Southeastern U.S. Upper Coastal Plain Ecological Sites for Dynamic Soil Property Characterization

by

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Abstract

The Ecological Site (ES) concept groups soils that respond similarly to management to meet conservation goals, develop site interpretations and models for ecological transitions, and construct restoration pathways. The USDA-NRCS and the National Cooperative Soil Survey (NCSS) have a nationwide plan to classify all lands into ESs. Dynamic soil properties (DSPs) are near-surface properties that respond to management and are critical to soil function and ecosystem services. Measurement of DSPs is also used to evaluate anthropogenic impacts on soil (termed *soil change*). The NCSS is developing methodologies to characterize and inventory DSPs, and we hypothesize the ES framework is a valid approach for doing this. The ability to characterize DSPs using ES would facilitate hydrological modeling, soil carbon sequestration, and provide soil health benchmarks and goals. In this study, we developed an ES for Longleaf Pine (*Pinus palustris*) -Bluestem (*Schizachrium scoparium* and *Andropogon* spp.) systems in the Alabama Fall Line Hills region, and subsequently characterized and inventoried DSPs for four states. The reference state consisted of relatively undisturbed Longleaf Pine and Bluestem sites; cultivated states included conventional row crop, pine plantation, and pasture sites that had been in place >20 yrs. The soil components in the ES were described, sampled, characterized, and verified to be Kanhap- and Kandiudults with sandy surfaces, loamy subsoils, and low activity mineralogy. Measured DSPs (0-50 cm) included carbon pools, chemical (e.g. extractable nutrients, exchangeable bases, CEC), and physical (bulk density, aggregate stability, clay dispersion ratio) properties critical to soil function. Soil organic carbon pools (0-30 cm, $p = 0.0037$) were higher (> 4 kg m^{-2}) in reference and pine plantation than pasture and row crop states (< 4 kg m^{-2}). However, the highest active carbon was found in the pasture state ($p = 0.0011$). As expected, intensive management (i.e. amendment additions) resulted in higher base

saturation ($p < 0.0001$) and Mehlich 1 extractable P ($p = 0.0004$), and lower Al saturation ($p < 0.0001$) in row crop and pasture states. Water stable aggregates (WSA) decreased with disturbance and tillage, with the lowest stable aggregates (77 %) in the row crop state. Surface bulk density (ρb) was highest in row crop (1.56 g cm^{-3}) and lowest in the reference state (1.07 g cm^{-3}). Bulk density decreased ($r = -0.83$) and CEC increased ($r = 0.79$) with increasing SOC, illustrating the critical role soil organic matter plays in soil quality for these systems. Multivariate analyses showed that measured sites generally grouped by state. While differences in DSPs were observed among states, differences were not as extensive as similar studies since the reference sites had legacy effects associated with a history of disturbance. However, the reference state represents a realistic management goal. Considering the range of a reference state concept, the aggregate of data suggests ESs are effective for characterizing DSPs and soil change in this region.

The second objective of this study was to measure and compare soil hydraulic properties and functions among states of the ecological site. Measured hydraulic properties include soil water retention (van Genuchten) parameters, infiltration rate, and saturated hydraulic conductivity (Ksat). van Genuchten moisture retention parameters were measured at 15 cm in each site. The moisture retention parameter alpha (α) was higher in the reference than other states, indicating that these states lose gravitational water more quickly ($p = 0.0058$). Infiltration rate, Ksat (five depths to 100 cm), and water retention parameters (three depths to 50 cm) were measured in all states within Marvyn units. Paired t-tests (by depth) indicated significantly higher ($p < 0.062$) Ksat to 50 cm in the reference as compared to other states. These differences among the reference and cultivated states suggested some change in hydrologic function with ecological state. HYDRUS 1-D was used to simulate water flow for the reference and row crop

states in Marvyn units under wet and dry conditions. In a 100-yr storm simulation (24 cm over 24 hour), the reference Marvyn site displayed no runoff while the row crop site showed 5.5 cm runoff. However, in a dry down event, the row crop Marvyn unit retained more water than the reference Marvyn unit over 60 days. These differences are likely due to inherent properties (e.g. soil texture) at sites rather than ecological state effects. Additional hydraulic data and simulations are necessary for further understanding of hydrologic function in states of an Alabama Fall Line Hills Ecological site. Comparisons of site and soil response to heavy rainfall and drought conditions under differing ecological states demonstrate the use of hydrologic modeling in Ecological Sites.

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In loving memory of Cecil Whaley and Marjo Willis.

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Chapter 1

Literature Review

Ecological Sites

The National Cooperative Soil Survey (NCSS) is our nation's most detailed natural resource inventory and the foundation of land use management and planning. The NCSS began as the National Soil Survey Program in 1896 with the goal to deliver soils information to farmers and assist agricultural decisions, and over the last century has provided soils information to users and informed local and national land use plans (Soil Science Division Staff, 2017). Soil surveyors use predictive soil-landscape models to develop soil inventories. NCSS maps embody the three dimensional nature of soils, and while these maps delineate areas occupied by different soils, the properties defined in those soils allows the user to understand the nature, formation, and pedogenic history (Soil Science Division Staff, 2017).

The Ecological Site program uses a soil survey foundation to group soils and landscapes with a similar response to management. The program is management driven with soil-vegetation models. It identifies a reference state, degraded states, and multiple land management states, as well as drivers and mechanisms for these changes (USDA, 2017). The program is intended to improve land management decisions and efforts to restore degraded systems (Karl and Talbot, 2016). The program is being adopted by USDA-NRCS and other state and federal agencies to administer and manage lands.

Ecological Sites (ESs) utilize soil and vegetation dynamics to develop state and transition models (STMs), site interpretations, and restoration pathways. For site descriptions, five main categories are characterized: climate, physiography, soils, plant communities, and hydrology. The ES concept groups soils based on their relationship to vegetative communities and ecological processes (Duniway et al., 2010). There are multiple approaches to developing ecological site descriptions (ESDs). To differentiate sites, many descriptions rely on vegetation and landscape but also consider soil properties related to soil function including water and nutrient availability (texture, gravels, depth of solum), rooting depth, and erodibility (texture, aggregation, aggregate stability) (Duniway et al., 2010; Caudle et al., 2013). Duniway et al. (2010) suggests using surface properties that change more rapidly with disturbance and land cover -- e.g., soil organic matter, compaction, and infiltration rates – to distinguish ecological states. ESDs require characterization data, descriptions, and interpretations. However, some advocate for a more dynamic, fluid approach to ESDs—quickly publishing preliminary sites for management uses, collecting additional data and changing them over time (Karl and Talbot, 2016; USDA-NRCS, 2017).

A state and transition model (STM) is the basis of an ESD, and it combines vegetation, management, and soil data to illustrate management response and mechanisms for transitions among states (Bestelmeyer et al., 2010; USDA-NRCS, 2017). Developing STMs often requires space for time substitution, and characterizing similar soils at different stages of management, degradation, and restoration. Plant community composition, productivity, and soil function are used to define reference and alternative states (Bestelmeyer et al., 2011).

In Northern New England, Johanson et al. (2016) based ESDs on landscape position with consideration of soil drainage class and particle size class; transitions between states were driven by disturbance. In the Northern Appalachians (USA), Drohan and Ireland (2016) used hierarchical clustering and principal components analysis in combination with datasets containing plant communities, topography, soils, and climate information to develop sites. Reference states were described as phases, a forested state was defined by sub-categories to delineate species mix, and transitional states were defined by disturbance (Drohan and Ireland, 2016). In the Carolina and Georgia Sandhills, NatureServ and USDA-NRCS developed six ESDs using NRCS soil inventories, U.S. National Vegetation Classification, and information from NatureServe's Ecological Integrity Assessment (EIA) work, U.S. NVC development, NC NHP, and Landfire (Nordman and Clendenin, 2013).

The ES program began in western rangeland ecosystems and has been adapted to describe ESs throughout the U.S. However, approved USDA-NRCS ESs are few in the southeastern U.S. due to challenges presented by intensive land management. Rangeland in the western U.S., where the ES concept was originally developed, was historically mapped at lower resolution (complexes, associations, undifferentiated groups) than row crop areas (Duniway et al., 2010). Western U.S. land use and management is more stable and longer term than the eastern US. The historic anthropogenic disturbance and intensive management of southeastern U.S. lands complicates ES development.

In addition, regions with excessive anthropogenic disturbance create uncertainty in reference state due to historical disturbance and its legacy effects on soil (Drohan and Ireland, 2016). For example, in forested soils at Fort Benning, Georgia, bulk density showed legacy effects of disturbance after 55 years of restoration even though carbon and nitrogen stocks had returned to near reference levels (Maloney et al., 2008). Two hundred years of Roman farming in England caused changes in nutrient availability and plant communities that can be observed and measured two thousand years later (Dupouey et al., 2002). All this uncertainty and legacy effect can make the reference state an unrealistic management target, leaving land managers with an unattainable goal. However, ES concepts have been utilized to further management goals in other areas. Spiegal et al. (2016) utilized ESD and STM concepts to define conservation interest areas of the 97,000 ha Tejon Ranch in Southern California. STMs developed for this area were used to adjust grazing management, pasture boundaries and size (Spiegal et al., 2016).

Ecological sites are also used as a framework to facilitate research. Nauman et al. (2015a) used spodic properties to indicate previous vegetative condition in the Appalachian forests of West Virginia, USA. Organic horizon (O) reduction and carbon loss have been documented within red spruce (*Picea rubens*) and eastern hemlock (*Tsuga canadensis*) ESs on spodosols when areas transitioned from reference vegetation suggesting possible avenues for soil and vegetative restoration (Nauman et al., 2015b). This research indicates the potential to use ESs to relate soil properties and vegetative condition both historically and presently. Williams et al. (2016) studied hydrologic function and management in the Great Basin region of the southwestern US, illustrating an increase in runoff and erosion of degraded states using modeling. This was accomplished in the frame of a representative ESD with a diverse perennial grass and sagebrush reference state and various degraded states, including a cheatgrass (*Bromus tectorum*) dominated state that encourages catastrophic fire (Williams et al., 2016). This study showed the utility of hydrologic data to inform ESDs and management decisions and is an example of using representative sites for larger management interests.

Soil Change

Soil change is a human centric area of study concentrated at human time scales. Soil change refers to the temporal variability of soil properties and how changes in these properties affect soil function (Tugel et al., 2008). Soil function encompasses the broad range of processes and interactions between soils and the environment, but the focus of soil change is on properties and processes relevant to humans such as a stable medium for plant growth and urban development, moderation of the hydrologic cycle, and maintenance of carbon, nutrient, and element cycles (Tugel et al., 2008). The ability and will of humankind to effect change on the natural world led Amundson and Jenny (1991) to present our species as a separate soil forming factor. We constantly alter the environment and impact soils in drastic and sometimes irreversible ways, and the study of soil change allows soils research to focus on these impacts.

Dynamic Soil Properties

Doran and Parkin (1996) recommended indicators (physical, chemical, and biological) for understanding the condition, quality, and health of soils. For example, water holding capacity was chosen for its relationship to water retention and solute transport, soil organic matter was chosen as it is related to soil fertility, soil stability and erosion, and microbial biomass was chosen for its indication of microbial activity and management effects on organic matter (Doran and Parkin, 1996). These properties are dynamic in nature and commonly used in soil health and quality studies.

Dynamic soil properties (DSPs) are near-surface properties that respond to management and are critical to soil function, health, and quality. DSPs are linked to many functions; for example, soil organic carbon, aggregate stability, bulk density, and infiltration rate are related to soil water relations (Wills et al., 2017). Characterization of DSPs is critical for understanding soil functions and ecosystem services. DSPs can also support ESDs by defining states, characterizing site and state variability, and clarifying thresholds and transitions among states (USDA-NRCS, 2017). Soil survey’s minimum data set for studying DSPs include carbon, pH, electrical conductivity, bulk density, aggregate stability, biological enzymes, particulate organic matter, nutrients, and soil hydrologic properties (infiltration rate, hydraulic conductivity) (Wills et al., 2017). Dynamic soil properties can be broken into three general categories: soil organic carbon pools, chemical DSPs, and physical DSPs.

Soil organic carbon (SOC) is an important component of soil function, affecting soil tilth, air and water permeability, water retention, and erodibility (Sikora and Stott, 1996). Organic matter quantities are dependent on the net primary productivity (NPP) of the vegetative state, soil texture, and decomposition (soil temperature, solar radiation, soil moisture, etc.) (Sikora and Stott, 1996). Surface residue carbon, particulate organic matter, and SOC increases with decreasing soil disruption (Franzluebbers et al., 1999; Franzluebbers and Stuedemann, 2002). Intermediate (particulate organic matter) and active, labile (soil microbial biomass carbon) forms of organic carbon have been suggested as more sensitive soil quality indicators (Franzluebbers et al., 1999; Weil et al., 2003). Active carbon has been successfully utilized to indicate differences in soil quality, though the magnitude and consistency of difference depends on the method of measurement (Weil et al., 2003).

Operationally, Sikora and Stott (1996) recommend automated dry combustion, direct determination of CO_2 by chromatography, and loss on ignition methods for measuring soil organic carbon. Soil carbon of different size fractions can be determined by dry combustion of sieved soil fractions (Causarano et al., 2008). Each particle size fraction has organic matter associated with it; particulate organic matter (POM) is the fraction of organic matter between 0.05 and 0.20 mm (Sikora and Stott, 1996). Active carbon can be measured through chloroform fumigation, basal respiration, and oxidation reactions. Weil et al. (2003) suggests using 0.02 M potassium permanganate to oxidize the labile fraction of SOC and a 550 nm wavelength to measure the absorbance of unreacted potassium permanganate.

Selected chemical DSPs include pH, cation exchange capacity (CEC), and exchangeable bases. Colloidal soil minerals and organic matter have negative charges that retain positively charged cations (USDA-NRCS, 2011). CEC is frequently used as an indicator of clay activity, but the role of organic matter in CEC makes it a useful soil health indicator and DSP. Fang et al. (2017) linked temporal decreases of CEC across China's grasslands to overgrazing, desertification, soil acidification, and extreme precipitation. The soil pH (concentration of hydrogen ions in soil solution) is a measure of active acidity and is essential in soil testing for agriculture (fertilizer recommendation, lime requirements, nutrient availability). Soil pH is mediated by many natural processes including microbial breakdown of organic matter, oxidation and reduction, atmospheric deposition, plant uptake, and precipitation and weathering. Many soils are naturally acidic due to rainfall and parent materials, including most in the southeastern US (Brady and Weil, 2008). It is a valuable indicator of rapid change in heavily managed lands as pH affects nutrient availability, the function of microbial communities, and the nitrogen cycle (Smith and Doran, 1997).

Physical DSPs are many, varied, and indicate a multitude of soil functions. Bulk density is the mass of oven dry soil per volume, and varies due to soil texture, sampling method, and management such as tillage or trafficking. Higher bulk densities reduce pore space and restrict plant root, water, and nutrient movement through soil (Brady and Weil, 2008). Water stable aggregates (WSA) and water dispersible clay (WDC) are frequently used to measure soil stability in soil health and quality studies (Kemper and Rosenau, 1986; Seyboldc, 1999; Levi et al., 2010). Measurements of soil stability are linked to erosion susceptibility and SOC (Pellant et al., 2005).

Previous research in the southeastern U.S. suggests near-surface soil physical properties vary systematically with land use and management. In Georgia Kanhapludults, Levi (2007) found DSPs clustered more similarly by land use and management than soil series. Previous studies using longleaf (*Pinus palustris*) reference systems in Alabama and Georgia have shown

DSP differences among states including soil organic carbon, Mehlich extractable P, saturated hydraulic conductivity, and CEC/clay ratio (Levi et al., 2010). In North Carolina, Price et al. (2010) found that forest lands had lower bulk densities and higher saturated hydraulic conductivities than more cultivated (lawn and pasture) land uses. In the southeastern U.S. Piedmont and Coastal Plain, Causarano et al. (2008) found that pasture systems had higher total organic carbon, particulate organic carbon, and microbial biomass carbon than row crop systems in the upper 5-cm of soil.

Hydrologic Soil Function

Hydrologic soil function is ecologically and economically important to runoff, plant available water, groundwater recharge, and water quality. Infiltration rate and saturated hydraulic conductivity are important measurements of water movement into and within the soil profile. Water holding capacities are dependent on pore size, arrangement, and pressure, and are essential to ecosystem services such as provisioning water. Due to the complex nature of soil pores and flow paths, soil water movement is often described and simulated as the average flow through a volume of soil over time (Hillel, 1982). Water flow in saturated media is described by Darcy's Law where flux density or the volume of water through a cross sectional area per unit time:

$$q = K\left(\frac{\Delta H}{L}\right) \quad \text{Equation 1}$$

where q is the flux density, $\Delta H/L$ is the hydraulic gradient, and K is the saturated hydraulic conductivity (Hillel, 1982).

Previous studies have indicated differences in hydrologic soil properties under different land use and management. In China, a study found that after 25 years grassland had higher infiltration rates than forests, due to root density and soil organic matter, while forest land had higher infiltration after 15 years due to more active root biomass (Kalhoro et al., 2018). In the

Southeastern U.S. Coastal Plain, Cochran (2010) found that reference longleaf system had the highest saturated hydraulic conductivity (0-50 cm) relative to row crop and pasture sites; this was attributed to the large plant roots and macropore development of the forested system.

Soil hydrologic function is often evaluated through simulation modeling. Hydrus 1D provides a simple user interface to simulate water movement in variably saturated and heterogeneous media (soil) over time; it utilizes the Richards equation for saturated-unsaturated water flow and incorporates soil hydraulic models such as the van Genuchten-Mualem and modified van Genuchten (Simunek et al., 2005). Hydrus models have been successfully calibrated and validated in multiple soil water studies (Xu et al., 2017; Wang et al., 2018; Contreras and Bonilla, 2018; Šípek et al., 2020). A study evaluating land cover and climate change in the Scottish highlands applied Hydrus 1D modeling to simulate land cover change from heather (*Ericaceae* spp.) to Scots pine (*Pinus sylvestris*) by replacing vegetation parameters with pine and maintaining soil parameters as those originally sampled under heather vegetation (Wang et al., 2018). Šípek et al. (2020) utilized HYDRUS 1D to study soil water dynamics showing higher transpiration in beech forests and higher drainage in spruce forests in the Czech Republic. Li et al. (2019) utilized HYDRUS 1D to investigate soil water balance in land use change from farmland to orchards in Chinese loess soils; they observed a decrease in groundwater recharge due to the high water demand of trees.

Natural Resources in the Fall Line Hills region of Alabama

The Fall Line separates the Appalachian Mountains from the Coastal Plain in the southeastern U.S. The Fall Line Hills make up the northern boundary of the Southern Coastal Plain Major Land Resource Area (MLRA 133A) in Alabama. This region of Alabama includes open hills with rounded tops at elevations 61 to 305 m above sea level and local relief of 61 to

122 m; it has a humid, temperate climate with a mean annual precipitation of 135 to 150 cm (Griffith et al., 2001). The geology of the region includes quaternary and cretaceous sediments, and the soils have thermic temperature and udic moisture regimes. The upland soils of this region are commonly Hapludults, Kanhapludults, and Kandiudults (Griffith et al, 2001). These are well developed soils with low organic matter, base saturation and clay activity, rendering them relatively infertile with reduced soil quality. In addition, the rolling hills of the area make many of these soils highly erodible.

Before European settlement, longleaf pine was a dominant tree species in the southeastern U.S. Coastal Plain; it has declined the last two centuries due to timber harvest, land use change, invasive species, and fire suppression (Brockway et al., 2005). Longleaf pine characteristically shapes the surrounding ecology through fire. Both pine growth and reproduction are dependent on frequent fire occurring every two to eight years. It protects itself from fire at the seedling stage, with thick grass-like foliage to guard the apical meristem, and at the adult stages by self-pruning, thick bark, and regeneration in open areas (Outcalt, 2000). In addition, frequent fire keeps susceptible species out of longleaf habitat (Brockway et al., 2005). Native grasses such as wiregrass (*Aristida beyrichiana)* and bluestem (*Schizachrium scoparium* and *Andropogon spp.*) dominate the diverse understory of the longleaf system; dry grasses and pine needles become the flammable understory needed to maintain the ecosystem fire regime (Outcalt, 2000).

Land use in Alabama has been dominated by cotton, field crop, and pine tree production for much of the region’s post-colonial history. Soils have been exposed to degradation and erosion by intensive cropping and clear cutting of lands. Historical conventional row crop production disturbed natural soil surfaces and structure, caused compaction, and made the soil more susceptible to erosion. Continual monoculture cropping and removal of ground cover depleted soil nutrient and carbon reserves.

Land use history in the Tuskegee National Forest (TNF) is well documented and can be used to describe Fall Line Hills history. Beginning with land clearing and Creek “allotments” in the Treaty of 1832, the area was heavily cropped by tenant farmers for the better part of a century (Warren and Zabawa, 1998). The intensive cultivation on sloping and highly erodible soils caused massive erosion and land degradation and a reduction in soil quality. The land composing TNF was bought by the US government in the 1930’s as part of the Submarginal Lands Program, and became what is now known as Tuskegee National Forest in 1959 (USDA-Forest Service, 2019).

Rationale for Study

USDA-NRCS programs provide support for land management and restoration efforts. The NCSS soil inventory is a foundational resource for land use management and planning. The ES program uses these soil inventories and vegetation models to describe reference and degraded lands. Ecological site descriptions (ESDs) utilize climate, physiography, plant communities, hydrology, and soils to provide a depiction of the functional capacity of the land and support decision making. State and transition models illustrate the transition among states, further informing policy makers and landowners of management response and change. Many data sets are available for delineation of sites and states, but how these ESs are delineated and defined differs by region, with soil disturbance and dynamic soil properties being important factors.

The legacy effects of historic anthropogenic disturbance and intensive land management in the Southeastern U.S. complicates ES development. A pristine reference state is an unrealistic management target due to the distortion and uncertainty in reference and associated states caused by this disturbance. ES descriptions in this complex environment can clarify this uncertainty, support research and management objectives, and define conservation interests. Dynamic soil properties support this effort as indicators of change and are critical for understanding soil function and ecosystem services. With rapid cultural and environmental change, it is vital that we characterize and understand soil change and its relevance to humans.

The Alabama Fall Line Hills region is composed of soils with low inherent and dynamic soil quality. The region was dominated by longleaf pine before European settlement, and as such, serves as a reference state. Dynamic soil properties serve as indicators of soil function and soil quality and are evaluated through space for time comparison studies. Previous research in other parts of this region has illustrated differences in DSPs by land use. However, this research does not provide the inventory of regional ecology and change that can be described in ESDs and STMs. We hypothesize that ecological sites provide a framework for characterizing and inventorying near-surface DSPs, and that soil properties and functions differ among states within ecological sites.

Objectives

Our first objective is to develop an ecological site and an associated state and transition model (with NRCS) for Longleaf -Bluestem systems in the Fall Line Hills region of Alabama and measure and characterize dynamic soil properties within states of the newly developed ecological site. The second objective is to measure and model soil hydraulic properties to characterize soil hydrologic function within states of the ecological site.

