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Soil Morphological, Physical, and Chemical Parameters Affecting Longleaf Pine (Pinus palustris) Site Quality and Ecosystem Restoration Potential in East Texas

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By

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ABSTRACT

There has been a large decline in coverage of longleaf pine (*Pinus palustris* Mill.) within its range in the southeastern United States since the time of European settlement. Due to this decline, interest has developed in the re-establishment of this species on suitable sites. However, many attempts have been unsuccessful in re-establishment, likely in part due to the lack of emphasis on selection of suitable soils. Historically, longleaf pine was found on soils with a wide range of soil properties, including higher quality soils, due to frequent fires which kept many competing species suppressed. Decline in longleaf pine coverage has been attributed to many factors, including both site conversion and fire exclusion. Much of the land that originally supported longleaf pine in the southeastern United States has been converted to agricultural use, loblolly pine (*Pinus taeda* Mill.) plantations, and urban development. Fire has often been excluded from longleaf pine ecosystems in recent history due to concern for human health, safety, and liability. Because of limited funding and reduced opportunities for prescribed fire use, longleaf pine ecosystem restoration efforts might be best focused on more marginal soils that have characteristics that naturally restrain herbaceous and hardwood competition. However, there is a need to quantify the potential productivity for longleaf

pine on these marginal soils and to develop understandings of edaphic factors limiting their growth.

Soil morphological, physical, and chemical properties in existing longleaf pine ecosystems on three soil series in the Angelina and Sabine National Forests in east Texas were evaluated to develop a better understanding of how variation in soil properties may affect longleaf pine site quality. Analysis of variance and regression techniques were used to compare soil properties for three different soil mapping units: Letney (Arenic Paleudults), Stringtown (Typic Hapludults), and Tehran (Grossarenic Paleudults). These soils all support natural longleaf pine stands, but vary in texture, depth to argillic horizons, nutrient availability, available water capacity, and other parameters which are likely related to site quality, as measured by site index, of longleaf pine.

Longleaf pine site index was influenced by depth to E horizon, depth to first argillic B horizon, texture of B horizon, and nutrients in the B horizon. B horizon physical and chemical variables appeared to be most influential on observed site index values for longleaf pine on the soils in the study.

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INTRODUCTION

An ecosystem is defined as a biological community and how it interacts with the abiotic community, and is often named after the dominant plant community, such as a longleaf pine ecosystem. Many ecosystems, including those of forests, savannas, marine, and aquatic environments, have been degraded through exploitation of their natural resources, or land-use conversion to agriculture and urban use, which has contributed to ecosystem fragmentation (Rapport et al. 1998).

Ecosystem restoration is the act of restoring ecosystems that have been degraded, often due to human activities, to a healthy state. Ecosystem restoration is sometimes very challenging due to previous modifications of soils, introduction of exotic invasive species, and lack of adequate funding and other resources to adequately conduct the restoration. Site selection is a very important step in ecosystem restoration because the original ecosystems may have been greatly altered due to human activities (Chazdon 2008).

The longleaf pine (*Pinus palustris* Mill.) ecosystems of the southeastern United States are no exception to this loss and degradation. Prior to European settlement, longleaf pine ecosystems occupied vast areas of the southern Atlantic and Gulf Coastal Plains regions of the United States, with approximately 30 million hectares extending between east

Texas to Virginia, and stretching as far South as Florida, covering several climatic, physiographic, and many soil types (Henderson and Grissino-Mayer 2008; Pessin 1938; Peet and Allard 1993; Patterson and Knapp 2016).

Longleaf pine was found on a range of soil types and geologic formations, as well as in range of ecosystems that included savannas, often described by early accounts as park-like with varied accompanying vegetation creating a diverse ecosystem, and on sites from excessively drained sandhills to poorly drained flatwoods (Chapman 1932; Harcombe et al. 1993; Landers et al. 1995; Drewa et al. 2002; Oswalt et al. 2012). A relatively frequent low intensity fire return interval, every two to eight years, often set by native peoples or from lightning, is regarded as a key factor in historically reducing hardwood and shrub encroachment (Christensen 1981; Outcalt 2000; McWhorter 2005; Brockway et al. 2006).

During the logging and naval stores industry boom of the 1920s, the amount of old growth longleaf pine was quickly reduced (Rosenberg and Trajtenberg 2001) as the invention of the steam engine locomotive and sawmills allowed the timber industry to efficiently exploit stands of longleaf pine. By the mid-1930s, 10% of the old growth longleaf pine forest remained in east Texas and west Louisiana; the remaining longleaf pine stands were mostly second growth (Frost 1993).

Following the timber boom, regeneration of many of the natural longleaf pine stands failed. The decline in the extent of the species has been attributed to many factors including urban development, aging and mortality of trees without replacement or regeneration, logging with the conversion to other species such as loblolly pine (*Pinus taeda*) and fire exclusion (Peet and Allard 1993). Today, approximately four percent (1.2 million ha), remain of this once dominant cover type (Outcalt and Sheffield 1996; Brockway and Outcalt 1999; Outcalt et al. 1999).

This dramatic decline has led conservation groups and government agencies to begin conserving the remaining longleaf stands, and also to initiate longleaf pine ecosystem restoration on sites where the ecosystem once existed. However, many challenges exist that hinder this process, including land availability, locating appropriate sites, invasive and woody species competition, reduced burning opportunities, and lack of economic incentives. Continued urban expansion also continues to threaten these ecosystems through land ownership fragmentation (Meyer and Turner 1992).

Fire exclusion played a significant role in the decline of the longleaf pine ecosystem. Due to expansion of the wildland-urban interface, a significant decrease in opportunities for prescribed fires has occurred. Prescribed fire is not only a key component in maintaining fire dependent ecosystems, but also serves as a means for reducing wildfire risk by reducing fuel loads. However, the smoke generated from the prescribed fires used to maintain this ecosystem may pose a threat to human health and safety. The smoke is a nuisance for those that live nearby and can reduce visibility to those traveling on nearby roads (Johnston et al. 2007). Due to these issues and concerns, reduced burning opportunity in these fire-dependent ecosystems has become a major hindrance to maintenance of these communities (Brown 1975). The reduction in the occurrence of fire, regarded as the most significant ecological reason for the decline in the ecosystem, leads to an increase in woody competition and a reduction in successful longleaf regeneration (Brockway and Outcalt 1999), as well as an increase in fuel loads that could lead to devastating wildfires.

The reduction of this ecosystem not only affects longleaf pine but also other elements, such as associated flora and fauna associated with this ecosystem. This ecosystem supports a wide diversity of plants and animals, some endemic, which exist mainly within the remaining portion of its range (Peet and Allard 1993). Species in particular that are affected include the red-cockaded woodpecker (RCW; *Leuconotopicus borealis*), which prefers older stands of longleaf that have the "typical" longleaf structure with relatively low basal area, 40-80 ft^2 ac^{-1}, and open understory, and the Louisiana Pine snake (*Pituophis ruthveni*), which are found in pine forests with deep, well-drained soils (Rudolph and Burgdorf 1997).

Restoring this ecosystem can become very expensive, ranging from approximately $370 to $740 per ha, depending on many factors including the use of containerized or bare root seedlings and site conditions (Outcalt 2000; Brockway et al. 2006). Other costs may include establishment of native grasses and other herbaceous plants if the seed bank does not contain the desired native species.

Many longleaf pine ecosystem restoration projects have not been successful. One cause of ecosystem restoration failure is the inadequate consideration of soil suitability for the longleaf ecosystem. Soil type can affect the vegetation present, while vegetation can affect the condition of the soils (Eviner and Hawkes 2008). Soils should be a key factor in the site selection process due to the strong influence on ecosystems. Ecosystem management will benefit from proper management practices by improving soil properties and reducing erosion (Sekercioglu, 2010).

Due to these challenges, restoration efforts should focus, at least initially, in areas that fit site specific soil/site parameters that support longleaf pine ecosystem restoration with the least management inputs. Boykin Springs Recreational Area and Fox Hunters Hill, located in the western extent of the longleaf pine range, contain soils with a range of properties which support existing longleaf pine ecosystems. These areas are also considered two of the most ecologically diverse areas of Texas, and are among the many areas in which longleaf pine ecosystem restoration efforts are taking place (Hung 2002). These longleaf pine communities, like most of the forest communities of the south, have been impacted severely by the early logging era (Maxwell and Baker 1983). Much of this land was purchased by the United States Forest Service (USFS) and attempts have been made toward converting this land back to its native vegetation with the help of prescribed burning. However, many of these attempts have been described as unsuccessful, with sometimes unclear reasons.

There is a need for research on specific soil parameters affecting longleaf pine ecosystem site suitability and productivity. The purpose of this study was to examine three soil series mapping units common to longleaf pine ecosystem areas for select soil morphological, physical, and chemical properties and then relate these properties to the above ground growth potential of existing longleaf pine. It is anticipated that the study will help develop better understanding of soils that are suitable for longleaf pine ecosystem restoration, with a focus on reduced risk of establishment failure.

