures (–1.0 to –20.0 kPa). A study conducted in northeastern Scotland found that burned plots retained more water than unburned sites compared at similar tensions (Mallik et al., 1984).

Conclusions

Increases in global populations require manipulation of the soil. Paddock et al. (1986) suggest that all life forms are a part of a great cycle, and all organisms serve a niche necessary for that cycle to function properly. They further suggest farmland, the primary human habitat, is rapidly diminishing in quantity and quality. It is true that human intervention can dramatically affect the soil, and both positive and negative effects occur (Norfleet et al., 2003); however, factors that affect a soil's state (human-induced and natural) are not constant. As a result, different management strategies are necessary to sustain soils of specific regions (Karlen et al., 1992).

Fesha (2004) suggested that agricultural row cropping systems were of lower quality compared to woodland and hayland in southeastern U.S. soils, supporting the concept that less human disturbance improves soil quality. Soil quality can be improved by "increasing infiltration, macroporosity, aeration, biological activity, water holding capacity, aggregate stability, SOC and decreasing bulk density, runoff, erosion, nutrient losses" (Granatstein and Bezdicek, 1992). By integrating both inherent and dynamic soil properties, improved understanding of management effects on soil properties can be obtained (Norfleet et al., 2003).

It is difficult to determine if the soil has improved, deteriorated, or been unaffected by management (Granatstein and Bezdicek, 1992); however, quantifying what Arshad and Coen (1992) call 'key attributes' of soil quality (physical, chemical and biological properties), enables comparison of soils. These soil properties are dynamic compared to such things as climate and geology, and can sometimes be challenging to quantify. Some indicators of soil quality include microbial biomass (diversity and activity), C and N content and dynamics, nutrient availability, soil structure, water infiltration and crop yield (Granatstein and Bezdicek, 1992). Paddock et al. (1986) suggest that an ethical approach to farmland requires only using amounts of land essential for subsistence and building back 'damaged' land or allowing it to fix itself. The current quality of a given soil can have an impact on what land use is possible and to what extent sustainability and productivity are possible (Turco et al., 1994). In order to know if the condition of a given soil is normal, an understanding of land use effects on dynamic soil properties is imperative.

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II. LAND MANAGEMENT EFFECTS ON SOIL CHEMICAL AND BIOLOGICAL PROPERTIES OF SOUTHEASTERN U.S. COASTAL PLAIN ECOSYSTEMS

Abstract

The soil resource is an integral part of sustainability, and management dependent properties describe dynamic soil quality. However, comparisons of disturbed to reference sites are not extensive in the southeastern U.S. due to scarcity of undisturbed land. Objectives of this study were to evaluate land use and management effects on dynamic soil properties of southeastern soils and investigate carbon stocks and soil quality of mature longleaf (*Pinus palustris* Miller) – wiregrass (*Aristida stricta* Michx.) habitat relative to more intensively cultivated Coastal Plain ecosystems. Sites in Thomas County, GA, representing three soil map units (sandy surfaces with loamy to clayey kandic subsurface horizons) were selected in each of three management systems for comparison of near surface (0–5, 5 –15, and 15–30 cm) soil chemical and biological properties. Land use included mature longleaf pine–wiregrass habitat (LL), slash pine (*Pinus elliottii* Engelm.) plantation (PP), and conventional row cropping systems (RC). Concentrations of microbial biomass C (0–5 cm) in LL were 9 and 69 % higher in PP and RC, respectively, while total organic C was 37 and 138 % higher in LL relative to PP and RC, respectively. Stratification of C pools was greatest in forested sites, and longleaf sequestered 13 and 64 % more total organic C than planted pine and row crop sites respectively. Potentially mineralizeable C (0–30 cm) was greatest in PP and potentially mineralizeable N was greatest in RC. Anthropogenic inputs were evident in RC (0–30 cm) based on higher total organic N (9 and 31 % >LL and PP), exchangeable Ca (23 and 102 % >PP and LL) and K (100 and 433 % >PP and LL), extractable P (165 and 1700 % >PP and LL), and base saturation (46 and 142 % >PP and LL). More intensive cultivation resulted in decreased C stocks and increased nutrients of cultivated relative to uncultivated sites.

Introduction

Several components have been recognized as indicators of soil quality including physical, chemical, and biological properties (Karlen et al., 1992). A review by Doran and Parkin (1994) concluded that soil quality is the capacity of a soil to function. Karlen et al. (1992) defined soil quality as “the ability of the soil to serve as a natural medium for the growth of plants that sustain human and animal life.” Several researchers have proposed a minimum data set of soil properties for use in soil quality assessment (Doran and Parkin, 1994 and 1996; Larson and Pierce, 1994).

Land use or management can have an impact on the overall state of dynamic soil properties. However, there are not predetermined standards by which to judge individual soils (Sarrantonio et al., 1996). Dynamic soil properties are those incurred on a human time scale of decades or centuries (Smeck and Olson, 2007) in response to use and management (Carter, 2002). Thus, management dependent soil properties are sensitive to shifts in land management practices. Soil quality can be linked to sustainability by interrelations of management dependent properties and production stability (Larson and

Pierce, 1994). Proper management of soil resources is the only way to truly maintain a sustainable agricultural system.

In order to evaluate sustainability or quality of a management system, it is useful to employ a comparative assessment (Larson and Pierce, 1994) to a natural or relatively undisturbed ecosystem (Sarrantonio et al., 1996). Natural limits of some soil properties may also be estimated from undisturbed ecosystems (Sarrantonio et al., 1996). Prior to European settlement, longleaf pine habitat dominated an estimated 30 million hectares of the southern U.S with an additional 7 million hectares in mixed stands (Frost, 1993). Forested land in the southern U.S. was converted to agricultural land around the turn of the twentieth century (Hamdar, 1993). Decimation of the longleaf by logging and turpentining began in the mid 1800s, and today only 3 percent of the original acreage remains (Frost, 1993). In the eastern Coastal Plain, longleaf – wiregrass habitat is an important habitat for certain endangered species (i.e., red cockaded woodpecker (*Picoides borealis*), gopher tortoise (*Gopherus polyphemus*) (Engstrom, 1993; Van Lear et al., 2005), and these ecosystems are among the most plant species-rich in temperate regions (Brockway et al., 2005).

Longleaf pine forests require frequent fire to maintain appropriate habitat structure and species composition. In addition, burning facilitates natural regeneration of longleaf pine because it exposes mineral soil and controls vegetation that may out-compete seedlings (Boyer, 1993; Chapman, 1932). The use of prescribed burning is a common practice in pine stands (Binkley et al., 1992; Carter and Foster, 2004). In as little as one year on mesic sites, wiregrass-dominated ground layer can accumulate a thick layer of litter that is particularly prone to fire (Chapman, 1932), allowing for frequent, evenly burned surfaces (Outcalt et al., 1999).

Over a wide range of ecosystems, burning can affect the chemistry of surface soils by impacting nutrient cycling (Biswell, 1989) and microbial activity in addition to altering water availability (Scifres and Hamiltion, 1993). Aside from nitrogen (N) and sulfur (S), nutrient concentrations of plant matter ash are generally elevated relative to unburned materials (Raison et al., 1985; Scifres and Hamilton, 1993). Most N loss occurs via ammonia (NH_3) volatilization (Christensen, 1993; Gray and Dighton, 2006). However, N deposition from the atmosphere, increased N-fixing plants, and increased N availability from microbial communities help replenish N lost in gaseous forms due to burning (Scifres and Hamiltion, 1993).

Carbon and N are often related to soil quality assessment (Bronson et al., 2004; Cambardella and Elliot, 1992; Fauci and Dick, 1994; Wood et al., 1992). Measurements of soil chemical properties are quite consistent (Granatstein and Bezdicek, 1992), and are often employed by researchers to evaluate management effects (Anderson and Browning, 1949; Binkley et al., 1992; Hussain et al., 1999). Distribution of organic C and N by either size or density fractions has been correlated with mechanical disturbance of soil (Balesdent et al., 1998; Cambardella and Elliot, 1992; Chan, 2001). Soil tillage in crop production can have more of an effect on soil organic C and N than rotation (Wood and Edwards, 1992). Particulate organic matter (POM) is thought to be protected by macroaggregates of minimally disturbed soils (Tan et al., 2007), and is a sensitive measure of soil quality (Liebig et al., 2004). Research has indicated that increased cultivation reduces particulate organic matter (POM) in soils of the Alabama Coastal Plain (Fesha, 2004).

Properties of soil are functionally related (Jenny, 1941), thus, categorization of soil properties can lead to a better understanding of a soil's state. The portion of the solum most affected by land use and management is the surface (Blank and Fosberg, 1989; Liebig et al., 2004; Wood et al., 1991; Wood and Edwards, 1992). Franzleubbers (2002) proposed a stratification ratio relating the depth distribution of certain soil properties for evaluating soil quality. The use of ratios has also been suggested for improved understanding of soil condition (Granatstein and Bezdicek, 1992).

The soil resource is an integral part of sustainability. Heterogeneity of soils is compounded by temporal variability resulting from both anthropogenic and natural processes. Land management decisions impact soil quality (Arshad and Coen, 1992), and comparisons of disturbed soils to reference sites are not extensive in the southeastern U.S. due to scarcity of undisturbed land. Evaluation of relationships between management dependent and inherent soil properties can potentially improve ecosystem management and soil interpretation (Norfleet et al., 2003). Additionally, an improved understanding of temporal soil variability can be useful for C sequestration efforts and longleaf restoration. Further understanding of management dependency of soils can also contribute to development of a minimum data set for soil quality.

Our objectives were to evaluate land use and management effects on dynamic soil properties, carbon stocks, and soil quality of mature longleaf-wiregrass habitat compared to more intensively cultivated Coastal Plain ecosystems. Relationships between management dependent soil properties were also evaluated for improving ecosystem management and soil interpretations of typical southeastern soils.

Materials and Methods

Management Systems

Land use impacts on soils in Thomas County, Georgia (Fig. 1) were determined by soil map unit and land use during 2005 – 2007. The experiment design was a randomized complete block with land use as the main treatment being replicated in three blocks of soil type. Land use included longleaf, planted pine, and row crop. Depth was a factor for some measurements and was properly accounted for by the model. Descriptions of the three land use systems are as follows:

Longleaf (LL) consists of mature, multi-aged longleaf pine forest (trees ranging in age from seedlings to 200+ yrs) with native groundcover of grass, legume, and composite species, [i.e., wiregrass]. The area has been prescribed burned once every 1–2 years for at least the last 75 years. Pines are replenished by natural regeneration, and the canopy is generally open. Soils have been subjected to minimal surface disturbance (i.e., no plowing).

Planted pine (PP) consists of a 22 year old planted slash pine stand in the first rotation managed for poles and/or saw timber. The area has been subjected to infrequent fire and mechanical treatment, with the most substantial soil disturbance taking place during site preparation.

Row crop (RC) has been in continuous cropping for 30–35 yrs with a rotation of corn (*Zea mays*) – peanut (*Arachis hypogaea* L.) – soybean (*Glycine max* (L.) Merr.) (some years fallow). Soils are under conventional tillage management with major soil disturbance (e.g., plowing, disking, cultivating, harvesting) taking place annually.

Pedon Selection and Characterization

Selection of sites involved the use of soil survey, digital ortho-quadrangle maps, and extensive ground-truthing. Prospective soils at the sites were described, sampled by horizon, analyzed in the laboratory, and classified to the family level according to Soil Taxonomy (Soil Survey Staff, 2003). Laboratory analyses included particle size determination by the <2-mm pipette method following soil organic matter removal with hydrogen peroxide and dispersion with sodium hexametaphosphate (Kilmer and Alexander, 1949), cation exchange capacity (CEC) and base saturation (Ca, Mg, K and Na) by the ammonium acetate method (pH 7) using an auto extractor (Soil Survey Investigation Staff, 2004), extractable aluminum (Al) using 1M KCl (Soil Survey Investigation Staff, 2004) (Al concentrations were determined via titration) and effective CEC (ECEC) by combining extractable Al with exchangeable bases (Soil Survey Investigation Staff, 2004).

Table 1 shows family classification of the soils evaluated (nine pedons total). For this study, Kandiudults (clay content does not decrease ≥ 20 % relative to the maximum within 1.5m) and Kanhapludults (clay content does decrease ≥ 20 %) were considered equivalent.

Field Sampling Procedures

Nine pedons (Table 1) from Thomas County, Georgia were sampled in 2006 and 2007 for chemical, biological, and physical analyses. Organic horizons were sampled in forested sites (three 0.25 m^2 quadrats), and the same horizons were removed before taking mineral soil samples. Composite soil samples (twenty cores taken with hand probes) were taken from three depths (0–5, 5–15, and 15–30 cm) before being transferred to cool storage for transport. Bulk density samples (three at each site) were obtained using a slide hammer with cylinder sleeves to collect samples from 0–5, 5–15, and 15–30 cm depths at each field location. Bulk density samples were dried at 105 °C for 48 hours before being weighed, and calculations made according to Blake and Hartge (1986).

Laboratory Procedures

Field moist samples were sieved (2 and 4 mm for mineralizeable C and N and microbial biomass C, respectively) to remove plant materials and other debris. Soil microbial biomass C was determined by the chloroform fumigation-incubation technique developed by Alef and Nannipieri (1995). Samples (25 g on dry weight basis) were pre-incubated at 50 % of water holding capacity for 5 days (25°C), fumigated with chloroform, and incubated for 10 additional days in the presence of a 1 *M* NaOH trap (5 ml). Evolved CO_2 was determined by acid titration (0.25 *M* HCl) in the presence of excess 1.5 *M* $BaCl_2$.

Potentially mineralizeable C and N (C_{min} and N_{min} respectively) were determined using techniques described by Wood et al. (1992). Cool, moist, sieved samples were weighed into plastic containers and brought to 85 % field capacity. Containers were placed in 1 quart mason jars with 20 ml of distilled water and a 1*N* NaOH (8 ml) CO_2 trap. Jars were incubated for 31 days at 25 °C (Anderson, 1982). Soil nitrate-N (NO_3- N) and soil ammonium-N (NH_4-N) were extracted with 2 *M* KCl and determined colorimetrically using a microplate method (Sims et al., 1995). Inorganic N fractions were determined before and after incubation for the treated soil. Evolved CO_2 was determined by acid titration (1*N* HCl) of the excess base in the traps following the addition of 4 ml of 1*M* $BaCl_2$ (Anderson, 1982). Soil total organic C (TOC) and total organic nitrogen (TON) were determined by the dry combustion method with a Tru Spec CN (St. Joseph, MI) (Yeomans and Bremmer, 1999).

Potentially mineralizeable N was calculated as the difference between final NO_3-N plus NH_4-N and initial NO_3-N plus NH_4-N (Wood et al., 1992). Potentially mineralizeable C was calculated as the difference between CO_2-C captured in the average of six blanks and respective samples (Anderson, 1982). Carbon turnover and relative N mineralization was calculated as the ratio of C_{min} and N_{min} to TOC and TON respectively.

Air dried samples were used to determine particulate organic matter C and N (> 53 µm) by the soil dispersion and wet sieving method outlined by Cambardella and Elliot (1992). Mineral-associated C and N (< 53 µm) were determined by difference (i.e., TOC or N – POMC or N).

Organic horizons (O) were air-dried and weighed, thoroughly mixed, and sampled for analysis of TOC and TON by dry combustion (LECO CN-2000). Two grab samples were taken from each field sample, and values were averaged to represent the sample.

Chemical analyses of mineral soil samples for the three depths were performed on air-dried samples (< 2 mm). CEC and base saturation (Ca, Mg, K and Na) were determined by the ammonium acetate (pH 7) method (bases read with Atomic Absorption Spectroscopy) (Soil Survey Investigation Staff, 2004). Extractable aluminum (Al) was determined using 1M KCl, and Al concentrations were determined via titration (Soil Survey Investigation Staff, 2004). Effective CEC (ECEC) was determined by combining extractable Al with exchangeable bases (Ca, Mg, K, and Na) (Soil Survey Investigation

Staff, 2004). Mehlich 1 extractable nutrients (P, Fe, Mn, Zn, Cu, and B) were determined via the method outlined by Hue and Evans (1984). Soil pH was measured in 1:1 (w/v) soil to water and 1:2 (w/v) 0.01 *M* $CaCl_2$ (Soil Survey Investigation Staff, 2004).

Statistical Analysis

Analysis of variance was performed on raw data using version 9.1 of SAS to test main effects and interactions (SAS Institute Inc., 2003). Where depth was a factor, data were analyzed using PROC GLM as a split plot with management as main plots and depth as subplots. Parameters without a depth factor were analyzed using PROC GLM as a randomized complete block with soil as the blocking factor. All statistical tests were made at the $\alpha = 0.10$ significance level.

Results and Discussion

Soils

Soils investigated in this study were similar with respect to the parent material, climate, and landscape position. Each management system possessed soils with a range of inherent soil properties (loamy to fine particle size families) representing well-drained, acid, low activity, upland soils of the southeastern Coastal Plain. Eight of the nine pedons classify as Ultisols, while one soil classifies as an Alfisol (Table 1). The high base saturation (BS) (>35 %) in the lower portion of the Alfisol was influenced by anthropogenic amendment additions (e.g., Ca in lime and gypsum applications), and was considered to be a 'cultural Alfisol.' As a check, a pedon in an adjacent wooded area (less cultivated) was sampled and analyzed, and classifies as an Ultisol. We utilized natural boundaries of the soils for blocking to improve comparison among treatments (Mead et al., 2003); therefore, differences between soils were assumed to reflect management practices.

In this study, C and N pools, and base cations were reported and analyzed as concentrations (mg kg^{-1}) and masses (kg ha^{-1}). Concentrations are commonly reported units of such measurements and are important for comparison to other studies. Accounting for soil bulk density in measured chemical and biological measurements allows for more complete analysis of C and N stocks that indicate C sequestration potential. Additionally, base cations reported as mass provide data important for estimating availability of nutrients for plants. Throughout the discussion, references to both concentrations and masses are made.

Total Organic Carbon and Nitrogen

The addition of organic horizons of the forested sites to the 0–30 cm mineral soil depth values did not result in significant management effects on mass of TOC or TON. There was a trend for TOC to decrease with increased tillage (Fig. 2). There was also a trend for increased TON under row crop management relative to forested sites, even with the inclusion of organic horizons for forested sites (Fig. 2).