Chapter 2

Characterizing Dynamic Soil Properties and Soil Change in an Alabama Fall Line Hills Ecological Site

Abstract

The Ecological Site (ES) concept groups soils that respond similarly to management to meet conservation goals, develop site interpretations and models for ecological transitions, and construct restoration pathways. The USDA-NRCS and the National Cooperative Soil Survey (NCSS) have a nationwide plan to classify all lands into ESs. Dynamic soil properties (DSPs) are near-surface properties that respond to management and are critical to soil function and ecosystem services. Measurement of DSPs is also used to evaluate anthropogenic impacts on soil (termed *soil change*). The NCSS is developing methodologies to characterize and inventory DSPs, and we hypothesize that the ES framework is a valid approach for doing this. The ability to characterize DSPs using ESs would facilitate hydrological modeling, soil carbon sequestration, and provide soil health benchmarks and goals. In this study, we developed an ES for Longleaf Pine (*Pinus palustris*) -Bluestem (*Schizachrium scoparium* and *Andropogon* spp.) systems in the Alabama Fall Line Hills region, and subsequently characterized and inventoried DSPs for four states. The reference state consisted of relatively undisturbed Longleaf Pine and Bluestem sites; cultivated states included conventional row crop, pine plantation, and pasture sites that had been in place >20 yrs. The soil components in the ES were described, sampled, characterized, and verified to be Kanhap- and Kandiudults with sandy surfaces, loamy subsoils, and low activity mineralogy. Measured DSPs (0-50 cm) included carbon pools, chemical (e.g. extractable nutrients, exchangeable bases, CEC), and physical (bulk density, aggregate stability, clay dispersion ratio) properties critical to soil function. Soil organic carbon pools (0-30 cm, p =

0.0037) were higher (> 4 kg m^{-2}) in reference and pine plantation than pasture and row crop states (< 4 kg m^{-2}). However, the highest active carbon was found in the pasture state (p = 0.0011). As expected, intensive management (i.e. amendment additions) resulted in higher base saturation (p <0.0001) and Mehlich extractable P (p = 0.0004), and lower Al saturation (p < 0.0001) in row crop and pasture states. Water stable aggregates (WSA) decreased with disturbance and tillage, with the lowest stable aggregates (77 %) in the row crop state. Surface bulk density (ρb) was highest in row crop (1.56 g cm^{-3}) and lowest in the reference state (1.07 g cm^{-3}). Bulk density decreased (r = -0.83) and CEC increased (r = 0.79) with increasing SOC, illustrating the critical role soil organic matter plays in soil quality for these systems. Multivariate analysis generally grouped sites by ecological state with principal components one and two representing 76 % of data variability. While differences in DSPs were observed among states, differences were not as extensive as similar studies as the reference sites had legacy effects associated with a history of disturbance. However, the reference state represents a realistic management goal. Considering the range of a reference state concept, the aggregate of data suggests ESs are effective for characterizing DSPs and soil change in this region.

Introduction

Ecological Sites (ESs) and State and Transition Models (STMs)

Ecological Sites (ES) are being adopted as an ecological inventory and land management tool (US Department of Agriculture, 2017). Regularly used in rangelands ecosystems of the western U.S., many are also being developed for forested and associated portions of the southeastern U.S. (Caudle et al., 2013; Nauman et al., 2015b). An ES describes climate, physiography, soil, plant community, and hydrology of an area to provide interpretations for land management and restoration practices (USDA, 2017). The USDA-NRCS ES program provides valuable land management information by grouping similar soils (as per soil survey) and describing them by land use and ecological state. Soil surveys are the nation’s most robust natural resource inventory and are the foundation of Ecological Site Descriptions (ESDs).

Ecological sites form a natural continuation of the soil-landscape paradigm upon which soil survey is based (Hudson, 1992). State and transition models (STMs) utilize land cover and management associations to infer dynamic, anthropogenic-induced changes in soils (*termed soil change*) (Bestelmeyer et al., 2009; Duniway et al., 2010). Ecological states describe and characterize current vegetative condition and soil properties resulting from consistent land use and management (Stringham et al., 2016). Transitions among states describe ecological and soil change as a movement or phase (Nauman et al., 2015a; Stringham et al., 2016). Sites are grouped by soil-landform processes, and the ecological state relies heavily on vegetation and land cover (Nauman et al., 2015b). Thus, land cover has served as the primary distinguishing factor for state in numerous ES studies (Bestelmeyer et al., 2009; Petersen et al., 2009). Land use history has also been evaluated as a key element of transition in otherwise similar land areas (Bestelmeyer et al., 2011; Stringham et al., 2016).

Dynamic Soil Properties (DSPs)

Dynamic soil properties (e.g. carbon pools, bulk density, aggregate stability, hydraulic properties) can serve as indicators of soil function and soil quality. These near-surface properties are management driven and subject to change in relatively short annual or decadal time spans (human time scales) (Wills et al., 2017). Temporal variability in DSPs allows them to serve as indicators of soil change and function (Tugel et al., 2008). Soil change studies often examine soil functional dynamics at human time scales.

Dynamic soil properties have been utilized to characterize states, illustrate transitions, and serve as indicators of change in soil health and quality studies (Doran and Parkin, 1996). They are also critical for soil functions including soil stability, erodibility, trafficability, carbon storage, and nutrient and water availability. Soil functions and DSPs can change based on land use (Giertz et al., 2005; Zhang et al., 2019). For example, Giertz et al. (2005) found cultivated lands to have lower infiltration rates and reduced water holding capacity than savannah and forested lands in Benin. Zhang et al. (2019) found that reforested Philippine lands had lower bulk density, higher organic carbon content, and higher saturated hydraulic conductivity than grasslands. Tye et al. (2013) found carbon and nutrient loss 100 years after land conversion from forested to agricultural use in England. Fesha et al. (2002) found conventional row crop sites in Alabama had lower water stable aggregates, soil organic carbon, microbial biomass carbon, and higher water dispersible clay than woodland and pasture sites, indicating better soil quality with less disturbance. Maloney et al. (2008) also observed a decrease in bulk density, and an increase in soil organic carbon and nitrogen upon transition from more disturbed to less disturbed ecological states in Georgia.

Southeastern U.S. Coastal Plain DSPs

There have been numerous efforts to characterize DSPs in the southeastern U.S. (Franzluebbers and Stuedemann, 2002; Franzluebbers and Brock, 2007; Causarano et al., 2008; Price et al., 2010; Tye et al., 2013a; Lavoie et al., 2014). DSPs have been documented under specific agronomic management (tillage and cropping systems) and general land use (forest and pasture). In North Carolina, Franzluebbers and Brock (2007) noted differences in bulk density, particulate carbon and nitrogen, and soil microbial biomass under differing crop and tillage systems. Price et al. (2010) found differences in hydraulic properties and bulk density in forested versus managed grasses (pasture and lawn) in North Carolina.

Carbon measurements are utilized as indicators of soil health and quality as higher active, particulate, and soil organic carbon (SOC) generally indicates better soil health (Doran and Parkin, 1996). Surface residue carbon, particulate organic matter, and SOC increases with decreasing soil disturbance (Franzluebbers, 1999; Franzluebbers and Stuedemann, 2002). Soil organic carbon fractions can vary at seasonal and longer time-scales in pasture and cropping systems (Franzluebbers and Stuedemann, 2002; Causarano et al., 2008; Tye et al., 2013a). In the southeastern Coastal Plain, higher SOC occurs in pasture systems (Causarano et al., 2008), and SOC stocks tend to increase with pasture age (Franzluebbers and Stuedemann, 2002). Levi (2007) and Cochran (2010) found increased carbon stocks in long-term longleaf pine (*Pinus palustris*) ecosystems over more highly disturbed and managed systems. Lavoie et al. (2014) found longleaf pine restoration techniques used in north Florida did not result in different soil carbon accumulation. In summary, SOC stocks are typically higher in relatively undisturbed systems (Franzluebbers and Stuedemann, 2002; Levi, 2007; Causarano et al., 2008; Cochran, 2010; Tye et al., 2013a; Lavoie et al., 2014).

Fall Line Hills Region of Southeastern U.S. Coastal Plain

Fall Line Hills (FLH) soils have developed in sandy fluvio-deltaic coastal plain sediments and mostly classify as Kanhapludults with loamy to sandy surfaces and low activity mineralogy (Griffith et al., 2001). These soils have inherently low soil quality (relatively acid with low organic matter, fertility, and water holding capacity). Before European settlement, longleaf pine ecosystems with intact groundcover were dominant in the southeastern U.S. Coastal Plain (> 90 million acres), but timber harvest, land use change, invasive species, and fire suppression over the last two centuries has reduced it to <3% of its original area (Brockway et al., 2005). The longleaf pine ecosystem relies on periodic fire, and protects itself from fire through a seedling grass stage, self-pruning, and thick bark (Outcalt, 2000). Longleaf naturally regenerates in open areas, encouraging a diverse understory with flammable wiregrass (*Aristida beyrichiana)* and bluestem (*Schizachrium scoparium* and *Andropogon spp.*) grasses and further promoting a fire climax state (Outcalt, 2000; Brockway et al., 2005). As native longleaf does not regenerate well under clearcutting and fire suppression, more easily managed trees like loblolly pine (*Pinus taeda*) have replaced it (Frost, 1993). With land clearing, agriculture, and intensive management, these ecosystems and the associated soils have been repeatedly disturbed. Land clearing and intensive cultivation have resulted in soil degradation, erosion, and reduction in dynamic soil quality (Frost, 1993; Warren and Zabawa, 1998; Baumhardt et al., 2015).

Rationale

Ecological site descriptions frame ecological and soil change to support land management. As indicators of soil health and quality, DSPs support ES development by characterizing soil change, ecological states, and transitions between states. Similarly, the ES framework can facilitate the inventory of DSPs in a management-based format with consideration of land use. Due to the intensive land management, disturbance, and soil degradation in the Alabama Fall Line Hills region, characterizing soil change is vital to understanding and managing this region’s natural resources. Thus, the objectives of this study were to:

1) develop an ecological site and the associated state and transition model, and
2) characterize DSPs among states for Longleaf-Bluestem systems in the FLH region of Alabama.

Comparing these DSPs among states of the ecological site provides feedback on soil change and land use management in the region.

Methods

Ecological Site Framework

A preliminary STM was developed in cooperation with the NRCS to determine potential sites for evaluation (Fig. 1). Four land use systems were chosen for evaluation as states: 1) reference longleaf-bluestem vegetation, 2) pine plantation, 3) pasture or hayland, and 4) conventional row crop. The reference state is described as Longleaf-Bluestem association with open spacing, natural regeneration, regular fire intervals, and an intact and diverse understory cover. This state also exists in a degraded condition characterized by fire suppression, hardwood encroachment, and loss of groundcover; evidence of previous disturbance may also be present. The pine plantation state is described as loblolly trees with mechanical planting and harvest, and row maintenance with herbicide, cutting, or prescribed fire. The pasture state is described as maintained pasture or hayland in bahia grass (*Paspalum notatum*) with regular hay harvesting or cattle grazing. The row crop state is in a rotation with primarily conventional management; common crops of the area include cotton (*Gossypium hirsutum*), soybean (*Glycine max*), peanut (*Arachis hypogaea*), and winter wheat (*Triticum aestivum*).

Site selection

Sites were selected in three dissimilar soil survey map units. Soil components within map units were described and sampled in the field and verified primarily through soil morphology and laboratory particle size analysis. Soil map units were selected that contained these components and similar inclusions (consociations): 1) Fine-loamy, kaolinitic, thermic Typic Kanhapludults and Kandiudults (Marvyn map unit), 2) Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludults and Kandiudults (Cowarts map unit), and 3) Loamy, kaolinitic, thermic Arenic Kanhapludults and Kandiudults (Uchee map unit). Consociations are used for discussion purposes.

Twelve sites were selected so that each soil component was represented in each state. Representatives of states were selected with a minimum of 20 years in the land use of the state. The length of land use and management of sites was verified through historical aerial photos, National Agricultural Statistics Service data, and landowner interviews.

Sampling

Composite soil samples were collected from 0-5, 5-15, 15-30, and 30-50 cm with a bucket auger. Relatively undisturbed bulk samples were collected from 0-5 and 5-15 cm for aggregate stability analyses. For active carbon measurement, composite samples were taken at 0-5 and 5-15 cm and placed in cold storage until evaluation. Leaf litter was collected from a 25 cm^2 area at three random locations of each reference site.

Physical Properties

Bulk density was measured at 0-5, 5-15, and 15-30 cm using the core method adjusted for coarse fragment content (Soil Survey Staff, 2014a). Water stable aggregates (WSA) were measured for the 1 to 2 mm size fraction collected from relatively undisturbed samples. Four grams of 1-2 mm aggregates were placed on a 0.26 mm mesh sieve, slowly moistened with a humidifier, sieved in distilled water for 3 minutes to remove the water dispersible portion, and then sieved in 100 ml of 0.05 M NaOH to remove the stable portion (Kemper and Rosenau, 1986). Water dispersible and stable fines were dried at 105 °C for 48 hours and weighed to determine percent water stable aggregates. Water dispersible clay was measured using a modification of the pipette method without dispersant (Soil Survey Staff, 2004).

Chemical Properties

Water (1:1) and calcium chloride (1:2) pH were analyzed as per standard methods (Soil Survey Staff, 2014b). Cation exchange capacity (CEC) and base saturation (BS) were determined by the ammonium acetate method (pH 7) using an auto-extractor (Soil Survey Staff, 2014b); bases (Ca, Mg, K, and Na) were measured by Inductively Coupled Plasma mass spectrometry (ICP-MS), and ammonium (CEC) was measured by absorbance (Sims et al., 1995). Extractable Al was determined by KCl extraction and measured with ICP-MS (Soil Survey Staff, 2014b). Mehlich I (double acid) extractable nutrients were measured at Waters Agricultural Laboratory (Camilla, GA) (Mehlich, 1953).

Soil Organic Carbon Pools

Soil organic carbon (SOC) was measured by dry combustion on a LECO Carbon Analyzer for the fine-earth (< 2mm), particulate (0.053 to 2mm), and leaf litter fractions (Soil Survey Staff, 2014b). The particulate fraction was separated by wet sieve and dried at 55 C (Soil Survey Staff, 2014b). The mineral fraction was determined by subtracting the particulate fraction from the fine earth fraction. The fine earth carbon was determined for 0-5, 5-15, 15-30, and 30-50 cm depths. Particulate and mineral carbon was determined for 0-5 and 5-15 cm depths. Active carbon was extracted with 0.02M $KMnO_4$ and measured by absorbance for 0-5 and 5-15 cm depths (Soil Survey Staff, 2014b).

Statistical analyses

The study was analyzed as a randomized complete block design with soil consociation as the blocking factor. Analysis of variance of main (state and depth) and interactive effects were performed on measurements using SAS version 9.4 (SAS Institute Inc., 2012). Response variables (DSPs) were analyzed using PROC GLIMMIX with state and depth as fixed explanatory variables. Soil consociations were considered random blocking factors. All statistical tests were made at the $\alpha = 0.1$ significance level, and post hoc tests were adjusted with Tukey's honest significant difference. Where significance was observed among state in main effects, simple effects were compared by depth. Pearson linear correlation coefficients (r) were calculated for all DSP data from 0 to 50 cm. Multivariate principal component analyses were performed on standardized DSP data averaged to 30 cm.

Results and Discussion

Ecological Site Development

The Unconsolidated Tuscaloosa - Loamy Hilly Woodland ecological site was developed with Marvyn, Cowarts, and Uchee soil map units within the Fall Line Hills of MLRA 133A (Fig. 2). The states described for this study included reference, pine plantation, pasture, and row crop. While the reference state utilized in this study was within the natural state category described by the STM, the sites did not represent a pristine, undisturbed state (Fig. 2). The overstory of reference sites was dominated by longleaf pines of uneven age, and sparse bluestem grass was present. However, most reference sites are not burned in a consistent <3 year interval and hardwood encroachment was present. In addition, the groundcover was not intact as sometimes observed in undisturbed longleaf ecosystems of the southeastern Coastal Plain. Sites in the reference state were located in the Tuskegee National Forest. Land clearing began here in the 1830s, and it was intensively farmed (primarily cotton) for 100 years before land rehabilitation projects began with the Tuskegee Land Utilization project in 1935; management by the Forest Service did not begin until 1959 (Warren and Zabawa, 1998).Thus, the reference state in this study represents an achievable management goal as opposed to an undisturbed native state used in similar studies (Levi, 2007; Cochran, 2010). Sites selected as cultural land use states (row crop, pasture, and pine plantation) had remained in that management for 20 years or more.

Carbon

Differences were observed among soil organic carbon pools by state and depth. Percent SOC significantly differed by state ($p = 0.0011$) (Table 1). Generally, SOC was highest in the reference state and decreased with disturbance (reference > pine planation > pasture > row crop). Significant differences were observable by depth from 15 to 50 cm where managed states had lower SOC (0.32-0.41%) and pine dominated states had higher SOC (0.66-0.91%). This aligns with previous studies (Franzluebbers and Stuedemann, 2002; Levi, 2007; Causarano et al., 2008; Maloney et al., 2008; Cochran, 2010; Tye et al., 2013b) that found more carbon in less disturbed systems.

Soil organic carbon pools (accounting for bulk density) were calculated to 30 cm ($p = 0.0037$). The highest carbon pools were seen in the reference (4.79 kg SOC m^{-2}) and pine plantation (5.51 kg SOC m^{-2}) states (Table 2, Fig. 3). Cochran (2010) found similar but slightly lower carbon stocks in south Alabama Coastal Plain soils with 4.9 kg SOC m^{-2} from 0 to 50 cm in longleaf and 5.0 kg SOC m^{-2} in planted pine. Maloney et al. (2008) also found similarities in carbon stocks between reference (3.6 kg SOC m^{-2} from 0 to 30 cm) and reforested (3.1 kg SOC m^{-2} from 0 to 30 cm) sites in Fort Benning, Georgia. Similarity in reference and pine planation states may indicate reference forest carbon stocks are achievable in the first decades of forest management. The more intensely managed states of row crop and pasture had lower carbon pools, 3.09 and 3.63 kg m^{-2}, respectively.

Particulate organic matter (POM C) did not significantly differ by state ($p = 0.4945$), but mineral associated carbon (mineral C) did ($p = 0.0454$) (Table 1). Mineral C and POM C were not reported for the Uchee row crop site due to measurement errors from soil amendments such as agricultural lime. Mineral C was slightly higher in the surface of pine plantation (0.63%) and reference (0.53%) states and lower in the row crop (0.19%) and pasture (0.30%) states; however, the reference was also similar to the pasture and row crop states. Levi (2007) found higher Mineral C and POM C in the surface of longleaf as compared to row crop sites. Averaged to 15 cm, mineral C was higher in the pine planation (0.43%) and reference (0.42%) state, but similar to the row crop (0.23%) state which was similar to the pasture state (0.19%). Larger carbon fractions like POM may be less likely to change with ecological state than smaller fractions like mineral C. In summary, POMC and mineral C results in this study differed from some studies which have shown these carbon pools often differ more significantly by management and disturbance (Cambardella and Elliott, 1992, 1993; Beare et al., 1994; Levi, 2007; Causarano et al., 2008; Cochran, 2010).

Higher soil active carbon generally indicates more microbial activity and better soil health (Doran and Parkin, 1996). Active carbon, measured as permanganate oxidizable carbon (POXC) in this study, was significantly different among state ($p = 0.0011$) (Table 1). The highest active carbon was measured as 913 mg kg^{-1} in the upper 5 cm of the pasture state and decreased with depth. Higher POXC may be related to the consistent groundcover and active growth in pasture and hay systems. The pine plantation state also had higher active carbon in the upper 5 cm but was also similar to reference and row crop states. From 5 to 15 cm, POXC was higher in the pasture state (556 mg kg^{-1}) followed by row crop (410 mg kg^{-1}); row crop was similar to the pine plantation (271 mg kg^{-1}) and reference (231 mg kg^{-1}) states. These results are similar to Cochran (2010) who found that active carbon was relatively higher in pasture than other sites.

Although differences were found, fewer differences in carbon pools were seen in this study as compared to similar studies. This is likely due to the history of disturbance and nature of the reference sites. As mentioned above, reference sites included in this study fit within the natural state description of the STM but did not replicate the native state represented in previous studies (Levi, 2007; Cochran, 2010).

Chemical DSPs

The CEC was significantly different among depths ($p = 0.0001$) but not among state (Table 3). CEC decreased with depth (Fig 4). The soils have similar near-surface soil textures and mineralogy, so differences in near-surface CEC would likely be due to SOC differences. Considering relatively small differences in SOC, it is not surprising differences in CEC were not found. Thus, our results differ from Cochran (2010) and Levi (2007) who found higher CEC in the reference condition and lower CEC in cultivated states, likely related to greater significant differences in SOC among states.

Differences in ammonium acetate extractable bases and percent base saturation (% BS) were found among states (Table 3). Row crop data were not reported due to unreacted lime from recent additions causing artificially high Ca and base saturation. Ammonium acetate extracted soil calcium and magnesium were highest in pasture sites. Similarly, Cochran (2010) found higher Ca and Mg in pasture sites as compared to longleaf and planted pine. Ammonium acetate extracted potassium was higher in row crop state than other states. Base saturation showed a clear progression from cultivated states to more natural states (pasture > pine plantation > reference). This is similar to results found in Levi (2007), where % BS was highest in row crop sites, followed by pine plantation and longleaf forest sites. The higher amount of bases in the more highly cultivated sites (pasture and row crop) is due to amendment additions.

Extractable Al and Al saturation was significantly different by state ($p < 0.0001$) (Table 3). Aluminum saturation was lower (near 0 %) in more managed states (row crop and pasture) and higher in pine plantation and reference states (12 to 45 %) (Fig. 5). High extractable aluminum is consistent with lower pH (particularly salt pH) values.

Mehlich 1 extractable phosphorous (P) was significantly different among state ($p = 0.0004$) (Table 4). The row crop state had significantly higher surface P (49 mg kg^{-1}, 5 times higher) in the surface than other states. Pasture, pine plantation, and reference states were statistically similar in the upper 5 cm at 9, 6, and 3 mg kg^{-1}, respectively (Fig, 6). Higher P values were due to soil amendment and animal waste applications to managed states. Similar differences in P values were found from 5 to 15 cm as from 0 to 5 cm but differences were not distinguishable from 15 to 50 cm, suggesting the relatively low mobility of P. These results are generally consistent with other studies that have found higher P values in cultivated sites (Levi, 2007; Cochran, 2010); however, Cochran (2010) saw larger differences between pasture and forested sites.

Total extractable P stocks (accounting for bulk density) were calculated to 30 cm. While these stocks were not significantly different by state ($p = 0.1712$), P stocks in the references state were 8 kg ha^{-1}. Previous studies in the southeastern Coastal Plain suggest that Mehlich 1 P < 5 kg ha^{-1} indicates minimal prior cultivation and disturbance (Cochran, 2010). Phosphorous stocks slightly higher than 5 kg ha^{-1} in the reference state of the FLH ES suggest a relatively undisturbed system with possible legacy effects of previous cultivation.

Mehlich 1 extractable potassium (K) was significantly different among state ($p = <0.0001$) and depth ($p <0.0001$) (Table 4). In the upper 5 cm, row crop had the highest K (82 mg kg^{-1}). Pasture, pine plantation, and reference states were statistically similar at 44, 25, and 25 mg

kg^{-1}, respectively. Potassium decreased with depth, but row crop remained significantly higher than all other states to 50 cm. Higher nutrients in the row crop state were due to soil amendment and fertilizer applications.

Soil pH (1:1) was significantly different among state ($p < 0.0001$) (Table 4). From 0 to 50 cm, the pine dominated states had the lowest pH (4.7-4.8). Lower pHs are typically associated with pine trees (Boyer, 1990), and cultivated soils have been shown to have higher pHs than non-cultivated soils due to more intensive management and lime additions (Fesha et al., 2002; Cochran, 2010; Levi et al., 2010). Thus, the more intensely managed states of pasture and row crops had higher pH values (5.8 and 6.1, respectively.) Salt pH (1:2) data were also significantly different among state ($p < 0.0001$). The row crop state had the highest salt pH at 5.8, pasture at 5.4, and reference and pine plantation were similar at 4.3 and 4.4 respectively.