OBJECTIVES

The purpose of this study was to evaluate select soil properties on three relatively pure soil mapping units (series) currently supporting longleaf pine stands in east Texas and relate these properties to longleaf pine site index. In order to locate these relatively pure soil mapping units, soil maps provided from the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) were used as a starting point; however, current maps are not mapped at a small enough scale needed for this project, so detailed site investigations were required to ensure soils were uniform within study sites. A companion study characterized understory vegetation. Results from the two studies should help assist in prioritizing site selections for longleaf pine restoration projects for the western portion of the range and provide information on expected longleaf pine growth.

Specific objectives of this study were to:

1. Determine select soil morphological properties on three relatively pure soil map units currently supporting longleaf pine ecosystems, including depth of A horizon, depth of E horizon, and depth to the first argillic B horizon.

2. Determine select soil physical properties on three relatively pure soil map units currently supporting longleaf pine ecosystems, including soil texture of the A, E, and B horizon and sand separates for the sand fraction of the A, E, and B horizon.
3. Determine select soil chemical properties on three relatively pure soil map units currently supporting longleaf pine ecosystems, including total nitrogen and organic carbon content, macronutrient concentrations, ammonium, and pH.
4. Determine site index on sites of the three relatively pure soil map units presently supporting longleaf pine ecosystems.
5. Determine if correlations exist between soil morphological, physical and chemical parameters, and observed longleaf pine site index values.

LITERATURE REVIEW

Longleaf Pine Ecosystem, Background, and History

Historically, longleaf pine, a long-lived tree species living up to 500 years, dominated 24 to 37 million ha and was also present in 7 million ha of mixed forest ecosystems between the Atlantic Coast and east Texas, reaching as far north as portions of Virginia and North Carolina and south into portions of northern Florida, usually within 150 km of the coastline (Pessin 1938; Frost 1993; Landers et al. 1995; Outcalt 2000; Brockway et al. 2006; Henderson and Grissino-Mayer 2008; Patterson and Knapp 2016). Mosaics of vegetation and plant communities of this ecosystem were attributed to the wide variations in topography, disturbance events (e.g., hurricanes or other high wind events, logging, fire, and edaphic factors) (Landers et al. 1995; Van Kley 1999). Due to these factors, longleaf ecosystems often have high biodiversity, considered the most diverse ecosystems outside of the moist tropics (Landers et al. 1995). Records have shown that fire typically occurred frequently, every two to eight years, and is regarded as the key factor in maintaining the longleaf pine ecosystem by reducing woody, herbaceous, and other competing vegetation components that may have encroached on many of the sites (Christensen 1981; Outcalt 2000; McWhorter 2005; Brockway et al. 2006; Stambaugh et al. 2014). This is especially true on sites with poorly drained to moderately well-drained soils, and loamy soils of higher quality.

Longleaf pine has a sufficient seed crop once every five to seven years (Wahlenberg 1946). Longleaf pine seedlings undergo what is known as the "grass stage", where the plant resembles a clump of grass until the root collar reaches approximately 2 cm in diameter (Haywood 2000). The grass stage can last over six years, but can be shortened with the use of fire or herbicide to control competition. Longleaf pine is shade-intolerant and highly intolerant of competition, especially during the grass stage, where it can become shaded by grasses and shrubs which can reduce growth or even be killed.

History of the Decline of Longleaf Pine Ecosystems

During European settlement and the industrial revolution, longleaf pine coverage declined. Many factors contributed to this phenomenon, including the naval stores industry, logging industry, fire exclusion, and land conversion. The naval stores industry often used longleaf pine for many of products including pine tar, turpentine, and rosin production (Peet and Allard 1993). With the use of mechanized logging operations, old growth longleaf forests were rapidly harvested, and with fire exclusion, many these locations lacked significant regeneration of longleaf pine. Fires that did occur were much more intense due to the logging slash on the ground (Frost 1993; Johnson and Hale 2002). It is estimated that all old growth longleaf pine stands had been harvested by the 1930s (Brockway et al. 2006). By 1985, approximately 90% of the longleaf remaining was naturally regenerated, but logging exceeded regeneration by approximately 45% resulting in an unsustainable decline, with most trees having diameters of 41 cm (16 inches) or less (Kelly and Bechtold 1990; Landers et al. 1995; Outcalt and Sheffield 1996). Trees larger than 41 cm continued to grow, but without adequate replacement.

Other secondary factors attributed to the decline of this ecosystem included land ownership fragmentation, urban development, as well as site conversion to alternative tree species or agriculture, poor seed production, blow downs from high winds, and slow growth in the grass stage causing the trees to become suppressed (Landers et al. 1995; Outcalt and Sheffield 1996; Outcalt et al. 1999; Brockway et al. 2006; Defries et al. 2010; Fill et al. 2014). Over the last two decades longleaf pine ecosystem restoration has become a common topic of study throughout its natural range (Brockway et al. 2006; Henderson and Grissino-Mayer 2008).

Current Management

Present Uses

The species has numerous desirable growth habits, including the ability to self-prune. Self-pruning can create stands of 30-80% pole quality timber, which is regarded as the highest value for southern pine timber, and is also useful for pilings, peelers, and many other products. This species is also more resistant to insect and diseases, such as southern pine beetle (Dendroctonus frontalis) and fusiform rust (*Cronartium quercuum* f. sp. *fusiforme*), than other southern pines (Van Lear and Saucier 1973; Boyer and White 1990). Longleaf pines produce a tap root of 2.4-3.7 m deep in some soils, reducing the risk of wind throw (Boyer 1990). Although a rather long-lived species, longleaf has traditionally been considered the slowest growing of the southern pine species; however, according to Outcalt (1993), longleaf can grow just as quickly, if not outperform, the other pines once out of the grass stage.

Pine straw is another valuable product that can be obtained from longleaf pine stands and the longer needles provide a premium price. Longleaf pine straw can be used for mulch for flower and shrub beds and provides a substrate for Native American basket weaving. However, frequent harvesting pine straw can be detrimental to the herbaceous layer and nutrient cycling (McLeod et al. 1979).

Silvopastures are another possible use of longleaf pine. Longleaf pine stands are generally more open, allowing increased light to reach the grasses that allow for cattle grazing, alleviating some of the need for fire to reduce vegetation competition. However, high pressure of cattle grazing could negatively affect the presence of native grass species (Brockway et al. 2006).

Fire

Fire plays an important role in maintaining ecosystems with fire-adapted vegetation and is frequent in the longleaf pine ecosystems, a key factor for ecosystem success (Brockway et al. 2006). Historically, fires in this ecosystem were known to be started by both man and lightning (Van Lear et al. 2005). Longleaf pine systems were noted to have surface fires approximately every two to eight years (Christensen 1981; Landers et al.

1995) and, unlike some hardwoods or other southern yellow pines with thinner bark, are more tolerant to frequent fires. Fires reduce competing species that could potentially occupy longleaf stands (Jacqmain et al. 1999), as well as non-native plants in these pine ecosystems (Landers et al. 1995). However, frequent fires have been shown to also significantly decrease longleaf pine height and diameter growth by up to 27% (Boyer and Miller 1994), partly caused by reductions in soil porosity and available water capacity (Sword-Sayer 2007). Brockway and Lewis (1997) concluded that a frequent fire regime increased understory diversity, species richness, and evenness by reducing foliar cover in the shrub layer, allowing for an increase in herbaceous grasses and vines. They also found that winter burns decreased the litter cover on the forest floor which also increased standing biomass of wiregrass (*Aristida spp*.), while regular burning can decrease diameter and height growth in young longleaf stands, which can still potentially produce pole-sized timber in 40-50 years (Christensen 1981). Compared to other southern pines, longleaf pine has thicker bark throughout its life cycle, and during its juvenile stage persists in a grass stage with thick needle coverage of the terminal bud, making them more resistant to injury during surface fires (Brockway et al. 2006). However, some landowners are opposed to frequent burning because it can reduces hardwood and shrub components they value for wildlife forage, as well as creating smoke that can become a liability. One study found that even without fire, longleaf pine could persist to be the dominant tree species with little or no encroachment of hardwoods. However, it was found that until wiregrass is well established around years four or five, burning is unnecessary to promote its growth (Outcalt et al. 1999).

Vegetation Communities Associated with Longleaf Pine Ecosystems

Due to the wide range of soils and fire regimes associated with longleaf pine ecosystems, it can be found with a variety of associated vegetation species and densities, including savannas with tallgrass to mixed forests with higher densities and more hardwoods. The distribution of herbaceous plants was found to be correlated with soil moisture and elevation in that different herbaceous communities were associated with slope position and the presences of seepage for both Louisiana and Florida (Drewa et al. 2002). The historical longleaf community has often been described as park-like, primarily dominated by fire-adapted species (Landers et al. 1995). However, alterations in vegetation structure and composition are thought to have occurred due to many factors including urbanization/fragmentation and the reduction of fire occurrence (Hardin and White 1989; Walker 1993; Drewa et al. 2002).