Stratification of soil TOC concentrations was significantly greater (i.e., higher concentrations in surface soils relative to lower depths) in longleaf management compared to planted pine and row crop sites (Fig. 3). Similarly, stratification of TON was significantly higher in longleaf management relative to row crop management, with planted pine being intermediate. Planted pine and row crop sites had similar TOC stratification, and all managements had similar stratification ratios of TOC and TON.

The C:N of mineral soil was significantly affected by management (ratios ranged from 16 to 37) (Table 2). Our results are in agreement with Ashagrie et al. (2007), who found that tillage significantly narrowed the C:N ratio of mineral soil in forested sites (after 26 years). Forested sites had similar ratios, but C:N values for row crop sites were approximately half of the forested sites for all depths.

Organic C concentrations in soils under longleaf management (unplowed) were higher than those in cultivated soils (Fig. 4), similar to findings of other researchers (Ashagrie et al., 2007; Blank and Fosberg, 1989; Bronson et al., 2004; Malo et al., 2005). Total organic C and N concentrations (Figs. 4 and 5) found in forested sites were higher than those found by Wood et al. (1992), but similar to values reported by Echeverría et al. (2004) in Coastal Plain soils under pine. Soil tillage is likely the main factor responsible for lower TOC and TON in our study, as this increases both oxidation of OM and erosion potential (Pasztor and Kristoferson, 1990).

Anderson and Browning (1949) found that average N loss in the upper 15 cm of cultivated plots was nearly 30 % when compared to virgin prairie soils; we found cultivation did not significantly affect TON in surface soils (0–5 cm), and actually increased subsurface N levels relative to the surface. This is likely due to the N inputs to row crop sites as applied amendments and legume species (peanuts and soybeans) (Fig. 5). A portion of the N differences may be attributed to N loss via NH_3 volatilization in the forested sites subjected to prescribed burning (Binkley et al., 1992; Gray and Dighton, 2006; Raison et al., 1985). The diversity of vegetation under longleaf may contribute to increased TOC and TON levels relative to the planted pine stands, where undergrowth was managed. This is similar to findings reported by Wood et al. (1992) who found lower organic C and N levels of surface soils (0-5 cm) in pine monocultures compared to more species-rich hardwood-loblolly communities.

Mineral and POM Fractions of Total Organic Carbon and Nitrogen

Particulate organic matter (POM) is the fraction of soil organic matter mainly composed of plant matter, and C and N in Coastal Plain soils has been shown to concentrate in POM (Echeverría et al., 2004). Similar to other studies (Ashagrie et al., 2007; Balesdent et al., 1998; Bronson et al., 2004), POM fractions in this study were influenced by management. Our results (Figs. 4 and 5) were in agreement with other researchers (Bronson et al., 2004; Cambardella and Elliot, 1992), who found the fraction of total organic C and N consisting of POMC and POMN was greatest in virgin, uncultivated land. The fraction of POMC found in the forested sites (0–5 cm) in this study (74 %) was similar to what Echeverría et al. (2004) found in Lower Coastal Plain pine plantations. Similar to our study, Hussain et al. (1999) found that POM made up a smaller portion of organic N than organic C.

Mineral-associated fractions (<53 μm) of C were significantly affected by management in the surface (0–5 cm), with longleaf higher than row crop sites (Fig. 4). Mineral-associated N was not affected by management (Fig. 5). Particulate fractions (>53 μm) of C and N were significantly different for individual depths ($P < 0.001$) (g kg^{-1}). Forested sites had more than twice the POMC of row crop sites in the surface, but lower depths showed no significant management effects (Fig. 4). Longleaf POMN was significantly higher (19 %) than planted pine in the surface (0–5 cm). Forested sites had nearly undetectable levels of POMN in the 15–30 cm depth.

Stratification of POM fractions of C and N are shown in Fig. 3. Management significantly affected stratification of POMC, with the largest ratio in longleaf followed by planted pine and row crop management. We found that increased soil tillage reduced stratification of POM fractions similar to results by Franzluebbers (2002). Longleaf and row crop managements showed similar stratification of POMN. It is likely that increased diversity of plant residues being returned to the soil contribute to higher POM fractions. This may provide some explanation for elevated POMC in forested sites that have more diverse plant communities compared to the cultivated sites (Fig. 4).

Microbial Biomass Carbon

Greater microbial biomass suggests good soil quality (Duxbury and Nkambule, 1994). In both 2006 and 2007, microbial biomass C was influenced by interaction of depth and land use indicating that microbial biomass C did not change similarly with depth among land uses. Our data are in agreement with Feng et al. (2003) and Fesha (2004), who found microbial biomass C and soil depth were inversely related. Forested sites generally had higher microbial biomass C than row crop sites, and longleaf had higher levels than planted pine to a depth of 15 cm (mg kg^{-1}). Increased cultivation decreased microbial biomass C levels, as other researchers have found (Feng et al., 2003; Follett and Schimel, 1989; Karlen et al., 1996).

Stratification ratios (0–5 to 15–30 cm depths) of microbial biomass C were highest for longleaf management in both years (Fig. 3). For 2007, data showed stratification ratios for row crop sites were not different ($\alpha = 0.10$) from either longleaf or planted pine management. Longleaf had significantly ($P = 0.098$) more stratification of microbial biomass C than planted pine in 2007. Stratification ratios of microbial biomass

C in this study were larger than those reported by Franzleubbers (2002) for cultivated sites in Texas and Georgia. However, the lower depth of sampling for our sites was 30 cm whereas the former had lower depths of 15 and 20 cm. Less stratification in the cultivated sites possibly resulted from increased biological activity at lower depths due to tillage (Lister et al., 2004).

Potentially Mineralizeable Carbon and Nitrogen

There were not significant management effects on concentrations of C_{min}, but C_{min} significantly decreased with depth (Table 2). Overall, concentrations of C_{min} in surface soils (0–5 cm) were 76 % > than those at 5–15 cm. Potential C mineralization values found in all management systems of this study were more than two times greater than those reported by Wood et al. (1992) for pine communities. Surface (0–5 cm) C_{min} determined for these southeastern U.S. soils was approximately 3 times greater than those found in cultivated sites in eastern Colorado (Wood et al., 1990). Stratification of C_{min} was highest for forested sites, but not significantly different from row crop sites (Fig. 3).

Management ($P= 0.031$) and depth ($P=0.001$) significantly affected N_{min} concentrations, with row crop management having the most potentially mineralizeable N (Table 2). Levels of N_{min} decreased with increasing depth, similar to data reported by Egelkraut et al. (2003) on a Georgia Coastal Plain site. Planted pine sites had the lowest levels of N_{min} and were not significantly different from longleaf sites. We found N_{min} values in row crop management that were generally 3 times > those reported for cultivated sites in northern Alabama (Wood and Edwards, 1992). Stratification ratios of N_{min} were similar across managements with higher values in cultivated sites (Fig. 3).

Piatek and Allen (1999) suggest that decreased N mineralization in 22 year old pines can be associated with assumed lower temperatures of surface soils compared to older stands (36 yr) that allow more solar energy to penetrate the more open canopy. Our data support this concept as our mature longleaf forest consists of a very open canopy. Conversely, the planted slash pines allow less solar penetration resulting in lower temperatures, and therefore, lower N_{min} rates (Table 2). Furthermore, the lack of tall growing vegetation in the row crop sites allows even higher soil temperatures to facilitate N mineralization. In addition, high levels of TON in the row crop sites provide more organic N to be converted to mineral forms (i.e., increased N_{min}). Although our measure of N mineralization reflects only the potentially mineralizeable N (25°C) based on the current substrate, it is possible that some of the long-term, residual field conditions carried over into the laboratory experiment.

The majority of the N_{min} in our study was composed of NO_3-N (data not shown), and highest phosphorus (P) quantities were found in row crop sites (Table 5). These data support findings of Hue and Adams (1984), who suggested low P levels slow nitrification rates. Malo et al. (2005) also found NO_3-N to be higher in cultivated soils when compared to paired non-cultivated soils.

Carbon turnover and relative N mineralization were not significantly different among land uses (Table 2). The range of C turnover was 9 to 28 %, with higher percentages in the surface, and the overall average of investigated sites for all depths was 16 %. There was generally more C turnover in row crop and longleaf management than planted pine. Longleaf sites were highest in relative N mineralization followed by row crop and planted pine (Table 2). Values of relative N mineralization ranged from 1 to 6

%, and generally increased with depth. The ratio of C_{min} to N_{min} was significantly (*P*=0.089) affected by management, and Table 2 shows that more N was available in the row crop sites relative to forested sites. For 0–30 cm depths, planted pine was most void of N_{min} relative to C_{min}. Depth did not significantly affect the C_{min} : N_{min} ratio.

Wood and Edwards (1992) found that rotations had higher long-term biomass production than continuous monocultures, suggesting species diversity may contribute to higher biomass. A diversity of vegetation in a forested ecosystem contributes a multitude of diverse organic material that is broken down at different rates, whereas row cropping systems have vegetation comparable to monoculture systems that produce organic matter that supports a less diverse microbial population. A comparison of C content of forested sites relative to cultivated sites for our sites supports this theory. The species richness of longleaf ecosystems, which are among the most species rich ecosystems in temperate regions (Brockway et al., 2005), may contribute to the elevated C parameters.

Soil pH and Extractable Acidity

Soil pH was significantly affected by both management and depth (Table 3). Row crop management had the highest pH values, while planted pine management was the most acidic (pH= 4.75) (0–30 cm). The pH of both forested sites was significantly lower than row crop sites (*P*= 0.010), similar to findings of Fesha (2004). Our results are in agreement with McCracken et al. (1989) (North Carolina Piedmont) and Blank and Fosberg (1989) (South Dakota), who found that soil pH values of virgin soils were considerably lower than adjacent cultivated soils. Sherman et al. (2005) reported fire-induced changes in pH were only temporary (<1 yr) after first-time prescribed burning; however, longer series of annual fire has been shown to maintain higher pH (Brye, 2006).

We found significant interaction of depth and management for concentrations of extractable Al (Table 3), however, mass of extractable Al was significantly greater in soils under forest compared to row crop sites (0–30 cm) (Table 4). Planted pine had the more Al at 0–30 cm than other managements (Table 4) followed by longleaf and row crop managements. Soil pH and extractable Al were inversely related (Table 3), similar to results reported by Brais et al. (2000) and Binkley et al. (1992). This was similar to data reported by Balesdent et al. (1998), who found soil pH directly affected exchangeable Al. Solid forms of Al begin to precipitate at pH values greater than 5.5, therefore, lime additions in the row crop sites reduced exchangeable Al.

Exchangeable Cations

Extractable bases generally decreased with increasing depth, and row crop management had the highest levels of Ca, Mg, and K (0–30 cm) relative to longleaf and planted pine sites (Tables 3 and 4). Our data are in agreement with other researchers (McCracken et al., 1989; Fesha, 2004), who found higher extractable bases in cultivated soils compared to adjacent virgin soils and uncultivated lands, respectively.

Concentrations of Ca were significantly affected by management ($P= 0.019$) and depth ($P< 0.001$) (Table 3). Row crop management had the highest Ca levels in all depths, with the largest management differences at lower depths. Masses (kg ha^{-1}) of Ca were significantly affected by management ($P< 0.001$) (Table 4). Longleaf had the most stratification of extractable Ca, and Ca decreased with increasing depth for all managements. Total Ca (0–30 cm) in row crop management was 275 % more than longleaf management (kg ha^{-1}), with planted pine intermediate.

Management did not significantly affect extractable Mg concentrations; however, depth was significant (*P*= 0.001) (Table 3). Levels of Mg generally decreased with depth, but cultivated sites increased slightly from the 5–15 to 15–30 cm depths. Cultivated sites had less stratification than the uncultivated longleaf. Total Mg (kg ha^{-1}) (0–30 cm) had significant management effects (*P* = 0.049) with row crop having 6 and 93 % more than planted pine and longleaf sites, respectively (Table 4).

There were significant management (*P*= 0.002) and depth (*P*= 0.001) effects on extractable K concentrations (Table 3). Cultivated sites had more K at all depths, with row crop management having more K than planted pine. Similar to our findings, Hussain et al. (1999) and Abbasi and Zafar (2007) found that K concentrations decreased with increasing depth. We found similar stratification of K between treatments. More intensive management significantly increased exchangeable K (0–30 cm) (kg ha^{-1}) (Table 4). Some researchers have found lower amounts of K in cultivated soils relative to uncultivated sites (Abbasi and Zafar, 2007; Anderson and Browning, 1949; Malo et al., 2005); however, we found the opposite. Data reported by Balesdent et al. (1998) from France indicated cultivation increased K concentrations, which is similar to what we found for these SE Coastal Plain soils.

Mehlich Nutrients

Levels of P concentration showed significant interaction between management and depth (*P*= 0.035) (Table 5). Cultivated sites had higher P levels than uncultivated sites, with row crop management having the highest P concentration at all depths. Row crop management had 1,912 % more P than longleaf in the 0–5 cm depth, and planted pine had 827 % more P than longleaf at the same depth. When evaluated for 0–30 cm, P concentrations in row crop management were 165% > planted pine sites and 1712 % > longleaf sites. Our data support findings of Brye (2006), who found prescribed burning significantly decreased extractable P ($P \leq 0.001$). Thus, extractable P differences between management in our study are assumed to be the result of both fertilizer and fire management.

Boron decreased with depth ($P<0.001$), and differences were not detectable among managements (Table 5). There was significant interaction between management and depth for extractable Cu, Mn, and Zn. More extractable Fe was found in soils with lower pH (forested) than for soils with higher pH (row crop), similar to findings of Shuman and Hargrove (1985). Unlike results of Follett and Peterson (1988) and Shuman and Hargrove (1985), we found that increased cultivation increased extractable Zn. Stratification of Fe, Mn, and Zn was generally more pronounced in longleaf relative to other managements.

Cation Exchange Capacity

A significant interaction between management and depth was observed for CEC ($P < 0.001$) (Table 3). Our results are in agreement with other researchers (Abbasi and Zafar, 2007; Balesdent et al., 1998; Fesha, 2004), who found higher CEC in forested sites compared to cultivated sites. Similarly, we found that highest CEC tended to occur in soils with higher TOC. Longleaf had the highest (6.8 cmol kg^{-1}) and lowest (2.1 cmol kg^{-1}) values of CEC found in all sites. Cultivated sites did not have the stratification of CEC found in longleaf, but mean CEC (0–30 cm) was similar across managements. Sherman et al. (2005) suggested that ash resulting from prescribed burning contribute to elevated CEC levels. This finding is supported by our data and may account for some of the stratification in forested sites. Average CEC was highest in the surface of investigated soils.

An interaction between management and depth for ECEC existed, however, depth effects were much more evident (P = <0.001) (Table 3). ECEC decreased with depth for longleaf and row crop sites, and the highest ECEC for planted pine was at the surface (0-5 cm). Longleaf management had the greatest stratification of ECEC relative to other managements. A study conducted in the Alabama Coastal Plain by Fesha (2004) found that pine plantations had lower ECEC relative to row crop management. A comparison of Longleaf to row crop management supports these findings; however, the ECEC in our study (0–30 cm) was highest in planted pine.

Base Saturation

Percent base saturation was significantly affected by management (P= 0.026) (Table 3). Base saturation (0–30 cm) was highest in row crop management (62.3 %) followed by planted pine (42.4 %) and longleaf (25.7 %). For all depths, row crop sites had more than twice the base saturation of longleaf sites. These results are similar to Fesha (2004), who found % BS in forested locations to be lower than hayland and row crop sites (Fesha, 2004). The elevated BS in row crop sites likely reflects the addition of amendments (e.g., lime, fertilizer), whereas the BS in longleaf and planted pine managements is likely more influenced by plant biocycling. For all managements, the highest % BS was found in the surface soil and significantly decreased with soil depth (P< 0.001). Calcium contributed the most to BS in all soils followed by Mg, K, and Na. In the forested sites, a large portion of the exchange sites were likely occupied by Al [as indicated by the ECEC (Table 3)], which existed in higher quantities and has a greater affinity for negatively charged soil colloids relative to other cations (i.e., Ca, Mg, K, Na). This contributed to the lower BS in longleaf and planted pine managements. Management of soil pH in the row crop sites increased the availability of bases by reducing extractable Al. As a result, the BS in row crop sites was higher than other managements.

Conclusions

Soils investigated in this study were similar with respect to the parent material, climate, and landscape position. Differences in management dependent properties were found in these Coastal Plain sites, with large differences observed for the composite 0-30 depth. The most significant differences were observed for C pools, where longleaf – wiregrass habitat had the highest concentrations of total organic C and particulate organic matter C relative to planted pine and row crop management. In addition, stratification of C pools and total organic N were greatest in longleaf management

Elevated soil bases, nutrients, pH and % base saturation in the row crop sites suggested the influence of amendments. The higher pH of the row crop sites reduced extractable Al, thereby allowing more base cations to be available. Row crop sites (0–30 cm) had 142 and 48 % higher base saturation than longleaf and planted pine, respectively. Soil P levels (0-30cm) in row crop sites were 1712 % > longleaf sites, and Zn levels (0–30 cm) were 338 % higher than longleaf management.

Our study indicated the metrics most sensitive to land management (0–30 cm) were particulate organic matter fractions of C and N, N_{min}, P, extractable Cu, pH, extractable bases, and exchangeable Al. Soil quality is specific to desired goals;

therefore, with respect to C stocks, the longleaf-wiregrass habitat and planted pine management had better soil quality; and the row crop management was better suited to cultivation. Longleaf sequestered 13 and 64 % more total organic C (kg ha^{-1}) than planted pine and row crop sites respectively. Information from this study provides insight about shifts in soil nutrient and C pools resulting from land management practices. Knowledge of soil properties under native longleaf – wiregrass ecosystems can aid longleaf restoration in the southeastern U.S.

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Tables

Table 1. Sample ID, field ID, land use, and taxonomic classification of studied Coastal Plain soils.