Physical DSPs

Bulk density was significantly different among state, and most differences were observed within 15 cm (Table 5). The highest bulk density at 0 to 5 cm (1.6 g cm^{-3}) was found in the row crop state and the lowest (1.1 g cm^{-3}) in the reference state. From 5 to 15 cm, the lowest bulk density (1.42 g cm^{-3}) was also found in the reference state; pasture bulk density (1.61 g cm^{-3}) was similar to the reference state but also to the row crop (1.72 g cm^{-3}) and pine plantation (1.72 g cm^{-3}) state. No significant differences were seen among state from 15 to 30 cm. The similar bulk density among all states at 15 to 30 cm may indicate a legacy compaction effect in the reference state. Average bulk density for 0 to 50 cm was also lowest (1.38 g cm^{-3}) in the reference state with the next lowest (1.55 g cm^{-3}) in the pasture state. The row crop and pine planation states had higher bulk densities from 0 to 50 cm, 1.70 and 1.64 g cm^{-3}, respectively. These data are consistent with other studies illustrating increasing bulk density increasing with traffic and disturbance (Levi, 2007; Maloney et al., 2008; Cochran, 2010).

Water stable aggregates were significantly different among states (Table 5). The lowest percent stable aggregates were found in the row crop from 0 to 5 cm (77%). Higher stable aggregate percentages were found in the pasture, pine plantation, and reference states: 91, 91, and 86%, respectively. Differences were also seen from 5 to 15 cm where row crop had 79 % stable aggregates and the reference was statistically similar with 88% stable aggregates; reference was also similar to higher stable aggregates found in pasture and pine plantation states, 93 and 94%, respectively. Average water stable aggregates from 0 to 15 cm were high (86 to 92 %) in reference, pasture, and pine planation states, but low (77%) in the row crop state that experienced regular tillage. This is consistent with Cochran (2010) and Levi (2007) who found lower stable aggregates in row crop in contrast to less cultivated sites. The lower water stable aggregates found in the row crop state are attributable to the higher frequency of soil disturbance.

Water dispersible clay (WDC) and clay dispersion ratio (CDR) were not significantly different by state or depth (Table 6). This may be due to the low clay content in surface soils of the FLH. Previous studies (Igwe, 2005; Cochran, 2010; Levi et al., 2010) saw larger differences in CDR and a significant correlation with soil carbon. However, differences in soil C were not as prevalent in this study which likely influences the lack of significant differences among WDC.

Pearson Linear Correlation Coefficients

Pearson linear correlation coefficients suggested the importance of organic matter in FLH soils (Table 6). While we did not see differences with CEC among states, CEC was positively correlated with % SOC (r = 0.79), active C (r = 0.71) POM C (r = 0.93), and Mineral C (r = 0.57). Bulk density was also negatively correlated with % SOC (r = -0.83), POM C (r = -0.73), and Mineral C (r = -0.63). The correlation of SOC with these properties supports the assumption that soil organic matter is essential to soil quality in these soils.

Principal Components Analysis

A multivariate analysis of standardized DSP data averaged to 30 cm was combined into principal component scores by site. Components 1 and 2 had eigenvalues >1 and represented 76% of total DSP data variability. Principal components 1 and 2 generally grouped the states, but the variability of DSP data within the states is noted (Fig. 11). Sites in the reference state grouped closely together, while sites in the pasture state displayed the most variability. The row crop state is also variable, but sites are still relatively grouped. Similar to univariate analyses, these data illustrate a relatively higher variability among more intensively managed compared to less disturbed states. Some variability in managed states may be explained by differences within management systems. Within the pasture state, fields used primarily for hay may differ from those primarily grazed by cattle. Sites in the row crop and pine plantation states, while similar in management within state, were managed by different producers. However, all sites in the reference state were managed by the National Forest Service.

Conclusions

Intensive disturbance in the Fall Line Hills region of Alabama caused soil degradation and a loss of dynamic soil quality. This widespread disturbance in the region rendered undisturbed, native reference conditions nonexistent. The legacy effects of previous disturbance were evident in the reference state with slightly higher phosphorous stocks and evidence of compaction (15 to 30 cm), and similar carbon stocks to those of the pine plantation state. Therefore, the reference state in this study provides a realistic management goal rather than an undisturbed native condition. Considering the management goals of ES development, the reference state in this study provides a valid benchmark.

Many of the measured DSPs provided evidence of soil change among states. Multiple significant differences in DSPs were observed among state, and multivariate analyses indicated sites generally grouped by state. Utilizing DSPs studies within the ES framework can provide realistic management goals and soil health benchmarks for conservation efforts. The aggregate of data within this study suggest that ESs are an effective means for characterizing and inventorying near-surface DSPs in the Fall Line Hills of Alabama.

Tables and Figures

Table 1. Carbon pools including active (mg kg^{-1}), mineral, particulate, and soil organic carbon (%) by depth for three reps of four states of an Ecological Site in the Fall Line Hills of Alabama.

Depth	State[a]	POXC[b]		Mineral C		POMC	SOC	
cm		--mg kg^{-1}--		-----------------		%	-----------------	
0-5	RC	481.34	B[†]	0.19	B	0.96	0.90	
	P	912.91	A	0.30	B	1.54	1.84	
	PP	620.01	AB	0.63	A	1.09	1.72	
	R	347.02	B	0.58	AB	1.51	2.09	
5-15	RC	409.62	AB	0.27		0.70	0.89	
	P	555.58	A	0.07		0.79	0.86	
	PP	270.78	B	0.24		0.82	1.06	
	R	231.08	B	0.25		0.79	1.04	
15-30	RC	-[c]		-		-	0.32	B
	P	-		-		-	0.41	B
	PP	-		-		-	0.91	A
	R	-		-		-	0.91	A
30-50	RC	-		-		-	0.32	B
	P	-		-		-	0.32	B
	PP	-		-		-	0.66	A
	R	-		-		-	0.69	A
Mean	RC	445.48	B	0.23	AB	2.63	0.61	C
	P	734.25	A	0.19	B	2.83	0.86	BC
	PP	445.39	B	0.43	A	2.67	1.09	AB
	R	289.05	B	0.42	A	2.91	1.18	A
		P>F		P>F		P>F	P>F	
State (S)		0.0011		0.0454		0.4945	0.0011	
Depth (D)		0.0023		0.0081		0.0115	<0.0001	
S x D		0.2400		0.1712		0.5858	0.2462	

a. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

b. POXC = permanganate oxidizable carbon; Mineral C = mineral (<53 μm) associated carbon; POMC = particulate organic matter (>53 μm) associated carbon; SOC = total soil organic carbon.

c. Dashes indicate data not collected.

† Main effect comparisons for state of LS-means by each depth within the same column; numbers with the same letter are not significantly different at the 0.1 confidence level.

Table 2. Soil organic carbon pools (kg m^{-2}) from 0 to 30 cm for three reps of four states of an Ecological Site in the Fall Line Hills of Alabama.

State[a]	SOC[b]	
	-------------kg m^{-2}-------------	
RC	3.09	B[†]
P	3.63	B
PP	5.51	A
R	4.79	A
	P>F	
State (S)	0.0037	

a. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.
b. SOC = soil organic carbon.
† Main effect comparisons for state of LS-means; numbers with the same letter are not significantly different at the 0.1 confidence level.

Table 3. Chemical properties including NH4OAc extractable Ca, K, Mg, KCl extractable Al (cmol kg^{-1}), effective cation exchange capacity (ECEC), cation exchange capacity (CEC), % base saturation, and % Al saturation by depth for three reps of four states of an Ecological Site in the Fall Line Hills of Alabama.

Depth	State[a]	Ca[b]		K		Mg		Al		ECEC		CEC	BS		AS	
cm		------------------------------cmol kg^{-1}-------------------------------											----------%----------			
0-5	RC	-[c]		0.50	A	-		0.00	B	-		2.19	-		0	B
	P	2.67	A	0.27	B	0.37	A	0.02	B	3.34		4.51	62	A	1	B
	PP	0.71	B	0.19	B	0.08	B	0.41	A	1.38		3.54	30	B	12	A
	R	0.59	B	0.16	B	0.04	B	0.63	A	1.44		4.26	16	B	18	A
5-15	RC	-		0.37	A	-		0.00	B	-		2.10	-		0	B
	P	1.23	A	0.11	B	0.14	A	0.01	B	1.49	A	1.93	81	A	1	B
	PP	0.28	B	0.19	B	0.03	AB	0.31	A	0.82	B	1.64	29	B	19	A
	R	0.12	B	0.06	B	0.01	B	0.47	A	0.66	B	1.68	8	B	29	A
15-30	RC	-		0.26	A	-		0.00	C	-		1.73	-		0	C
	P	0.77	A	0.05	B	0.11		0.01	C	0.94	A	1.64	55	A	1	C
	PP	0.27	B	0.09	B	0.03		0.20	B	0.58	B	1.44	31	B	15	B
	R	0.05	B	0.03	B	0.01		0.63	A	0.72	AB	1.39	6	B	45	A
30-50	RC	-		0.39	A	-		0.14	B	-		2.02	-		4	B
	P	0.62		0.05	B	0.12		0.00	B	0.80		1.34	88	A	0	B
	PP	0.44		0.13	B	0.08		0.21	AB	0.86		1.85	31	B	14	B
	R	0.09		0.04	B	0.02		0.53	A	0.68		1.32	9	B	39	A
Mean	RC	-		0.38	A	-		0.03	C	-		2.36	-		1	C
	P	1.33	A	0.11	BC	1.18	A	0.00	C	1.64	A	2.16	65	A	1	C
	PP	0.42	B	0.13	B	0.06	B	0.28	B	0.91	B	2.12	29	B	15	B
	R	0.21	B	0.05	C	0.02	B	0.57	A	0.87	B	2.01	11	C	33	A
		P>F		P>F		P>F		P>F		P>F		P>F	P>F		P>F	
State (S)		0.0004		<0.0001		0.0002		<0.0001		0.0217		0.8867	<0.0001		<0.0001	
Depth (D)		0.0088		0.0005		0.0435		0.7248		0.0018		0.0001	0.5384		0.0266	
S x D		0.24		0.7756		0.1553		0.6130		0.1307		0.4418	0.9384		0.0112	

a. RC = conventional or conservation row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

b. Ca, Mg, and K = NH4OAc extractable calcium, magnesium, and potassium; Al = KCl extractable aluminum; AS = aluminum saturation; ECEC = effective cation exchange capacity; CEC = cation exchange capacity, NH4OAc, pH 7; BS = base saturation, NH4OAc, pH 7; AS = aluminum saturation.

c. Dashes indicate data not reported.

† Main effect comparisons for state of LS-means by each depth within the same column; numbers with the same letter are not significantly different at the 0.1 confidence level. Letters were not included if significance did not occur.

Table 4. Chemical properties including Mehlich extractable P and K (mg kg^{-1}), and pH by depth for three reps of four states of an Ecological Site in the Fall Line Hills of Alabama.

Depth	State[a]	P[b]		K		pH		pH	
cm		----- mg kg^{-1} -----				1:1		1:2	
0-5	RC	49	A†	82	A	6.22	A	5.98	A
	P	9	B	44	B	5.77	A	5.44	A
	PP	6	B	25	B	4.58	B	4.16	B
	R	3	B	25	B	4.55	B	4.13	B
5-15	RC	50		60	A	6.24	A	5.94	A
	P	5		18	B	5.83	A	5.37	A
	PP	7		15	B	4.81	B	4.39	B
	R	2		14	B	4.74	B	4.38	B
15-30	RC	25		43	A	6.22	A	5.74	A
	P	2		10	B	5.92	A	5.35	A
	PP	5		13	B	4.9	B	4.51	B
	R	2		13	B	4.82	B	4.37	B
30-50	RC	5		45	A	5.91	A	5.67	A
	P	1		8	B	5.75	A	5.27	A
	PP	2		17	B	4.9	B	4.59	B
	R	1		14	B	4.83	B	4.4	B
Mean	RC	32	A	57	A	6.15	A	5.83	A
	P	4	B	20	B	5.82	A	5.36	A
	PP	5	B	17	B	4.8	B	4.41	B
	R	2	B	16	B	4.73	B	4.32	B
		P>F		P>F		P>F		P>F	
State (S)		0.0004		<0.0001		<0.0001		<0.0001	
Depth (D)		0.1600		<0.0001		0.7339		0.9422	
S x D		0.5206		0.1424		0.9799		0.8183	

a. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

b. P, K = Mehlich I extractable phosphorus, potassium; pH = pH in 1:1 soil:water (w/v), pH in 1:2 soil:CaCl2 (w/v).

† Main effect comparisons for state of LS-means by each depth within the same column; numbers with the same letter are not significantly different at the 0.1 confidence level. Letters were not included if significance did not occur.

Table 5. Physical properties including bulk density (ρb), % clay, % water dispersible clay, clay dispersion ratio, and water stable aggregate ratio by depth for three reps of four states of an Ecological Site in the Fall Line Hills of Alabama.

Depth	State[a]	ρ_b[b]		Clay	WDC	CDR	WSA	
cm		g cm^{-3}		-----%-----		-----ratio-----		
0-5	RC	1.56	A	4.34	3.97	0.91	0.77	B
	P	1.26	BC	4.48	3.26	0.74	0.91	A
	PP	1.38	AB	4.18	3.01	0.72	0.91	A
	R	1.07	C	2.83	2.44	0.87	0.86	A
5-15	RC	1.72	A	5.29	4.52	0.88	0.79	B
	P	1.61	AB	5.35	4.34	0.79	0.93	A
	PP	1.72	A	4.24	3.66	0.86	0.94	A
	R	1.42	B	4.21	3.08	0.73	0.88	AB
15-30	RC	1.81		-[c]	-	-	-	
	P	1.77		-	-	-	-	
	PP	1.83		-	-	-	-	
	R	1.68		-	-	-	-	
Mean	RC	1.7	A	4.82	4.25	0.89	0.77	B
	P	1.55	B	4.91	3.8	0.76	0.92	A
	PP	1.64	A	4.21	3.34	0.79	0.92	A
	R	1.38	C	3.52	2.76	0.8	0.86	A
		P>F		P>F	P>F	P>F	P>F	
State (S)		<0.0001		0.1867	0.2	0.5202	0.0003	
Depth (D)		<0.0001		0.1082	0.1486	0.9107	0.02944	
S x D		0.172		0.7995	0.9793	0.4714	0.9882	

a. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

b. ρ_b = soil bulk density; Clay = particle size separate (<0.002 mm); WDC = water dispersible clay; CDR = clay dispersion ratio (Clay/WDC); WSA = water stable aggregates.

c. Dashes indicate data not collected.

† Main effect comparisons for state of LS-means by each depth within the same column; numbers with the same letter are not significantly different at the 0.1 confidence level. Letters were not included if significance did not occur.

Pearson Correlation Coefficients

	SOC[a]	pH (1:1)	pH (1:2)	P	K	CEC	BS	AS	ECEC	ρ_b	WDC	CDR	POXC	WSA	POM C
pH (1:1)	**-0.33**[b]														
pH (1:2)	**-0.33**	**0.96**													
P	-0.03	**0.34**	**0.41**												
K	0.12	**0.51**	**0.59**	**0.55**											
CEC	**0.79**	-0.01	-0.02	0.01	**0.35**										
BS	-0.23	**0.59**	**0.65**	**0.45**	**0.68**	-0.05									
AS	0.08	**-0.70**	**-0.72**	**-0.31**	**-0.42**	-0.20	**-0.52**								
ECEC	**0.32**	**0.51**	**0.56**	**0.39**	**0.83**	**0.58**	**0.71**	**-0.44**							
ρ_b	**-0.83**	**0.35**	**0.31**	0.20	-0.09	**-0.71**	0.15	-0.08	-0.27						
WDC	-0.26	**0.56**	**0.56**	0.03	0.15	-0.13	0.14	-0.28	0.16	**0.37**					
CDR	-0.31	0.08	0.11	0.10	0.12	**-0.36**	0.12	0.05	-0.11	0.21	**0.41**				
POXC	**0.52**	**0.36**	**0.36**	0.04	0.33	**0.71**	0.11	**-0.59**	**0.62**	-0.31	0.05	**-0.38**			
WSA	0.23	-0.32	**-0.39**	**-0.74**	**-0.61**	0.12	-0.34	0.16	-0.28	-0.15	-0.02	-0.15	0.14		
POM C	**0.94**	-0.10	-0.10	-0.10	0.26	**0.93**	-0.06	-0.17	**0.60**	**-0.73**	-0.34	-0.33	**0.60**	0.15	
Mineral C	**0.74**	-0.30	-0.34	-0.26	-0.03	**0.57**	-0.33	0.12	0.11	**-0.63**	-0.06	-0.01	0.16	0.21	**0.46**

Table 6. Pearson linear correlation coefficients for select dynamic soil properties of the Fall Line Hills Ecological Site in Alabama. a. SOC = soil organic carbon, pH (1:1) = pH in 1:1 soil:water (w/v), pH (1:2) = pH in 1:2 soil:CaCl2 (w/v); P, K = Mehlich I extractable phosphorus, potassium (mg kg^{-1}); pH = pH in 1:1 soil:water (w/v), pH in 1:2 soil:CaCl2 (w/v); CEC = cation exchange capacity, NH4OAc, pH 7; BS = base saturation, NH4OAc, pH 7; AS = aluminum saturation; ECEC = effective cation exchange capacity; ρ_b = soil bulk density; WDC = water dispersible clay; CDR = clay dispersion ratio (Clay/WDC); WSA = water stable aggregates; POXC = permanganate oxidizable carbon; Mineral C = mineral (<53 μm) associated carbon; POM C = particulate organic matter (>53 μm) associated carbon. b. Correlations in bold are statistically significant at $\alpha = 0.1$.

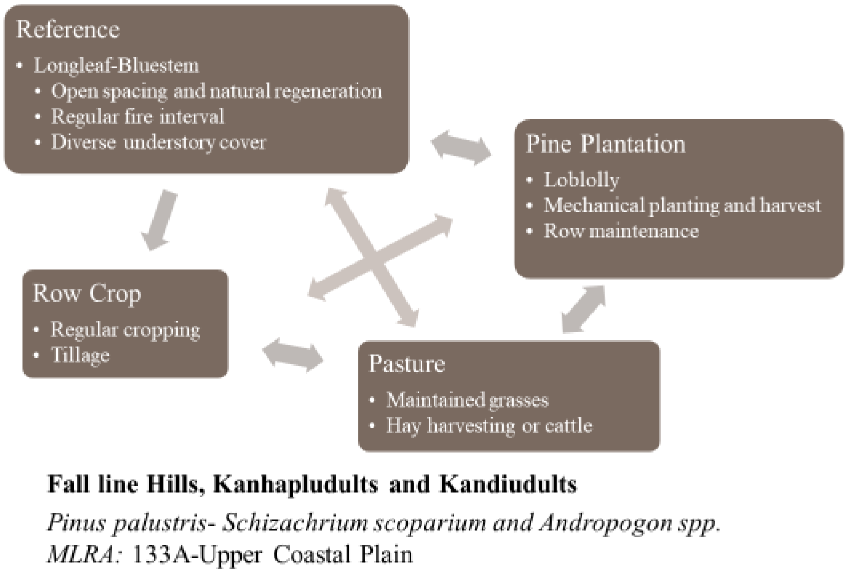
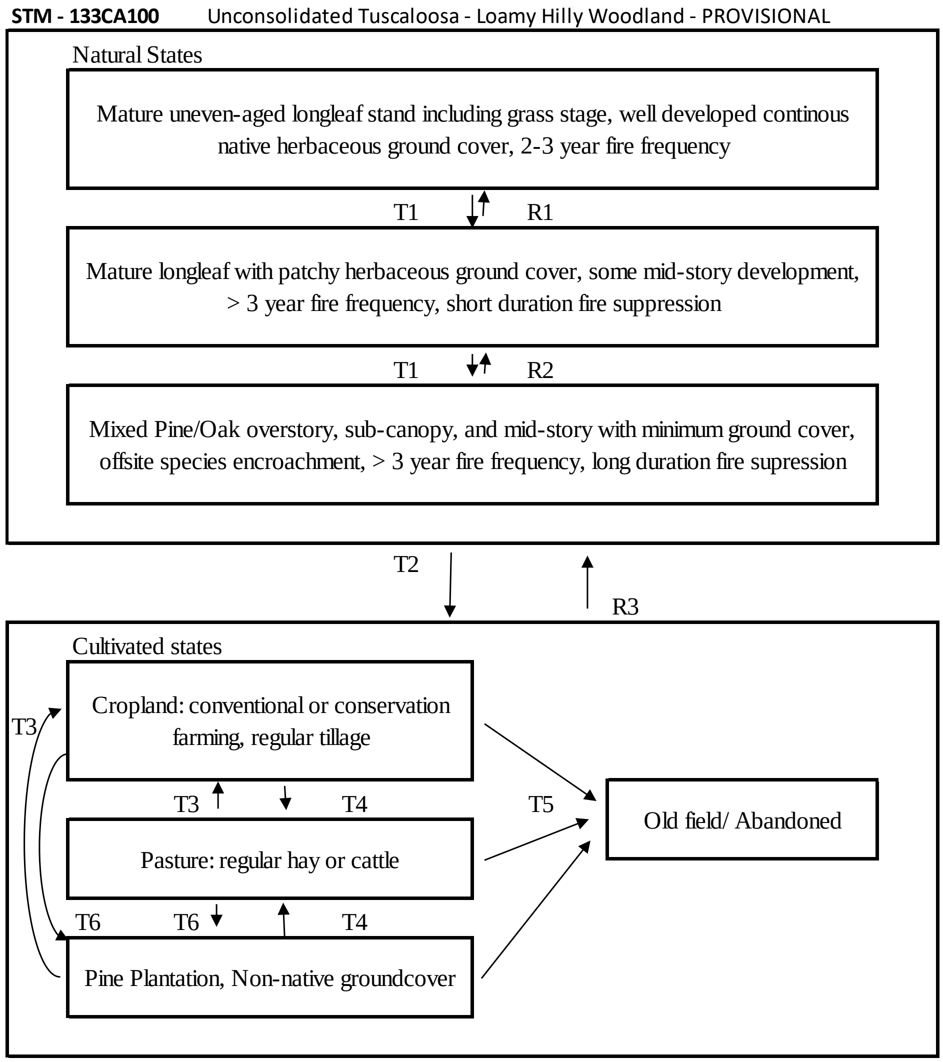


Figure 1. Preliminary State and Transition Model for the Ecological Site Study in the Alabama Fall Line Hills. This model was utilized to describe states and select study sites. Selected sites have been in the described land use and ecological state for a minimum of 20 years.



T1	Fire supression.
T2	Clear cutting, fire suppression.
T3	Clear cutting, stump and brush removal, tillage, esablish crops.
T4	Clear cutting, stump and brush removal, tillage, esablish pasture.
T5	Clear cut and/or abandonment.
T6	Plant pines (loblolly, longleaf, slash), 2-3 year fire frequency.
R1	Return to 2-3 year fire frequency.
R2	Hardwood removal, herbicide if necessary, re-establish native ground cover.
R3	Estabishment of longleaf, reintroduction of 2-3 year fire frequency, mechanical and chemical removal of hardwoods and other pines, uneven aged management.

Figure 2. Provisional State and Transition Model, Unconsolidated Tuscaloosa - Loamy Hilly Woodland. This STM was described for the Ecological Site study in the Alabama Fall Line Hills. States included in this study were mature longleaf with patchy herbaceous ground cover, cropland, pasture, and pine plantation.