The vegetation associated with longleaf pine includes bunchgrasses, such as little bluestem (*Schizachyrium scoparium*), pineywoods dropseed (*Sporobolus junceus*) and Curtis dropseed (*Sporobolus curtissii*), with wiregrass, forbs, legumes, and woody species such as bluejack oak (*Quercus incana*), turkey oak (*Quercus laevis*), and post oak (*Quercus stellata*). This fire-adapted system has promoted wiregrass and bunch grasses in the longleaf pine ecosystem because of the accumulation of fine litters which provide fuel for frequent fires (Outcalt 1993; Outcalt et al. 1999). Bunch grasses tend to have an outward inclination from the middle of the bunch often connecting canopies of each individual plant which, when added to the pine needles that reach the forest floor, combine to make an extremely flammable mix (Brockway et al. 2006). The combinations of these vegetative mosaics have been created in many areas by frequent, low-intensity fires. For this reason, the associated vegetation could be the key in the re-establishment of this historically fire-prone community (Outcalt et al. 1999).

Outcalt (2000) mentioned some forb/herbaceous species found in the mix including yellow-eyed grass (*Xyris spp*.), beakrush (*Rhynchospora spp*.), wild sun flowers (*Helianthus spp*.), beggarweeds (*Desmodium spp*.), dogfennels (*Eupatorium spp*.), gayfeathers (*Liatris spp*.), goldenrods (*Solidago spp*.), and legumes like lespedeza (*Lespedeza spp*.). Some of these plants are very fire adapted and have higher seeding success following a burn than on sites that are not burned (Outcalt et al. 1999). They also found that when herbaceous competition was high from invasive species, such as bahia grass (*Paspalum notatum*), longleaf pine responded well to herbicide treatments, unless woody species like blueberries (*Vaccinium spp.*) were present.

Geology and Climate

The southeastern portion of the United States, located on the edge of the North American continent, is located in the middle of the North American plate which is considered tectonically inactive (Allmon et al. 2016). Within the southeastern United

States, three regions are present: the Blue Ridge and piedmont, the inland basin, and the coastal plains.

The east Texas portion of the longleaf pine ecosystem is located within the Cenozoic Gulf Coastal Plain region, as subcategory of the coastal plains, covering approximately 25% of Texas, stretching from Galveston to approximately Dallas. The coastal plains are described as gently sloping terrain, 0.4 m per km, between the coast and main inland and were created during the late Cretaceous period due to high sea levels caused by plate tectonics. Receding oceanic waters resulted in deposition of finer particles followed by weathering and erosion, particularly on south-facing slopes.

Longleaf pine site zones, developed by Craul et al. (2005), divide the area occupied by longleaf pine into six climatic regions and 21 zones. The area for this study is located within region five or the Louisiana-East Texas Coastal Plains climatic zone. Within this area, the state lines have been considered the boundary for the sub-climatic zone with substantial differences in the average rainfall. The Texas side of this region receives on average, 10.2 cm (4 in) less precipitation per year than the Louisiana side of the region. Within this region, sites are divided into three zones: the Nacogdoches Cuesta and Terrace, Kisatchie Terrace, and Pine Flats. These regions are located in region 5 and have multiple soil orders associated with the area including Ultisols, Alfisols, and in some areas Entisols. The Nacogdoches Terrace is characterized by the relatively higher concentration of iron in the soils, which explains the typical red and orange colors. The

Kisatchie terrace is on the Catahoula Formation which gives much of the relief features in the area. The Pine Flats are located on the seaward facing scarp.

Soils

Alfisols and Ultisols are the most common soil orders supporting the longleaf pine ecosystem. Alfisols are characterized as having a base saturation of greater than 35% in the argillic horizon that increases with depth and has little organic build up. Ultisols have a base saturation of less than 35% in the argillic horizon that decreases with depth.

Longleaf pine are found on a wide range of soil mapping units, textures, and drainage classes that range from excessively-drained deep sands to poorly drained soils, and even areas that are inundated for short periods of the year (Chapman 1932; Gilliam et al. 1993; Harcombe et al. 1993; Drewa et al. 2002; Brockway et al. 2006; Oswalt et al. 2012). However, sites occupied by longleaf pine are often described as having low fertility (Landers et al. 1995). Due to the ability to grow on a wide range of soil types, longleaf pine is capable, over time, of becoming relatively pure stands (Brockway et al. 2006).

Although longleaf pine is capable of sustaining itself on a wide range of soil types, the iconic soil type for longleaf pine stands is described as deep sandy soils. However, there can be large variations in these soils in terms of sand fraction particle size distribution, drainage class, and depth to argillic B horizons. Some studies suggest that longleaf prefer coarse sands with low percentages of clay and silt within the soil profile (Gilliam et al.

1993; Brockway et al. 2006), while others found that longleaf pine could also do well on better quality soils that are more fertile containing higher amounts of clay and silt (Provencher et al. 2003). However, plant species richness had a positive correlation with the amount of silt and clay content. Soil texture has been found to influence plant communities associated with the longleaf ecosystem (Gilliam et al. 1993). As a result, these better soils provide greater interspecific competition for longleaf pine seedlings and require greater management inputs to achieve successful longleaf pine establishment. Risk of failure of restoration of the ecosystem is, therefore, greater on these soils. Higher clay and silt content in soils allows for better water retention due to an increase in total pore space. Archmiller and Samuelson (2015) correlated various understory species with soil texture, likely due to water retention capabilities. Boyer and Miller (1994) found that frequent fires increased bulk density by decreasing the number of macropores, but did not affect total nitrogen and phosphorus in the soil or foliar content of other nutrients including potassium, calcium, magnesium, manganese, copper, iron, and zinc.

Particle Size Distribution and Determination

Soil horizons are differentiated by physical and chemical properties including color, texture, structure, and organic matter content (Buol et al. 2011). The distribution of soil particle sizes, or texture, is important for land use managers, including those involved with longleaf pine ecosystem restoration. The distribution of particle sizes can affect many things including available water capacity, infiltration and percolation rates, soil compaction potential, as well as erodibility (Kettler et al. 2001; Eccles and Ekwue 2008).

Soil texture, or mechanical composition, is the percentage of sand, silt, and clay content of a given soil. The separation of particle size classes can be very time consuming and very laborious if done by hand, which resulted in the development of mechanical sieve methods (Ali et al. 2013; Eccles and Ekwue 2008; Ekwue 1990). Several other methods can be used in determining soil texture, including two laboratory methods such as the hydrometer (Bouyoucous) method and the pipette method. These methods are termed fractionation; the process of physically separating particles into different size classes is based on Stokes Law which states the rate of the fall of spherical particles in suspension is a function of the radius.

For sand fraction separation, two types of sieve methods are often utilized: wet sieving and dry sieving. Wet sieving is associated with determining stable soil aggregate proportions that are resistant to water disruption associated with rain events, while dry sieving is associated with tests that include evaluation of wind erosion potential (Ekwue 1990; Eccles and Ekwue 2008; Chepil 1953). Soils with higher clay content are less erodible because they are more cohesive and better able to bind to surrounding particles (Chepil 1953).

Ro-Tap® is a shaker produced by W.S. Tyler Ro-Tap® Sieve shakers, one of the leading producers of mechanical sieves (Eccles and Ekwue 2008). This shaker works in two ways, a movement of the sample horizontally in a circular motion and a tapping rod that gives vertical force to the samples. Ali et al. (2013) found that the Ro-Tap® shaker produced the highest curves and better results with a higher degree of accuracy than the three-sieve shaker that they produced to allow for multiple samples to be processed at one time. Three different times were run: five minute, ten minute, and 15 minute intervals, which determined that 15 minutes produced the best results. Some negatives of the mechanical dry sieving shaker system are cost and noise, while positives include increased accuracy and consistency (Ali et al. 2013; Ekwue 1990; Eccles and Ekwue 2008). Wet sieving is a method often used for extracting fine roots, water stable aggregates, and mycorrhiza spores in the soils (Pojasok and Kay 1990).

Available Water Capacity

Soils act as a reservoir that can hold water, a portion of which can be utilized by plants. However, the amount of available water that can be held varies within a soil profile and is dependent upon many properties including soil texture, organic matter content, micro-porosity, and bulk density and can vary within a soil profile.

Field capacity is the amount of soil moisture remaining after downward movement of gravitational water has ceased, while the wilting coefficient is the point at which plants wilt due to the lack of available water content within the soil. The difference between field capacity and wilting coefficient varies between species. Briggs and Shantz (1912) found that some plants are still capable of extracting water below the wilting coefficient.