Sample ID	Field ID	Land use†	Soil family
LL3	WT1	LL	loamy, kaolinitic, thermic Arenic Kandiudult
RC3	S2	RC	loamy, kaolinitic, thermic Arenic Kandiudalf ‡
PP3	P4	PP	loamy, kaolinitic, thermic Arenic Kandiudult
LL1	WT4	LL	fine, kaolinitic, thermic Typic Kandiudult
RC1	S3	RC	fine, kaolinitic, thermic Typic Kandiudult
PP1	P2	PP	fine, kaolinitic, thermic Typic Kandiudult
LL2	WT2	LL	fine-loamy, kaolinitic, thermic Typic Kanhapludult
RC2	S1	RC	fine-loamy, kaolinitic, thermic Typic Kandiudult
PP2	P3	PP	fine-loamy, kaolinitic, thermic Typic Kandiudult

† LL =Mature longleaf pine habitat, PP= Managed pine plantation, and RC= Conventional row crop.

‡ An Alfisol due to amendment applications (see methods section).

Table 2. Soil microbial biomass C (mg kg^{-1}), potential C and N mineralization (mg kg^{-1}), C turnover, relative N mineralization, C/N mineralized, and C:N of soils for three management systems in the South Georgia Coastal Plain.

Management	Depth	2006 Biomass C‡	2007 Biomass C	C_{min}	N_{min}	C turnover	Relative N mineralization	C/N mineralized	C/N soil
	cm	mg kg^{-1}				%		g g^{-1}	
Longleaf-wiregrass†	0-5	560	522	2014	8.62	19.02	2.4	365	37
	5-15	214	183	920	5.69	9.37	5.83	171	29
	15-30	94	91	857	3.07	27.91	6.19	274	32
	Mean	289	265	1264	5.79	18.77	4.8	270	32
Planted pine	0-5	---	481	2126	6.47	10.78	1	360	31
	5-15	---	156	1294	3.37	16.97	1.59	437	31
	15-30	---	134	775	2.05	12.05	1.29	514	33
	Mean	---	257	1398	3.96	13.27	1.29	437	32
Row crop	0-5	278	309	1876	16.09	18.25	3.57	118	16
	5-15	193	182	1208	10.70	13.96	2.72	113	17
	15-30	77	70	872	4.68	13.71	2.88	193	19
	Mean	182	187	1318	10.49	15.31	3.06	141	17
Management mean	0-5	419	437	2005	10.39	16.02	2.32	281	28
	5-15	203	174	1141	6.59	13.43	3.38	240	26
	15-30	85	98	834	3.26	17.89	3.45	327	28
	Mean	236	236	1327	6.75	15.78	3.05	283	27

ANOVA	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$
Management (M)	0.183		0.074	57	0.706		0.031	3.32	0.55		0.293		0.089	206	0.031	8
Depth (D)	<.001	49	<.001	30	<.001	272	0.001	2.40	0.744		0.755		0.511		0.565	
M x D	0.002	120	<.001	67	0.661		0.313		0.498		0.792		0.581		0.468	

† Longleaf-wiregrass= Mature longleaf pine habitat, Planted pine= Managed pine plantation, and Row crop= Row crop.

‡ 2006 Biomass C= soil microbial biomass for 2006, 2007 Biomass C= soil microbial biomass for 2007, C_{min}= potentially mineralizeable C, N_{min}= potentially mineralizeable N, C turnover= C_{min}/TOC, Relative N mineralization= N_{min}/TON, C/N mineralized= C/N ratio calculated from C_{min} and N_{min}, C/N soil= C/N ratio calculated from TOC and TON concentrations.

Table 3. Cation exchange capacity, exchangeable bases, extractable Al (cmol kg^{-1}), percent base saturation, and pH for three management systems in the South Georgia Coastal Plain.

Management	Depth	CEC7‡	ECEC	Ca	Mg	K	Na	Al	BS	pH
	cm	---------- cmol kg^{-1} ----------							%	
Longleaf-	0-5	6.84	3.13	1.77	0.48	0.05	0.02	0.81	33.8	4.85
wiregrass †	5-15	2.79	1.24	0.44	0.17	0.02	0.01	0.60	24.0	4.90
	15-30	2.07	0.96	0.14	0.15	0.01	0.01	0.64	19.2	4.70
	Mean	3.90	1.78	0.78	0.27	0.03	0.02	0.68	25.7	4.82
Planted	0-5	4.69	2.75	1.89	0.37	0.12	0.03	0.34	51.0	4.86
pine	5-15	3.18	1.91	1.06	0.23	0.06	0.01	0.56	41.9	4.79
	15-30	3.88	2.29	0.89	0.34	0.06	0.02	0.98	33.8	4.60
	Mean	3.92	2.32	1.28	0.32	0.08	0.02	0.63	42.2	4.75
Row crop	0-5	3.46	2.64	1.97	0.43	0.19	0.01	0.03	76.2	5.65
	5-15	3.19	2.06	1.52	0.30	0.18	0.01	0.06	63.2	5.47
	15-30	3.82	1.81	1.24	0.32	0.10	0.00	0.15	47.6	5.17
	Mean	3.49	2.17	1.58	0.35	0.16	0.01	0.08	62.3	5.43
Management	0-5	5.00	2.84	1.88	0.43	0.12	0.02	0.39	53.6	5.12
mean	5-15	3.05	1.74	1.01	0.23	0.09	0.01	0.40	43.1	5.05
	15-30	3.26	1.69	0.76	0.27	0.06	0.01	0.59	33.5	4.83
	Mean	3.77	2.09	1.21	0.31	0.09	0.01	0.46	43.4	5.00
ANOVA		P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$	P>F LSD$_{0.1}$
Management (M)		0.859	0.341	0.019 0.34	0.255	0.002 0.03	0.127	0.053 0.39	0.026 17.2	0.001 0.26
Depth (D)		<.001 0.55	<.001 0.45	<.001 0.36	0.001 0.08	0.001 0.02	0.017 0.01	0.045 0.14	<.001 6.3	<.001 0.08
M x D		<.001 1.79	0.098 0.91	0.393	0.118	0.148	0.391	0.016 0.40	0.546	0.106

† Longleaf-wiregrass= Mature longleaf pine habitat, Planted pine= Managed pine plantation, and Row crop= Row Crop.

‡ CEC7= cation exchange capacity pH 7; ECEC= effective cation exchange capacity; Ca, Mg, K, and Na are NH_4OAc extractable bases; Al is KCl exchangeable Al; BS = base saturation; pH= pH in 1:1 soil:water (v/v).

Table 4. Exchangeable bases and extractable Al (kg ha^{-1}) for three management systems in the South Georgia Coastal Plain.

Management †	Depth	Ca	Mg	K	Na	Al
	cm	----------	----------	kg ha^{-1}	----------	----------
Longleaf-wiregrass	0-30	373	99	31	13	243
Planted pine	0-30	1043	180	128	17	333
Row crop	0-30	1397	191	265	6	44

ANOVA	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$
Management	<0.001	177	0.0494	57	0.001	45	0.1222		0.0521	171

† Longleaf-wiregrass= Mature longleaf pine habitat, Planted pine= Managed pine plantation, and Row crop= Row crop.

‡ Ca, Mg, K, and Na are NH_4OAc exchangeable bases and Al is KCl exchangeable Al.

Table 5. Mehlich I extractable nutrients (mg kg^{-1}) for three management systems in the South Georgia Coastal Plain.

Management	Depth	P‡	B	Cu	Fe	Mn	Zn
	cm	mg kg^{-1}					
Longleaf-wiregrass †	0-5	2.6	0.3	2.6	22.7	20.4	1.0
	5-15	2.0	0.2	2.7	19.6	7.2	0.8
	15-30	1.5	0.1	3.0	12.5	3.6	0.8
	Mean	2.0	0.2	2.8	18.3	10.4	0.9
Planted pine	0-5	24.1	0.3	1.0	20.0	31.1	2.1
	5-15	13.2	0.2	1.3	17.2	14.9	1.0
	15-30	4.4	0.2	1.1	13.6	13.6	0.7
	Mean	13.9	0.2	1.1	16.9	19.9	1.3
Row crop	0-5	52.3	0.3	1.6	9.3	13.5	5.6
	5-15	41.0	0.2	1.1	11.6	11.0	4.3
	15-30	17.3	0.1	2.1	9.1	6.5	1.7
	Mean	36.8	0.2	1.6	10.0	10.3	3.9
Management mean	0-5	26.3	0.3	1.7	17.3	21.6	2.9
	5-15	18.7	0.2	1.7	16.1	11.1	2.0
	15-30	7.7	0.2	2.1	11.7	7.9	1.1
	Mean	17.6	0.2	1.8	15.0	13.5	2.0

ANOVA	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$
Management (M)	0.037	18	0.983		0.008	0.6	0.055	5.3	0.058	6.6	0.017	1.3
Depth (D)	0.001	7	<.001	<0.1	0.039	0.3	0.005	2.6	<0.001	2.8	0.005	0.8
M x D	0.035	19	0.958		0.051	0.6	0.138		0.028	7.1	0.049	1.7

† Longleaf-wiregrass= Mature longleaf pine habitat, Planted pine= Managed pine plantation, and Row crop= Row crop.

‡ P, B, Cu, Fe, Mn, and Zn are Mehlich 1 extractable.

Figures

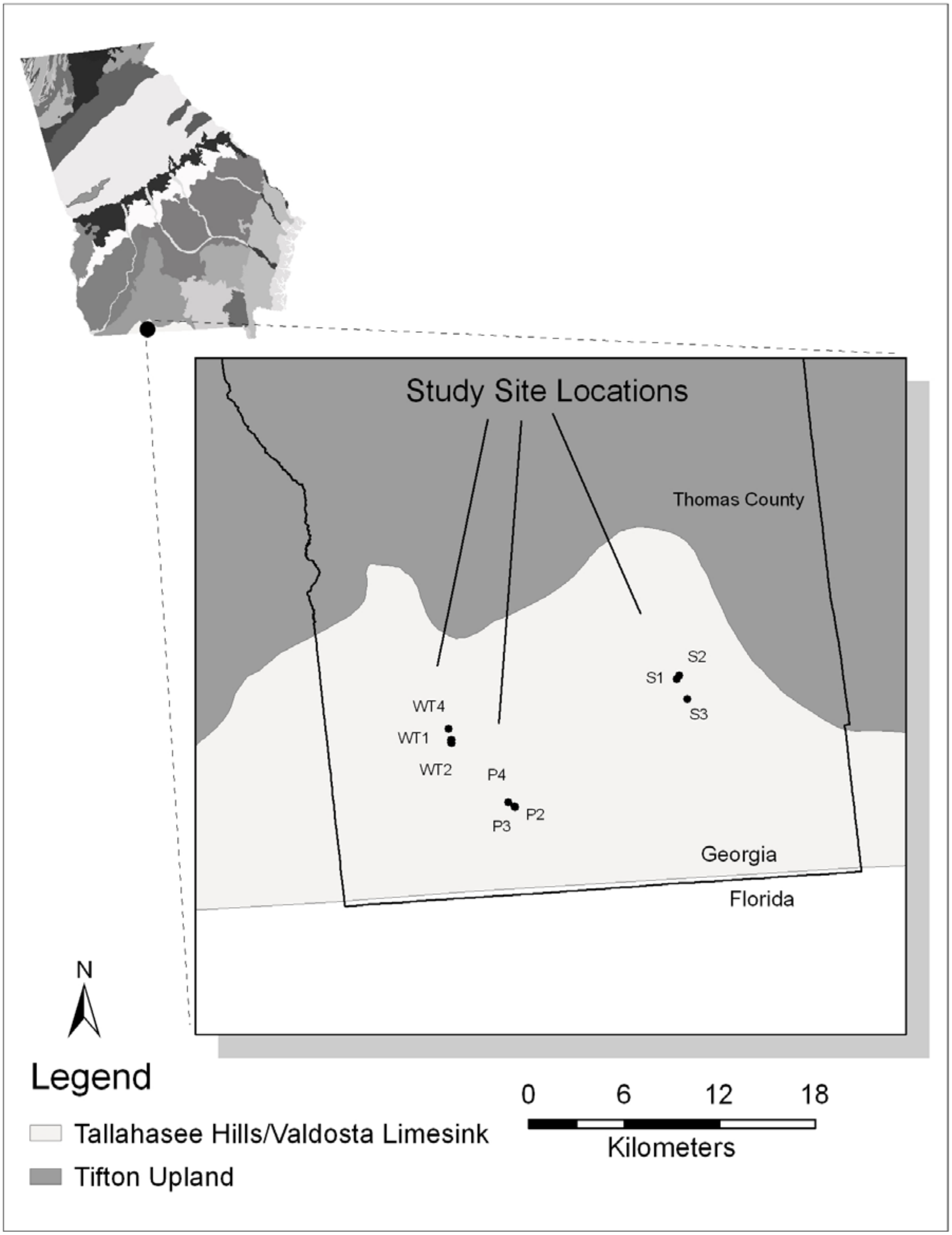

Fig. 1. Study site location displayed with ecoregions of the Georgia Coastal Plain.

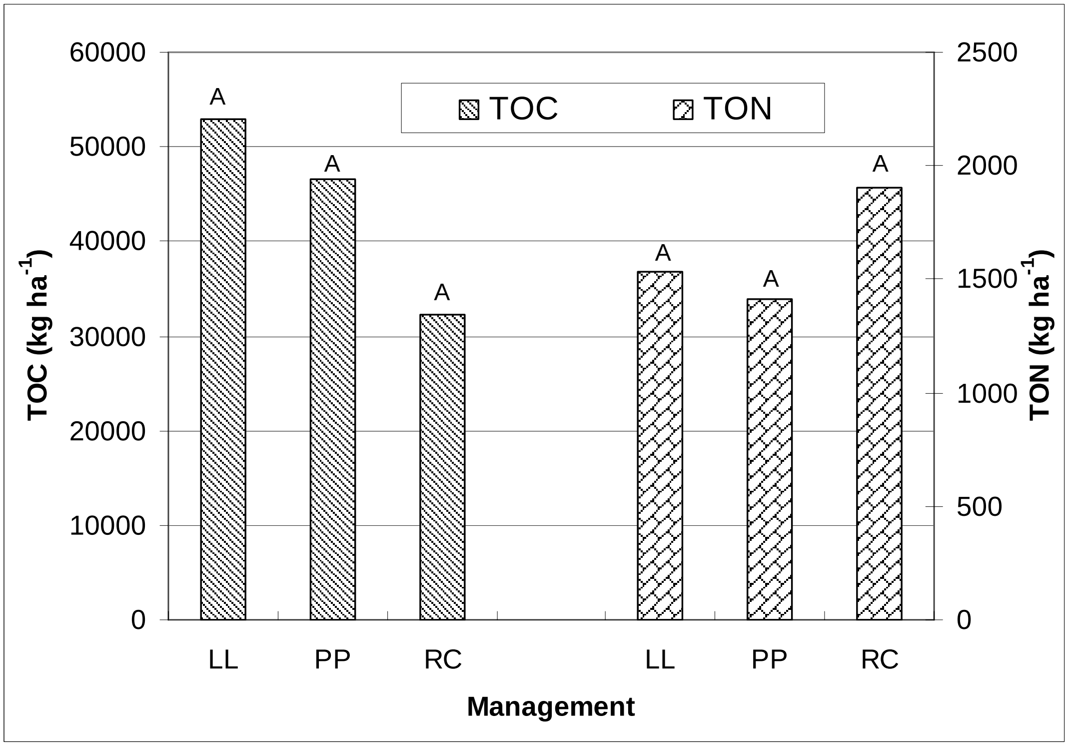

Fig. 2. Total organic C and N (0-30 cm (kg ha^{-1}) including organic horizons of forested sites) for three management systems in the Georgia Coastal Plain. Same letters for like columns in the same depth are not significantly different at the 0.10 confidence level. TOC= total soil organic C and TON= total soil organic N. LL =Mature longleaf pine habitat, PP=Managed pine plantation, and RC=Row crop.

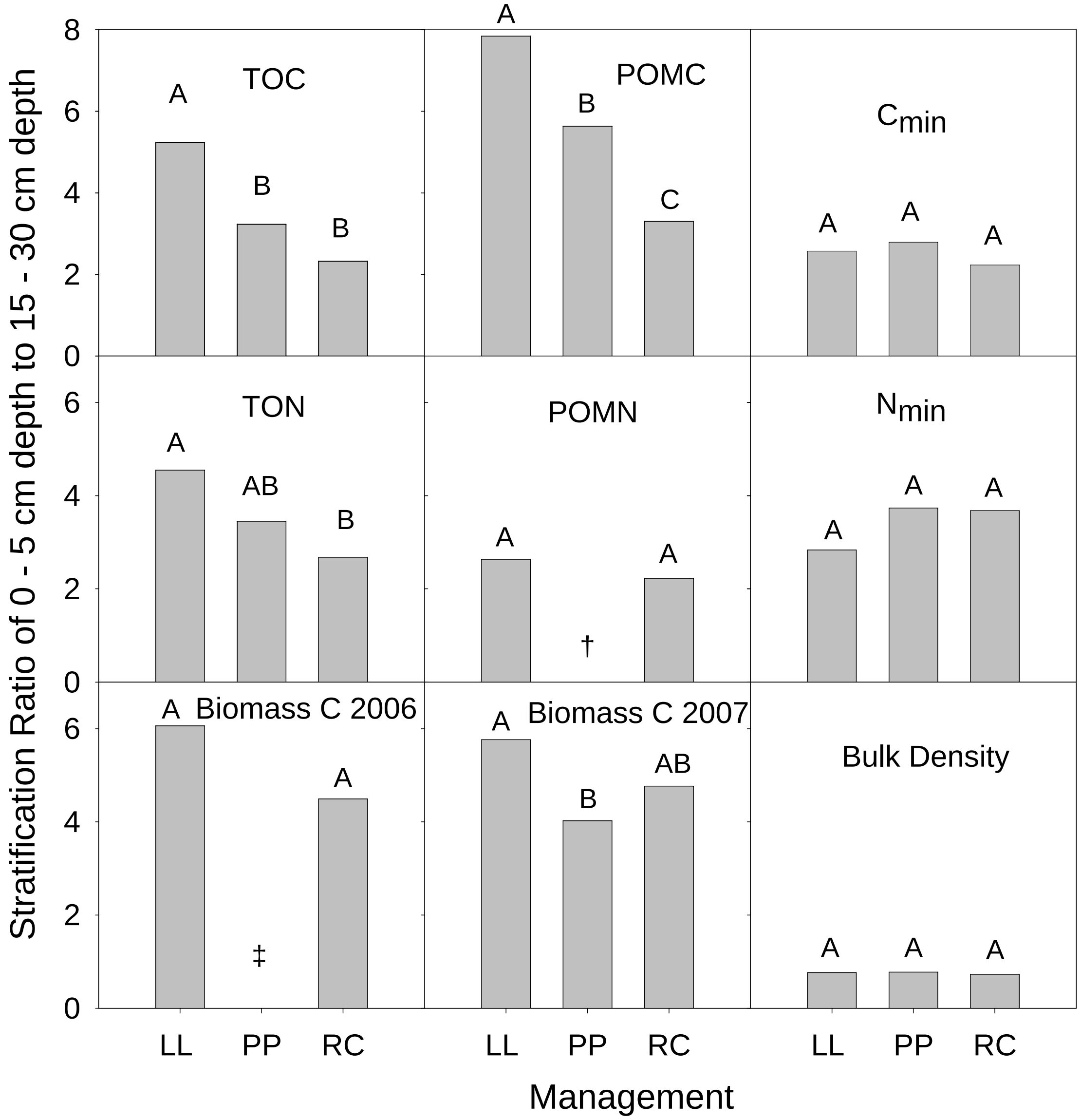

Fig. 3. Stratification ratio of carbon and nitrogen pools and bulk density averaged by management. Same letters for a column in the same plot are not significantly different ($p \leq 0.01$). LL =Mature longleaf pine habitat, PP=Managed pine plantation, and RC=Row crop. [TOC= total soil organic C, POMC= particulate organic matter C (>53 µm), C_{min}= potentially mineralizeable C, TON= total soil organic N, POMN= particulate organic matter N (>53 µm), N_{min}= potentially mineralizeable N, Biomass C 2006= soil microbial biomass for 2006, Biomass C 2007= soil microbial biomass for 2007.]