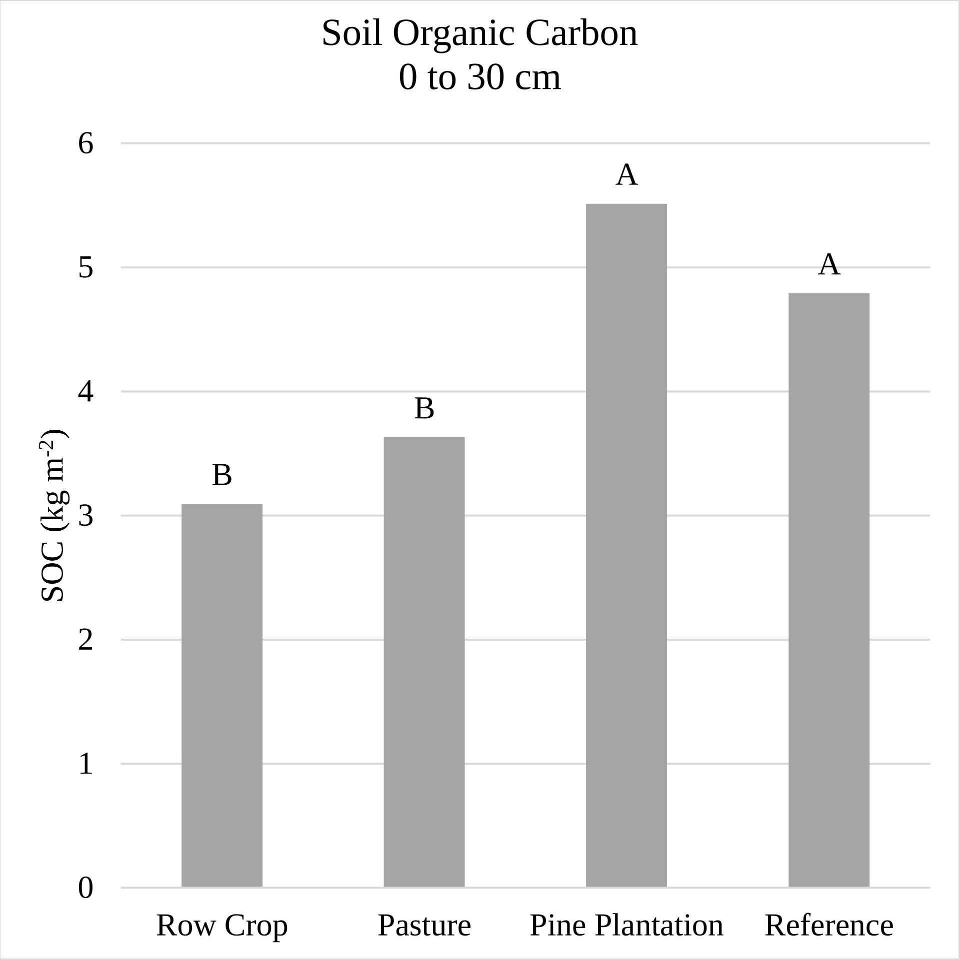


Figure 3. Soil Organic Carbon Pool (kg m^{-2}) to 30 cm for three reps of four states of an Ecological site in the Fall Line Hills of Alabama. Bars with the same letter are not significantly different at the 0.1 confidence level ($p = 0.0037$). Row Crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine Plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state.

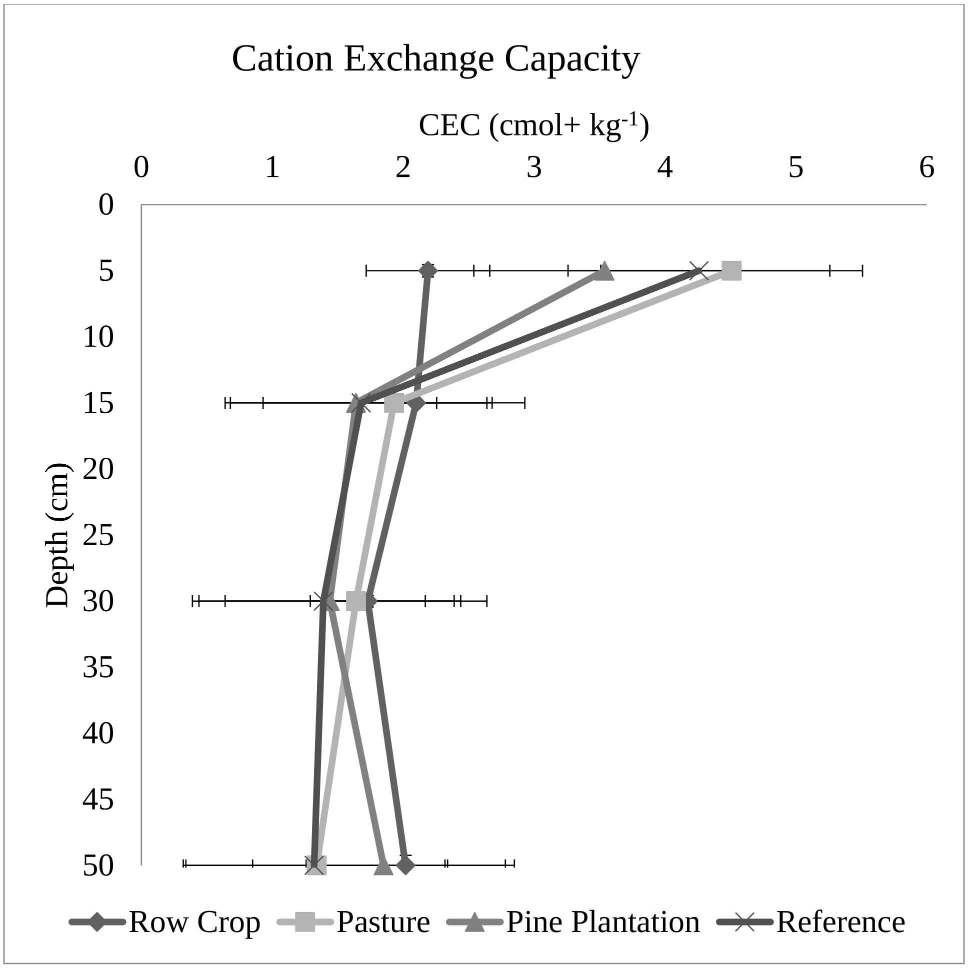


Figure 4. Cation Exchange capacity (cmol+ kg^{-1}) decreases with depth ($p < 0.0001$) but was not different among state for 3 reps of four states in the Fall Line Hills Ecological Site in Alabama. Row Crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine Plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

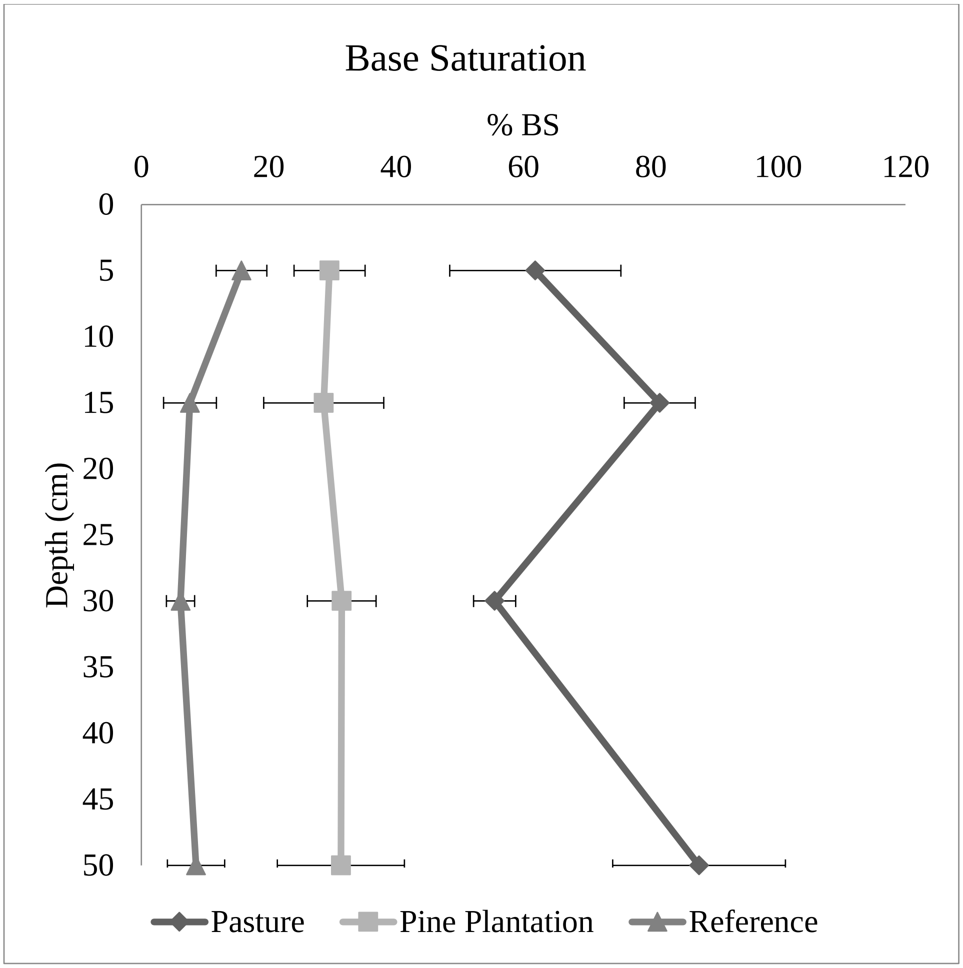


Figure 5. Base saturation (% NH_4Oac extractable bases) was significantly different among state ($p < 0.0001$) for 3 reps of three states in the Fall Line Hills Ecological Site in Alabama. Pasture = grazed or hayed pasture state; Pine Plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

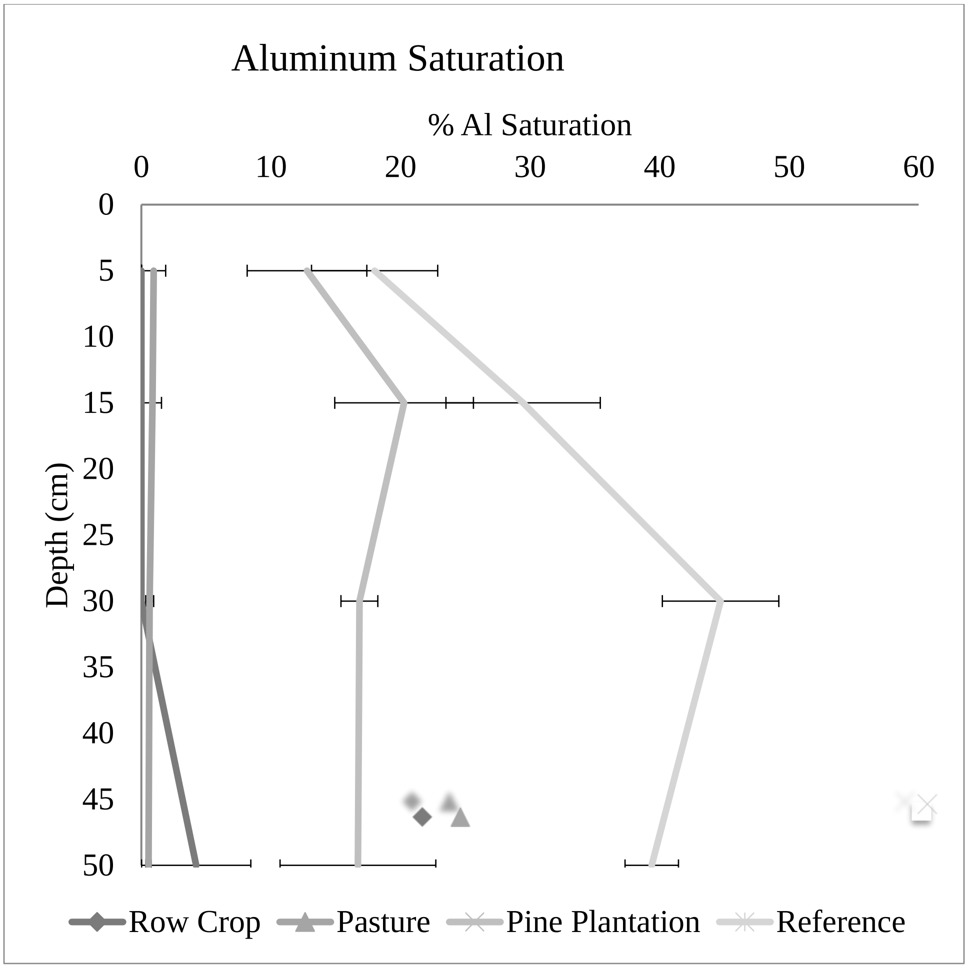


Figure 6. Aluminum saturation increases with depth (P>F = 0.0266) and is significantly different among state ($p < 0.0001$) for three reps of four states in the Fall Line Hills Ecological Site in Alabama. Row crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

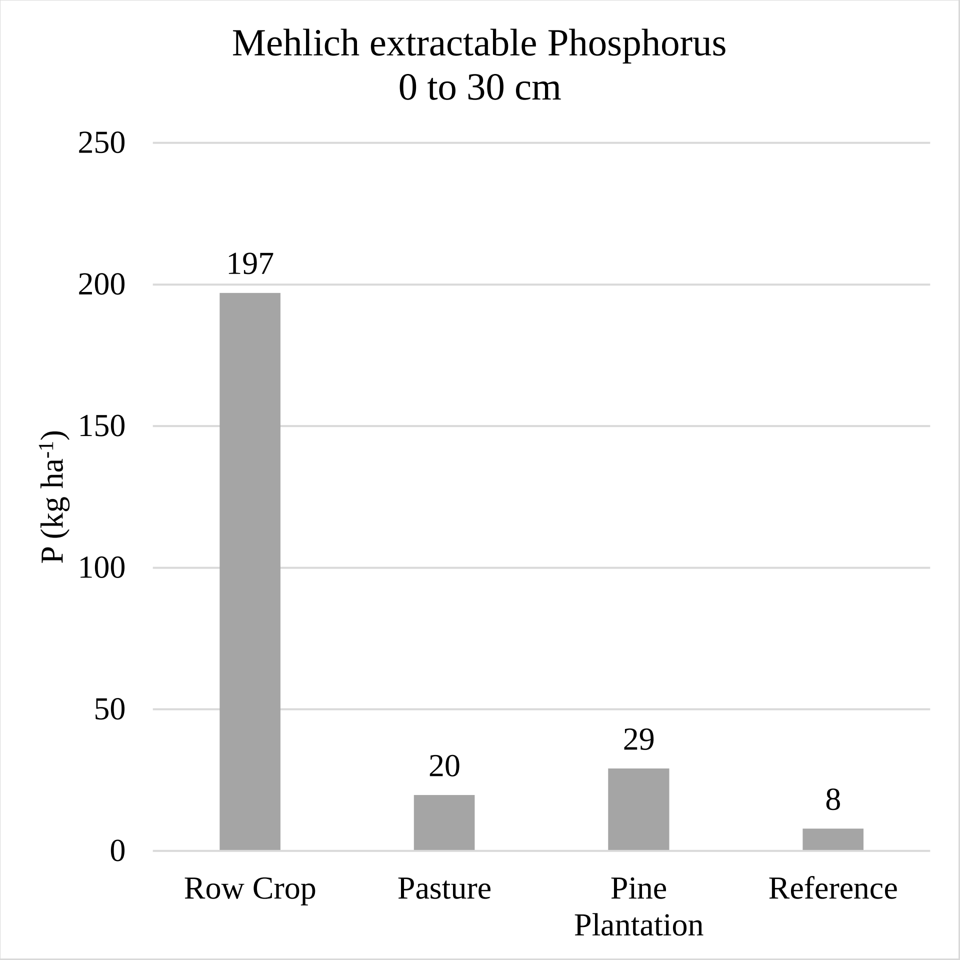


Figure 7. Mehlich extractable P (kg ha^{-1}) to 30 cm was not significantly different among state in the Fall Line Hills Ecological Site in Alabama. Row crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state.

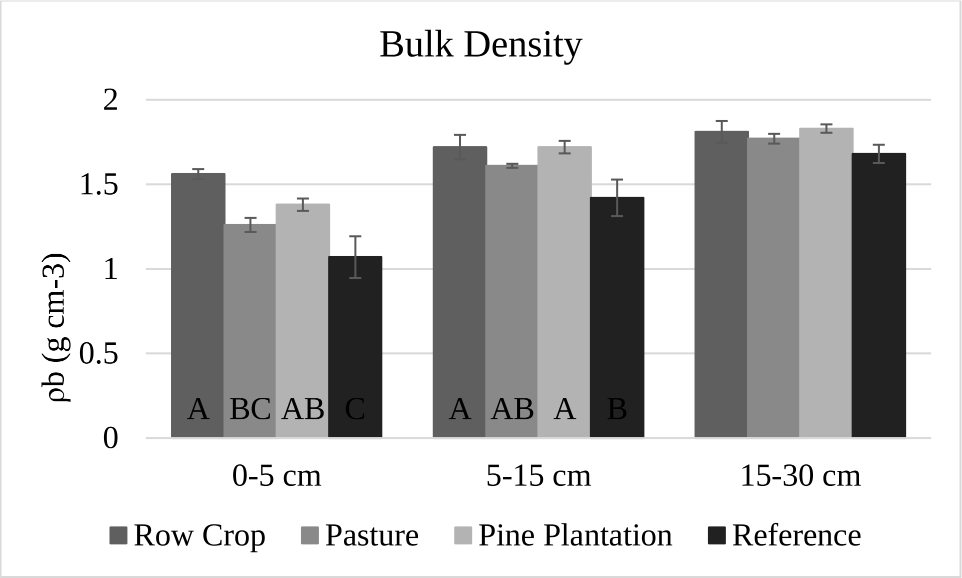


Figure 8. Bulk density was significantly different by state ($p < 0.0001$) and depth ($p < 0.0001$) in the Fall Line Hills Ecological Site in Alabama. Row crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

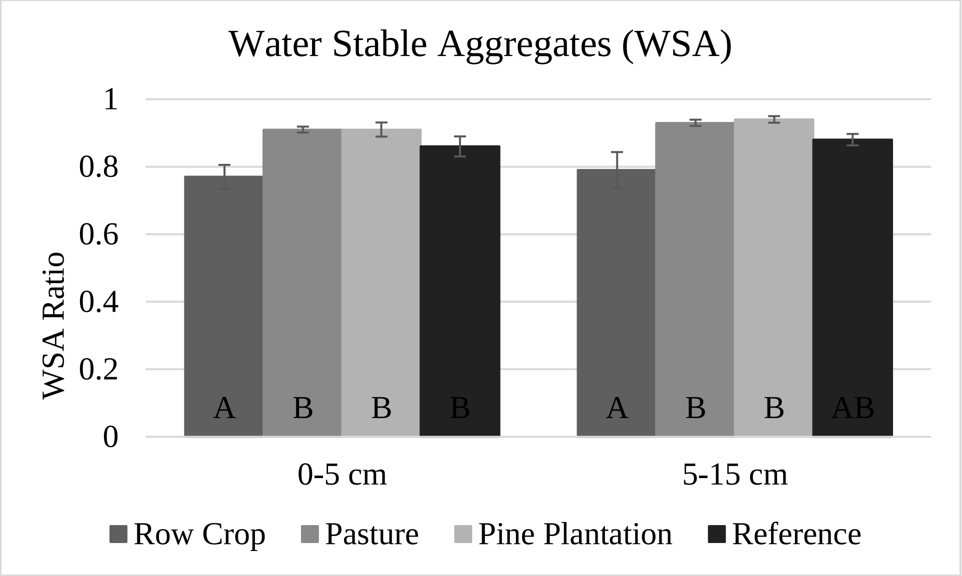


Figure 9. Water Stable Aggregates were significantly different by state ($p = 0.0003$) and depth ($p = 0.0294$) in the Fall Line Hills Ecological Site in Alabama. Row crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

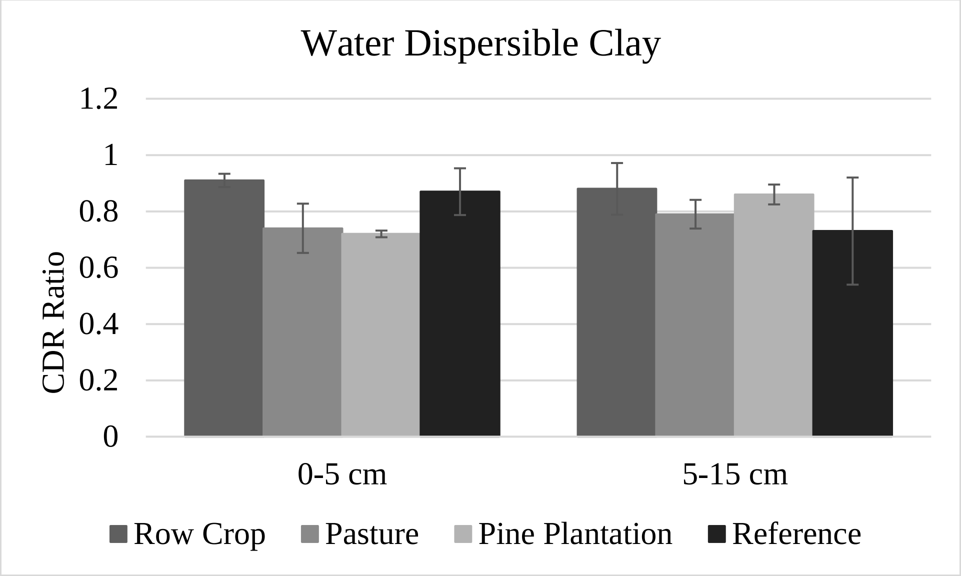


Figure 10. Water Dispersible Clay was not significantly different by state or depth in the Fall Line Hills Ecological Site in Alabama. Row crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

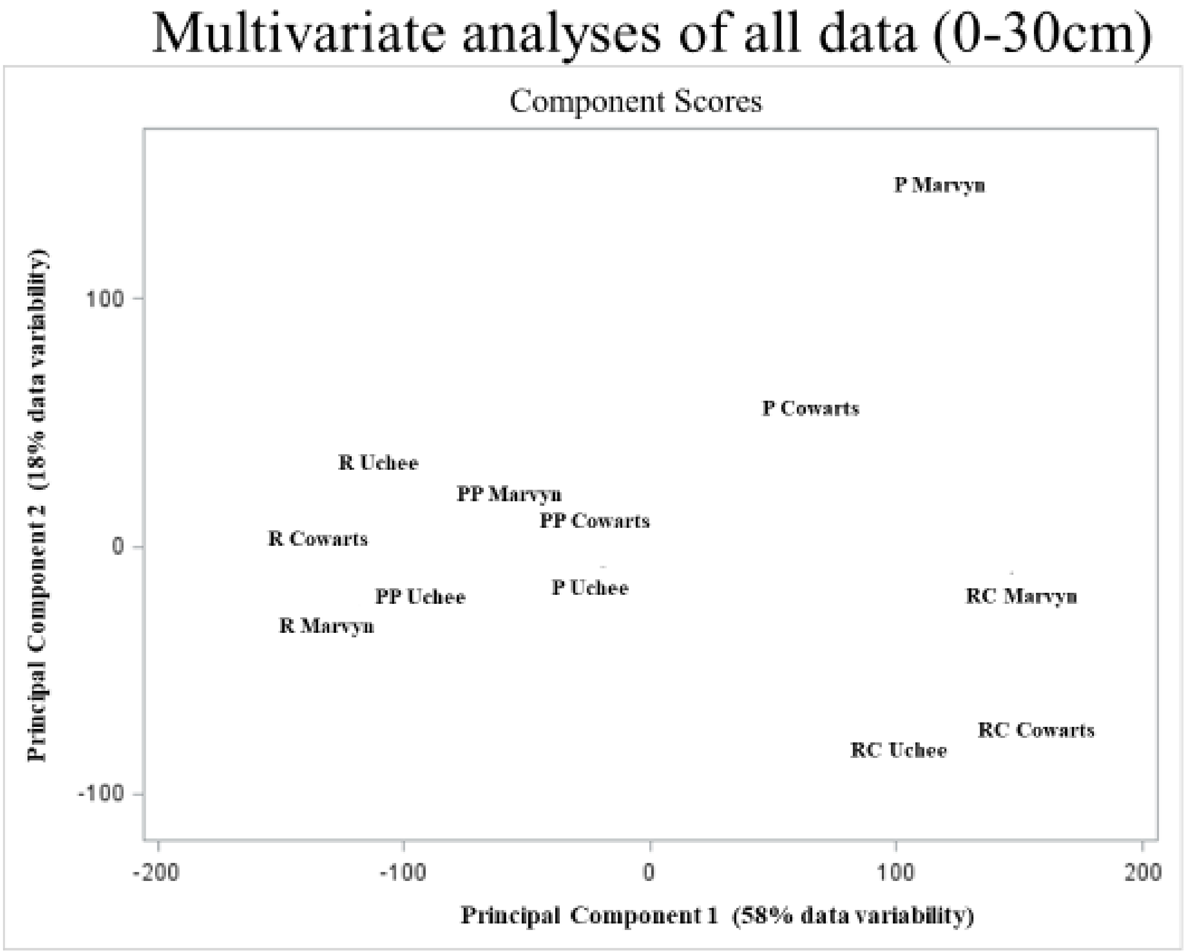


Figure 11. Graph of principal component scores of standardized DSP data (0-30 cm) for sites in the Fall Line Hill Ecological Site in Alabama. Principal component 1 (y) represented 58% of DSP data variability, while PC 2 (x) represented 18% of data variability. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

Chapter 3

Soil Hydraulic Property Characterization in a Fall Line Hills Ecological Site

Abstract

The Ecological Site (ES) concept groups soils that respond similarly to management to meet conservation goals, develop site interpretations and models for ecological transitions, and construct restoration pathways. The USDA-NRCS and the National Cooperative Soil Survey (NCSS) have a nationwide plan to classify all lands into ESs. The NCSS is also developing improved methods to characterize and inventory near-surface soil hydraulic properties that vary by land use and management, and we hypothesize the ES framework is a valid approach for doing this. Characterizing hydraulic properties within ESs would facilitate watershed hydrological modeling and management. The objective of this study was to measure and compare soil hydraulic properties and hydrological functions among states of a Longleaf Pine (*Pinus palustris*) -Bluestem (*Schizachrium scoparium* and *Andropogon* spp.) ES in the Alabama Fall Line Hills region. The reference state consisted of relatively undisturbed Longleaf Pine and Bluestem sites; cultivated states included conventional row crop, pine plantation, and pasture sites that had been in place >20 yrs. The soil components in the ES were described, sampled, characterized, and verified to be Kanhap- and Kandiudults with sandy surfaces, loamy subsoils, and low activity mineralogy. Measured hydraulic properties include soil water retention (van Genuchten) parameters, infiltration rate, and saturated hydraulic conductivity (Ksat). van Genuchten moisture retention parameters were measured at 15 cm in each site. The moisture retention parameter alpha (α) was higher in the reference than other states, indicating these states may lose gravitational water more quickly ($p = 0.0058$). Infiltration rate, Ksat (five depths to 100 cm), and water retention parameters (three depths to 50 cm) were measured in all states within

Marvyn units. Paired t-sets (by depth) indicated significantly higher ($p < 0.062$) Ksat to 50 cm in the reference as compared to other sites. These differences among the reference and cultivated states suggested some change in hydrologic function with increased management, but there were no differences in hydraulic properties among cultivated states.