Rooting depth is another major factor that affects plant available water due to the amount of water that may be available to plants within the rooting depth deeper in the soil.

Site Productivity

Site productivity in forests is dependent upon natural factors inherent to a site. These factors are based on soil characteristics which influence the growth of a specific species and can be measured by site index. Site index is the most common method for directly estimating site quality for forest trees and is one of the most widely accepted methods for determining site productivity (Gale et al. 1991). Site index is determined from the relationship between tree age and height of the dominant and co-dominant trees within a stand; two measurements that are relatively easy to obtain in the field. While site index is an effective means of determining potential site productivity, it is species specific and varies within the range of the species due to a wide array of environmental and genetic factors. Site index curves have been developed for a range of species, including all of the commercial southern yellow pine and some hardwoods, and have been developed in many cases for both plantations and for naturally regenerated stands; however, they are not always reliable (Boyer 1990).

A study performed by McKenney and Pedlar (2003) on jack pine (*Pinus banksiana*) site index found that soils that had less organic matter accumulation and had a deeper mineral soil were often more productive. They also found that location also had an effect on site productivity due to temperature. Sites that were found in colder environments often had lower site indices. Hunter and Gibson (1984) found that site index of Monterrey pine (*Pinus radiata*) can be greatly affected by rainfall which can vary across the extent of the area occupied. They also found that soils with relatively low resistance to root penetration had an increased height/growth response.

Many site index curves exist for longleaf pines, including those planted, naturally regenerated, and for isolated regions within the range. However, no curve has been developed for old growth, naturally-regenerated longleaf pine in east Texas. The USDA-NRCS in the region uses curves for longleaf pine developed by the USFS (USDA 1929). These curves were used in this study to be consistent with the USDA-NRCS database.

METHODS

Study Area

This study was conducted in the Western Gulf Region of the native longleaf pine range in eastern Texas in portions of the Angelina National Forest and Sabine National Forest (Figure 1).

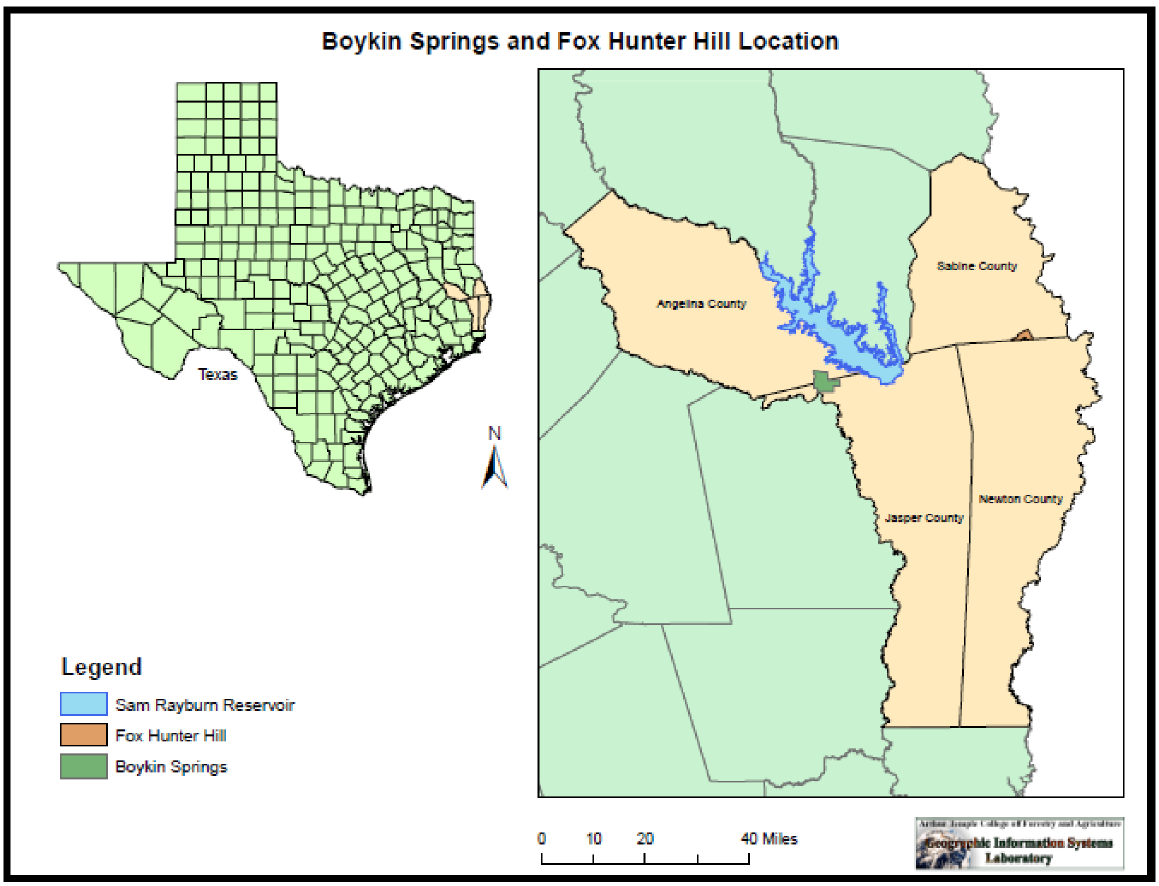

Figure 1. Study sites located near Boykin Springs Recreational Area of the Angelina National Forest and Fox Hunters Hill of the Sabine National Forest in Texas.

Boykin Springs Recreational Area, in the Angelina National Forest, is located within Angelina and Jasper counties. Fox Hunters Hill, a portion of the Sabine National Forest, is located in Sabine County. Sites selected near the Boykin Springs Recreational Area and Fox Hunters Hill were used because they historically contained longleaf pine ecosystems before and after the logging boom.

These sites are located on the Catahoula geologic formation, stretching from east Texas to the Mississippi River, that consisted of sandstone, often cemented with silica and quartz in localized areas, ranging from a few meters to approximately 18 m thick (Matson 1916). This formation has been documented as resisting erosion by creating what is known as the "Kisatchie wold", a north-facing cuesta of rocky hills. The Catahoula formation shows no evidence of previous marine life, but does contain freshwater shells and aquatic plants and is tuffaceous, containing volcanic ash.

Sampling locations were located on three different soil series mapping units, exhibiting different soil characteristics on well-drained or excessively-drained soils and ranged in depth and texture to the argillic B horizon. The three soil series were the Letney Series (loamy, siliceous, semi-active, thermic Arenic Paleudults), Tehran Series (loamy, siliceous, semiactive, thermic Grossarenic Paleudults), and the Stringtown Series (fine-loamy, siliceous, semiactive, thermic Typic Hapludults).

Climate

The climate for east Texas is described as humid and subtropical. The winters are mild with mean low temperatures in January of about 2.8 to 3.9^{O}C, with summer temperatures reaching 33.3 to 34.4^{O}C for annual high in August. Annual rainfall ranges from 124 to 151 cm with a relatively long growing season (U.S. climate data 2017) (Table 1).

Table 1. Mean annual precipitation, January mean low, and August mean high for three counties located in East Texas.

County	Mean Annual Precipitation (cm)	January Average Low (^{0}C)	August Average High (^{0}C)
Angelina	124	3.3	34.4
Jasper	151	3.9	33.3
Sabine	140	2.8	34.4

Field Sampling

Ten, 50 m radius circular plots were established in each soil series (Figure 2), in natural longleaf pine ecosystems in east Texas, for a total of 30 plots. These plots were located on relatively pure soil map units determined by careful evaluation of soil profiles at five points, one point in the center and four in each cardinal direction 50 m from the center point, at each location prior to site selection. This data was confirmed by on-site investigations to verify boundaries and soil identification. Verification and identification of the soil series was accomplished using bucket auger borings. Any of the points that failed to be consistent with the range of characteristics for the given soil map unit for the site were rejected. Within each plot, longleaf pine trees and soil parameters were evaluated.