† Stratification ratio could not be determined because value of 15–30 cm depth was 0.

‡ No data.

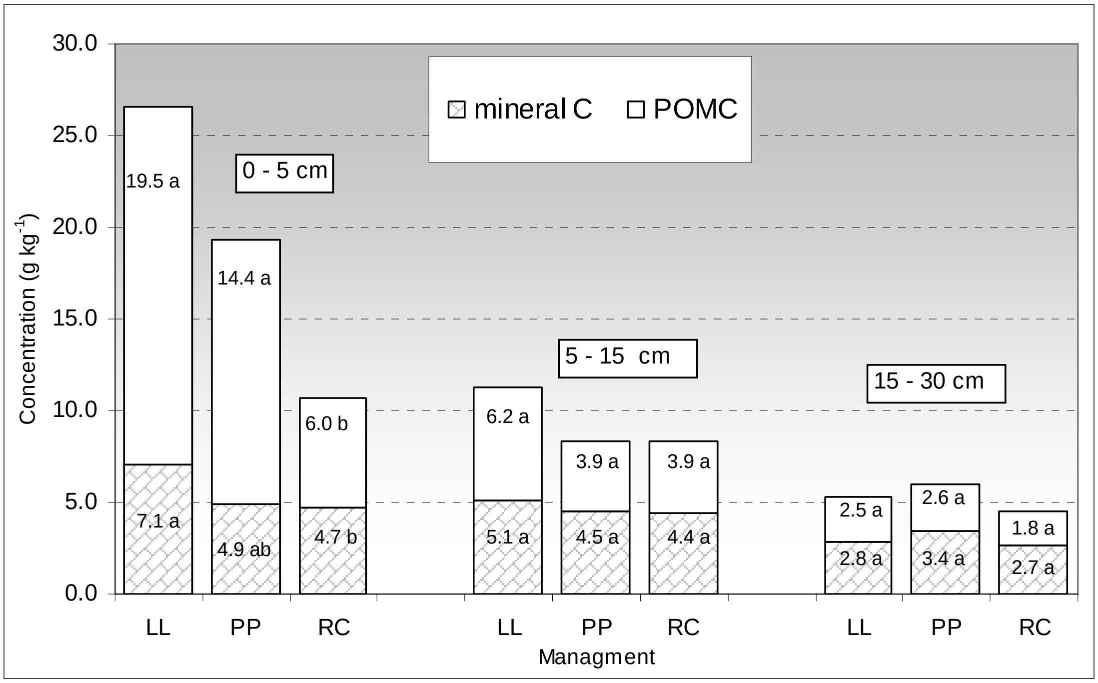

Fig. 4. Carbon pools for three management systems in the Georgia Coastal Plain. Same letters for like columns in the same depth are not significantly different at the 0.10 confidence level. Mineral C= mineral associated C (< 53 µm), POMC= particulate organic matter C (> 53 µm). LL =Mature longleaf pine habitat, PP=Managed pine plantation, and RC=Row crop.

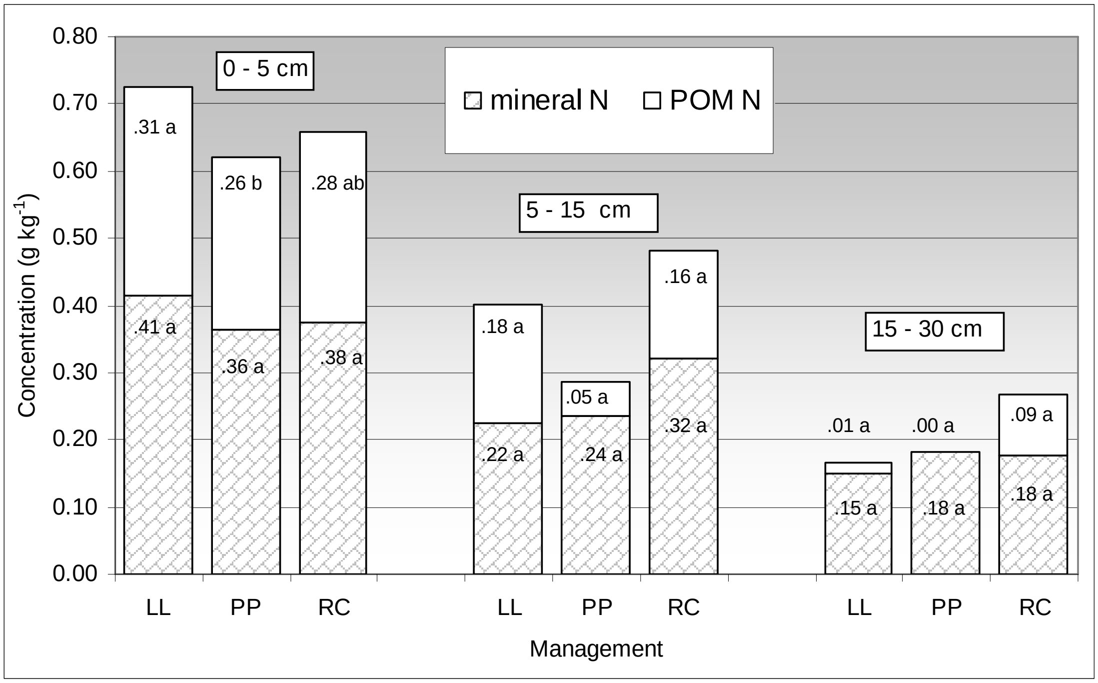

Fig. 5. Nitrogen pools for three management systems in the Georgia Coastal Plain. Same letters for like columns in the same depth are not significantly different at the 0.10 confidence level. Mineral N= mineral associated N (< 53 µm), POMN= particulate organic matter N (> 53 µm). LL =Mature longleaf pine habitat, PP=Managed pine plantation, and RC=Row crop.

III. LAND MANAGEMENT EFFECTS ON SOIL PHYSICAL PROPERTIES OF SOUTHEASTERN U.S. COASTAL PLAIN ECOSYSTEMS

Abstract

Near-surface soil properties indicate differences in management practices that are important for soil quality. Objectives of this study were to evaluate land use and management effects on dynamic soil physical properties of southeastern Coastal Plain ecosystems, with emphasis on mature longleaf pine (*Pinus palustris* Miller) – wiregrass (*Aristida stricta* Michx.)habitat relative to more intensively cultivated management. Multivariate analyses (clustering and principal component analyses) were used to investigate relationships between chemical, physical and biological properties among managements. Sites in Thomas County, GA, representing three soil map units (sandy surfaces with loamy to clayey kandic subsurface horizons), were selected in each of three management systems for comparison of near surface (0-5, 5-15 and 15-30 cm) soil physical properties. Land management/use included mature longleaf pine habitat (LL), slash pine (*Pinus elliottii* Engelm.) plantation (PP), and conventional row cropping systems (RC). Management significantly increased bulk density (ρ_b) (P=0.029) in cultivated sites relative to LL. Soil strength (SS) (0–50 cm) in PP was 106 % > LL (P= 0.061) and 19 % > RC. The highest infiltration rate (IR) was in LL (42.5 cm hr $^{-1}$) (P= 0.038), and was 207 and 1015 % higher than RC and PP respectively. The IR and saturated hydraulic conductivity (Ksat) were lowest in PP (3.8 and 5.7 cm hr $^{-1}$ respectively). Percent water stable aggregates in PP was 21 % > RC and LL had 18 % more WSA than RC. Multivariate analysis indicated 79% of variability in the data was explained by exchangeable bases, C pools, and hydraulic soil properties. More intensive cultivation increased soil compaction, reduced water permeability and structure, and generally reduced the inherent variability of near-surface properties.

Introduction

Land management affects certain near-surface soil properties in a relatively short time. These dynamic properties are indicative of soil quality (Larson and Pierce, 1994; Norfleet et al., 2003). Doran and Parkin (1994) define soil quality as the capacity of a soil to function. Multiple functions are often performed simultaneously by soils which complicate estimates of soil quality (Nortcliff, 2002). Soil quality is a relative interpretation of a soil's condition, and determining criteria will change for the desired use (Nortcliff, 2002). Several components have been recognized as indicators of overall sustainability including soil physical, chemical, and biological properties and general interpretations of soil tilth and productivity (Karlen et al., 1992). Researchers have suggested soil properties for use in a minimum data set for soil quality assessment (Doran and Parkin, 1994 and 1996; Larson and Pierce, 1994).

The southern U.S once had an estimated 37 million hectares of longleaf pine (*Pinus palustris* Miller) habitat (Frost, 1993). However, because of conversion to agricultural land around the turn of the twentieth century (Hamdar, 1993), and decimation of longleaf by logging and turpentining, only three percent remains today (Frost, 1993).

Some endangered species [i.e., red cockaded woodpecker (*Picoides borealis*), gopher tortoise (*Gopherus polyphemus*)] rely on longleaf – wiregrass (*Aristida stricta* Michx.) habitat (Engstrom, 1993; Van Lear et al., 2005) in the eastern Coastal Plain. This native ecosystem is among the most plant species-rich ecosystems in temperate regions (Brockway et al., 2005) and restoration efforts are underway to expand current acreage (Outcalt et al., 1999; Van Lear et al., 2005; Varner et al., 2005).

Fire is imperative for longleaf forest management and restoration because it maintains appropriate habitat structure and species composition. In addition, burning facilitates naturally regeneration of longleaf pine because it exposes mineral soil and controls vegetation that may out-compete seedlings (Boyer, 1993; Chapman, 1932). Prescribed burning is a common practice in managed pine plantations in the southeastern U.S. (Binkley et al., 1992; Carter and Foster, 2004) because it is a cost-effective way to control competing vegetation. Burning can influence physical properties of surface soils (Scifres and Hamiltion, 1993) including bulk density (Brye, 2006), moisture holding capacity, macropore space (Boyer and Miller, 1994), and infiltration rate (Robichaud, 2000). Fire can also affect hydrologic properties of soil by cycling and concentrating hydrophobic compounds naturally present in plant debris (Scifres and Hamiltion, 1993). Persistence of fire-induced water repellency may only be short term (Hubbert et al., 2006), but, natural water repellency does exist in soils and has been highly correlated with C content (r = 0.64) (Varela et al., 2005).

Soil erosion is a major component of soil sustainability affected by land management. Karlen and Stott (1994) proposed a conceptual soil quality model related to water erosion. A number of physical soil properties were incorporated in the model including infiltration rate, hydraulic conductivity, porosity, aggregate stability, soil strength, texture, bulk density, plant available water, and mineralogy. Water dispersible clay (WDC) has also been identified as a soil property related to erosion, and is highly correlated with total clay (Brubaker et al., 1992; Igwe, 2005). Fire can remove vegetative cover and litter from the soil surface potentially leaving the soil prone to erosion, although prescribed fires rarely leave bare surfaces (Biswell, 1989; Ralston and Hatchell, 1971) because they are generally low intensity (Carter and Foster, 2004).

Other practices such as tillage (surface disturbance) and residue management affect soil physical properties. For example, properties associated with soil bulk density can be viewed as ‘red flag’ indicators of general soil quality because they change rapidly (Brady and Weil, 2002). Bulk density is also an indicator of soil compaction (Arshad et al., 1996). Likewise, soil strength (cone index) measurements indicate soil compaction (mechanical impedance) (Duffera et al., 2007), and have been negatively correlated with crop yield (Abu-Hamdeh, 2003; Botta et al., 2006). Aggregate stability (AS) relates to the ability of an aggregate to resist disruption by mechanical or chemical means (Arshad et al., 1996), and is affected by management (Ashagrie et al., 2007). Hydraulic measurements such as infiltration rate (Hartemink, 1998), hydraulic conductivity (Seobi, et al., 2005) and soil water retention (Fesha, 2004) can also be important indicators of management effects.

Soil properties are functionally related (Jenny, 1941). Diferent researchers have utilized various methods of reducing and combining variables in order to understand and interpret overall soil condition. Granatstein and Bezdicek (1992) suggested the use of soil ratios for improved understanding of soil conditions. Igwe (2005) suggested a dispersion ratio to assess soil erodibility that encompassed water dispersible and total silt and clay fractions. Some researchers have used regression to identify relationships among soil properties (Blanco-Canqui et al., 2005; Rhoton et al., 2002), whereas others have used multivariate techniques (Duffera et al., 2007; Liebig et al., 2004; Yemefack et al., 2006). Multivariate statistics have been used to determine which chemical, biological, and physical properties are most important for explaining variability among investigated soils. Some common methods include principal component and cluster analyses.

Human actions can quickly change soil quality (Karlen et al., 1992), thus, many ecosystems have experienced soil change (Granatstein and Bezdicek, 1992). Comparisons of disturbed soils to reference sites are not extensive in the southeastern U.S. due to scarcity of undisturbed land. By evaluating relationships between management dependent and inherent soil properties, ecosystem management can be improved (Norfleet et al., 2003). Soil quality can be linked to sustainability by interrelations of management dependent properties and production stability (Larson and Pierce, 1994), and an improved understanding of temporal soil variability may improve soil management and aid longleaf restoration. Further understanding of management dependency of soils can also contribute to development of a minimum data set for soil quality.

Our objectives were to evaluate land use and management effects on dynamic soil physical properties and soil quality of mature longleaf-wiregrass habitat compared to more intensively cultivated Coastal Plain ecosystems. Relationships between management dependent and inherent soil properties were also evaluated for improving ecosystem management and soil interpretations of typical southeastern soils. In addition, we utilize multivariate statistical techniques to further evaluate soil property differences. For these multivariate analyses, we combine soil physical property data from this manuscript with soil chemical and biological data from a companion manuscript (chapter 2 of thesis).

Materials and Methods

Management Systems

Land use impacts on soils in Thomas County, Georgia (Fig. 6) were determined by soil map unit and land use during 2005 – 2007. The experiment design was a randomized complete block with land use as the main treatment being replicated in three blocks of soil type. Land use included Longleaf, planted pine, and row crop. Depth was a factor for some measurements and was properly accounted for by the model. Descriptions of the three land use systems are as follows:

Longleaf (LL) consists of mature, multi-aged longleaf pine (*Pinus palutris* Miller) forest (trees ranging in age from seedlings to 200+ yrs) with native groundcover of grass, legume, and composite species, [i.e., wiregrass (*Aristida stricta* Michx.)]. The area has been prescribed burned once every 1–2 years for at least the last 75 years. Pines are replenished by natural regeneration, and the canopy is generally open. Soils have been subjected to minimal surface disturbance.

Planted pine (PP) consists of a 22 year old planted slash pine (*Pinus elliottii* Engelm.) stand in the first rotation managed for poles and/or saw timber. The area has been subjected to infrequent fire and mechanical treatment, with the most substantial soil disturbance taking place during site preparation.

Row crop (RC) has been in continuous cropping for 30–35 yrs with a rotation of corn (*Zea mays*)-peanut (*Arachis hypogaea* L.)-soybean (*Glycine max* (L.) Merr.) (some years fallow). Soils are under conventional tillage management with major soil disturbance (e.g., plowing, disking, cultivating, harvesting) taking place annually.

Pedon Selection and Characterization

Selection of sites involved the use of soil survey and extensive ground-truthing. Prospective soils at the sites were described, sampled by horizon, characterized in the laboratory, and classified to the family level according to Soil Taxonomy (Soil Survey Staff, 2003). Laboratory analyses included particle size determination by the <2-mm pipette method following soil organic matter removal with hydrogen peroxide and dispersion with sodium hexametaphosphate (Kilmer and Alexander, 1949), cation exchange capacity (CEC) and base saturation (Ca, Mg, K and Na) by the ammonium acetate method using an auto extractor (Soil Survey Investigation Staff, 2004), extractable aluminum (Al) using 1M KCl (Soil Survey Investigation Staff, 2004) (Al concentrations were determined via titration) and effective CEC (ECEC) by summing extractable Al and exchangeable bases (Soil Survey Investigation Staff, 2004).

Table 6 shows family classification of the soils evaluated (nine pedons total). For this study, Kandiudults (clay content does not decrease ≥ 20 % relative to the maximum within 1.5m) and Kanhapludults (clay content does decrease ≥ 20 %) were considered equivalent.