HYDRUS 1-D was used to simulate water flow for the reference and row crop states in Marvyn units under wet and dry conditions. In a 100-yr storm simulation (24 cm over 24 hour), the reference Marvyn site displayed no runoff while the row crop site showed 5.5 cm runoff. However, in a dry down event, the row crop Marvyn unit retained more water than the reference Marvyn unit over 60 days. These differences are likely due to inherent properties (e.g. soil texture) at sites rather than ecological state effects. Additional hydraulic data and simulations are necessary for further understanding of hydrologic function in states of an Alabama Fall Line Hills Ecological site. Comparisons of site and soil response to heavy rainfall and drought conditions under differing ecological states demonstrate the use of hydrologic modeling in Ecological Sites.

Introduction

Ecological Sites (ESs) and the Fall Line Hills

Ecological Sites (ES) are being adopted as an ecological inventory and land management tool (US Department of Agriculture, 2017). Regularly used in rangeland ecosystems of the western U.S., many are also being developed for forested and associated portions of the southeastern U.S. (Caudle et al., 2013; Nauman et al., 2015a). An ES describes climate, physiography, soil, vegetation, and hydrology of an area to provide interpretations for land management and restoration practices (USDA, 2017). The USDA-NRCS ES program provides valuable land management information by grouping similar soils (as per soil survey) and describing them by land use and ecological state. Soil surveys are the nation’s most robust natural resource inventory and are the foundation of Ecological Site Descriptions (ESDs).

Ecological Sites form a natural continuation of the soil-landscape paradigm upon which soil survey is based (Hudson, 1992). State and transition models (STMs) utilize land cover and management associations to infer dynamic, anthropogenic-induced changes in soils (*termed soil change*) (Bestelmeyer et al., 2009; Duniway et al., 2010). Ecological states describe and characterize current vegetative condition and soil properties resulting from consistent land use and management (Stringham et al., 2016). Transitions among states describe ecological and soil change as a movement or phase (Nauman et al., 2015; Stringham et al., 2016). Sites are grouped by soil-landform processes, and the ecological state relies heavily on vegetation and land cover (Nauman et al., 2015). Thus, land cover has served as the primary distinguishing factor for state in numerous ES studies (Bestelmeyer et al., 2009; Petersen et al., 2009). Land use history has also been evaluated as a key element of transition in otherwise similar areas (Bestelmeyer et al., 2011; Stringham et al., 2016).

The Fall Line Hills of Alabama makes up the northern portion of the Southern Coastal Plain Major Land Resource Area (MLRA 133A) with soils developed in unconsolidated fluviomarine coastal plain sediments. The upland soils of this region are primarily Kanhapludults and Kandiudults with sandy surfaces, low activity minerology, and inherently low soil fertility. Extensive cultivation and land use change have led to extensive disturbance and loss of dynamic soil quality throughout this region (Levi, 2007; Maloney et al., 2008; Cochran, 2010). Long-term intensive management and cultivation affects near-surface soil hydraulic properties which therefore impacts soil hydrological functions.

Hydrologic Soil Function

Hydrologic soil functions including infiltration/runoff, water storage and provisioning, groundwater recharge, and water quality protection are ecologically and economically important. Hydrology is also functionally relevant to ES descriptions and use. Hydraulic properties are highly spatially and temporally variable (Dane et al., 2002a; b). At a landscape scale, some of this variability can be characterized with knowledge of land use and management. Comparing hydrologic function among ecological state may lead to a better understanding and characterization of land use and management effects.

Hydraulic property characterization is fundamental to hydrologic function assessment. Infiltration rate is defined as the hydraulic conductivity (K) at the soil surface, or the volume flux water flow per unit of soil surface area (Hillel, 1982). Infiltration is related to soil pore space, texture, and aggregation (soil structure). Low infiltration rates combined with heavy rains, poor vegetative cover, and weak aggregation can lead to runoff and erosion. A meta-analysis of infiltration studies in the US indicated a perennial cover, like grassland and forest, as well as cover cropping increases infiltration rates (Basche and DeLonge, 2019). A similar meta-analysis looking at land use conversion in China showed that conversion to agroforestry typically increased infiltration while conversion to cropland typically decreased infiltration; conversion away from natural forest decreased infiltration (Sun et al., 2018). A study in Scotland found surface hydraulic conductivity to differ based on forest type [Scots pine (*Pinus Sylvestris*) > sycamore (*Acer pseudoplatanus*)] and that grazing significantly reduced surface hydraulic conductivity (Chandler et al., 2018). In China, a study found grassland had higher infiltration rates than forests after 25 years due to root density and soil organic matter, while forest land had higher infiltration after 15 years due to more active root biomass (Kalhoro et al., 2018).

Saturated hydraulic conductivity (Ksat) can be measured throughout the vadose zone. It relates the flux or rate of water flow to the hydraulic gradient using Darcy’s law which describes water flow in saturated media (one-dimensional saturated form):

$$q = K\left(\frac{\Delta H}{L}\right) \quad \text{Equation 1}$$

where q is the flux density, ΔH/L is the hydraulic gradient, and K is the saturated hydraulic conductivity (Hillel, 1982). The Ksat typically decreases with clayier textures, poor aggregation, and higher bulk density. Cochran (2010) found hydraulic conductivity at 15 cm to be higher in longleaf forests than managed areas including row crop, pastures, and pine plantations in the Alabama Coastal Plain. Zhang et al. (2019) found that reforested lands had lower bulk density, higher organic carbon content, and higher saturated hydraulic conductivity than grasslands in the Philippines.

Water retention measurements relate soil water content to the tension by which that water is held. Soil water retention measurements have commonly been performed with TEMPE cells to measure water content under specific tensions. Recently developed instruments such as the HYPROP device by UMS GmbH (Munich, Germany) allow continuous measurements at higher temporal resolution, but with a limited range of measurement (UMS, 2010). There are multiple models to develop and parameterize soil water retention curves that represent the relationship between water content and soil tension across wet, moist, and dry conditions. One of the more common is the van Genuchten-Maulem model where van Genuchten models water retention and Maulem models conductivity based on water retention (van Genuchten, 1980). Bimodal forms of these models interpose multiple curves and parameters for each curve. Bimodal characterization can lead to a more comprehensive representation of the heterogeneous nature of soils, pore structure and water retention.

Water retention parameters developed through these measurements and mathematical expressions have physical relevance. The parameter α, related to the inverse of air-entry, is a shape parameter helping relate how quickly soils lose gravitational water (Pertassek et al., 2011). The n is a parameter that together with α describes the shape of the curve as it bends around the air-entry region and asymptotic slope of the descending curve towards a residual water content (Pertassek et al., 2011). The parameter θ_s is the saturated water content of the sample which is directly related to bulk density and total porosity (Hillel, 1982). The parameter θ_r refers to the residual (dry) water content of the sample. Functional water retention capacities are also developed from moisture retention curves. Field capacity (FC) is often described as the soil water content at -1/3 bar and permanent wilting point (PWP) is the soil water content at -15 bar. Plant available water (PAW) is often calculated by subtracting water content at the PWP from FC.

Soil water retention parameters have been compared in previous land use and management studies. McVay et al. (2006) found differences in retention parameters but not water holding capacity among tillage systems that increased soil carbon in Kansas. Giertz et al. (2005) found cultivated lands to have lower infiltration rates and reduced water holding capacity than savannah and forested land uses in Benin. In the southeastern U.S. Coastal Plain, Cochran (2010) found higher alpha values for row crop sites as opposed to forest and pasture sites from 0-20 cm. Cochran (2010) also found water content at field capacity to be correlated to carbon and bulk density and higher in pastures as compared to row crop sites.

Soil hydrologic functions are often evaluated through simulations and modeling. HYDRUS-1D simulates water movement in variably saturated and heterogeneous media (soil) over time; it utilizes the Richards equation for saturated-unsaturated water flow and incorporates soil hydraulic models such as the van Genuchten-Mualem and modified van Genuchten (Simunek et al., 2005). HYDRUS models have been successfully calibrated and validated in multiple soil water studies (Xu et al., 2017; Wang et al., 2018; Contreras and Bonilla, 2018; Šípek et al., 2020). A study evaluating land cover and climate change in the Scottish highlands applied HYDRUS-1D modeling to simulate land cover change from heather (*Ericaceae* spp.) to Scots pine (*Pinus sylvestris*) by replacing vegetation parameters with pine and maintaining soil parameters as those originally sampled under heather vegetation (Wang et al., 2018). Šípek et al. (2020) utilized HYDRUS-1D to illustrate higher transpiration in beech forests and higher drainage in spruce forests in the Czech Republic. Li et al. (2019) utilized HYDRUS 1-D to investigate soil water balance in land use change from farmland to orchards in Chinese loess soils; they observed a decrease in groundwater recharge due to the high water demand of trees.

Rationale

Characterizing and understanding hydrologic soil functions including infiltration/runoff, water storage and provisioning, groundwater recharge, and water quality protection is ecologically valuable and functionally relevant to ES descriptions and use. Hydraulic properties are spatially and temporally variable (Dane et al., 2002a; b), and at landscape scales, some of this variability can be characterized with knowledge of land use and management. Comparing hydrologic function among ecological state will lead to a better understanding and characterization of land use and management effects. The variable land use and intensive management within the Southeastern US necessitates characterization of land use effects on soil hydraulic properties and hydrologic function. The Alabama Fall Line Hills Ecological Site provides a framework for inventory of soil hydraulic properties and hydrologic function. This inventory could facilitate estimates of runoff, erosion, water storage, and recharge, and increase watershed modeling accuracy. The objectives of this study are to: 1) measure and compare soil hydraulic properties among states of the Alabama Fall Line Hills ecological site, and 2) utilize Hydrus to simulate soil hydrological functions among states of the ecological site.

Methods

Site selection

A preliminary Unconsolidated Tuscaloosa - Loamy Hilly Woodland ecological site was developed in cooperation with the NRCS to determine sites for evaluation (Fig. 2). The ES is described within Marvyn, Cowarts, and Uchee map units within the Fall Line Hills region of the upper Coastal Plain (MLRA 133A) of Alabama. Sites were selected in three dissimilar soil survey map units. Soil components within map units were described and sampled in the field and verified primarily through soil morphology and laboratory particle size analysis. Soil map units were selected that contained these components and similar inclusions (consociations): 1) Fine-loamy, kaolinitic, thermic Typic Kanhapludults and Kandiudults (Marvyn map unit), 2) Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludults and Kandiudults (Cowarts map unit), and 3) Loamy, kaolinitic, thermic Arenic Kanhapludults and Kandiudults (Uchee map unit). Consociations will be used for discussion purposes.

Four land use systems were chosen from the STM for evaluation as states: 1) reference longleaf-bluestem vegetation, 2) pine plantation, 3) pasture or hayland, and 4) conventional row crop. While the reference state utilized in this study was within the natural state category described by the STM, the sites did not represent an undisturbed, natural state (Fig. 2). The overstory of reference sites was dominated by longleaf pines (*Pinus palustris*) of uneven age, and sparse bluestem grass (*Schizachrium scoparium* and *Andropogon spp.*) was present. However, most sites are not burned in a consistent <3 year interval and hardwood encroachment was present. In addition, the groundcover was not as intact as sometimes observed in undisturbed longleaf ecosystems of the southeastern Coastal Plain. Sites in the reference state were located in the Tuskegee National Forest. Land clearing began here in the 1830s, and it was intensively farmed (primarily cotton) for 100 years before land rehabilitation projects began with the Tuskegee Land Utilization project in 1935; management by the Forest Service did not begin until 1959 (Warren and Zabawa, 1998). Thus, the reference state in this study represents an achievable management goal as opposed to an undisturbed native state used in similar studies (Levi, 2007; Cochran, 2010). The pine plantation state was described as loblolly (*Pinus taeda*) trees with mechanical planting and harvest, and row maintenance with herbicide, cutting, or prescribed fire. The pasture state was described as maintained pasture or hayland with regular hay harvesting or cattle grazing. The row crop state was typically in a rotation with primarily conventional management; common crops of the area include cotton (*Gossypium hirsutum*), soybean (*Glycine max*), peanut (*Arachis hypogaea*), and winter wheat (*Triticum aestivum*).

Twelve sites were selected so that each soil component was represented in each state. Representatives of states were selected with a minimum of 20 years in the land use of the state. The length of management of sites was verified through historic aerial photos, National Agricultural Statistics Service data, and landowner interviews.

Hyprop Sampling and Measurement

Hydraulic properties were measured from UMS-Hyprop cores within the epipedon (15 cm) of each site. Additional measurements were taken at 30 and 50 cm for sites in the Marvyn units. Two 250 cm^2 UMS-Hyprop cores were collected from each measured depth. Each sample was covered in cheesecloth and saturated in tap water for a minimum 24 hours. Measurements were obtained with the UMS-HYPROP device where tension and soil weight were measured over time as moisture evaporated (UMS, 2010). Additional measurements for the dry end of the curve were obtained using Vapor Sorption Analysis of disturbed, air-dried samples (Decagon Devices, 2016). Soil water retention curves were developed using HYPROP-FIT software with the constrained bimodal van Genuchten-Maulem (Durner, 1994).

Water contents are expressed as effective saturation (S_e):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad \text{Equation 2}$$

Where θ represents the volumetric water content, θ_r the residual water content, and θs the saturated water content. The bimodal van Genuchten model (Durner, 1994) yields two van Genuchten functions that are superimposed and weighted ($w_1 + w_2 = 1$):

$$S_e = \sum_{i=1}^{2} w_i \left[\frac{1}{1 + (\alpha_i\,|h|)^{n_i}}\right]^{1-\frac{1}{n_i}} \quad \text{Equation 3}$$

Where Se represents effective saturation at variable pressure head (h) (cm). The parameters α_1 and α_2 are shape parameters for each function that relate to the inverse of air entry pressure. The parameters n_1 and n_2 are shape parameters representing the bending of the curve around air entry and asymptotic behavior of the descending curve toward residual water content.

Water content at field capacity (-1/3 bar) and permanent wilting point (-15 bar) were determined from the water retention curve for each site. Available water holding capacity was calculated as the percent water content at field capacity minus water content at permanent wilting point.

Field Measurements

Infiltration rate was measured in Marvyn units with a Saturo ring infiltrometer (Meter Group, 2017). The ring insertion depth was 10 cm. Hydraulic conductivity below the surface was measured with a compact constant head permeameter (Amoozemeter) at 15, 30, 50, 75 and 100 cm in Marvyn units (Amoozegar, 1989). Constant head was maintained at 10 cm at the 15 cm depth and 15 cm at every other depth. Data represent averages of three replications per site.

HYDRUS Simulation

Water retention and hydraulic conductivity measurements from Marvyn units were utilized for soil hydrologic function simulation with HYDRUS-1D (Šimůnek et al., 2013). Simulations were performed for the reference and row crop states from 0 to 100 cm. The model was parameterized by horizon using soil morphology of each site. The van Genuchten parameters were obtained from samples taken at 15, 30, and 50 cm and applied to layers grouped by similar soil horizons. Because the morphology from 50 to 100 cm was similar, van Genuchten parameters from 50 cm were also utilized for 75 and 100 cm. Upper boundary conditions were set to atmospheric with surface runoff and lower conditions to free drainage. Initial conditions were set to default (-100 cm pressure head) and allowed to equilibrate during simulation. Two simulations were conducted:

1) A 100-year rainfall event (1 cm hr^{-1} over 24 hours) was simulated over 24 hours to evaluate runoff. Time to initial runoff and runoff quantity over 24 hours was compared for each state.

2) Following this event, dry down was simulated, and water content was evaluated throughout the 100 cm profile over 60 days.

Statistical analyses

Hydraulic measurements at 15 cm were analyzed as a randomized complete block design with soil consociation as the blocking factor. Analysis of variance of main effects (state) were performed on measurements using SAS version 9.4 (SAS Institute Inc., 2012). Response variables were analyzed using PROC GLIMMIX with state as the fixed explanatory variable.

Soil consociations were considered random blocking factors. Paired t-tests (by depth) comparing Ksat were conducted for sites within Marvyn units. All statistical tests were made at the $\alpha = 0.1$ significance level, and post hoc tests were evaluated with Tukey's honest significant difference.

Results and Discussion

Water Retention Parameters

Water retention parameters are vital to describing soil hydrologic function. Residual water content and saturated water content describe the amount of water in the soil when dry and wet, respectively. As expected, residual water content (at 15 cm) was zero or near zero in all sites (Table 7). This is likely due to the very sandy textures (loamy sand or sandy loam textured) at this depth across sites. Saturated water content (at 15 cm) was between 30% and 36% with no significant difference among state (Table 7). Cochran (2010) also found θs values around 30% at 15 cm in sites within the Alabama coastal plain. McVay et al. (2006) found θr values from 0 to 10% and θs values from 40% to 60% in in the surface of various row crop systems in Kansas. However, the Kansas soils had loamier textures with higher porosity (and higher θ_S) than southeastern U.S. Coastal Plain soils.

Alpha is a water retention shape parameter that helps describe the shape of the water retention curve and the descending asymptotic slope (moisture release) towards θr. Alpha_1 was significantly different among state with the highest α_1 being found in the reference state (0.04) (Table 7). Row crop, pasture and pine plantation states had α_1 of 0.02, 0.02, and 0.01, respectively. Previous studies using the original van Genuchten-Maulem model have used pedotransfer functions to estimate α based on texture; loamy sand and sandy loam textured soils have been estimated at 0.035 and 0.027, respectively (Schaap and Leij, 1998). Cochran (2010) utilized the original van Genuchten model at 15 cm for sites in the Alabama Coastal Plain and found slightly higher α values than those found in the FLH ES; for example, α was described as 0.04 in conventional row crop, 0.05 in pasture, and 0.05 in pine plantation land uses. The higher α in reference state of our study indicated that soils in the reference state may lose gravitational water more quickly than cultivated states. As α_1 is also a shape parameter, the water retention curve at 15 cm depth in the reference state differs from other states in this study with a more rapid loss of gravitational water and onset of field capacity (Fig. 12). Other shape parameters including α_2, n_1 and n_2 did not differ significantly by state (Table 7).

Plant Available Water

Water storage in soils is an essential ecosystem service. Water contents at field capacity (FC) and permanent wilting point (PWP) were calculated from the water retention curve and utilized to determine plant available water (PAW) at 15 cm. Water contents at FC and PWP were not significantly different among states (Table 7). Calculated PAW also did not differ significantly by state. The PAW was lowest in the reference state at 8.1% and highest in the pine plantation state at 9.4%. Row crop and pasture states had PAW values of 8.9% and 8.3%, respectively. While some studies have seen differences in PAW by land use (Cochran, 2010), others have shown no differences in PAW despite other differences in water retention parameters (McVay et al., 2006). Although some differences in water retention were observed in the Fall Line Hills of Alabama, differences in available water at 15cm were not observed.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) was measured in situ at five depths within Marvyn units (Table 9). Reference Ksat was significantly higher than row crop Ksat from 15 to 50 cm ($p = 0.037$). Reference Ksat was also significantly higher than pasture ($p = 0.062$) and pine planation ($p = 0.046$) states from 15 to 50 cm. The Ksat decreased with depth, and while variable, was higher in the reference state (Fig. 13). These differences may be related to lower bulk density and other differences in dynamic soil properties, but they may also be related to inherent soil differences among sites such as soil texture. The reference site exhibits a sandier surface with loamy sand textures (<3% clay) to 33 cm while sites in other units had sandy loam textures (>8% clay) at the surface.

The Infiltration rate (IR) was measured in Marvyn sites, but no differences were observable among state (Figure 13). The IR was highly variable and ranged from 2.5 to 36 cm hr^{-1}. The majority of this variation was seen in reps of the row crop state with the lowest IR at 4 and highest at 37 cm hr^{-1}. The row crop state had the highest average IR at 16 cm hr^{-1}, followed by pasture at 14 cm hr^{-1}. Lower IR was seen in the reference (8 cm hr^{-1}) and pine plantation (10 cm hr^{-1}). While hydraulic properties are known to be highly variable, previous studies have found more significant differences among infiltration measurements with ecological state, typically increasing with forest or perennial cover (Kalhoro et al., 2018; Sun et al., 2018; Basche and DeLonge, 2019).