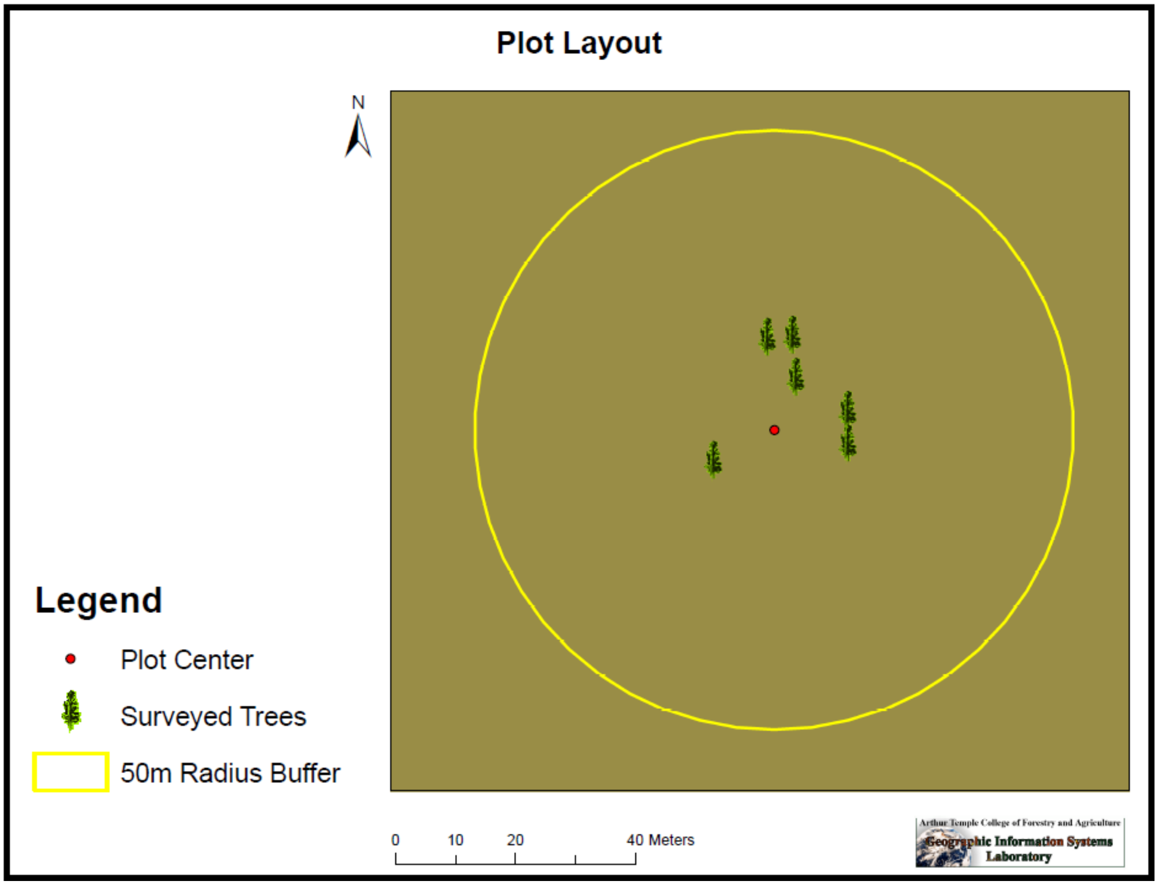

Figure 2. 50 m radius circular plot displaying homogenous soil map unit and an example of six site index trees that fall within the relatively pure soil map units.

Soil Sampling

Detailed soil samples and soil analyses from plot center were taken to correlate with the collected longleaf pine data. Relatively pure soil map units were first identified by using updated spatial soil mapping data provided by the NRCS of the National Forests.

Soil samples were taken from the first three horizons (A, E, and the first argillic B) while horizon depths were measured to a depth of 150 cm.

Basal Area and Site Index Estimations

To determine longleaf pine over-story composition and densities, a 10 Basal Area Factor (BAF) prism was used to determine basal area. Site index trees were chosen by selecting the six closest trees to plot center that were either dominant or codominant and free of wounds from the trees selected with the prism. If six suitable longleaf pine trees were not available in the prism plot, the nearest suitable trees still within the plot were measured. Annual growth rings from the six trees were quantified in a single tree core extracted at DBH (Diameter at Breast Height) to determine age. A laser range finder was used to estimate total height to the nearest tenth of a foot. Total age and height were used in the site index curves developed for longleaf pine (USDA 1929).

Laboratory Methods

Soil Texture

Soil textural analyses of soil samples (sand, silt, and clay) were conducted using the hydrometer texture method (Klute 1986). Soil samples were divided into the A, E, and B horizons. For coarse textured soils, 100 g of oven-dried soil was used, while 50 g was used for medium and fine textured soils. Each sample was placed in a mixing cup with 100 ml of sodium hexametaphosphate and filled half way with deionized water and left for 12 hours, then mixed for 15 minutes. Readings of the hydrometer were measured at 40 seconds and at two hours after agitation had ceased to obtain total suspended solids. A blank containing 100 ml of sodium hexametaphosphate solution with no soil added was used to calibrate the hydrometer.

Following completion of the hydrometer method, the sample was poured into a series of sieves dividing the sample into the five sand particle sizes and clay plus silt according to USDA (1993): very coarse sand, coarse sand, medium sand, fine sand, and very fine sand with the range in sizes being 1-2 mm, 0.5-1 mm, 0.25-0.5 mm, 0.10-0.25 mm, 0.05-0.10 mm, and < 0.05 mm, respectively. The sieves were rinsed with tap water to ensure the soil had moved through the series of sieves. The sieved samples were then removed from the sieves and placed in a forced-draft drying oven of 105^{O}C until a constant weight was reached and then weighed.

Soil samples were dry-sieved using a Ro-Tap® Shaker utilizing the same size classification as the wet-sieving method. Soil samples were dried to a constant weight in a 105^{O}C forced-draft drying oven. The samples were then weighed prior to sieving and each sand fraction was weighed upon completion of the sieving.

Bulk Density

Bulk density was measured using standard procedures provided by the Soil Science Society of America using a core sampler with 48.25 mm diameter rings (Klute 1986).

Samples were oven-dried at 105^{O}C until constant weight was achieved. The weights of the dried samples were divided by the volume of the cylinder to determine bulk density.

Field Capacity and Wilting Coefficient

Field capacity and wilting coefficient were measured using a soil pressure plate apparatus and chambers. Field moist samples were soaked in water for 24 hours prior to being put under pressure using the pressure plates at both -31 kPa and -1,500 kPa. Subsamples were weighed moist and then oven-dried at 105^{o}C to constant weight and then reweighed.

Soil Chemical Properties

Standard lab methods were performed to obtain pH, buffer pH, electrical conductivity (E.C.), available phosphorus, potassium, calcium, magnesium, and sulfur, total nitrogen and organic carbon, and ammonium in the Stephen F. Austin State University Plant, Soil, and Water Laboratory. To obtain pH, a measurement of the number of hydrogen atoms in solution, a two to one ratio of soil to water, respectively, using 12.5 g of soil and 25 ml of deionized water method was used. The samples were stirred a total of three times, once every ten minutes. Immediately following the stirring, a pH probe was then inserted into the sample. Electrical conductivity was taken following the completion of the pH using the same prepared sample using an E.C. meter.

To obtain the available macronutrients excluding the nitrogen, a Mehlich III extraction was used to mimic the nutrient availability for plants. This method simulates the chemical reactions occurring in the plant root extraction. The results were reported as mg kg^{-1} of each extractable nutrient.

Total nitrogen and organic carbon were measured using combustion analysis. Organic matter was estimated at two times the organic carbon level. The total nitrogen of the sample from the combustion was expressed in mg kg^{-1}.

Statistical Procedure

Analysis of Variance

Analysis of variance (ANOVA) using the Proc GLM procedure, was used to determine significant differences ($p=0.05$) of all physical, chemical, and morphological parameters, and site index among the different soil mapping units. Once unit differences were found among variables, Tukey's mean separation test was used to do further pair-wise comparisons.

Ordinations-Principal Component Analysis

A large set of variables that are inherently correlated. Because of this, principal component analysis (PCA) was used summarize all of the variables into unrelated variables (PC_1, PC_2…). Important or significant PCs were selected to do regression. This was done using both SAS and PC-ORD. The number of principal components evaluated was determined by using randomization, done in PC-ORD, which determined the significance of variation explained (p=0.05) rather than selecting only the first two or three variables. The principal component that were determined to be significant by randomization were then used in step-wise regression to determine which variables significantly affect site index for longleaf pine.

Regression

Two types of site index equations were developed. One using individual soil variables and the other using significant PCs. Site index regression equations were developed by utilizing multiple linear regression. The key soil variables were selected based on the method of maximizing R^2 in longleaf pine site index. The probability of the significant differences was tested with an alpha level of 0.05. The top 10 composite variables from each principal component analysis that was determined to be significant to site index were selected and also used in step wise regression to determine individual variables that best fit the site index regression equation to determine which specific variables influence site index the most.

RESULTS/DISCUSSION

Soil Profile Morphological Parameters

In the soil profiles evaluated in this study, depth to the first argillic horizon ranged from 23 to 49 cm, with a mean of 42.5 cm in the Stringtown series; from 55 to 88 cm with a mean of 67.1 cm in the Letney series; and from 101 to 155 cm with a mean of 111 cm in the Tehran series. The official soil series descriptions for Stringtown, Letney, and Tehran are described as being deep well drained to excessively drained, with some variations in the ranges of texture, color, and depth of each horizon (USDA-NRCS). The greatest difference distinguishing the three soil series is depth to the first argillic (Bt1) horizon: Stringtown < 50cm, Letney 50 to 100 cm, and Tehran Bt1 of > 100 cm.