Field Sampling Procedures

Soil samples representing nine pedons (Table 6) from Thomas County, Georgia were sampled in 2006 and 2007 for physical analyses. Organic horizons were removed before taking mineral soil samples. Composite soil samples (twenty cores taken with hand probes) were taken at three depths (0–5, 5–15, and 15–30 cm). Bulk density samples (three reps at each site) were obtained using a slide hammer with cylinder sleeves to collect samples from 0–5, 5–15, and 15–30 cm depths. Three samples at each site were taken with a shovel at two depths (0–5 and 5–15 cm) for determination of water stable aggregates. Undisturbed soil cores (6 cm high x 5.4 cm diameter) (three at each site – depth combination) were taken with a hammer apparatus at three depths (0–6, 7–13, and 20–26 cm) for measurement of soil water content at field capacity (0.1 bar). For each undisturbed sample taken, there was an adjacent disturbed sample taken for measurement of soil water content at the permanent wilting point (15 bar). Samples for moisture determination were taken with an auger from two locations per site and composited in 10 cm increments from 0–50 cm.

In-situ Field Measurements

Soil strength (0–50 cm) was measured using a CP40II recording cone penetrometer (ICT International Pty Ltd, Armidale, New South Wales, 2350, Australia). Each datum is the average of 10 insertions made within individual sites, with readings taken in 1 cm increments. Infiltration rate was determined (two per site) with plant residue intact using a Cornell Sprinkle Infiltrometer (Ogden et al., 1997). Saturated hydraulic conductivity (3 per site) at a depth of 15 ± 1 cm was determined using a compact constant head permeameter (Ammoozemeter) (Ksat, Inc., Raleigh, North

Carolina). Tap water (pH=7.6, EC= 34.6 μS cm^{-1}) was used for on-site hydraulic measurements. Field replicates were averaged to represent the site.

Laboratory Methods

Air dried samples (<2-mm) were used to determine water dispersible clay (WDC), particle size distribution (PSD) and soil water retention at 15 bar (pwp). Determination of PSD by the <2-mm pipette method followed soil organic matter removal with hydrogen peroxide and dispersion with sodium hexametaphosphate (Kilmer and Alexander, 1949). Water dispersible clay was determined using a modification of the method outlined by Miller and Miller (1987) (4 grams of soil). Four replicates of WDC were averaged to represent sites. The clay dispersion ratio (CDR) was determined as the ratio of WDC to total clay (Igwe, 2005). Water stable aggregates were determined according to methods of Kemper and Rosenau (1986). Bulk density samples were dried at 105 °C for 48 hours before weighing, and calculations were made according to the method outlined by Blake and Hartge (1986). Undisturbed soil cores for volumetric water content at field capacity (0.1 bar) ($\theta_{v\ 0.1\ bar}$) were saturated with 0.01 M $CaCl_2$ and placed on a pressure plate until equilibrium was reached (48 hours). Moist samples were weighed, dried at 105 °C for 48 hours, and weighed again to determine gravimetric water content ($\theta_{g\ 0.1\ bar}$) (Klute, 1986). Gravimetric water content (w/w) at the permanent wilting point (15 bar) ($\theta_{g\ 15\ bar}$) was determined using a pressure plate with brass rings (1 cm high x 5.4 cm diameter). Plant available water (PAW) was determined as the difference between gravimetric water content at 0.1 bar ($\theta_{g\ 0.1\ bar}$) – 15 bar ($\theta_{g\ 15\ bar}$).

Statistical Analysis

Analysis of variance was performed using version 9.1 of the SAS Package to test main effects and interactions (SAS Institute Inc., 2003). Where depth was a factor, data were analyzed using PROC GLM as a split plot with management as main plots and depth as subplots. Parameters without a depth factor were analyzed using PROC GLM as a randomized complete block with soil as the blocking factor. All statistical tests were made at the $\alpha = 0.10$ significance level.

Chemical and biological properties reported in chapter 2 of this thesis were combined with physical properties reported in this chapter for multivariate analysis. The intent of the multivariate procedures was to determine the similarity of soil properties among land managements and which soil properties were most critical for differentiating land use systems. A weighted average (0–30 cm) of data for the 3 depths (0–5, 5–15, and 15–30 cm) was normalized (0-100) prior to principal component analysis (PCA) and multivariate clustering. Criteria for principal component (PC) selection included: 1) eigenvalues >1, and 2) proportion of variance explained > 6%. A dendrogram depicting soil similarity was created using a cluster analysis. Clustering was performed between soil properties for the land use systems using a single linkage Euclidean distance between normalized, multivariate data (Der and Everitt, 2002).

Results and Discussion

Soils investigated in this study were well-drained, acid, upland soils common to the southeastern Coastal Plain. Surface soil textures ranged from loamy sand to sandy loam, and family particle size classes (i.e., in the control section) ranged from loamy to fine (Table 6). All soils formed on similar parent materials with a similar climate. Selection of sites for comparison was determined by soil map unit and land management. Eight of the nine pedons classify as Ultisols with the remaining soil classifying as an Alfisol (Table 6). The high BS (>35 %) in the lower portion of the soil was thought to have been influenced by amendments and was considered to be a ‘cultural Alfisol.’ A pedon in an adjacent wooded area (likely uncultivated) classifies as an Ultisol.

Bulk Density

Bulk density (ρ_b) was significantly affected by both management (P=0.029) and depth (P< 0.001). This was similar to results of Seobi et al. (2005), however, they also found significant interaction between treatment and depth (Table 7). Cultivated sites (planted pine and row crop) had similar ρ_b values, which were significantly greater than longleaf sites (Table 7). Other researchers have also found that increased cultivation causes higher ρ_b (Blanco-Canqui et al., 2005; Follett and Peterson, 1988; Abbasi et al. 2007; Tan et al. 2007). Relative to the other managements, planted pine had the greatest ρ_b in surface soils (0–15 cm), while ρ_b at the 15–30 cm depth was greatest in the row crop management. Annual tillage, trafficking, and plow pans in the row crop sites likely resulted in the higher ρ_b at 15–30 cm.

We found that longleaf (burned) had lower ρ_b in surface soils than row crop management (unburned). Although the planted pine sites were also burned, it was infrequent and surface ρ_b of these areas closely resembled row crop sites. Accumulation of organic matter was greatest in forested sites (chapter 2), and comparison of longleaf to row crop sites supports findings of Blanco-Canqui and Lal (2007) who found increased residue reduced ρ_b. Across all managements, ρ_b increased with depth, which is similar to other findings (Follett and Peterson, 1988; Liebig et al., 2004; Tan et al., 2007). Under longleaf management, shallow depths (0–5 and 5–15 cm) were very similar (1.16 and 1.18 g cm^{-3} respectively); however, ρ_b in the 15–30 cm depth was significantly higher (1.54 g cm^{-3}).

Water Dispersible Clay

Water dispersible clay significantly increased with depth (P= 0.011), similar to results of Rhoton et al. (2002) (Table 7). Like others (Brubaker et al., 1992; Igwe, 2005), we found a relationship between WDC and total clay (R^2= 0.50). Sites under cultivation had more WDC concentrated in the 15–30 cm depth relative to longleaf management. Our results differ from other researchers (Rhoton et al., 2002; Shaw et al., 2002), who found that WDC increased with increased cultivation. We found planted pine management had the greatest WDC values (0–30 cm) (3.50 %) followed by longleaf (2.74 %) and row crop management (2.37 %). Stratification of WDC was most evident in cultivated sites, whereas longleaf sites had more uniform distribution of WDC. Forested sites had the more WDC in surface soils (0–15 cm) relative to row crop sites.

Soils with a high clay dispersion ratio (CDR) are considered to be highly dispersible (Igwe, 2005). Comparison of CDR among surface soils (0–5 cm) showed that planted pine sites are 68 and 45 % more dispersible than row crop and longleaf management respectively (Table 7). We found a maximum CDR (32 %) of surface soils (0–5 cm) similar to those reported by Shaw et al. (2002) for surface soils (0–1 cm) in the Alabama Coastal Plain. A linear relationship also existed between WDC and WSA (R^2= 0.52). (data not shown).

Water Stable Aggregates

Wet aggregate stability is often used to assess management effects on soil properties (Eynard et al., 2004). There was significant interaction between management and depth (*P*= 0.004) for water stable aggregates (WSA) (Table 7). Percent WSA (0–15 cm) decreased in the order planted pine (96.1 %), longleaf (93.3 %) and row crop (79.4 %). These results concur with findings by Eynard et al. (2004) (grassland), Rachman et al. (2003) (grassland), and Shrestha et al. (2007) (forest), who found significantly more WSA in uncultivated relative to cultivated sites. The most noticeable management effects (0–15 cm) were between row crop management (79.4 %) and longleaf sites (93.3 %). Similar to results of Ashagrie et al. (2007), we found that row crop cultivation significantly reduced aggregate stability relative to forested soils. Differences among forested sites may be partially explained by varying hydrophobicity levels of the soils (Mataix-Solera and Doerr, 2004).

For all managements, WSA increased with depth. Other researchers have reported similar results (Eynard et al. (2004) in South Dakota; Rachman et al. (2003) in Missouri); however, in grasslands studied by Rachman et al. (2003) and corn – soybean rotations in southern Illinois studied by Hussain et al. (1999), WSA decreased with depth. Rhoton et al. (2002) also found WSA generally decreased with increasing soil depth for soils cropped to corn and cotton in Ohio and Mississippi, but they did not pre-wet aggregates prior to analysis. Pre-wetting aggregates increases wet aggregate stability relative to air dry samples (Eynard et al., 2004).

Our data showed an inverse relationship between WSA and sand content (R^2 = 0.48) (data not shown). In addition, the C:N was positively related to WSA (R^2 = 0.48) and N_{min} was negatively related to WSA ($R^2 = 0.64$), suggesting a possible relationship between soil OM and WSA. Rhoton et al. (2002) found that WDC and WSA were inversely related; however, we found that soils with relatively high WDC (0–30 cm) (planted pine) had the highest percentage of WSA (Table 7).

Soil Strength

Soil strength (SS) was greatest for cultivated sites relative to longleaf (Fig. 7). Soil strength in longleaf sites generally increased with depth, and had a narrower range of SS relative to other sites (132–1666 kPa). Abu-Hamdeh (2003) (wheat system in northern Jordan) and Blanco-Canqui et al. (2005) (uncropped no-tillage systems in Ohio) also found that SS increased with depth. Cultivated sites had a depth (15-35 cm) of relatively high SS, likely coinciding with a traffic and/or tillage pan. Duffera et al. (2007) found increased SS at similar depths in soils of the North Carolina Coastal Plain. These results concur with other researchers (Busscher and Bauer, 2002; Singh and Malhi, 2006), who have found SS decreases with depth below a compacted layer in cultivated soils. The highest average value of SS measured (3196 kPa) (planted pine) was slightly less than that found by Duffera et al. (2007) in the North Carolina Coastal Plain.

Comparison of 10 cm increments (averaged data) illustrated significant differences in planted pine and longleaf soils for the 10–20 and 20–30 cm depths (P= 0.029 and 0.081 respectively) (data not shown). Blanco-Canqui et al. (2005) found higher SS in conventional row crop sites relative to forested sites, however, we found lower SS in row crop management (0–10 cm) that likely resulted from loosening by tillage (Busscher and Bauer, 2002). At the 30–40 cm depth, soil strength under row crop management was significantly greater than longleaf (P= 0.010). Residual effects of management may have contributed to higher SS in cultivated sites with depth (Busscher and Bauer, 2002).

Water Holding Capacity

Volumetric water content at field capacity ($\theta_{v\ 0.1\ bar}$) was significantly affected by depth (*P*= 0.085) when all managements were included; however, values for longleaf were uniform across all depths (Table 8). Similar to results of Seobi et al. (2005), we found volumetric water content at field capacity increased with depth and management differences (0–30 cm) were small. The largest variation in $\theta_{v\ 0.1\ bar}$ was in planted pine, which ranged from 0.14–0.21 $cm^3\ cm^{-3}$. Differences between management for (0–30 cm) were not detected for $\theta_{v\ 0.1\ bar}$. Blanco-Canqui and Lal (2007) found that soil $\theta_{v\ 0.1\ bar}$ (0–10 cm) was higher in treatments receiving straw mulch relative to those not receiving inputs; however, we found that little or no difference (0.1 bar) existed between soils receiving OM inputs (forested) and those not receiving litter.

Gravimetric water content (w/w) ($\theta_{g\ 15\ bar}$ and $\theta_{g\ 0.1\ bar}$) showed some differences between management, with larger differences owing to soil depth (Table 8). Longleaf management had higher plant available water (PAW) ($\theta_{g\ 0.1\ bar}$ - $\theta_{g\ 15\ bar}$) relative to cultivated sites, likely due to differences in organic matter content. Duffera et al. (2007) (North Carolina Coastal Plain) and Mallik et al. (1984) (Scotland) found that PAW generally increased with depth; however, we found the opposite was true. This is likely due to differences in genetic soil properties between the studies.

Infiltration Rate

Management significantly affected surface infiltration rate (IR) of investigated soils (*P*= 0.038) (Table 8). We found IR in longleaf sites was 207 and 1015 % higher than row crop and planted pine sites, respectively. Increased biomass in longleaf may have contributed to higher IR relative to cultivated sites (Blanco-Canqui and Lal, 2007). Row crop and planted pine sites had similar values of IR. Similarly, Van Es et al. (1999) indicated that management (tillage) was the dominant source of variation in IR in some Northeastern U.S. soils, and Rhoton et al. (2002) found runoff increased with increased cultivation. Possible differences of IR in our study may be attributed to varying water repellency levels at different sites (Varela, et al., 2005), or compaction due to management. Increased compaction due to traffic can reduce IR (Abu-Hamdeh, 2003; Hartemink, 1998; Rhoton et al., 2002) and is likely responsible for reduced IR in cultivated relative to longleaf sites.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) values were not significantly affected by management (Table 8). However, cultivated sites had similar values of Ksat, and were much lower than the uncultivated longleaf. Longleaf management had Ksat values that were 109 % higher than row crop and 127 % higher than planted pine. The lower Ksat in cultivated sites likely resulted from the dense soil layer indicated by SS measurements, as also found by Duffera et al. (2007). The relatively higher additions of organic matter in longleaf management likely affected the Ksat relative to row crop sites. Similarly, Blanco-Canqui and Lal (2007) found addition of wheat straw residues in conservation systems of Ohio increased Ksat of surface soils, and Seobi et al. (2005) found forested sites had higher Ksat than row crop sites in Missouri.

Multivariate Analyses

Four principal components explained 85 % of the soil data variability across all nine sites (Table 9). Principal component (PC) 1 explained 40 % of the data variability, and loading factors were highest for exchangeable bases, soil P, and bulk density. The second PC (28 % of the variability) was dominated by C and N pools and cation exchange capacity. Physical soil properties including surface infiltration rate, soil strength, plant available water, and water stable aggregates dominated PC 3 (11%). The fourth PC was somewhat mixed, and explained much less data variability (6%). Duffera et al. (2007) found that four PCs developed from soil physical properties (4–27 cm) explained 90 % of the data variability in soils of the North Carolina Coastal Plain. Cumulative explained variability by four PCs in our study (85 %) was similar to that reported by Fesha (2004) for Alabama soils in the Appalachian Plateau (81 %) and Coastal Plain (85 %). Yemefack et al. (2006) identified five soil properties (pH, exchangeable Ca, extractable P, ρ_b, and organic C) as indicators of cultivation systems; these properties were of varying significance for depicting data variability in our study.

A plot of PC1 (y) to PC2 (x) showed that management was separated well by PC1 (Fig. 8). Replications of management (i.e., soil map unit) were grouped similarly with respect to PC1, and the greatest separation of PC1 was between longleaf and row crop sites. Planted pine sites were intermediate. Considering PC1 had high loading factors for soil nutrient status, these properties may be helpful in differentiating management effects for SE Coastal Plain ecosystems.

Cluster analysis using single linkage Euclidean measures revealed that near-surface soil properties in planted pine sites were most similar to each other relative to other sites (i.e., short minimum distance between clusters) (Fig. 9). The longleaf sites clustered together, indicating similarity between the sites; however, the long distance between clusters indicated more variability between soil map units relative to other sites. With the exception of the fine-loamy site in row crop management, cultivation reduced the variability of the soil properties as expressed within. Longleaf management resulted in unique expression of near-surface properties in each soil map unit investigated. This is similar to what Fesha (2004) found on the Appalachian Plateau of Alabama, where cultivation reduced the variability of soils, and hayland and woodland clustered separately from the cultivated sites.

Conclusions

Longleaf ecosystems had highest soil quality as indicated by lower bulk density and soil strength, and higher infiltration rate, saturated hydraulic conductivity, and plant available water. Planted pine had lower soil quality with low infiltration rate and saturated hydraulic conductivity, and high soil strength and clay dispersion ratios as compared to the other systems. Soil quality of row crop management was intermediate to other systems based on similar properties. The infiltration rate and saturated hydraulic conductivity in longleaf was higher than row crop and planted pine sites, and decreased with increasing bulk density and soil strength. Increased water infiltration in longleaf is important for recharging groundwater and reducing runoff that may contribute negatively to surface water quality. Longleaf and planted pine management had significantly more water stable aggregates than row crop sites. There were no significant effects of management on volumetric water content at field capacity or gravimetric water content at field capacity and permanent wilting point; however, longleaf had significantly more gravimetric plant available water (0–30 cm) than cultivated sites. Increased cultivation significantly increased bulk density and soil strength (0–50 cm), and reduced permeability and water storage capacity of investigated soils.

Multivariate analysis indicated 79% of the soil data variability was explained by exchangeable bases, C pools, and hydraulic properties. Therefore, these properties can be considered a minimum data set for soil quality in similar agroecosystems of the southeastern U.S. Ranges of measured near-surface properties reported for similar managements and map units in upland soils of the southeastern Coastal Plain were obtained, providing base knowledge of phenotypic and genotypic expression useful for improving ecosystem management. Clustering of raw data indicated near-surface soil properties were more similar by management than by soil map unit (taxonomic separation). Cultivation reduced the inherent variability of near-surface properties, whereas soils under longleaf expressed much higher variability within soil map units. Identifying sensitive measures of surface soil properties is important for monitoring shifts in ecosystem dynamics and evaluating the suitability of a soil for longleaf restoration.

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Tables

Table 6. Sample ID, field ID, land use, and taxonomic classification of studied Coastal Plain soils.