Simulated Hydrologic Function

HYDRUS 1-D is a model utilized to simulate water flow in soils. In this study, soil water flow was simulated to illustrate hydrologic function in the FLH ES. Simulations were run in Marvyn units as a representative soil for the ES, and comparisons were made between reference and row crop states. Input parameters were determined from Ksat, van Genuchten parameters, and soil descriptions from each site (Table 9, Table 10).

Runoff conditions were simulated for a 100-year storm event with one cm hr^{-1} rainfall over 24 hours. In the row crop state, runoff occurred after 13 hours during the simulation with 5.5 cm total runoff after 24 hours (Table 9). However, the reference state did not reach runoff conditions, with a total infiltration of 24 cm (Table 9). Cumulative infiltration tapered off in the row crop state as runoff increased (Figure 14, Figure 15). HYDRUS simulations suggest the row crop site is more likely to experience runoff during intense rainfall events than the reference site.

Dry down conditions were simulated over 60 days from initial saturation. The water content decreased throughout the profile of both sites during the dry down event. Generally, more water was retained deeper in the profile, which is likely due to clayier textures with depth. However, at 75 cm, water content dropped below 20% in the reference state while remaining around 30% in the row crop state after 60 days (Fig. 16, Fig. 17). Similar trends were seen at 15, 30, and 50 cm, where the reference state retained less water over time than the row crop state (Fig 16, Fig. 17). This is likely related to the sandier textures and higher Ksat resulting in greater deep percolation in the reference state of the Marvyn unit.

Overall, the row crop state showed greater water storage than the reference state. After five days, the surface of both the reference and row crop state had similar water contents to approximately 20 cm; however, from 20 to 100 cm, the row crop state retained more water than the reference state (Fig. 18). At 10 and 30 days, the surface of both sites were dry to 5 cm, but the row crop state continued to retain more water throughout the profile as compared to the reference state (Fig. 19, Fig. 20). At 60 days, the reference state was much drier than the row crop state to around 80 cm, but from 80 to 100 cm, both states had similar water content around 18% (Fig. 21). Although greater water storage is observed in the reference site, further investigation of matric potentials is needed to evaluate differences in plant available water.

HYDRUS modeling provides an approach to utilize measured hydraulic properties to simulate hydrologic function. Comparison of soil response to heavy rainfall and drought conditions under differing ecological states illustrates the use of hydrologic modeling in

Ecological Sites. Although differences in runoff and water storage between states were observed in these simulations, these effects were likely due to differences in inherent soil properties (e.g. soil texture) as opposed to state. Additional data and simulations are necessary for further understanding of hydrologic function in states of an Alabama Fall Line Hills Ecological site.

Conclusions

Measurement of hydraulic soil properties in the Alabama Fall Line Hills supports inventory of hydraulic properties in the region and improves understanding of the relationship between ecological state and hydrologic function. Hydraulic properties are highly variable, and this variability is exhibited with measurements in the Alabama FLH ES. Some significant differences were observed among hydraulic properties, with the most notable differences between reference and cultivated states. The reference state exhibited a difference in the shape of the water retention curve and saturated hydraulic conductivity as opposed to cultivated states. The higher Ksat and difference in the shape of the water retention curve found in the reference state suggest slight functional differences in reference as compared to cultivated states. However, many hydraulic parameters were not significantly different among state. Field capacity, permanent wilting point, and plant available water were similar in all states.

Hydrological modeling was used to relate hydraulic properties to hydrologic function. These simulations utilize measured parameters to illustrate hydrologic function and support land management decisions. In this study, the reference state exhibited less runoff, but the row crop exhibited greater water storage. These comparisons of soil response to heavy rainfall and drought conditions under differing ecological states demonstrates the usefulness of hydrologic modeling in Ecological Sites. However, differences seen in these comparisons were likely due to differences in inherent soil properties (e.g. soil texture) as opposed to state. Additional data and simulations are necessary for further understanding of hydrologic function in states of an Alabama Fall Line Hills Ecological site. Improved understanding of hydrologic function in the FLH can support Ecological Site development and land management goals in the region.

Tables and Figures

Table 7. Bimodal van Genuchten parameters measured at 15 cm depth for three reps of four states in the Alabama Fall Hills Ecological Site.

State	α_1[b]	n_1	θr	θs	α_2	n_2	w_2	FC	WP	PAW
RC[a]	0.02 b†	3.04	0.00	0.30	0.04	2.32	0.56	11.0	2.1	8.9
P	0.02 b	3.50	0.00	0.34	0.04	2.72	0.57	11.6	3.3	8.3
PP	0.01 b	2.01	0.00	0.31	0.03	3.00	0.50	11.6	2.2	9.4
R	0.04 a	3.06	0.00	0.36	0.03	1.95	0.49	10.9	2.8	8.1
	P>F	P>F	P>F	P>F	P>F	P>F	P>F	P>F	P>F	P>F
State	0.0058	0.4148	0.7760	0.1941	0.9341	0.5916	0.6655	0.9856	0.7333	0.7905

a. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

b. α, n = shape parameters, θr = residual water content, θs = saturated water content, w2 = weight of second expression (w1 + w2 = 1), FC = water content at field capacity (-1/3 bar), WP = water content at permanent wilting point (-15 bar), PAW = plant available water (FC-WP).

† Main effect comparisons for state of LS-means within the same column; numbers with the same letter are not significantly different at the 0.1 confidence level. Letters were not included if significance did not occur.

Table 8. Paired t-tests for Ksat and bimodal van Genuchten parameters by state in Marvyn units of the Alabama Fall Line Hills Ecological Site.

Analyses	Ksat[b]	Ksat	P>F
	cm hr^{-1}		
RC[a] vs R	1.87	12.04	**0.037**[†]
RC vs P	1.87	2.87	0.161
RC vs PP	1.87	3.10	0.232
P vs PP	2.87	3.10	0.771
P vs R	2.87	12.04	**0.062**
PP vs R	3.10	12.04	**0.046**

a. RC = conventional row crop state; P = grazed or hayed pasture state; PP = managed pine plantation state; R = reference longleaf pine/bluestem forested state.

b. Ksat = saturated hydraulic conductivity (cm hr^{-1}).

† Comparisons in bold are significant at the 0.1 confidence level.

Table 9. Hydraulic input parameters for HYDRUS 1-D simulation of water flow for the soil profile of a reference state in a Marvyn unit in the Alabama Fall Line Hills Ecological Site.

Horizon[a] cm	θr[b]	θs	α_1	n_1	Ksat cm hr^{-1}	Tau	w_2	α_2	n_2
0-33	0.00	0.32	0.04	2.25	14.52	1.40	0.34	0.02	3.23
33-48	0.00	0.34	0.03	1.89	7.12	0.92	0.30	0.02	2.70
48-81	0.00	0.37	0.00	1.52	14.49	2.95	0.51	0.03	2.28
81-98	0.00	0.37	0.00	1.42	1.43	-0.02	0.45	0.03	2.46
98-100	0.00	0.37	0.00	1.39	0.38	-1.83	0.45	0.03	2.46

a. Similar horizons grouped by site morphology.

b. α, n = shape parameters, θr = residual water content, θs = saturated water content, w2 = weight of second expression (w1 + w2 = 1), Ksat = saturated hydraulic conductivity.

Table 10. Hydraulic input parameters for HYDRUS 1-D simulation of water flow for the soil profile of a row crop state in a Marvyn unit in the Alabama Fall Line Hills Ecological Site.

Horizon cm	θr	θs	α_1	n_1	Ksat cm hr^{-1}	Tau	w_2	α_2	n_2
0-21	0.00	0.23	0.02	1.95	3.99	1.32	0.31	0.07	3.34
21-31	0.00	0.31	0.02	8.27	0.59	0.58	0.74	0.02	1.33
31-52	0.00	0.41	0.02	1.48	1.02	0.88	0.40	0.02	1.75
52-79	0.00	0.41	0.03	2.05	0.68	1.16	0.72	0.00	1.36
79-100	0.00	0.40	0.02	1.81	0.38	0.50	0.55	0.01	1.76

a. Similar horizons grouped by site morphology.

b. α, n = shape parameters, θr = residual water content, θs = saturated water content, w2 = weight of second expression (w1 + w2 = 1), Ksat = saturated hydraulic conductivity.

Table 11. Simulation of a 100-year rainfall event (1 cm hr^{-1} for 24 hours) in Marvyn units in the Alabama Fall Line Hills Ecological Site.

	Reference	Row Crop
Time to runoff (hours)	-	13
Sum Runoff (cm)	0	5.46
Sum Infiltration (cm)	24	18

a. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state.

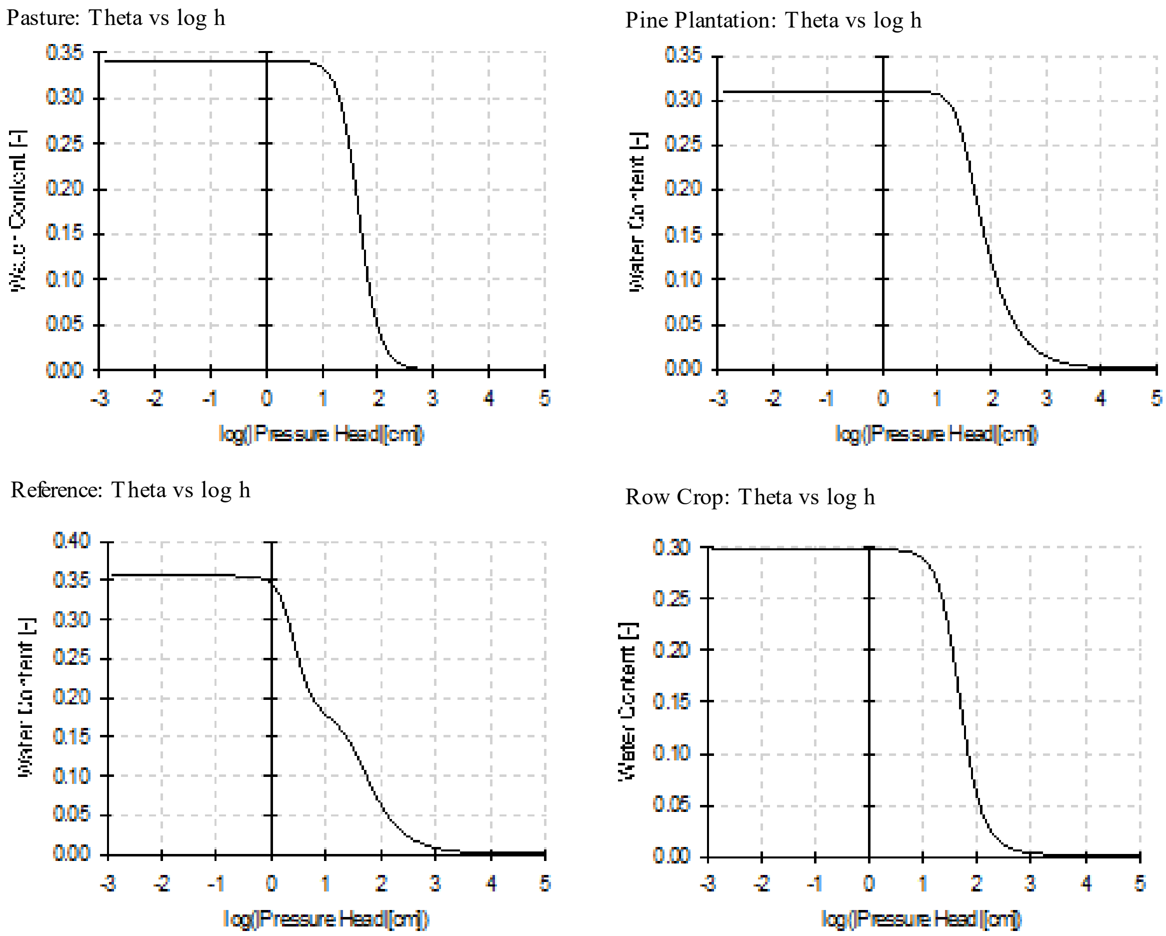


Figure 12. Water retention curves measured at 15 cm depth for three reps of four states in an Alabama Fall Line Hills Ecological Site. Row Crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine Plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state.

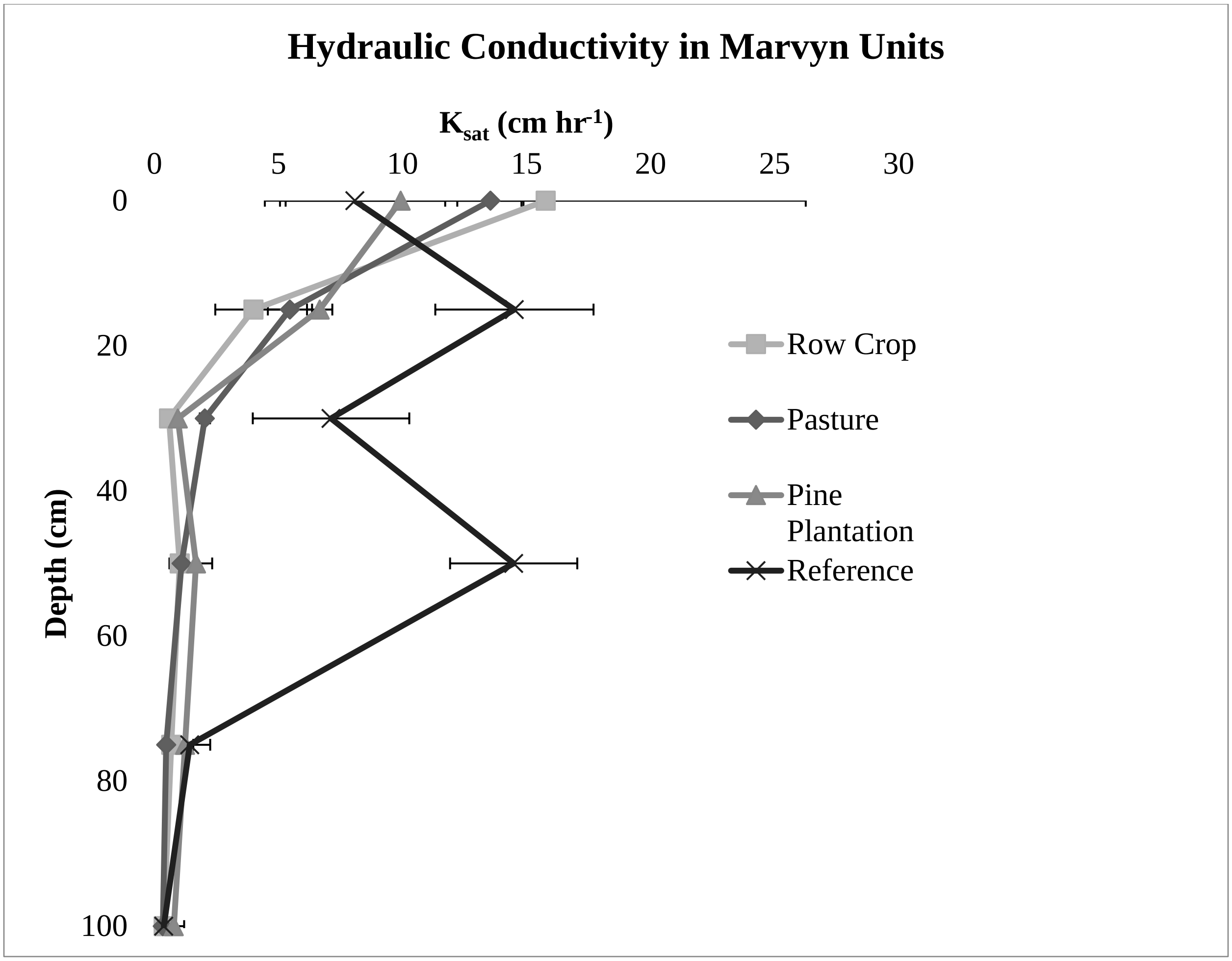


Figure 13. Infiltration rate and Ksat to 100 cm depth for four states in Marvyn units of the Alabama Fall Line Hills Ecological Site. Row Crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine Plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state. Bars represent estimated measurement error.

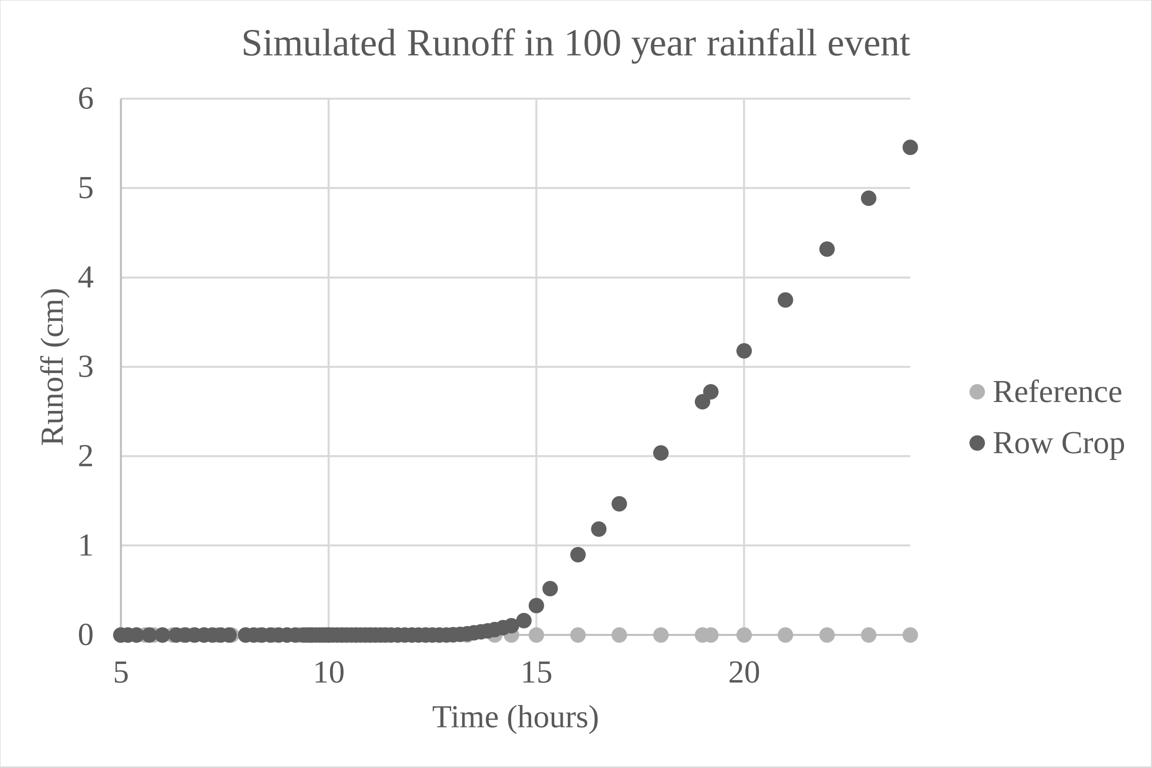


Figure 14. Cumulative runoff (cm) over time (hours) for a 100 year (1 cm hr^{-1} for 24 hours) in the Alabama Fall Line Hills Ecological Site. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state.

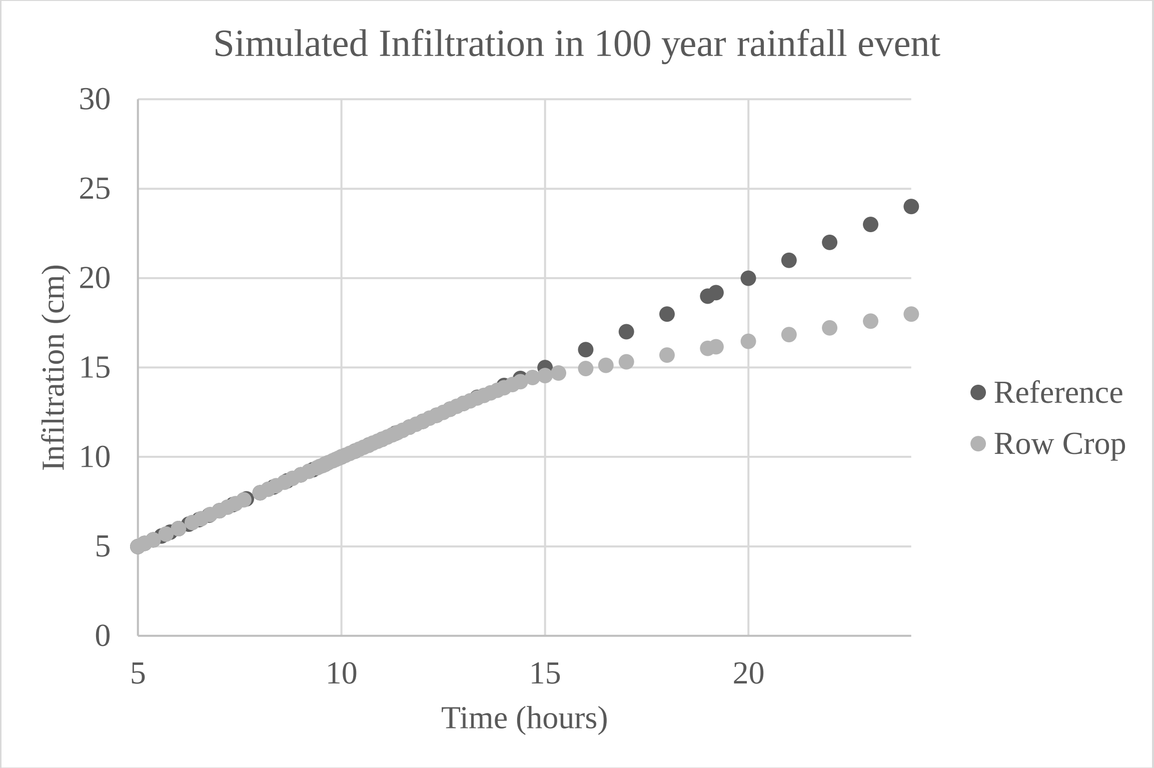


Figure 15. Cumulative infiltration (cm) over time (hours) for a 100 year (1 cm hr^{-1} for 24 hours) in the Alabama Fall Line Hills Ecological Site. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state.

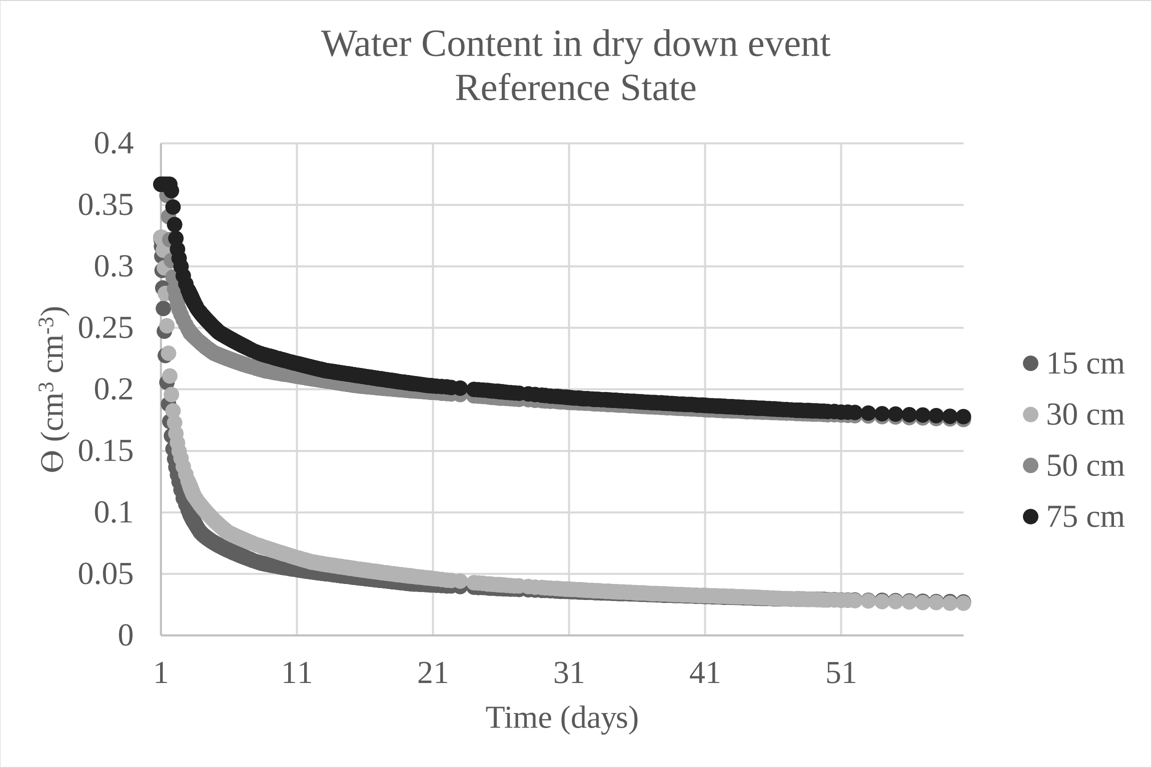


Figure 16. Water content (Θ) over time (days) during a dry down event in the Reference (longleaf pine/ bluestem forest) state of the Alabama Fall Line Hills Ecological Site. Water contents reported from observation nodes at 15, 30, 50, and 75 cm.