Longleaf Pine Site Indices

One-way analysis of variance indicated significant differences ($p<0.001$) among the three soil series for longleaf pine site index (Table 2), with the site index for longleaf pine on Letney and Stringtown soil series not significantly different from each other, but were both significantly different from Tehran. These mean site indices for Letney and Stringtown soils were within the NRCS range of site indices, but was below for Tehran soils (Table 3). Many site factors affect site index, but the factors that may affect it the most are soil physical, chemical and biological properties. This study focused on soil physical and chemical, as well as soil morphology.

Table 2. Means, standard deviations, and coefficient of variations for site index (base age 50) for natural longleaf pine stands (n=30) on three soil series (p=0.0079) located in the Angelina and Sabine National Forests in Texas. Same letters in a column indicate no significant difference (α=0.05).

Soil Series	n	Site Index (m)	Standard Deviation	Coefficient of Variation
Stringtown	10	22.2 a	2.35	10.579
Letney	10	22.6 a	1.28	5.564
Tehran	10	20.0 b	1.60	7.980

Table 3. Mean, low, and high site index values (base age 50) collected by the USDA-NRCS on Stringtown, Letney and Tehran soils.

Soil Series	n	Average Site Index (m)	Low Site Index (m)	High Site Index (m)
Stringtown	6	24.5	20.7	26.5
Letney	12	24.8	21.3	32.0
Tehran	5	26.2	24.1	30.8

Soil Physical Parameters

Soil Physical Parameters

Within the unweighted soil physical parameters, 12 of the 63 variables were determined to be significantly different (α=0.05) among the three soils using one-way analysis of variance (Table 4): depth to E, depth to B, thickness of A, thickness of E, thickness of B, wilting coefficient of A , wilting coefficient of B, medium sand in A, medium sand in B, silt and clay in B, total sand in B, and total clay in B.

Since depth of A and depth to E are essentially the same variable, both found that Tehran was significantly deeper than Stringtown, although Letney was not statistically different form either of the other two soils (Table 4). Depth to B was significantly different among all three soils, with Tehran being the deepest and Stringtown being the shallowest, which was expected. Thickness of E was also found to be significantly different among each soil series with Tehran being greater than Stringtown and Letney. Thickness of B was also significantly different among soil series, with Stringtown approximately 73 cm thicker than Tehran in the 150 cm soil profile depth and 31 cm thicker than Letney.

Wilting coefficient of the A horizon showed significant differences between Stringtown and Letney soils, with 50% more water held at the wilting coefficient in Stringtown series (Table 4). However, Tehran soils were not significantly different than either of those soil series. The wilting coefficient of the B horizon was significantly greater in Stringtown over that of the Tehran soils, but Letney soils were not significantly different from either of the other two soils.

Medium sand in the A horizon had the highest percent by weight in Tehran soils over Stringtown soils, while Letney did not significantly differ from either soil (Table 4). Medium sand in the B horizon for Tehran was significantly greater than Letney and Stringtown soils which were not significantly different than each other, but medium sand in the A horizon was determined to be significantly greater in Tehran than Stringtown soils, but Letney was not significantly different from Stringtown or Tehran soils. Medium sand in the B and wilting coefficient of the B horizon were inversely correlated; as medium sand increased, wilting coefficient decreased.

As the depth to the first argillic B horizon increased, total silt + clay and total clay in the B horizon decreased (Table 4). Tehran soils contained less clay than Stringtown soils, while Letney soils were not statistically different than either of the other soils. Total sand in the B horizon was inversely correlated with clay content in Stringtown soils, containing less sand than Tehran soils.

The A horizon, as expected, contained more organic matter than either of the other two horizons (Table 4). The E horizon is characterized as the zone of eluviation, where leaching of humus, silt and clay, and various ions occurs, while the B horizon is the zone of illuviation where accumulation of humus, silt and clay, and various ions occur. The B horizon did in fact contain considerably higher percentages of silt and clay than did the A and E horizons. Within all soils, as depth to the first argillic B horizon increased, the percentage of silt and clay decreased in the B horizon. Conversely, sand, as expected, increased as depth to the first argillic horizon increased. The wilting coefficient is affected by the amount of silt and clay within the profile, as silt and clay decreased, so did the water held at the wilting coefficient. Field capacity and available water capacity should be affected by this texture correlation; however, it was not found to be true in this study. In fact, available water capacity was highest in the deeper sand soils, which indicated that the pressure plate method used in the study may have not produced reasonable results.

Table 4. Soil physical parameters not weighted by horizon thickness with means by soil series and ANOVA (α=0.05) p values. Values with the same letter in a row were not significantly different as determined by Tukey's mean separation test.

Horizon	Variable	Stringtown		Letney		Tehran		P-Value	Unit
A	Thickness of	14.80	a	19.23	ab	25.35	b	0.008	cm
	Db	1.398		1.380		1.352		0.682	g cm^{-3}
	FC	0.179		0.182		0.177		0.998	g cm^{-3}
	Wilt. Coeff.	0.094	a	0.064	b	0.070	ab	0.026	g cm^{-3}
	AWC	0.085		0.118		0.108		0.884	g cm^{-3}
	VCS	3.02		1.52		0.95		0.434	%
	CS	9.25		3.18		6.02		0.184	%
	MS	28.74	a	31.77	ab	40.59	b	0.049	%
	FS	28.00		28.63		24.35		0.560	%
	VFS	8.49		7.14		6.75		0.688	%
	Silt+Clay	22.51		27.77		21.34		0.191	%
	SAND	86.46		83.95		85.36		0.357	%
	SILT	7.65		9.93		9.51		0.370	%
	CLAY	5.89		6.12		5.13		0.126	%
	OM	2.37		2.83		2.98		0.324	%
E	Depth to	14.80	a	20.53	ab	25.15	b	0.010	cm
	Thickness of	24.20	a	49.17	b	86.45	c	<0.001	cm
	Db	1.511		1.548		1.579		0.412	g cm^{-3}
	FC	0.130		0.125		0.224		0.177	g cm^{-3}
	Wilt. Coeff.	0.052		0.036		0.054		0.754	g cm^{-3}
	AWC	0.078		0.089		0.170		0.193	g cm^{-3}
	VCS	1.86		1.43		0.94		0.604	%
	CS	9.36		5.98		6.24		0.455	%
	MS	28.50		32.12		35.89		0.274	%
	FS	29.69		24.43		26.03		0.476	%
	VFS	6.07		8.76		5.25		0.148	%
	Silt+Clay	24.53		27.28		25.66		0.777	%
	SAND	85.20		81.35		84.62		0.128	%
	SILT	7.66		11.75		9.50		0.065	%
	CLAY	7.14		6.91		5.88		0.064	%
	OM	1.61		1.40		1.39		0.199	%

B	Depth to	38.90	a	70.40	b	111.80	c	<0.001	cm
	Thickness of	111.10	a	79.60	b	38.80	c	<0.001	cm
	Db	1.635		1.706		1.731		0.109	g cm^{-3}
	FC	0.324		0.280		0.248		0.605	g cm^{-3}
	Wilt. Coeff.	0.237	a	0.148	ab	0.075	b	0.004	g cm^{-3}
	AWC	0.087		0.132		0.172		0.453	g cm^{-3}
	VCS	1.57		1.66		1.16		0.847	%
	CS	7.08		14.29		8.29		0.344	%
	MS	20.99	a	23.21	a	36.14	b	0.003	%
	FS	17.11		20.93		20.71		0.699	%
	VFS	7.15		4.45		4.11		0.134	%
	Silt+Clay	46.11	a	35.46	ab	29.60	b	0.014	%
	SAND	64.92	a	72.58	ab	78.27	b	0.004	%
	SILT	8.13		8.97		8.20		0.926	%
	CLAY	26.95	a	18.45	ab	13.53	a	0.013	%
	OM	1.76		1.61		1.87		0.878	%

*FC = Field Capacity
*Wilt. Coeff = wilting coefficient
*AWC = Available Water Capacity
*OM = Organic Matter

Soil Physical Properties Weighted by Horizon Thickness

Six physical variables weighted by horizon thickness were determined to be significantly different (α=0.05) by soil series: E horizon field capacity, B horizon field capacity, B horizon wilting coefficient, A horizon organic matter content, E horizon organic matter content, and B horizon organic matter content (Table 5). Field capacity weighted by horizon thickness in the E horizon was determined to be higher in Tehran soils than in Stringtown and Letney soils, while Stringtown and Letney soils were not statistically different. Stringtown soils were significantly different from Letney and Tehran soils for field capacity and wilting coefficients weighted by thickness of the B horizon; Letney and Tehran were not statistically different. Stringtown soils held more moisture at field capacity in the B horizon than Letney and Tehran. Stringtown soils held more moisture at wilting coefficient in the B horizon than Tehran and Letney soils; Letney and Tehran soils were not statistically different. A horizon organic matter content was highest in Tehran, significantly greater than Stringtown, while Letney soils were not statistically different than either of the other two soils. Organic matter content in the E horizon was also determined to be highest in Tehran soils; however, Letney and Stringtown were not statistically different. Organic matter content in the B horizon had the opposite trend were Stringtown soils were significantly greater than Tehran soils, while Letney soils were not statistically different than either of the other two soils.