Sample ID	Field ID	Land use†	Soil family
LL3	WT1	LL	loamy, kaolinitic, thermic Arenic Kandiudult
RC3	S2	RC	loamy, kaolinitic, thermic Arenic Kandiudalf ‡
PP3	P4	PP	loamy, kaolinitic, thermic Arenic Kandiudult
LL1	WT4	LL	fine, kaolinitic, thermic Typic Kandiudult
RC1	S3	RC	fine, kaolinitic, thermic Typic Kandiudult
PP1	P2	PP	fine, kaolinitic, thermic Typic Kandiudult
LL2	WT2	LL	fine-loamy, kaolinitic, thermic Typic Kanhapludult
RC2	S1	RC	fine-loamy, kaolinitic, thermic Typic Kandiudult
PP2	P3	PP	fine-loamy, kaolinitic, thermic Typic Kandiudult

† LL =Mature Longleaf Pine Habitat, PP= Managed Pine Plantation, and RC= Conventional row crop.

‡ An Alfisol due to amendment applications (see methods section).

Table 7. Bulk density, particle size distribution , WDC, CDR, and WSA averaged by depth for three reps for three management systems in the South Georgia Coastal Plain.

Management	Depth	ρ_b‡	Sand	Silt	Clay	WDC	CDR	WSA
	cm	g cm^{-3}	------------------------%------------------------					
Longleaf-	0-5	1.16	79.6	10.7	9.7	2.1	22	91.5
wiregrass†	5-15	1.18	82.2	8.8	9.0	2.9	32	95.0
	15-30	1.54	76.5	7.5	16.0	3.2	25	nd
	Mean	1.29	79.4	9.0	11.6	2.7	26	93.3
Planted	0-5	1.34	82.3	10.6	7.1	2.3	32	95.8
pine	5-15	1.63	82.5	9.5	8.0	3.0	38	96.4
	15-30	1.72	70.9	9.2	19.9	5.2	29	nd
	Mean	1.56	78.6	9.7	11.7	3.5	33	96.1
Row crop	0-5	1.30	84.7	9.1	6.2	1.2	19	74.3
	5-15	1.58	84.3	9.4	6.3	1.7	27	84.5
	15-30	1.78	75.9	8.8	15.3	4.2	35	nd
	Mean	1.55	81.6	9.1	9.3	2.4	27	79.4
Management	0-5	1.26	82.2	10.1	7.7	1.9	24	87.2
mean	5-15	1.46	83.0	9.2	7.8	2.5	32	92.0
	15-30	1.68	74.4	8.5	17.1	4.2	30	nd
	Mean	1.47	79.9	9.3	10.8	2.9	29	89.6

ANOVA	P>F	LSD$_{0.1}$	P>F	LSD$_{0.1}$	P>F	LSD$_{0.1}$	P>F	LSD$_{0.1}$	P>F	LSD$_{0.1}$	P>F	LSD$_{0.1}$	P>F	LSD$_{0.1}$
Management (M)	0.029	0.15	0.619		0.409		0.698		0.457		0.495		0.984	12.7
Depth (D)	<.001	0.09	0.005	4.1	<.001	0.5	0.002	4.2	0.011	1.2	0.304		<.001	1.4
M x D	0.179		0.668		0.008	1.2	0.848		0.621		0.510		0.004	12.1

† Longleaf= Mature longleaf pine habitat, Planted pine= Managed pine plantation, and Row crop= Conventional row crop

‡ ρ_b= Soil bulk density WSA= Water stable aggregates, Sand, Silt, and Clay= Particle size separates, WDC= Water dispersible clay, CDR= Clay dispersion ratio.

Table 8. Soil water content, infiltration rate and saturated hydraulic conductivity averaged for three reps for three management systems in the South Georgia Coastal Plain

Management	Depth	$\theta_{v\ 0.1\ bar}$ ‡	$\theta_{g\ 0.1\ bar}$	$\theta_{g\ 15\ bar}$	PAW	IR	Ksat @ 15 cm
	cm	$cm^3\ cm^{-3}$	----------------------g g^{-1}		-----------------------	-------------cm hr^{-1}	-------------
Longleaf-	0-5	0.16	0.15	0.07	0.08	42.5	13.0
wiregrass†	5-15	0.16	0.14	0.05	0.09	.	.
	15-30	0.16	0.12	0.06	0.06	.	.
	Mean	0.16	0.14	0.06	0.07	.	.
Planted	0-5	0.15	0.11	0.05	0.07	3.8	5.7
pine	5-15	0.14	0.10	0.04	0.06	.	.
	15-30	0.21	0.14	0.09	0.05	.	.
	Mean	0.16	0.12	0.06	0.06	.	.
Row	0-5	0.16	0.11	0.04	0.07	13.9	6.2
crop	5-15	0.15	0.10	0.04	0.06	.	.
	15-30	0.18	0.12	0.07	0.05	.	.
	Mean	0.16	0.11	0.05	0.06	.	.
Management	0-5	0.15	0.13	0.05	0.07	.	.
mean	5-15	0.15	0.11	0.05	0.07	.	.
	15-30	0.18	0.13	0.07	0.05	.	.
	Mean	0.16	0.12	0.06	0.06	.	.

ANOVA	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$	P>F	$LSD_{0.1}$
Management (M)	0.980		0.434		0.764		0.059	0.01	0.038	21.0	0.359	
Depth (D)	0.085	0.03	0.476		0.038	0.02	0.014	0.01				
M x D	0.441		0.388		0.289		0.604					

† Longleaf= Mature longleaf pine habitat, Planted pine= Managed pine plantation, and Row crop= Conventional row crop

‡ $\theta_{v\ 0.1\ bar}$ = Volumetric water content at 0.1 bar, $\theta_{g\ 0.1\ bar}$ = Gravimetric water content at 0.1 bar, $\theta_{g\ 15\ bar}$ = Gravimetric water content at 15 bar, PAW= Plant available water ($\theta_{g\ 0.1\ bar} - \theta_{g\ 15\ bar}$), IR= Surface infiltration rate, Ksat= Saturated hydraulic conductivity (15 cm).

Table 9. Loading factors of the first four principal components of near-surface soil properties of nine Coastal Plain sites.

Variable†	PC1‡	PC2	PC3	PC4
BD	0.26	0.14	-0.17	-0.13
CEC	0.08	0.30	0.30	-0.02
ECEC	0.19	0.27	-0.04	-0.02
BS	0.27	-0.14	-0.13	0.19
Ca	0.29	0.03	0.03	0.01
Mg	0.26	0.17	0.01	-0.04
K	0.31	-0.01	0.08	0.02
Al	-0.13	0.25	-0.18	-0.07
P	0.26	-0.11	0.06	-0.03
SMB	-0.06	0.30	-0.12	-0.16
Nmin	0.24	-0.20	0.13	0.03
Cmin	0.22	0.19	-0.05	0.27
TON	0.22	-0.02	0.24	0.28
TOC	-0.15	0.29	0.20	0.01
POMN	0.13	-0.29	0.02	0.31
POMC	-0.23	0.19	0.10	-0.12
mineralN	0.14	0.23	0.26	0.05
mineralC	0.02	0.30	0.25	0.18
IR	-0.21	-0.11	0.37	0.21
Ksat	-0.13	-0.24	-0.01	0.04
Awater	-0.21	-0.04	0.39	-0.03
SS	0.18	0.14	-0.27	-0.16
WDC	-0.01	0.25	-0.03	0.50
WSA5	-0.20	0.11	-0.32	0.33
WSA15	-0.20	0.06	-0.30	0.43
Eigenvalue	10.03	6.94	2.76	1.57
Proportion Variance Explained (%)	40	28	11	6
Cumulative Variance Explained (%)	40	68	79	85

† BD= Soil bulk density (0-30 cm), CEC= Cation exchange capacity (0-30 cm), ECEC= Effective cation exchange capacity (0-30 cm), BS= % base saturation (0-30 cm), Ca= NH_4OAc extractable calcium (0-30 cm), Mg= NH_4OAc extractable magnesium (0-30 cm), K= NH_4OAc extractable potassium (0-30 cm), Al= KCl extractable aluminum (0-30 cm), P= Mehlich 1 extractable phosphorous (0-30 cm), SMB= Soil microbial biomass C (0-30 cm), Nmin= Potentially mineralizeable N (0-30 cm), Cmin= Potentially mineralizeable C (0-30 cm), TON= Total organic N (0-30 cm), TOC= Total organic C (0-30 cm), POMN= Particulate organic matter N (0-30 cm), POMC= Particulate organic matter C (0-30 cm), mineralN= mineral associated N (0-30 cm), mineralC= mineral associated C (0-30 cm), IR= Surface infiltration rate, Ksat= Saturated hydraulic conductivity (15 cm), Awater= Plant available water (0-30 cm), SS= Soil strength (0-50 cm), WDC= Water dispersible clay (0-30 cm), WSA5= Water stable aggregates (1-2 mm size) (0-5 cm), WSA15= Water stable aggregates (1-2 mm size) (0-15 cm).

‡ PC= Principal component

Figures

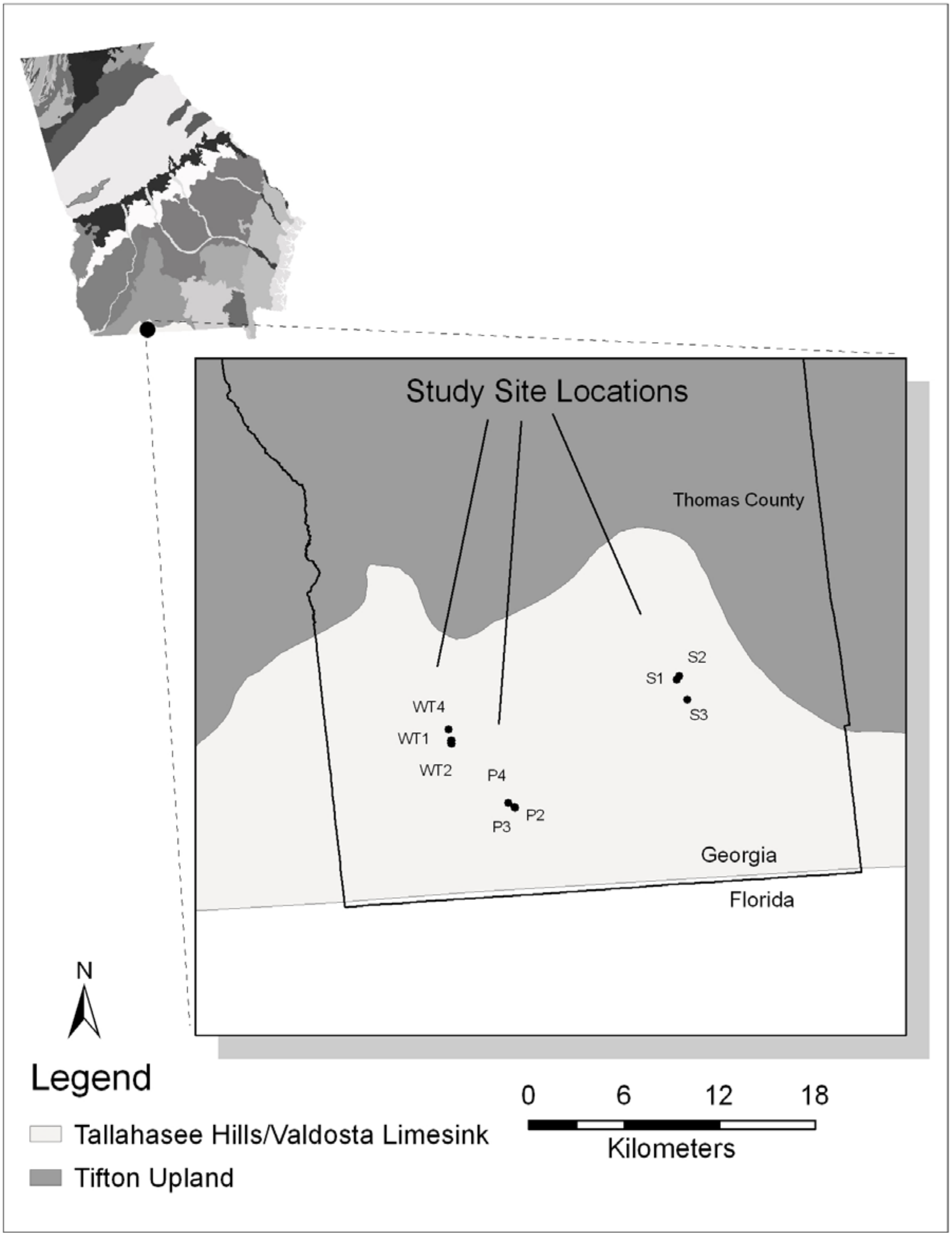

Fig. 6. Study site location displayed with ecoregions of the Georgia Coastal Plain.

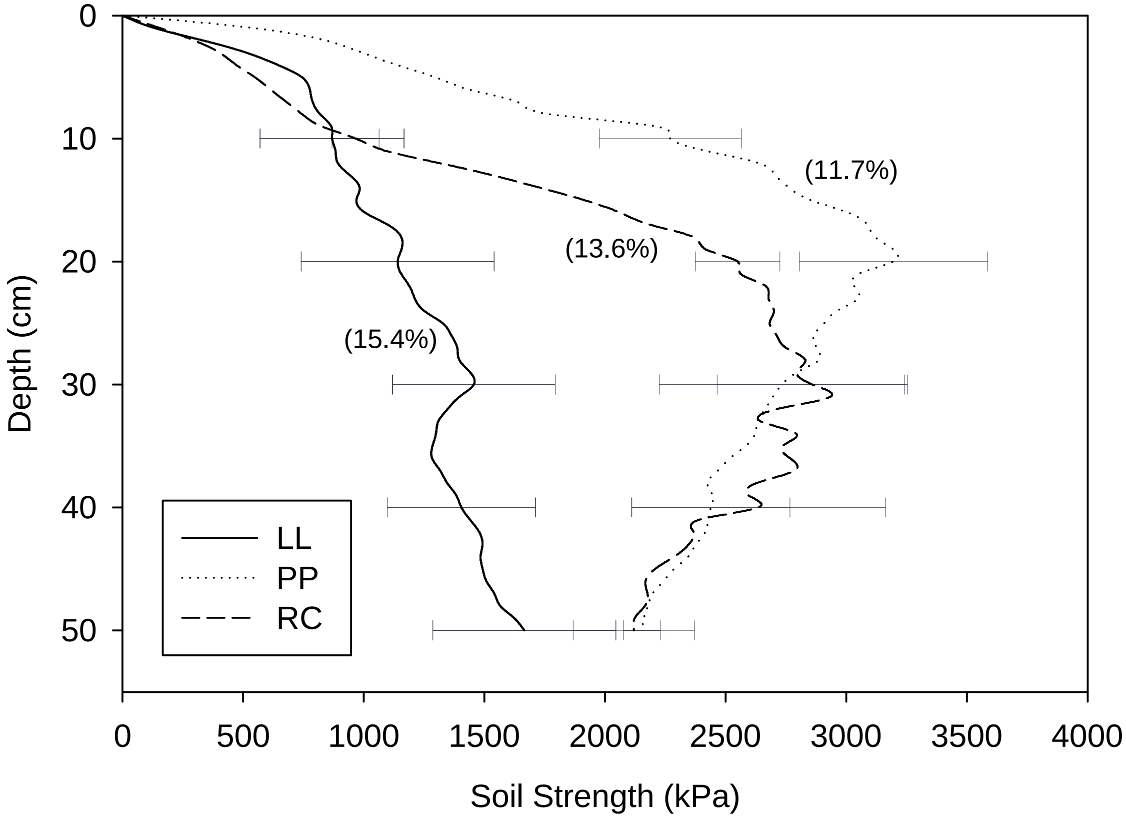

Fig. 7. Soil strength averaged for three reps of three management systems in the Georgia Coastal Plain. Bars represent standard errors of 10 cm averages for each management. Values in parenthesis indicate average gravimetric moisture content for 0–50 cm depth (n=3). LL= Mature longleaf pine habitat, PP= Managed pine plantation, and RC= Conventional row crop.

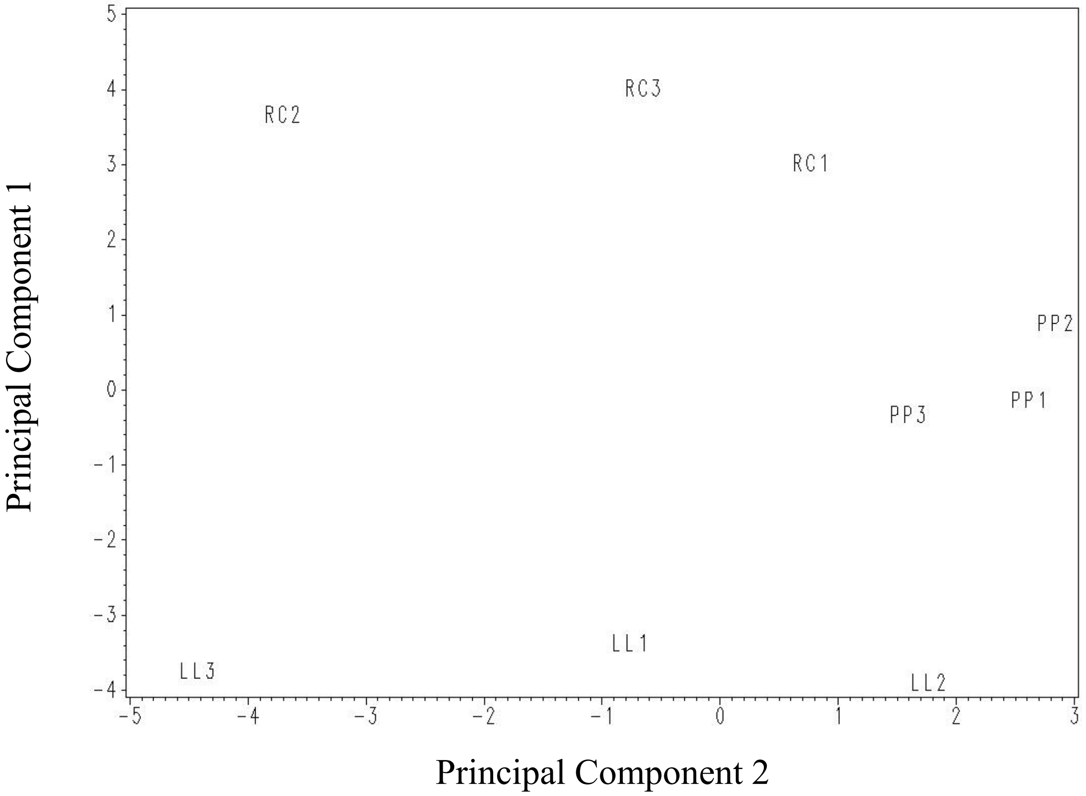

Fig. 8. Principal component score 1 versus principal component score 2 developed from near-surface soil properties of nine sites with three land use types in the South Georgia Coastal Plain.