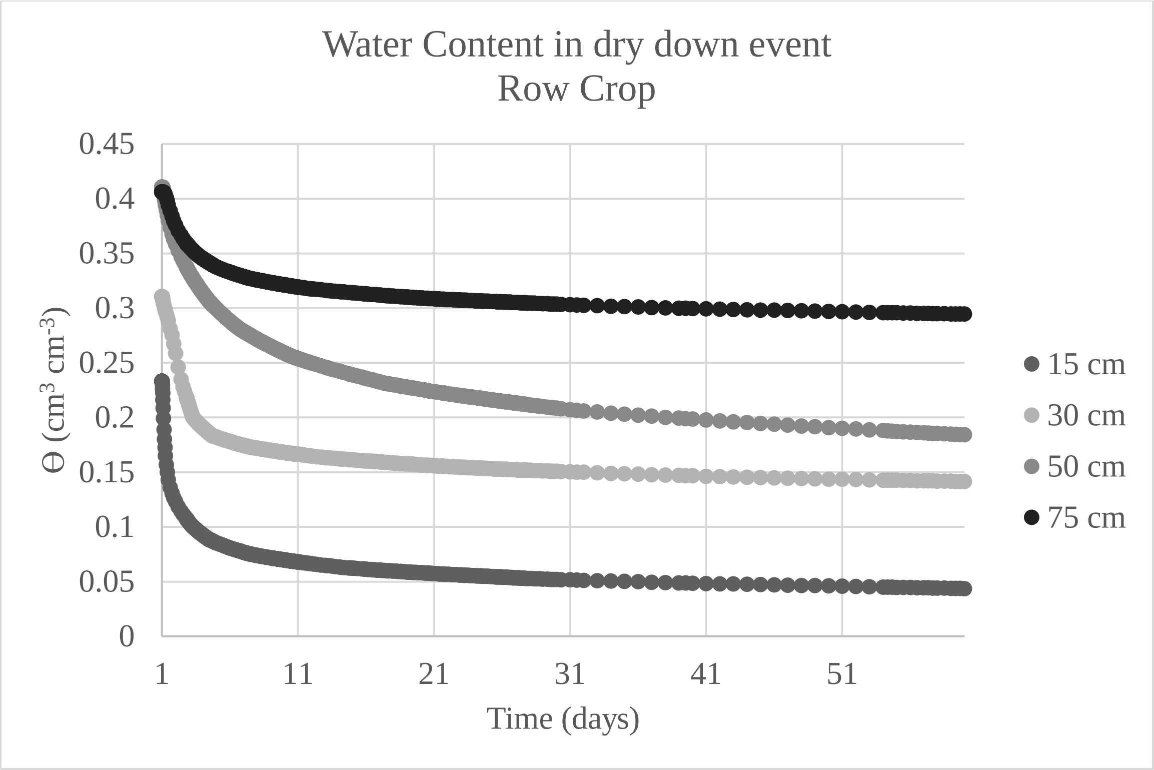


Figure 17. Water content (Θ) over time (days) during a dry down event in the conventional Row Crop state of the Alabama Fall Line Hills Ecological Site. Water contents reported from observation nodes at 15, 30, 50, and 75 cm.

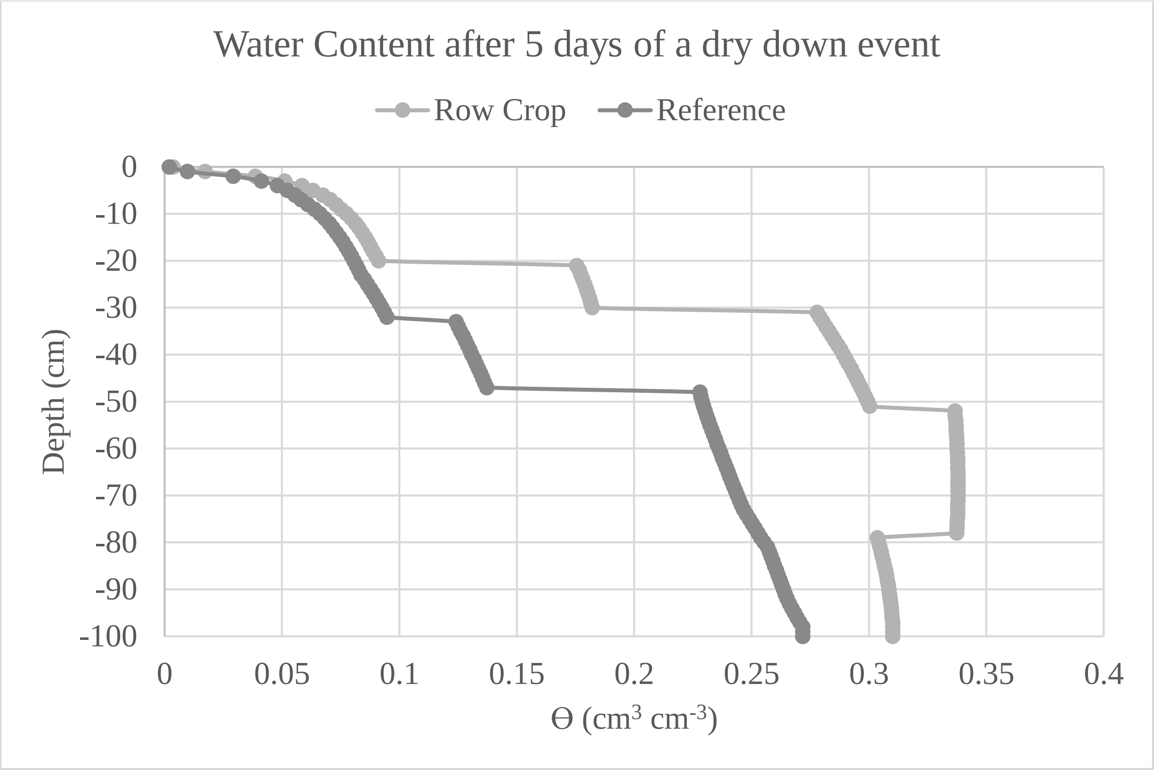


Figure 18. Water content (ϴ) by depth to 100 cm reported after 5 days during a dry down event in the Alabama Fall Line Hills Ecological Site. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state

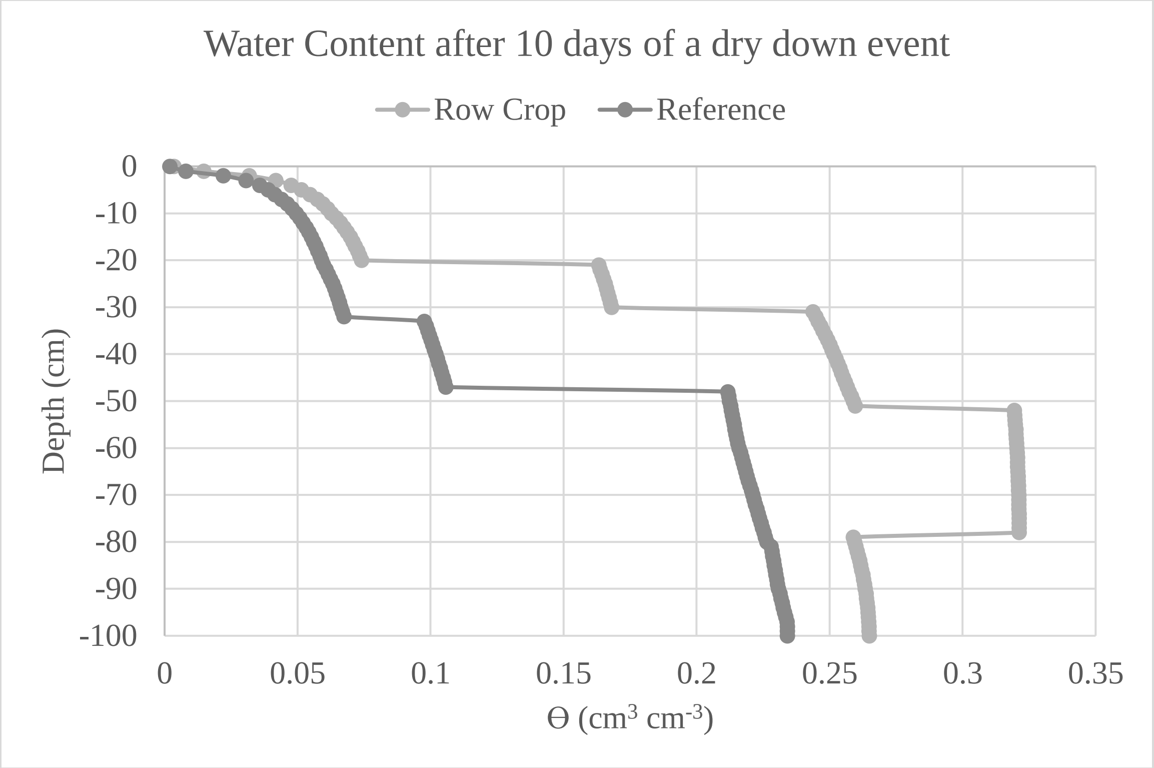


Figure 19. Water content (ϴ) by depth to 100 cm reported after 10 days during a dry down event in the Alabama Fall Line Hills Ecological Site. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state.

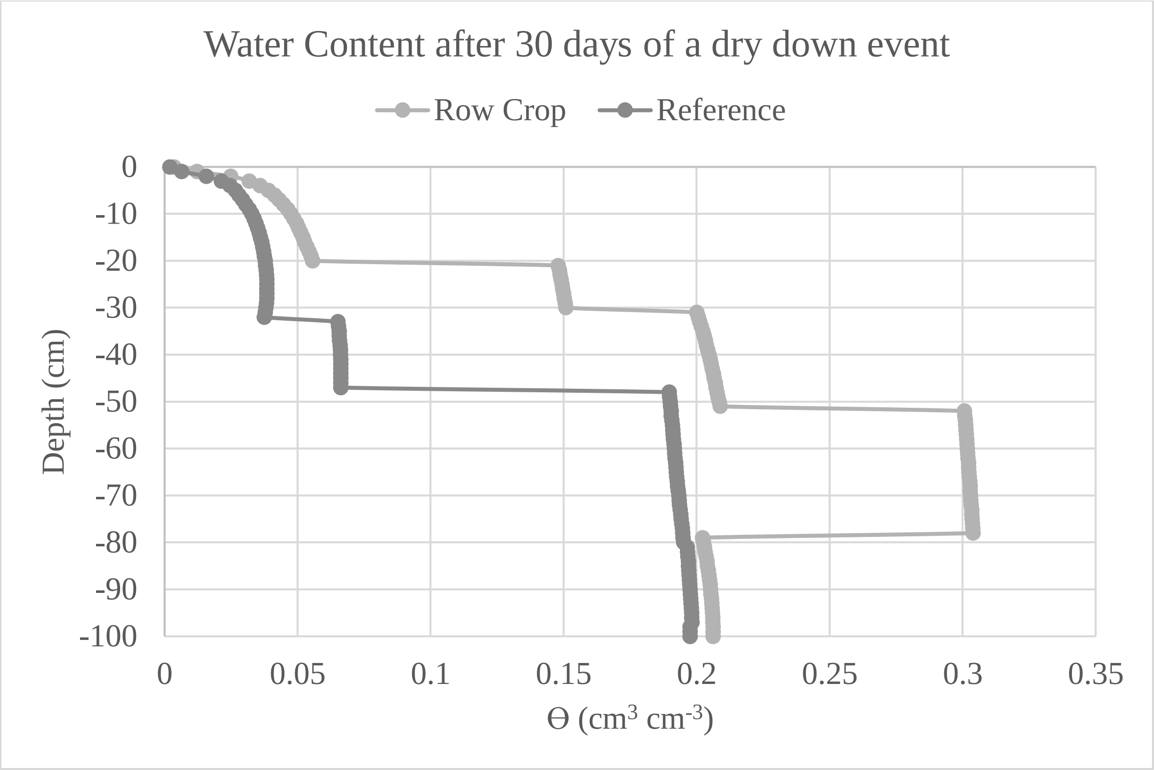


Figure 20. Water content (Ɵ) by depth to 100 cm reported after 30 days during a dry down event in the Alabama Fall Line Hills Ecological Site. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state.

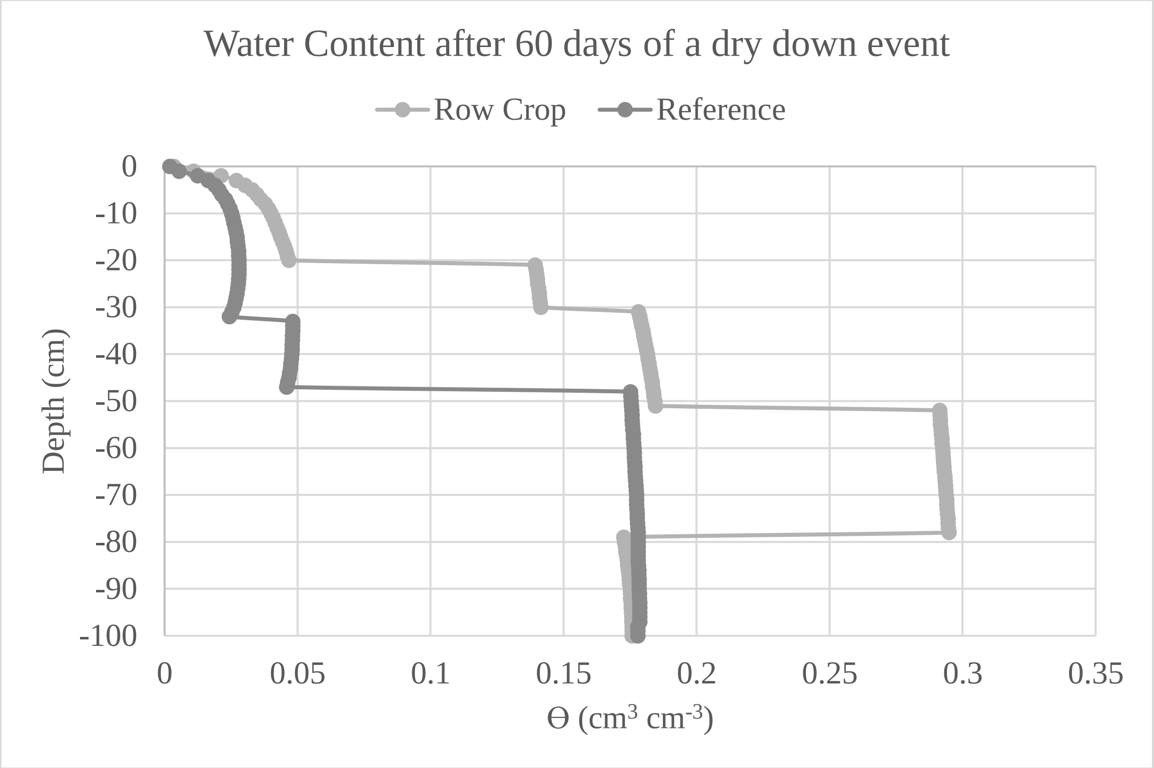


Figure 21. Water content (Ө) by depth to 100 cm reported after 60 days during a dry down event in the Alabama Fall Line Hills Ecological Site. Reference = reference longleaf pine/ bluestem forested state; Row Crop = conventional row crop state.

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Appendix

Site Locations

Table 12. Geographic coordinates of study site locations in Lee and Macon Counties, Alabama in decimal degrees. Projection= Geographic, Datum= WGS 1984, Spheroid= WGS1984.

Field ID	State	Map Unit	Longitude	Latitude
TNAT1	Reference	Marvyn	32.45063889	-85.63125
TNAT3	Reference	Cowarts	32.45682538	-85.62834953
TNAT4	Reference	Uchee	32.47747222	-85.58
IF1	Row Crop	Marvyn	32.439493	-85.392398
IF3	Pine Plantation	Marvyn	32.439300	-85.391188
MF1	Row Crop	Cowarts	32.56858333	-85.58897222
IF4	Row Crop	Uchee	32.4498553	-85.3972931
TU4	Pasture	Marvyn	32.44011	-85.73601
TU2	Pasture	Cowarts	32.4368355	-85.7256508
IF5	Pasture	Uchee	32.443519	-85.3802228
IF6	Pine Plantation	Uchee	32.443202	-85.38004
MA2	Pine Plantation	Cowarts	32.42469	-85.7879

Row Crop = conventional row crop state; Pasture = grazed or hayed pasture state; Pine Plantation = managed pine plantation state; Reference = reference longleaf pine/bluestem forested state.

Figure 22. Map of Fall Line Hills region in Alabama with research sites for the Fall Line Hills Ecological Site.

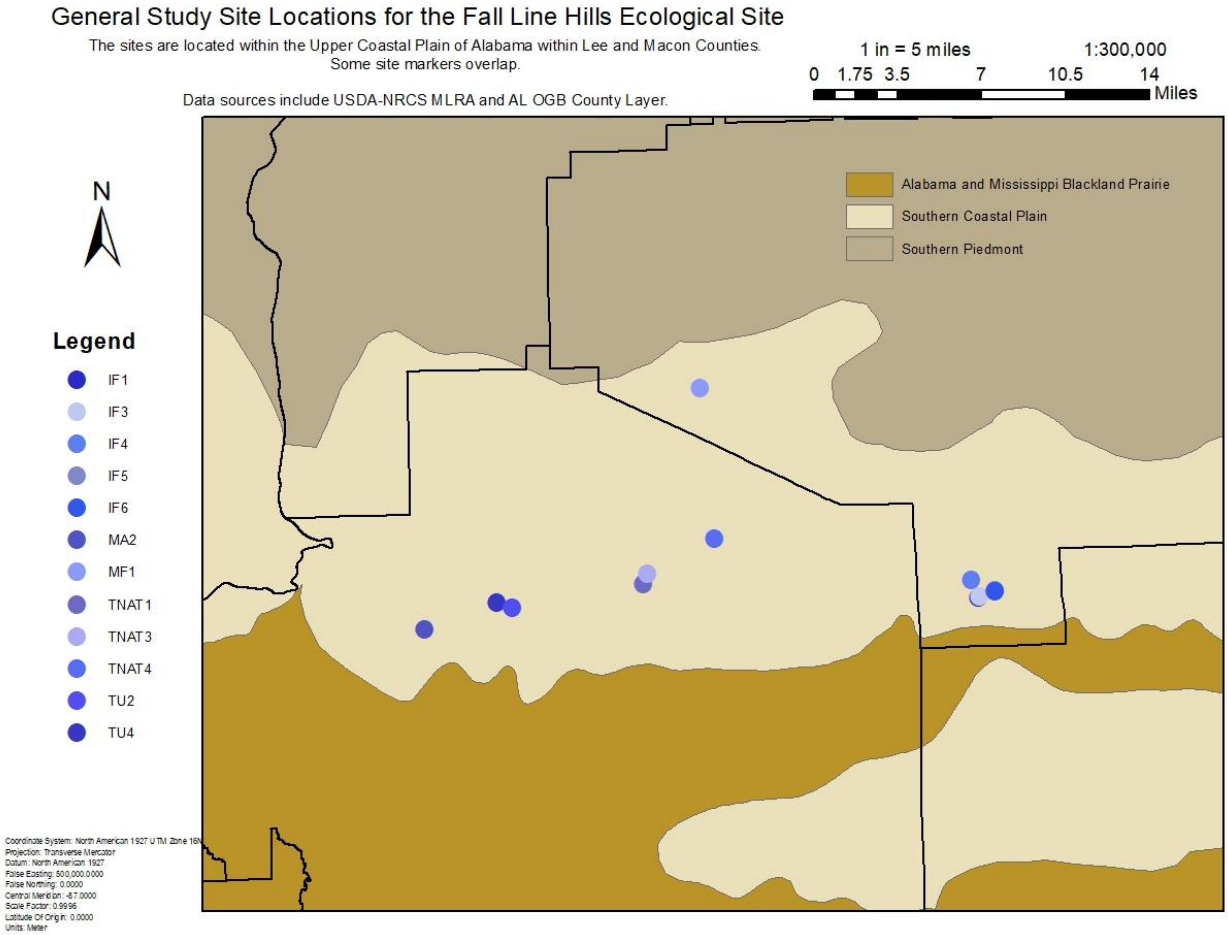

Figure 23. Map of research sites in Lee and Macon Counties, Alabama, for the Fall Line Hills Ecological Site.

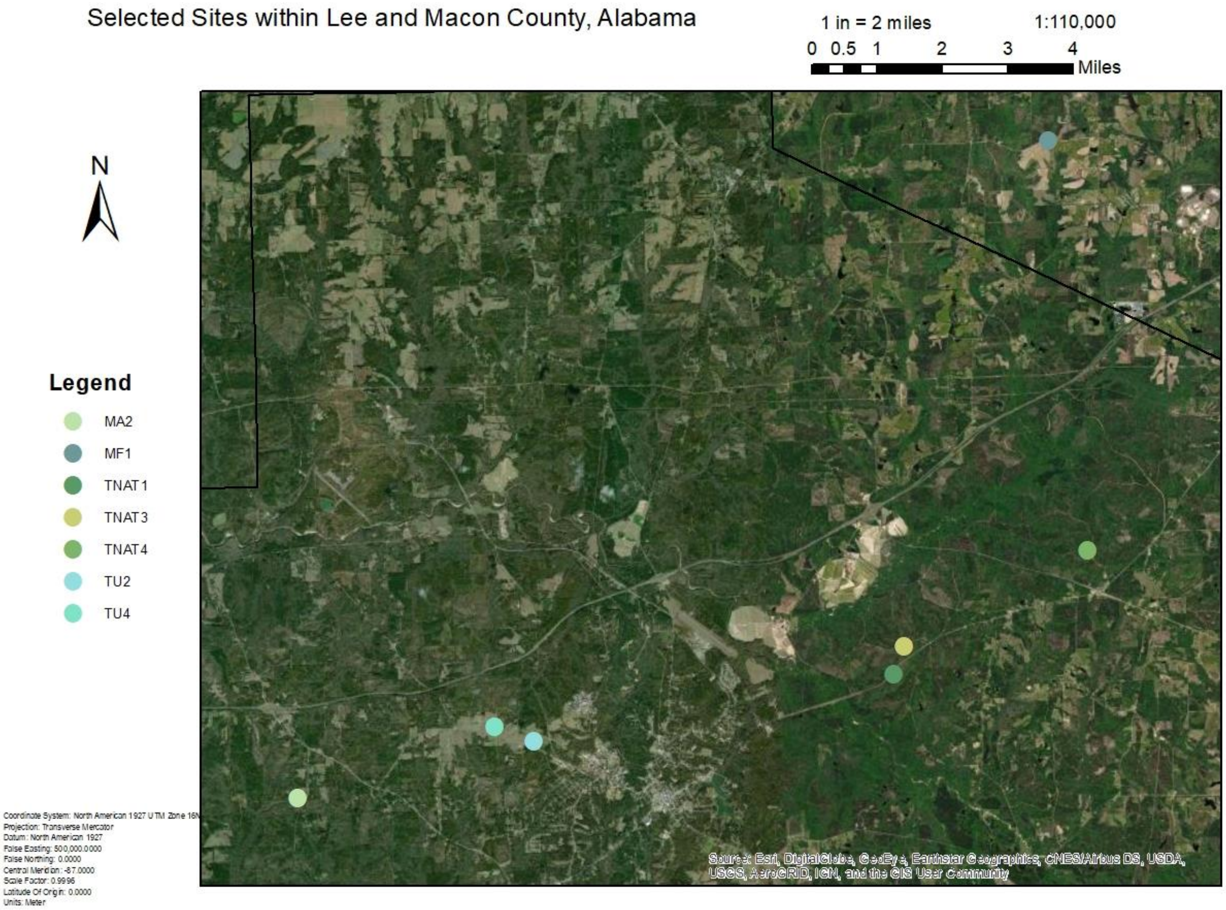

Figure 24. Map of research sites in Lee County, Alabama, for the Fall Line Hills Ecological Site.