The E horizon total potential field capacity was highest in the Tehran series, indicating that the pressure plate method used in the study did not produce reasonable results (Table 5). The B horizon total potential field capacity was significantly highest in the Stringtown soils, which is likely a result of the increase in silt and clay content in the B horizon and the thickness of the B horizon being greatest in those soils.

Table 5. Physical parameter means weighted by horizon thickness (g cm^{-3}) by soil series ANOVA (α=0.05) p values. Values with the same letter in a row are not significantly different as determined by Tukey's mean separation test.

Horizon	Variable	Stringtown		Letney		Tehran		P-Value
A	Field Capacity	2.451		3.42		4.282		0.399
	Wilting Coefficient	1.287		1.209		1.677		0.090
	AWC	1.164		2.212		2.605		0.531
	Organic Matter	0.04	a	0.05	ab	0.07	b	0.005
E	Field Capacity	3.317	a	6.253	a	18.943	b	0.006
	Wilting Coefficient	1.191		1.796		4.686		0.242
	AWC	2.126		4.457		14.257		0.019
	Organic Matter	0.06	a	0.11	a	0.19	b	<0.001
B	Field Capacity	36.048	a	22.242	b	10.592	b	0.000
	Wilting Coefficient	26.702	a	12.137	b	2.994	b	<0.001
	Organic Matter	0.32	a	0.23	ab	0.13	b	0.012
	AWC	9.346		10.105		7.597		0.803

*FC = Field Capacity
*Wilt. Coeff = wilting coefficient
*AWC = Available Water Capacity

Physical Properties within the Total 150 cm Soil Profile

Among the four physical variables that were evaluated by total soil profile, only one was determined to be significantly different among the soil series (Table 6). Soil textures within the profiles were not used because average texture throughout the profile would be the same percentage, therefore being the same variable and not adding value to the dataset. Wilting coefficient of the whole profile was greater in the Stringtown soils compared to the Letney soils, although was not found to be significantly different from the Tehran soils.

The wilting coefficient within the profile was significantly influenced by the proportion of B horizon, which had higher wilting coefficients in all soils, as confirmed by the results of Saxton et al. (1986) (Table 6). Texture and B horizon thickness played a big role in this due to the inherent ability of fine textured soils to hold more water than coarse soils at the wilting coefficient. However, neither field capacity or available water capacity were statistically different between soils. This is likely due to the pressure plate system retaining more water than it should have at the wilting coefficient, skewing the overall results.

Table 6. Total physical parameters within the 150 cm profiles with means (g cm^{-3}) by soil series and (α=0.05). Values with the same letter in a row are not statistically different.

Variable	Stringtown		Letney		Tehran		P-Value
Field capacity	41.816		31.915		33.817		0.362
Wilting Coefficient	29.181	a	15.142	b	9.357	b	0.002
AWC	12.635		16.773		24.459		0.202
Organic Matter	0.41	a	0.39	b	0.40	b	0.882

*FC = Field Capacity
*Wilt. Coeff = wilting coefficient
*AWC = Available Water Capacity
*OM = Organic Matter

Soil Chemical Parameters

Soil Chemical Parameters not Weighted by Horizon Thickness

Of the 36 soil chemical parameters not weighted by horizon thickness, exchangeable Ca in the A horizon was found to be significantly different among the soil series (Table 7). All other chemical variables were not found to be significantly different among soil horizons.

Concentration of Ca in the Letney soils was significantly higher than both of the other two soils as was the silt and clay in the A horizon (Table 4 and 7). The higher percentage of clay may have reduced Ca leaching to the lower profile. The presence of finer texture soils increases cation exchange capacity (CEC) in the soil, which helps retain cations. It is unclear why Stingtown had lower concentrations of Ca than Letney and Tehran, or why concentrations of other nutrients were not significantly different.

Table 7. Soil chemical parameters not weighted by horizon thickness (nutrients mg Kg^{-1}, E.C. µs cm^{-1}) with means by soil series and ANOVA (α=0.05) p values. Values with the same letter in a row were not significantly different as determined by Tukey's mean separation test.

Horizon	Variable	Stringtown		Letney		Tehran		P-Value
A	Total N	1286		1294.01		1388.05		0.43
	NH_4	2.6794		4.1741		2.9917		0.4816
	P	1.730004		4.789826		3.575485		0.0571
	K	18.18185		28.04284		22.68664		0.1474
	Ca	154.4599	a	314.4244	b	173.6974	a	0.016
	Mg	24.68351		36.86306		25.72009		0.1324
	S	4.874196		5.284574		3.441477		0.311
	B	0.010172		0.004629		0.009303		0.5743
	C	11874.89		14172.90		14881.61		0.3243
	pH	5.04		5.62		5.1		0.1564
	EC	103.41		34.205		50.436		0.1539
E	Total N	1164.72		1075.89		1106.24		0.4568
	NH_4	2.57		1.90		2.63		0.07
	P	1.23		1.33		1.08		0.7566
	K	23.21		18.24		12.92		0.3404
	Ca	251.48		203.67		104.96		0.0673
	Mg	53.48		31.42		17.49		0.1318
	S	11.18		3.14		2.39		0.2591
	B	0.05		0.01		0.01		0.1769
	C	8048.51		6988.59		6953.95		0.1991
	pH	5.62		5.63		5.49		0.6455
	EC	43.301		19.91		20.31		0.134
B	Total N	1200.12		1204.51		1261.42		0.7194
	NH_4	2.61		2.41		3.17		0.44
	P	1.14		2.08		2.70		0.5189
	K	26.66		34.05		21.44		0.2482
	Ca	379.02		465.93		210.25		0.0543
	Mg	119.89		105.19		37.29		0.0576
	S	15.00		10.47		6.80		0.2911
	B	0.06		0.05		0.03		0.3486
	C	8778.05		8067.37		9356.01		0.8783
	pH	5.29		5.49		5.4		0.5291
	EC	32.879		53.21		18.589		0.1268

Soil Chemical Properties Weighted by Horizon Thickness

Chemical variables weighted by horizon thickness had 17 variables determined to be significantly different (α=0.05) by soil series (Table 8): total organic C; total N; extractable P; exchangeable K; and exchangeable Ca in the A horizon; NH_4^+; total organic C; total N; extractable P; and exchangeable K in the E horizon; and NH_4^+; total organic C; total N; extractable K; extractable Ca; extractable Mg; and soluble S in the B horizon.

Ca weighted by thickness of the E horizon was not significantly different (Table 8); however, the total grams of Ca in the A and B horizons were found to be significantly different. The Letney soils had more total grams of Ca in the A horizon than Stringtown, but Tehran soils were not statistically different from either of the other two soils. Tehran soils contained almost 359% less Ca than either of the Letney and Stringtown soils in the B horizon; the latter two were not found to be significantly different from each other.

Organic C in the A horizon was greater in Tehran than in Stringtown soils; however, Letney was not statistically different than either of the other two soils. Organic C in the E horizon of the Tehran soils was greater than in Stringtown and Letney soils, the latter two were not statistically different. Organic C in the B horizon had the opposite effect, as Stringtown soils contained more organic C than Tehran. Letney was not statistically different than either of the other soils.

Stringtown contained more total N than Tehran soils. Letney was not statistically different from either of the other two soils. Total N in the E horizon was statistically different among all three soils. Tehran had more total N than Letney and Stringtown soils. Letney contained more total grams of N than Stringtown soils. Total N in the B horizon was also statistically different among all three soils. Stringtown had more total grams of N in the B horizon than Letney soils, which had more total grams of N in the B horizon than Tehran soils.

Tehran had more NH_4^+ in the E horizon than Stringtown and Letney Soils. The latter two soils were not statistically different from each other. Stringtown had more NH_4^+ in the B horizon than Tehran soils, but Letney soils were not statistically different from either of the other two soils in the B horizon.

Tehran had more P in the A horizon than Stringtown soils, but Letney soils were not statistically different from either of the other two soils. Tehran contained more P in the E horizon than Stringtown, but Letney soils were not significantly different from either of the other two soils. No statistical difference was found among the soils in the B horizon for P.

Tehran soils contained more K in the E horizon than Stringtown soils, but Letney soils were not significantly different from either of the other two soils. Stringtown and Letney soils, which were not statistically different, contained more K in the B horizon than Tehran soils.