LL= Mature longleaf pine habitat, PP= Managed pine plantation, and RC= Conventional row crop. 1= fine, 2= fine-loamy, and 3= loamy family particle size classes.

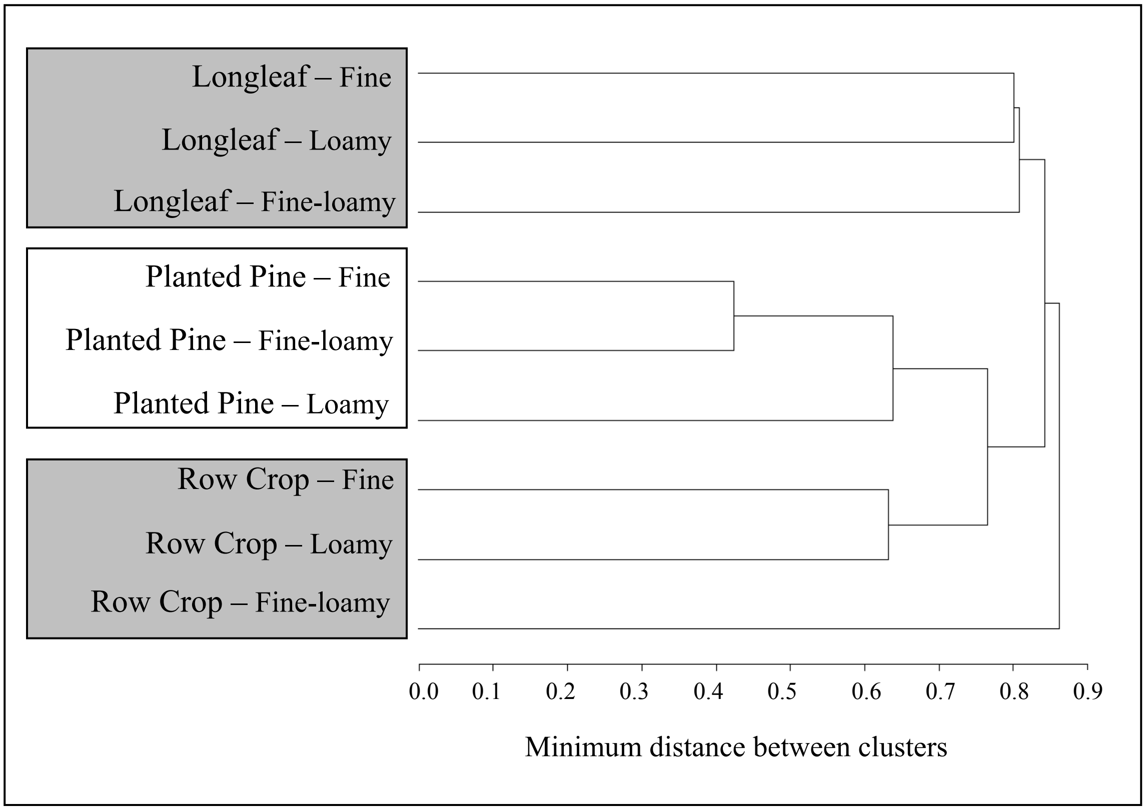

Fig. 9. Multivariate clustering dendrogram of near-surface soil properties (normalized 0-100) of nine pedons in the South Georgia Coastal Plain.

IV. APPENDIX

Laboratory characterization data of investigated soils

Table 10. Soil characterization data for WT1 pedon (Laboratory numbers 040055 to 040060) in longleaf-wiregrass habitat (loamy, kaolinitic, thermic Arenic Kandiudult).

					<--------------------Sand fractionation				---------------------->	<-------pH	------->
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	Cm	<------------------------------------				%			------------------------------------>		
						loamy, kaolinitic, thermic Arenic Kandiudult					
A	0-14	84.18	13.25	2.58	0.61	2.74	9.25	56.22	15.35	4.24	3.94
AE	14-26	85.29	8.23	6.48	0.30	1.02	6.10	60.28	17.59	4.22	4.02
E1	26-58	86.67	7.85	5.48	0.00	0.40	4.04	62.25	19.98	4.35	4.18
E2	58-70	83.26	12.45	4.29	0.10	0.40	4.23	60.61	17.92	4.16	4.12
Bt1	70-94	71.10	9.41	19.49	0.00	0.41	3.46	50.96	16.28	4.24	4.14
Bt2	94-130	69.52	9.11	21.37	0.00	0.31	3.37	50.94	14.90	4.30	4.24

										<-------BS	------->
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<--------------------------------			meq 100 g soil^{-1}			--------------------------------------->	<-meq 100 g clay^{-1}	-->	<--------%	------->
A	1.05	0.53	0.05	0.02	0.72	5.65	2.38	219.13	92.20	29.39	-‡
AE	0.30	0.19	0.08	0.06	0.28	2.55	0.91	39.35	14.06	24.77	18.84
E1	0.16	0.18	0.02	0.10	0.02	1.41	0.48	25.76	8.73	32.52	24.17
E2	0.11	0.27	0.02	0.06	0.08	1.37	0.54	32.00	12.60	33.80	24.36
Bt1	0.30	0.57	0.02	0.06	0.37	2.60	1.32	13.36	6.78	36.68	25.99
Bt2	0.35	0.60	0.02	0.06	0.06	2.62	1.09	12.25	5.09	39.36	26.90

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

‡Insufficient sample.

Table 11. Soil characterization data for WT2 pedon (Laboratory numbers 040061 to 040066) in longleaf-wiregrass habitat (fine-loamy, kaolinitic, thermic Arenic Kandiudult).

					<--------------------Sand fractionation				--------------------->	<-------pH------->	
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<--------------------------				%			-------------------------->		
				fine-loamy, kaolinitic, thermic Arenic Kandiudult							
A	0-18	79.08	7.25	13.67	1.22	1.93	6.82	55.26	13.84	4.30	4.09
AB	18-27	79.84	12.36	7.79	0.61	0.91	4.35	57.99	15.99	4.19	4.16
Bt1	27-38	80.79	4.64	14.57	0.21	0.73	3.78	59.81	16.26	4.18	4.10
Bt2	38-70	58.87	3.36	37.77	0.31	0.42	2.51	44.02	11.61	4.21	4.05
Bt3	70-105	59.72	3.58	36.70	0.00	0.21	1.67	43.05	14.80	4.47	4.10
Bt4	105-136	66.57	6.44	26.99	0.00	0.20	0.71	43.47	22.19	4.40	4.18

										<-------BS------->	
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<-----------------			$\text{meq 100 g soil}^{-1}$			----------------->	<--meq 100 g clay^{-1}	-->	<--------%------->	
A	2.21	1.10	0.10	0.03	0.33	11.33	3.77	82.90	27.56	30.34	36.75
AB	0.31	0.26	0.04	0.06	0.94	3.88	1.62	49.80	20.80	17.44	14.72
Bt1	0.18	0.15	0.03	0.05	0.57	2.69	0.97	18.45	6.69	15.12	11.27
Bt2	0.08	0.28	0.02	0.07	0.77	3.03	1.22	8.02	3.22	14.69	10.58
Bt3	0.05	0.24	0.01	0.05	0.21	3.11	0.56	8.49	1.53	11.33	12.82
Bt4	0.07	0.17	0.02	0.05	0.17	1.84	0.48	6.83	1.78	16.73	13.35

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 12. Soil characterization data for WT4 pedon (Laboratory numbers 050239 to 050245) in longleaf-wiregrass habitat (fine, kaolinitic, thermic Typic Kandiudult).

					<----------Sand fractionation----------				----------->	<--------pH-------->	
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<----------				%			---------->		
					fine, kaolinitic, thermic Typic Kandiudult						
A	0-8	79.45	10.35	10.20	1.76	1.86	5.49	46.14	24.20	4.51	4.21
AE	8-19	82.27	8.67	9.06	0.49	0.69	3.26	49.68	28.15	4.71	4.35
E	19-30	79.96	6.85	13.20	0.49	0.49	2.55	45.96	30.47	4.76	4.25
Bt1	30-65	51.78	4.45	43.78	0.00	0.31	2.14	30.43	18.89	4.81	4.19
Bt2	65-85	46.82	5.42	47.75	1.49	1.17	2.65	26.33	15.18	4.93	4.22
Bt3	85-118	47.89	6.87	45.24	0.51	0.51	2.68	28.43	15.76	4.87	4.18
Bt4	118 +	51.25	6.88	41.87	0.66	0.99	3.18	30.01	16.43	4.74	4.09

										<--------BS-------->	
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<----------			meq 100 g soil^{-1}			---------->	<--meq 100 g clay^{-1}	-->	<---------%-------->	
A	0.56	2.15	0.03	0.18	0.92	5.02	3.85	49.17	37.72	58.38	37.13
AE	0.20	1.22	0.01	0.20	0.29	2.91	1.92	32.09	21.17	55.88	34.25
E	0.11	1.07	0.00	0.19	0.26	2.03	1.63	15.38	12.37	67.79	36.44
Bt1	0.07	3.09	0.00	0.17	0.50	3.94	3.83	8.99	8.75	84.69	40.59
Bt2	0.06	1.87	0.00	0.13	0.50	4.22	2.55	8.83	5.35	48.79	28.35
Bt3	0.05	1.24	0.00	0.17	0.90	4.34	2.35	9.60	5.20	33.54	22.42
Bt4	0.08	0.48	0.00	0.20	1.11	4.26	1.89	10.19	4.51	18.10	13.66

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 13. Soil characterization data for P2 pedon (Laboratory numbers 070114 to 070118 & 070124) in planted pine management (fine, kaolinitic, thermic Typic Kandiudult).

					<---Sand fractionation				--->	<---pH	--->
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<---				%			--->		
					fine, kaolinitic, thermic Typic Kandiudult						
Ap	0-22	83.93	8.57	7.50	0.20	0.91	6.65	53.60	22.57	4.78	4.35
Bt1	22-47	57.43	7.83	34.74	0.10	0.61	3.44	33.97	19.31	4.30	3.89
Bt2	47-72	54.74	5.87	39.38	0.00	0.51	2.94	33.15	18.05	4.42	4.10
Bt3	72-81	48.14	5.65	46.21	0.10	0.10	3.05	31.24	13.64	-‡	-
Bt4	81-114	48.09	4.67	47.24	0.00	0.20	3.57	32.81	11.41	4.55	3.98
Bt5	114-151	48.33	13.54	38.14	0.00	0.08	4.45	37.84	5.96	4.37	3.91

										<---BS	--->
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<---			meq 100 g soil^{-1}			--->	<--meq 100 g clay^{-1}	-->	<---%	--->
Ap	0.61	0.23	0.05	0.11	0.74	2.53	1.73	33.68	23.07	39.08	33.95
Bt1	1.10	0.53	0.10	0.10	1.55	4.82	3.38	13.88	9.74	38.08	27.66
Bt2	1.65	0.67	0.10	0.18	0.92	4.67	3.52	11.85	8.94	55.80	36.75
Bt3	-	-	-	-	-	-	-	-	-	-	-
Bt4	1.03	0.65	0.08	0.12	1.84	5.77	3.72	12.21	7.87	43.35	27.12
Bt5	0.66	0.52	0.07	0.04	2.02	4.84	3.31	12.69	8.69	32.52	23.76

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

‡Insufficient sample.

Table 14. Soil characterization data for P3 pedon (Laboratory numbers 050396 to 050400) in planted pine management (fine-loamy, kaolinitic, thermic Typic Kandiudult).

					Sand fractionation					pH	
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	%									
		fine-loamy, kaolinitic, thermic Typic Kandiudult									
Ap	0-14	81.97	8.55	9.48	0.10	0.70	6.02	53.07	22.07	4.58	3.94
Bt1	14-34	61.02	7.47	31.52	0.00	0.61	4.34	39.20	16.87	4.38	3.88
Bt2	34-65	58.53	5.66	35.81	0.10	0.60	4.43	37.48	15.92	4.86	4.68
Bt3	65-125	54.38	4.81	40.80	0.00	0.40	3.92	35.08	14.98	5.21	5.34
Bt4	125-175	49.93	5.28	44.79	0.20	0.51	3.65	32.81	12.76	4.75	4.15

										BS	
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	meq 100 g soil^{-1}							meq 100 g clay^{-1}		%	
Ap	0.35	0.17	0.06	0.05	0.67	2.23	1.30	23.51	13.70	28.29	19.28
Bt1	0.54	0.34	0.09	0.12	1.34	4.38	2.43	13.91	7.71	24.90	20.48
Bt2	0.91	0.47	0.12	0.10	0.00	3.58	1.60	10.01	4.46	44.54	32.74
Bt3	1.03	0.47	0.14	0.06	0.01	3.32	1.72	8.13	4.21	51.45	37.20
Bt4	0.33	0.32	0.02	0.05	0.18	3.45	0.90	7.71	2.01	20.88	17.00

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 15. Soil characterization data for P4 pedon (Laboratory numbers 050402 to 050409 & 050401) in planted pine management (loamy, kaolinitic, thermic Arenic Kandiudult).

					<---Sand fractionation				--->	<---pH	--->
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<---				%			--->		
					loamy, kaolinitic, thermic Arenic Kandiudult						
Ap	0-20	81.63	11.45	6.92	0.10	0.71	5.85	49.58	25.40	5.29	4.82
A	20-28	82.45	10.72	6.83	0.30	0.70	6.03	50.62	24.81	5.30	4.79
E1	28-41	82.31	10.00	7.69	0.00	0.60	5.81	51.53	24.36	5.03	4.48
E2	41-58	82.35	9.62	8.02	0.00	0.80	6.69	52.11	22.76	5.03	4.46
BE	58-75	75.00	8.14	16.86	0.00	0.60	5.62	47.19	21.59	5.13	4.58
Bt1	75-110	66.63	7.17	26.21	0.00	0.60	4.83	40.66	20.53	4.96	4.65
Bt2	110-145	59.96	6.88	33.16	0.00	0.60	4.33	36.62	18.41	4.86	4.45
Bt3	145-180	54.21	5.32	40.47	0.00	0.61	4.15	33.38	16.08	4.66	4.11

									<---BS	--->
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<---		meq 100 g $soil^{-1}$			--->		<--meq 100 g $clay^{-1}$->		<---%	--->
Ap	2.06	0.52	0.07	0.04	0.00	4.78	2.69	69.08	38.84	56.43	56.45
A	1.54	0.35	0.05	0.10	0.02	3.57	2.05	52.33	30.04	56.84	54.73
E1	0.76	0.30	0.05	0.11	0.31	2.50	1.52	32.48	19.79	48.68	38.77
E2	0.57	0.26	0.02	0.18	0.20	2.11	1.22	26.27	15.21	48.43	41.48
BE	0.81	0.34	0.05	0.06	0.16	2.17	1.43	12.84	8.47	58.57	41.88
Bt1	1.09	0.31	0.07	0.05	0.12	2.91	1.64	11.09	6.27	52.41	42.27
Bt2	0.97	0.41	0.06	0.04	0.19	3.70	1.68	11.17	5.07	40.27	33.50
Bt3	0.37	0.40	0.03	0.06	0.76	3.90	1.62	9.64	3.99	21.90	20.28

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 16. Soil characterization data for S1 pedon (Laboratory numbers 050246 to 050249 & 050416) in row crop management (fine-loamy, kaolinitic, thermic Arenic Kandiudult).

					<---------------------Sand fractionation				---------------------->	<--------pH	------->
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<--			--%--				-->		
					fine-loamy, kaolinitic, thermic Arenic Kandiudult						
Ap	0-19	86.17	9.34	4.49	0.00	0.81	6.41	52.09	26.86	5.78	5.52
Bt1	19-53	64.05	9.11	26.84	0.20	0.81	4.89	38.39	19.75	5.72	5.63
Bt2	53-107	60.96	8.65	30.39	0.10	0.73	4.67	37.28	18.17	5.59	5.67
Bt3	107-156	65.28	6.77	27.94	0.31	0.61	4.90	39.78	19.69	4.96	5.00
Bt4	156-184	67.01	6.10	26.89	0.10	0.40	4.24	40.37	21.90	4.40	4.07

										<--------BS	------->
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<---------------------------------			meq 100 g soil^{-1}			--->	<--meq 100 g clay^{-1}->		<---------%-------->	
Ap	1.52	0.38	0.15	0.11	0.05	2.77	2.20	61.74	48.95	77.51	64.19
Bt1	1.73	0.69	0.22	0.09	0.05	4.10	2.78	15.29	10.37	66.62	53.25
Bt2	1.40	0.93	0.20	0.09	0.05	4.10	2.67	13.50	8.79	63.87	47.64
Bt3	1.00	0.71	0.18	0.14	0.05	3.66	2.08	13.09	7.45	55.55	42.76
Bt4	0.72	0.43	0.10	0.08	0.66	2.86	1.99	10.64	7.40	46.52	31.02

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 17. Soil characterization data for S1 (woods) pedon (Laboratory numbers 050410 to 050415) adjacent to row crop management (fine-loamy, kaolinitic, thermic Arenic Kandiudult).