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Field descriptions of investigated soils

Sample ID: TNAT1
Taxonomic Classification: Fine-loamy, kaolinitic, thermic Typic Kandiudult
Soil Consociation: Marvyn unit
State: reference longleaf pine/bluestem forest
Described: 2019 by Cooper Nichols, John Burns, Jenna Platt

Profile: (Colors are for moist soil)

A	0 to 5 cm	Salt and pepper very dark grayish brown and very pale brown (10YR 3/2 and 10YR 8/3) loamy coarse sand.
E	5 to 33 cm	Yellowish brown (10YR 5/4) loamy sand.
BE	33 to 48 cm	Yellowish brown (10YR 5/6) sandy loam; few clay films.
Bt1	48 to 81 cm	Yellowish red (5YR 4/6) sandy clay loam; common clay films.
Bt2	81 to 98 cm	Yellowish red (5YR 4/6) sandy clay loam; common clay films.
Bt3	98 to 122 cm	Yellowish red (5YR 4/6) sandy clay loam; fine medium distinct brownish yellow (10YR 6/6) mottles; common clay films.
BC	122 to 152 cm	Yellowish red (5YR 5/6) sandy clay loam; common medium distinct reddish yellow mottles (7.5YR 6/6); common clay films.
CB	152 to 200 cm	Reddish yellow (7.5YR 6/6) sandy clay loam; yellowish red concentrations (5YR 4/6); light brownish gray depletions (10YR 6/2).

Table 13. Soil characterization data for TNAT1 pedon (Laboratory numbers 110637 to 110644) sampled as Marvyn in reference longleaf state (Fine-loamy, kaolinitic, thermic Typic Kandiudult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
A	5	83	14	3	2.2	4.46	3.89
E	33	83	15	2	3.4	4.91	4.31
BE	48	67	23	10	2.2	4.83	4.09
Bt1	81	54	19	27	2.0	5.01	4.33
Bt2	98	54	15	31	1.8	5.03	4.19
Bt3	122	54	14	32	2.3	4.81	4.16
BC	152	54	14	32	2.8	5.05	4.14
CB	200	61	13	25	7.1	5.05	4.17

Sample ID: TNAT3
Taxonomic Classification: Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludult
Soil Consociation: Cowarts unit
State: reference longleaf pine/bluestem forest
Described: 2019 by Joey Shaw, Jenna Platt

Profile: (Colors are for moist soil)

Ap	0 to 9 cm	Salt and pepper very dark grayish brown and yellowish brown (10YR 3/2 and 10YR 5/4) loamy coarse sand.
AE	9 to 23 cm	Yellowish brown (10YR 5/4) loamy coarse sand.
E	23 to 38 cm	Light yellowish brown (10YR 6/4) loamy coarse sand.
Bt1	38 to 60 cm	Yellowish brown (10YR 5/6) coarse sandy loam; common clay films.
Bt2	60 to 80 cm	Strong brown (7.5YR 4/6) sandy clay loam; common clay films.
Bt3	80 to 98 cm	Strong brown (7.5YR 4/6) sandy clay; common clay films; grayish brown depletions (10YR 5/2); yellowish red concentrations (5YR 5/8).
Bt4	98 to 130 cm	Yellowish red and yellowish brown (5YR 4/6 and 10YR 5/8) sandy clay loam; common clay films; dark grayish brown depletions (10YR 4/2); red concentrations (2.5YR 5/8).
BC	130 to 160+ cm	Yellowish brown and yellowish red (10YR 5/8 and 5YR 5/8) sandy clay loam; gravel.

Table 14. Soil characterization data for TNAT3 pedon (Laboratory numbers 110645 to 110652) sampled as Cowarts in reference longleaf state (Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap	9	84	12	4	19.4	4.16	3.55
AE	23	81	13	5	10.8	4.68	4.04
E	38	77	17	6	11.6	4.71	4.08
Bt1	60	62	21	17	5.9	4.56	3.99
Bt2	80	55	12	33	7.1	4.72	4.01
Bt3	98	47	10	43	5.9	4.80	3.96
Bt4	130	57	10	32	7.6	4.95	4.08
BC	160	67	8	25	13.5	4.98	4.11

Sample ID: TNAT4
Taxonomic Classification: Loamy, kaolinitic, thermic Arenic Kanhapludult
Soil Consociation: Uchee unit
State: reference longleaf pine/bluestem forest
Described: 2019 by Cooper Nichols, John Burns, Joey Shaw, Jenna Platt

Profile: (Colors are for moist soil)

A	0 to 5 cm	Salt and pepper brown and black (10YR 4/2 and 10YR 3/2) loamy sand.
Ap	5 to 25 cm	Brown (10YR 4/3) sand.
E1	25 to 56 cm	Yellowish brown (10YR 5/4) loamy sand.
E2	56 to 77 cm	Yellowish brown (10YR 6/4) loamy sand; few fine faint dark red (2.5YR 3/6) iron accumulations; strong brown (7.5YR 5/6) B bodies; gravels.
Bt1	77 to 104 cm	Strong brown (7.5YR 5/8) sandy loam; common clay films; few fine faint red (2.5YR 4/6) iron accumulations increasing to common with depth.
Bt2	104 to 120 cm	Multicolor 30% red, 30% strong brown, 20% light gray, 10% light yellowish brown (2.5YR 4/6, 7.5YR 5/8, 10YR 7/2, 10YR 6/4) sandy clay loam; common clay films.
BC	120 to 134 cm	Multicolor 50% red, 25% strong brown, 15% light gray, 10% light yellowish brown (2.5YR 4/6, 7.5YR 5/8, 10YR 7/1, 10YR 6/4) sandy clay loam; common clay films.
CB	134 to 160+ cm	Red (2.5YR 4/6) sandy clay loam; few common films; white (10YR 8/1) kaolins.

Table 15. Soil characterization data for TNAT4 pedon (Laboratory numbers 110675 to 110682) sampled as Uchee in longleaf reference longleaf state (Loamy, kaolinitic, thermic Arenic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
A	5	83	14	3	4.7	4.43	4.19
Ap	25	90	7	3	3.7	4.66	4.43
E1	56	79	16	6	3.4	4.88	4.47
E2	77	79	16	5	11.6	4.89	4.56
Bt1	104	70	10	19	4.4	4.76	4.23
Bt2	120	58	8	34	3.9	4.58	4.12
BC	134	60	8	33	5.9	4.63	4.16
CB	160	67	7	27	6.5	4.51	4.11

Sample ID: IF1, IF3
Taxonomic Classification: Fine-loamy, kaolinitic, thermic Typic Kanhapludult
Soil Consociation: Marvyn unit
State: conventional row crop, pine plantation
Described: 2019 by Joey Shaw, Jenna Platt.

Profile: (Colors are for moist soil)

Ap	0 to 21 cm	Dark yellowish brown (10YR 3/4) sandy loam.
BA	21 to 31 cm	Dark yellowish brown (10YR 4/6) sandy loam; few clay films.
Bt1	31 to 52 cm	Yellowish brown (10YR 5/6) sandy clay loam; common clay films.
Bt2	52 to 79 cm	Yellowish brown (10YR 5/8) sandy clay; common clay films.
Bt3	79 to 106 cm	Yellowish brown (10YR 5/8) sandy clay; common clay films; common red (2.5YR 4/6) iron accumulations.
Bt4	106 to 120 cm	Yellowish brown (10YR 5/4) sandy clay; common clay films; common red (2.5YR 4/6) iron accumulations.
BC	120 to 140 cm	Yellowish brown (10YR 5/6) sandy clay; common clay films; common red (2.5YR 4/6) iron accumulations; common gray (10YR 6/1) depletions.
C	140 to 160+ cm	Mixed yellowish brown and yellowish red (10YR 5/6 and 5YR 5/8) sandy clay loam.

Table 16. Soil characterization data for IF1/IF3 pedon (Laboratory numbers 110667 to 110674) sampled as Marvyn in row crop and pine plantation states (Fine-loamy, kaolinitic, thermic Typic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap	21	63	29	8	4.7	6.37	6.46
BA	31	63	21	16	2.4	5.38	5.30
Bt1	52	52	17	31	2.1	5.16	4.72
Bt2	79	50	14	36	1.9	4.85	4.41
Bt3	106	52	9	39	2.0	4.65	4.33
Bt4	120	51	11	38	4.0	4.44	4.26
BC	140	49	10	40	3.8	4.10	4.18
C	160	62	10	28	7.1	4.30	4.21

Sample ID: MF1
Taxonomic Classification: Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludult
Soil Consociation: Cowarts unit
State: conventional row crop
Described: 2019 by Joey Shaw, John Burns, Cooper Nichols, Jenna Platt.

Profile: (Colors are for moist soil)

Ap1	0 to 12 cm	Brown (10YR 4/3) loamy sand.
Ap2	12 to 24 cm	Dark yellowish brown (10YR 4/4) sandy loam; gravels.
Bt1	24 to 40 cm	Yellowish brown (10YR 5/6) sandy clay loam; common clay films; gravels.
Bt2	40 to 68 cm	Strong brown (7.5YR 5/8) sandy clay; common clay films.
Btv1	68 to 81 cm	Strong brown (7.5YR 5/6) clay; common clay films; 2% plinthite nodules; common fine distinct pale brown (10YR 6/3) and light yellowish brown (10YR 6/4) depletions.
Btv2	81 to 102 cm	Strong brown (7.5YR 4/6) clay; common clay films; 2% plinthite nodules; white (10YR8/1) kaolinite; red (10R 4/6) concentrations; light brownish gray (10YR 6/2) depletions.
BC	102 to 133 cm	Red (2.5YR 4/6) sandy clay loam; few clay films; 25% dark yellowish brown (10YR 4/6) concentrations; 15% light brownish gray (10YR 6/2) depletions; quartz auger refusal at 133cm.

Table 17. Soil characterization data for MF1 pedon (Laboratory numbers 110707 to 110713) sampled as Cowarts in row crop state (Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap1	12	81	13	5	11.9	5.50	5.43
Ap2	24	74	18	7	14.8	5.56	5.81
Bt1	40	64	16	20	6.2	4.76	5.98
Bt2	68	50	12	38	5.6	5.68	6.07
Btv1	81	40	11	49	5.9	5.18	4.40
Btv2	102	45	11	45	16.0	4.67	4.32
BC	133	58	13	29	9.7	4.42	4.45

Sample ID: IF4
Taxonomic Classification: Loamy, kaolinitic, thermic, Arenic Kanhapludult
Soil Consociation: Uchee unit
State: conventional row crop
Described: 2019 by John Burns, Cooper Nichols, Jenna Platt.

Profile: (Colors are for moist soil)

Ap	0 to 24 cm	Brown (10YR 4/3) loamy coarse sand.
E1	20 to 40 cm	Yellowish brown (10YR 5/4) loamy sand.
E2	40 to 60 cm	Yellowish brown (10YR 5/4) loamy sand.
BE	60 to 76 cm	Yellowish brown (10YR 5/8) loamy coarse sand.
Bt1	76 to 91 cm	Yellowish brown (10YR 5/6) loamy coarse sand; common clay films.
Bt2	91 to 120 cm	Brownish yellow (10YR 6/6) coarse sandy loam; common clay films.
Bt3	120 to 138 cm	Multicolor 30% light brownish gray, 25% strong brown, 25% yellowish brown, 20% dark yellowish brown (10YR 6/2, 7.5YR 4/6, 10YR 5/6, 10YR 4/6) sandy clay loam; common clay films.
BC	138 to 160+ cm	Multicolor 50% dark yellowish brown, 25% yellowish brown, 25% light brownish gray, 20% strong brown (10YR 4/6, 10YR 5/6, 10YR 6/2, 7.5YR 4/6) sandy clay loam.

Table 18. Soil characterization data for IF4 pedon (Laboratory numbers 11747 to 110754) sampled as Uchee in row crop state (Loamy, kaolinitic, thermic, Arenic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap	24	82	13	5	3.6	5.22	5.11
AE	44	81	14	5	4.4	5.74	5.52
E	75	84	12	4	9.1	5.68	5.51
BE	86	77	15	8	5.0	5.95	5.69
Bt1	100	66	13	21	9.4	6.05	5.92
Bt2	122	60	11	28	2.4	6.34	5.90
BC	174	66	11	24	9.2	5.51	5.41
CB	184	70	11	19	1.8	4.59	4.39

Sample ID: TU4
Taxonomic Classification: Fine-loamy, kaolinitic, thermic Typic Kandiudult
Soil Consociation: Marvyn unit
State: pasture or hayland
Described: 2019 by Cooper Nichols, Jenna Platt.

Profile: (Colors are for moist soil)

Ap	0 to 20 cm	Dark brown (10YR 3/3) loamy sand.
Bt1	20 to 36 cm	Dark yellowish brown (10YR 4/6) sandy clay loam; common clay films.
Bt2	36 to 64 cm	Strong brown (7.5YR 4/6) sandy clay loam; common clay films.
Bt3	64 to 88 cm	Strong brown (7.5YR 5/6) sandy loam; common clay films; common medium distinct red (2.5YR 5/6) concentrations; few medium distinct yellowish brown (10YR 5/8) concentrations.
Bt4	88 to 115 cm	Strong brown (7.5YR 5/6) sandy clay loam; common clay films; common medium distinct (2.5YR 4/6, 10YR 6/8) concentrations; common medium distinct (10YR 6/3) depletions.
Btv1	115 to 144 cm	Reddish yellow (7.5YR 6/6) sandy clay loam; common clay films; common medium distinct red (2.5YR 4/8) concentrations; common medium distinct pale brown and light brownish gray (10YR 6/3, 10YR 6/2) depletions, 2% weakly cemented plinthite nodules.
Btv2	144 to 174 cm	Strong brown (7.5YR 5/6) sandy clay loam; common clay films; common medium distinct brownish yellow (10YR 6/6) concentrations; common medium distinct pale brown (10YR 6/3) depletions; few medium distinct gray (10YR 6/1) depletions; 3% dusky red (10R 3/4) plinthite and ironstone nodules.
BCv	174 to 175+ cm	Multicolor dark red, strong brown, and brownish yellow (10R 3/6, 7.5YR 5/6, 10YR 6/8) sandy clay loam; common white (10YR 8/1) kaolin; 4% intermixed reddish brown (5YR 5/4) ironstone and plinthite nodules.

Table 19. Soil characterization data for TU4 pedon (Laboratory numbers 110729 to 110736) sampled as Marvyn in pasture state (Fine-loamy, kaolinitic, thermic Typic Kandiudult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap	20	81	10	9	7.9	5.88	5.43
Bt1	36	61	18	21	7.0	6.14	5.35
Bt2	64	56	12	32	4.1	5.11	5.66
Bt3	88	54	12	34	4.1	5.30	4.16
Bt4	115	58	10	32	4.0	4.92	4.22
Btv1	144	62	9	29	4.1	4.98	4.08
Btv2	174	61	9	31	4.5	4.68	4.30
BCv	175	61	10	29	3.2	4.53	4.09

Sample ID: TU2
Taxonomic Classification: Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludult
Soil Consociation: Cowarts unit
State: pasture or hayland
Described: 2019 by Joey Shaw, John Burns, Cooper Nichols, Jenna Platt.

Profile: (Colors are for moist soil)

Ap1	0 to 6 cm	Dark brown (10YR 3/3) loamy sand.
Ap2	6 to 24 cm	Brown (10YR 4/3) loamy sand.
E	24 to 43 cm	Yellowish brown (10YR 5/4) loamy sand.
Bt1	43 to 61 cm	Yellowish brown (10YR 5/6) sandy clay loam; common clay films.
Bt2	61 to 76 cm	Yellowish brown (10YR 5/6) sandy clay; common clay films; common medium distinct strong brown (7.5YR 5/8) iron concentrations; fine medium distinct light reddish brown (5YR 4/6) iron concentrations.
Bt3	76 to 92 cm	Light yellowish brown (10YR 6/4) sandy clay; common clay films; 30% strong brown (7.5YR 5/6) concentrations; 20% light gray (10YR 7/1) depletions.
BC	92 to 130 cm	Red (2.5YR 5/6) sandy clay; common clay films; 30% light gray (10YR 7/1) depletions; 20% red (2.5YR 4/8) concentrations; mica flakes.
CB	130 to 160 cm	Multicolor 40% strong brown, 40% light gray, and 20% red (7.5YR 5/6, 10YR 7/1, 2.5YR 5/6) sandy clay loam.

Table 20. Soil characterization data for TU2 pedon (Laboratory numbers 110691 to 110698) sampled as Cowarts in pasture state (Fine-loamy, kaolinitic, thermic Oxyaquic Kanhapludult).

	Particle Size Distribution						
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap1	6	79	17	5	2.8	5.10	4.73
Ap2	24	85	12	3	6.2	5.08	4.49
E	43	80	15	5	6.7	5.32	4.91
Bt1	61	61	15	25	3.6	5.58	5.16
Bt2	76	54	10	37	0.2	5.24	4.52
Bt3	92	54	9	37	0.1	4.71	4.14
BC	130	52	9	39	0.1	4.87	4.14
CB	160	60	10	29	0.4	4.71	4.03

Sample ID: IF5, IF6
Taxonomic Classification: Loamy, kaolinitic, thermic, Arenic Kanhapludult
Soil Consociation: Uchee unit
State: pasture or hayland, pine plantation
Described: 2020 by Joey Show, Cooper Nichols, Jenna Platt.

Profile:		(Colors are for moist soil)
Ap1	0 to 12 cm	Brown (10YR 4/3) loamy sand.
Ap2	12 to 28 cm	Dark yellowish brown (10YR 4/4) loamy sand.
E	28 to 52 cm	Light yellowish brown (10YR 6/4) loamy sand.
EB	52 to 69 cm	Yellowish brown (10YR 5/4) loamy sand.
Bt1	69 to 88 cm	Yellowish brown (10YR 5/6) sandy loam; common clay films.
Bt2	88 to 106 cm	Brownish yellow (10YR 6/6) sandy loam; common clay films; common medium distinct strong brown and reddish yellow (7.5YR 5/8, 7.5YR 6/6) concentrations.
Bt3	106 to 116 cm	Brownish yellow (10YR 6/6) sandy clay loam; common clay films; common medium distinct strong brown (7.5YR 5/8) concentrations and light gray (7.5YR 7/1) deletions.
Bt4	116 to 133 cm	Mixed 60% brownish yellow, 25% yellowish brown, 10% red (10YR 6/6, 10YR 5/4, 10R 4/6) sandy clay loam; common clay films; 5% light brownish gray (10YR 6/2) depletions; red increases with depth.
BC	133 to 150+ cm	Mixed 65% light gray, 30% reddish brown, 5% reddish yellow (7.5YR 7/1, 2.5YR 4/4, 7.5YR 6/8) sandy clay loam; perched water.

Table 21. Soil characterization data for IF5/IF6 pedon (Laboratory numbers 110755 to 110763) sampled as Uchee in pasture and pine plantation states (Loamy, kaolinitic, thermic, Arenic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap1	12	80	17	3	4.0	4.62	4.52
Ap2	28	81	16	3	2.8	5.21	4.81
E	52	78	19	3	3.1	5.27	4.91
EB	69	76	19	5	4.5	5.38	5.10
Bt1	88	76	17	7	3.7	5.65	5.41
Bt2	106	68	15	17	1.5	4.99	4.75
Bt3	116	62	9	29	1.2	4.36	4.17
Bt4	133	60	9	32	1.7	4.13	4.01
BC	150				0.4	4.97	3.85

Sample ID: MA2
Taxonomic Classification: Fine-loamy, kaolinitic, thermic, Oxyaquic Kanhapludult
Soil Consociation: Cowarts unit
State: pine plantation
Described: 2019 by Cooper Nichols, Jenna Platt.

Profile: (Colors are for moist soil)

Ap	0 to 10 cm	Dark brown (10YR 3/3) loamy sand.
AE	10 to 25 cm	Brown (10YR 3/4) loamy sand.
EB	25 to 50 cm	Yellowish brown (10YR 5/4) sandy loam.
Bt1	50 to 76 cm	Yellowish brown (10YR 5/6) sandy loam; common clay films; few reddish yellow (5YR 6/8) iron concentrations.
Bt2	76 to 96 cm	Yellowish brown (10YR 5/6) sandy clay loam; common clay films; common yellowish red (5YR 5/6) iron concentrations; common light brownish gray (10YR 6/2) depletions.
Bt3	96 to 106 cm	Mixed 40% light brownish gray, 30% yellowish red, 30% yellowish brown (10YR 6/2, 5YR 5/6, 10YR 5/6) sandy loam; common clay films.
Btg	106 to 128 cm	Mixed 50% light brownish gray, 25% dark yellowish brown, 25% yellowish red (10YR 6/2, 7.5YR 4/6, 5YR 5/6) sandy loam; common clay films.
BCg	128 to 158 cm	Mixed 60% gray, 20% strong brown, 20% yellowish red (10YR 6/1, 7.5YR 5/8, 5YR 4/6) sandy clay loam.
C1	158 to 176 cm	Mixed 60% gray, 20% strong brown, 20% reddish brown (10YR 6/1, 7.5YR 5/8, 5YR 5/4) sandy clay loam.
C2	176 to 176+ cm	Light gray (10YR 7/1) sandy clay loam; many reddish yellow and light reddish brown (7.5 YR 6/6, 5YR 6/4) concentrations.

Table 22. Soil characterization data for MA2 pedon (Laboratory numbers 110737 to 110746) sampled as Cowarts in pine plantation state (Fine-loamy, kaolinitic, thermic, Oxyaquic Kanhapludult).

		Particle Size Distribution					
Horizon	Lower Depth	Sand	Silt	Clay	Coarse Fragments	pH	pH
	(cm)	% of <2 mm mineral soil			% of whole soil	1:1	1:2
Ap	10	84	11	4	3.7	5.17	4.92
AE	25	81	13	6	3.5	5.14	4.72
E	50	77	14	9	4.6	4.72	4.26
Bt1	76	68	14	18	8.2	4.58	4.07
Bt2	96	67	10	23	6.7	4.41	4.05
Bt3	108	71	9	20	4.1	4.48	4.01
Bt4	128	74	7	19	4.8	4.44	4.04
BC	158	70	7	22	5.5	5.57	4.00
C1	176	70	6	23	3.0	4.52	4.00
C2	177	70	8	22	2.2	4.55	3.97