					<---------------------Sand fractionation---------------------->					<--------pH-------->	
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O	$CaCl_2$
	cm	<--%-->									
					fine-loamy, kaolinitic, thermic Arenic Kandiudult						
A	0-21	87.57	8.66	3.77	0.10	1.71	9.86	52.44	23.45	4.91	4.38
E	21-40	84.54	9.20	6.26	0.10	1.70	10.81	50.82	21.11	4.98	4.55
Bt1	40-62	77.00	7.82	15.18	0.10	1.31	8.25	47.51	19.83	4.46	3.91
Bt2	62-88	68.84	6.76	24.40	0.40	1.51	7.34	40.80	18.79	4.69	4.38
Bt3	88-148	59.55	5.93	34.52	0.30	1.21	6.15	35.57	16.32	4.49	4.08
Bt4	148-181	57.83	5.51	36.66	0.10	0.71	5.27	36.16	15.60	4.68	4.11

										<--------BS-------->	
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<---------------------------------meq 100 g soil^{-1}--->							<--meq 100 g clay^{-1}->		<---------%-------->	
A	1.06	0.24	0.05	0.09	0.30	3.79	1.73	100.61	45.97	37.80	42.76
E	0.59	0.17	0.03	0.10	0.22	1.89	1.10	30.22	17.66	46.83	42.46
Bt1	0.13	0.22	0.03	0.07	0.85	1.99	1.30	13.10	8.55	22.57	16.21
Bt2	0.97	0.46	0.06	0.07	0.24	3.00	1.80	12.29	7.39	52.12	41.98
Bt3	0.95	0.46	0.09	0.06	0.60	3.94	2.16	11.42	6.24	39.40	30.61
Bt4	0.47	0.57	0.03	0.10	0.39	3.59	1.55	9.79	4.22	32.24	28.10

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 18. Soil characterization data for S2 pedon (Laboratory numbers 050250 to 050257 & 050417-18) in row crop management (loamy, kaolinitic, thermic Arenic Kandiudalf).

					<-----Sand fractionation				----->	<----pH	---->
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<-----	-----	-----	-----	%	-----	-----	----->		
					loamy, kaolinitic, thermic Arenic Kandiudalf						
Ap1	0-15	86.89	10.66	2.45	0.50	2.11	11.55	48.52	24.21	5.36	5.00
Ap2	15-29	86.30	11.21	2.49	0.40	1.81	10.46	49.19	24.44	5.12	4.88
E1	29-38	84.65	11.34	4.01	0.70	1.81	9.73	48.24	24.17	5.30	5.02
E2	38-55	82.68	9.05	8.28	0.50	1.40	8.73	46.76	25.28	5.23	5.03
BE	55-72	79.96	10.30	9.75	0.71	1.52	8.79	44.78	24.16	4.84	4.59
Bt1	72-103	70.33	9.55	20.11	0.41	1.43	7.95	39.14	21.41	4.56	4.31
Bt2	103-124	61.72	6.68	31.61	0.20	1.23	6.95	34.23	19.11	4.87	4.92
Bt3	124-144	58.16	6.72	35.12	0.00	1.22	6.70	32.07	18.17	5.06	5.33
Bt4	144-165	62.99	7.92	29.10	0.30	1.01	7.56	35.07	19.05	4.65	4.76
Bt5	165-185	61.37	7.08	31.56	0.20	1.41	7.73	33.24	18.78	4.79	4.72

										<----BS	---->
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<-----	-----	-----	meq 100 g soil^{-1}	-----	----->		<--meq 100 g clay^{-1}	->	<----%	---->
Ap1	1.71	0.37	0.04	0.07	0.05	3.81	2.24	155.77	91.53	57.46	53.30
Ap2	1.31	0.32	0.06	0.14	0.05	2.88	1.88	115.64	75.38	63.48	52.12
E1	0.91	0.25	0.07	0.10	0.02	2.33	1.35	58.02	33.60	57.06	46.63
E2	0.53	0.30	0.11	0.11	0.03	1.66	1.08	20.01	13.08	63.61	45.15
BE	0.40	0.43	0.11	0.19	0.10	1.79	1.23	18.41	12.63	63.12	40.27
Bt1	0.74	0.59	0.13	0.23	0.40	3.33	2.09	16.54	10.40	50.86	37.66
Bt2	1.19	0.55	0.13	0.17	0.02	4.26	2.07	13.48	6.54	48.09	37.88
Bt3	1.28	0.71	0.08	0.11	0.04	4.54	2.23	12.94	6.35	48.19	40.03
Bt4	0.82	0.91	0.17	0.07	0.08	3.00	2.04	10.30	7.01	65.46	45.81
Bt5	0.81	0.83	0.19	0.09	0.03	3.17	1.95	10.03	6.17	60.60	42.09

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 19. Soil characterization data for S3 pedon (Laboratory numbers 050258 to 050263) in row crop management (fine, kaolinitic, thermic Typic Kandiudult).

					<---Sand fractionation--->					<---pH--->	
Horizon	Depth	Sand	Silt	Clay	2-1 mm	1-.5 mm	.5-.25 mm	.25-.1 mm	.1-.05 mm	H_2O†	$CaCl_2$
	cm	<---%--->									
		fine, kaolinitic, thermic Typic Kandiudult									
Ap	0-16	82.89	9.27	7.84	0.60	1.71	9.97	46.43	24.17	5.00	4.87
Bt1	16-32	62.40	7.93	29.67	0.41	1.12	6.20	34.45	20.22	4.64	4.36
Bt2	32-61	54.54	5.52	39.93	0.21	0.64	4.92	30.16	18.61	4.92	5.12
Bt3	61-92	55.36	5.71	38.93	0.41	0.82	5.33	32.81	15.99	4.87	5.11
Bt4	92-117	53.49	7.83	38.68	0.51	0.81	3.03	36.40	12.74	4.64	4.26
BC	117-150	62.23	5.38	32.39	0.00	0.00	1.32	48.52	12.38	4.43	4.11

										<---BS--->	
	Ca	Mg	K	Na	Al	CEC-7	ECEC	CEC-7	ECEC	NH_4OAc	Sum
	<---meq 100 g soil^{-1}--->							<--meq 100 g clay^{-1}->		<---%--->	
Ap	1.25	0.13	0.10	0.14	0.20	2.67	1.80	34.03	23.03	60.34	40.14
Bt1	1.08	0.35	0.15	0.12	0.35	3.42	2.05	11.52	6.92	49.84	33.12
Bt2	1.37	0.59	0.15	0.11	0.05	3.24	2.28	8.11	5.70	68.63	26.78
Bt3	1.03	0.55	0.10	0.10	0.05	2.81	1.82	7.22	4.68	62.96	39.42
Bt4	0.62	0.38	0.05	0.12	0.11	3.55	1.28	9.19	3.32	33.07	29.57
BC	0.22	0.26	0.03	0.09	0.64	2.74	1.23	8.45	3.81	21.57	18.28

†H_2O pH= pH in 1:1 soil to water, $CaCl_2$ pH= pH in 1:2 soil to 0.01M $CaCl_2$, Ca, Mg, K, and Na are NH_4OAc exchangeable bases, Al= KCl extractable Al, CEC-7= cation exchange capacity (pH 7), ECEC= effective cation exchange capacity, BS NH_4OAc= base saturation (pH 7), BS Sum= base saturation by the summation method (pH 8.2).

Table 20. Geographic coordinates of study site locations in Thomas County, Georgia in degrees, minutes, seconds.

Field ID	Longitude	Latitude
WT2	-84° 0' 2.6418"	30° 45' 36.8274"
WT1	-84° 0' 1.944"	30° 45' 43.128"
WT4	-84° 0' 4.7952"	30° 46' 5.9622"
S1	-83° 50' 54.0162"	30° 46' 48.0612"
S3	-83° 50' 34.7454"	30° 46' 4.4718"
S2	-83° 50' 46.9098"	30° 46' 53.9364"
P4	-83° 58' 6.837"	30° 43' 22.6596"
P3	-83° 57' 54.018"	30° 43' 11.787"
P2	-83° 57' 52.686"	30° 43' 10.7616"

Note: Units= Degrees, minutes, seconds, Projection= Geographic, Datum= WGS 1984, Spheroid= WGS1984.

Field descriptions of investigated soils

Sample ID: WT1
Taxonomic Classification: loamy, kaolinitic, thermic Arenic Kandiudult
General Description: This soil was sampled on a nearly level (0–2 % slope) upland in mature longleaf pine stand (2004 by Joey Shaw).

Profile: (Colors are for moist soil.)

A	0 to 14 cm	Very dark grayish brown (10YR 3/2) loamy fine sand; weak fine granular structure; very friable.
AE	14 to 26 cm	Pale brown (10YR 6/3) loamy fine sand; weak fine granular structure; very friable.
E1	26 to 58 cm	Yellowish brown (10YR 5/6) loamy fine sand; moderate fine granular structure; very friable.
E2	58 to 70 cm	Yellowish brown (10YR 5/6) loamy fine sand; moderate fine granular structure; very friable; common pale brown (10YR 6/3) stripped sand grains.
Bt1	70 to 94 cm	Yellowish red (5YR 4/6) sandy loam; moderate medium subangular blocky structure; friable; sand grains bridged with clay.
Bt2	94 to 130+ cm	Yellowish red (5YR 4/6) sandy clay loam moderate medium subangular blocky structure; friable; common faint clay films on faces of peds.

Sample ID: WT2
Taxonomic Classification: fine-loamy, kaolinitic, thermic Typic Kanhapludult
General Description: This soil was sampled on a nearly level (0–2 % slope) upland in mature longleaf pine stand (2004 by Joey Shaw).

Profile: (Colors are for moist soil.)

A	0 to 18 cm	Dark brown (10YR 3/3) sandy loam; weak fine granular structure; very friable.
AB	18 to 27 cm	Brown (10YR 4/3) loamy sand; weak fine granular structure; very friable.
Bt1	27 to 38 cm	Strong brown (7.5YR 4/6) sandy loam; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt2	38 to 70 cm	Red (2.5YR 4/6) sandy clay; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt3	70 to105 cm	Red (2.5YR 4/6) sandy clay; moderate medium subangular blocky structure; common clay films on faces of peds.

Bt4	105 to 136+ cm	Yellowish red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; common clay films on faces of peds.

<u>Sample ID:</u> WT4
<u>Taxonomic Classification:</u> fine, kaolinitic, thermic Typic Kandiudult
<u>General Description:</u> This soil was sampled on a nearly level (0–2 % slope) upland in mature longleaf pine stand (July 2005 by Joey Shaw, Matt Levi, and Sharon Hermann).

<u>Profile:</u> (Colors are for moist soil.)

A	0 to 8 cm	Dark brown (10YR 3/3) sandy loam; weak fine granular structure; very friable.
AE	8 to19 cm	Dark yellowish brown (10YR 4/6) loamy sand; weak fine granular structure; very friable.
E	19 to30 cm	Strong brown (7.5YR 5/6) sandy loam; weak fine granular structure; very friable.
Bt1	30 to 65 cm	Yellowish red (5YR 4/6) sandy clay; moderate medium subangular blocky structure; friable; common distinct clay films on faces of peds.
Bt2	65 to 85 cm	Red (2.5YR 4/6) sandy clay; moderate medium subangular blocky structure; friable; common distinct clay films on faces of peds; few ironstone.
Bt3	85 to 118 cm	Yellowish red (5YR 4/6) sandy clay; moderate medium subangular blocky structure; friable; common clay film s on faces of peds; common red (2.5YR 4/6) and strong brown (7.5YR 4/6)
Bt4	118+ cm	Yellowish red (5YR 4/6) sandy clay; moderate medium subangular blocky structure; friable; common clay films on faces of peds; common red (2.5YR 4/6), strong brown (7.5YR 4/6) and dark yellowish brown (10YR 4/6) concentrations.

<u>Sample ID:</u> P2
<u>Taxonomic Classification:</u> fine, kaolinitic, thermic Typic Kandiudult
<u>General Description:</u> This soil was sampled on a gently sloping (2–5 % slope) side-slope in a pine stand (9 February 2007 by Matt Levi and John Owen).

<u>Profile:</u> (Colors are for moist soil.)

Ap	0 to 22 cm	Brown (10YR 4/3) loamy sand; weak fine granular structure; very friable.
Bt1	22 to 47 cm	Yellowish red (5YR 5/8) sandy clay loam; moderate medium subangular blocky structure; very friable; common distinct clay films on faces of peds.

Bt2	47 to 72 cm	Yellowish red (5YR 5/8) sandy clay; moderate medium subangular blocky structure; very friable; common distinct clay films on faces of peds.
Bt3	72 to 81 cm	Red (2.5YR 5/8) sandy clay; moderate medium subangular blocky structure; very friable; common distinct clay films on faces of peds.
Bt4	81 to 114 cm	Red (2.5YR 5/8) sandy clay; moderate medium subangular blocky structure; very friable; common clay films on faces of peds; few reddish yellow (7.5YR 6/8) concentrations.
Bt5	114 to 151+ cm	Red (2.5YR 5/6) sandy clay; moderate medium subangular blocky structure; friable; common clay films on faces of peds; few light red (2.5Y 6/6) concentrations.

Sample ID: P3
Taxonomic Classification: fine-loamy, kaolinitic, thermic Typic Kandiudult
General Description: This soil was sampled on a gently sloping (2–5 % slope) side-slope in a pine stand (15 December 2005 by Joey Shaw and Matt Levi).

Profile: (Colors are for moist soil.)

Ap	0 to 14 cm	Brown (10YR 4/3) loamy fine sand; weak fine granular structure; very friable.
Bt1	14 to 34 cm	Yellowish red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; clay films on faces of peds.
Bt2	34 to 65 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; common clay films on faces of peds.
Bt3	65 to 125 cm	Red (2.5YR 4/6) sandy clay; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt4	125 to 175+ cm	Yellowish red (5YR 4/6) sandy clay; moderate medium subangular blocky structure; common clay films on faces of peds.

Sample ID: P4
Taxonomic Classification: loamy, kaolinitic, thermic Arenic Kandiudult
General Description: This soil was sampled on a gently sloping (2–5 % slope) side-slope in a pine stand (15 December 2005 by Joey Shaw and Matt Levi).

Profile: (Colors are for moist soil.)

Ap	0 to 20 cm	Brown (10YR 4/3) loamy fine sand; weak fine granular structure; very friable.

A	20 to 28 cm	Dark yellowish brown (10YR 4/4) loamy fine sand; weak fine granular structure; very friable.
E1	28 to 41 cm	Brown (7.5YR 5/4) loamy sand; weak fine granular structure; very friable.
E2	41 to 58 cm	Reddish brown (5 YR 5/4) loamy sand; weak fine granular structure; very friable.
BE	58 to 75 cm	Red (2.5YR 4/6) sandy loam; weak medium subangular blocky structure; very friable.
Bt1	75 to 110 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable.
Bt2	110 to 145 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; very friable.
Bt3	145 to 180+ cm	Red (2.5YR 4/6) sandy clay loam moderate medium subangular blocky structure; friable.

Sample ID: S1
Taxonomic Classification: fine-loamy, kaolinitic, thermic Typic Kandiudult
General Description: This soil was sampled on a level (0–2 % slope) upland in a row crop field (8 August 2005 by Joey Shaw, Wes Wood, Matt Levi, and Sharon Hermann)

Profile: (Colors are for moist soil.)

Ap	0 to 19 cm	Dark brown (10YR 3/3) loamy fine sand; weak fine granular structure; very friable.
Bt1	19-53 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt2	53-107 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt3	107-156 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt4	156-184+ cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; common clay films on faces of peds.

Sample ID: S1(Woods)
Taxonomic Classification: fine-loamy, kaolinitic, thermic Typic Kandiudult
General Description: This soil was sampled on a level (0–2 % slope) upland in a pine stand adjacent to a row crop field (15 December 2005 by Joey Shaw and Matt Levi)

Profile: (Colors are for moist soil.)

A	0 to 21 cm	Brown (10YR 4/3) loamy fine sand; weak fine granular structure; very friable.

E	21 to 40 cm	Yellowish brown (10YR 5/4) loamy sand; weak fine granular structure; very friable.
Bt1	40 to 62 cm	Red (2.5YR 4/6) sandy loam; moderate medium subangular blocky structure; friable; common distinct clay films on faces of peds.
Bt2	62 to 88 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; common clay films on faces of peds.
Bt3	88 to 148 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; common clay films on faces of peds.
Bt4	148 to 181+ cm	Yellowish red (5YR 4/6) sandy clay; moderate medium subangular blocky structure; common clay films on faces of peds.

Sample ID: S2
Taxonomic Classification: loamy, kaolinitic, thermic Arenic Kandiudalf
General Description: This soil was sampled on a level (0–2 % slope) upland in a row crop field (8August 2005 by Joey Shaw, Wes Wood, Matt Levi, and Sharon Hermann)

Profile: (Colors are for moist soil.)

Ap1	0 to 15 cm	Dark reddish brown (10YR 3/3) loamy fine sand; weak fine granular structure; very friable.
Ap2	15 to 29 cm	Brown (10YR 4/3) loamy fine sand; weak fine granular structure; very friable.
E1	29 to 38 cm	Yellowish brown (10YR 5/4) loamy fine sand; weak fine granular structure; very friable.
E2	38 to 55 cm	Brown (7.5YR 5/4) loamy fine sand; weak fine granular structure; very friable.
E3	55 to 72 cm	Yellowish red (5YR 4/6) sandy loam; weak subangular blocky structure; very friable; few gravel.
Bt1	72 to 103 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; clay films on faces of peds.
Bt2	103 to 124 cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; common clay films on faces of peds.
Bt3	124 to 144cm	Red (2.5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; common clay films on faces of peds.
Bt4	144 to 165 cm	Red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; common clay films on faces of peds.
Bt5	165 to 185+ cm	Red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; common clay films on faces of peds.

Sample ID: S3
Taxonomic Classification: fine, kaolinitic, thermic Typic Kandiudult
General Description: This soil was sampled on a level (0–2 % slope) upland flat in a row crop field (8 August 2005 by Joey Shaw, Wes Wood, Matt Levi, and Sharon Hermann)

Profile: (Colors are for moist soil.)

Ap	0 to 16 cm	Brown (10YR 4/3) loamy sand; weak fine granular structure; very friable.
Bt1	16 to 32 cm	Yellowish red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; very friable; common clay films on faces of peds.
Bt2	32 to 61 cm	Red (2.5YR 4/6) sandy clay; moderate medium subangular blocky structure; very friable; common clay films on faces of peds.
Bt3	61 to 92 cm	Yellowish red (5YR 4/6) sandy clay; moderate medium subangular blocky structure; very friable; common clay films on faces of peds.
Bt4	92 to 117 cm	Strong brown (7.5YR 4/6) sandy clay; moderate medium subangular blocky structure; very friable; common clay films on faces of peds; common red (2.5YR 4/6) and dark yellowish brown (10YR 4/6) concentrations.
BC	117 to 150+ cm	Mixed strong brown (7.5YR 4/6) and dark yellowish brown (10YR 4/6) sandy clay loam; weak medium subangular blocky structure; friable.