Stringtown soils contained more Mg in the B horizon than Tehran, but Letney was not statistically different from either of the other two soils (Table 8). Stringtown soils contained more S in the B horizon than Tehran, but Letney soils were not statistically different from either of the other two soils.

Generally, Stringtown had higher concentrations of nutrients in the B horizon than in Tehran soils, although Tehran had higher concentrations in the A and E horizons. Finer texture soils have higher CEC, which can result in the presence or ability to hold more cations (Bortoluzzi et al. 2006). Within the A horizon, clay content was highest in the Letney soils which would provide a higher cation exchange capacity. This can be seen in K and Ca within the A horizon which contained higher quantities in Tehran and Letney soils. Stringtown averaged lower silt and clay in the A horizon resulting in lower quantities of those nutrients within the A. Total N was highest in the A horizon in the Tehran which also contained the most organic C. Total N is highly correlated to organic matter content.

Table 8. Chemical parameter means (mg Kg^{-1}) weighted by horizon thickness by soil series ANOVA (α=0.05) p values. Values with the same letter in a row are not significantly different as determined by Tukey's mean separation test.

Horizon	Variable	Stringtown		Letney		Tehran		P-Value
A	Total N	19.36	a	24.60	ab	34.64	b	0.0034
	NH_4^+	0.04		0.08		0.07		0.2641
	P	0.03	a	0.10	b	0.09	ab	0.0308
	K	0.26	a	0.53	ab	0.60	b	0.0345
	Ca	2.41	a	6.39	b	4.35	ab	0.0444
	Mg	0.37		0.73		0.64		0.0832
	S	0.07		0.10		0.09		0.4934
	B	0.13		0.03		0.02		0.0744
	C	181.17	a	269.76	ab	361.33	b	0.0054
E	Total N	42.84	a	82.11	b	152.10	c	<0.0001
	NH_4^+	0.10	a	0.15	a	0.36	b	<0.0001
	P	0.05	a	0.09	ab	0.14	b	0.0042
	K	0.87	a	1.30	ab	1.70	b	0.0461
	Ca	9.57		14.61		14.20		0.1942
	Mg	2.04		2.24		2.35		0.9204
	S	0.41		0.22		0.30		0.6566
	B	0.00		0.00		0.00		0.3634
	C	292.42	a	534.65	a	959.73	b	<0.0001
B	Total N	217.14	a	164.65	b	84.74	c	<0.0001
	NH_4^+	0.48	a	0.32	ab	0.22	b	0.0105
	P	0.20		0.32		0.21		0.7349
	K	4.75	a	4.86	a	1.51	b	0.0062
	Ca	67.87	a	65.92	a	14.35	b	0.0026
	Mg	21.21	a	15.04	ab	2.55	b	0.0056
	S	2.62	a	1.54	ab	0.50	b	0.0254
	B	0.01		0.01		0.00		0.0753
	C	1577.93	a	1125.85	ab	669.62	b	0.0118

Total Nutrients within the 150 cm Soil Profiles

Total soil profile nutrients were weighted by horizon depth and then summed for the whole 150 cm soil profiles. Using one-way analysis of variance (α=0.05) among the soil series, three variables were found to be significantly different: Ca, Mg, and S within the

150 cm profile (Table 9). Stringtown and Letney soils contained more total Ca in the 150 cm profile than Tehran soils. Stringtown soils contained more total Mg and S in the 150 cm soil profile than Tehran soils, but Letney soils were not statistically different from either of the other soils. Soils with argillic B horizons closer to the surface (Stringtown and Letney) tended to have higher total available nutrient contents than Tehran, which had greater depths to the argillic B horizon.

Total amounts of Ca, Mg, and S were found to be greatest in the Stringtown soils, significantly different from Tehran. Stringtown had the thickest B horizon relative to the 150 cm profile depth, and also had the highest amounts of silt and clay. The higher clay content and associated CEC for the B horizon which is most dominant in the 150 cm profile for Stringtown.

Although not significantly different in the soils, the mean content of boron was seven times higher in Stringtown soils than in Tehran and Letney soils. Boron has been shown to be a limiting nutrient for southern pine growth on some soils and has been reported as reducing height growth and malformations (Mead and Gadgil 1978).

Table 9. Total chemical parameters within the 150 cm soil profiles with means (g) by soil series and (α=0.05). Values with the same letter in a row are not statistically different.

Variable	Stringtown		Letney		Tehran		P-Value
Total N	279.34		271.36		271.49		0.8196
NH4+	0.61		0.55		0.65		0.6438
P	0.27		0.51		0.43		0.4219
K	5.88		6.69		3.80		0.0683
Ca	79.85	a	86.93	a	32.90	b	0.004
Mg	23.62	a	18.01	ab	5.53	b	0.0048
S	3.11	a	1.86	ab	0.88	b	0.0174
B	0.14		0.03		0.02		0.0612
C	2051.52		1930.25		1990.67		0.8816

Ordinations using Principal Component Analysis

Soil Physical and Morphological Variable Ordination

Using Principal Component Analysis with randomization in PC-ORD, five uncorrelated variables that accounted for approximately 62% of the variation (Table 10) were selected from the new 63 soil physical and morphological variables. Principal component one (21% of the variance) is strongly driven by depth to the B horizon, thickness of the E horizon, thickness of the B horizon, percent silt and clay in the B horizon, total wilting coefficient of the B horizon, total wilting coefficient of the profile, and total organic matter in the E horizon. Principal component two (15% of the variance) is driven by percent medium sand, total sand and silt in the A horizon as well as percent medium sand, total sand, and silt in the E horizon. Principal component three (10% of the variance) is driven by field capacity and available water capacity of the A horizon, field capacity and available water capacity of the B horizon, total potential field capacity and available water capacity of the A horizon, total potential available water capacity of the B horizon, and total potential available water capacity for the profile. Principal component four (7% of the variance) is driven by field capacity, wilting coefficient, and available water capacity of the E horizon and total field capacity of the entire profile. Principal component five (7% of the variance) is driven by percentage of very coarse sand, coarse sand and medium sand in the A horizon, percentage of very coarse sand and medium sand in the E horizon, and percentage of very coarse sand, coarse sand, total sand, and total clay in the B horizon.

Table 10. Randomization results displaying the P-values from each of the first 10 principal components from 999 randomizations produced from PC-ORD to determine significant components based on relationship to the maximum theoretical eigenvalue versus the true eigenvalue for all physical variables with associated % variance.

Axis	Eigenvalue	Maximum Eigenvalue	% of Variance	Cumulative Variance	P-value
1	13.09	7.467	20.779	20.779	0.001
2	9.683	5.829	15.371	36.15	0.001
3	6.585	5.187	10.452	46.602	0.001
4	4.892	4.895	7.765	54.367	0.002
5	4.519	4.54	7.173	61.54	0.002
6	3.243	4.075	5.147	66.687	1
7	2.999	3.751	4.76	71.447	1
8	2.525	5.532	4.008	75.455	1
9	2.212	3.294	3.511	78.966	1
10	2.082	3.05	3.305	82.271	1

Regression of Soil Physical Variables Ordination Values

Of the five principal components created through ordination, only principal component one (p=0.0186) and five (p=0.0010) were found to be significantly but negatively related to site index, but were negatively correlated to site index. The physical variables that drive these two principal components are depth to B horizon, thickness of E and B horizons, percent silt and clay in the B horizon, total wilting point of the B horizon and the entire profile, and organic matter of the E horizon for component one and percentage of very coarse sand, coarse sand, medium sand in the A horizon, percentage of very coarse sand and medium sand in the E horizon, and percentage of very coarse sand, coarse sand, total sand, and total clay in the B horizon. Morphological and physical properties of soils are a few of the variables used to help predict forest productivity. The following had an R^2 value of 0.4249:

Site index = 21.61416 – (Principal Component 1 * 0.758884) - (Principal Component 5 * -1.12095).

Principal component one was primarily a factor of B horizon texture and depths to each horizon while principal component five was driven primarily by the soil textures of each horizon. Many studies have looked at the relationship between the depth of horizons and site index. McWhorter (2005) did not find a correlation between site index and depth to the first argillic horizon B for longleaf pine in east Texas. Farrish et al. (1990) found a negative correlation between site index and depth to finer textured layers in sandy soils for white oak (*Quercus alba*) in Michigan, but the influence began to wane at depths greater than 1.5 m. Hunter and Gibson found (1984) found that site index of radiata pine (*Pinus radiata*) increased with increasing depth of the topsoil. Corona et al. (1998) evaluated total soil depths in Douglas-fir and did not find any significance with soil ranges from 50 cm to 100 cm. Coile (1935) concluded that no one physical variable had a well-defined correlation with site index for shortleaf pine; however, depth to the Bt1 horizon and texture of that horizon was found to be a good indicator of shortleaf pine on the soils studied, is similar to what our study discovered.

Dexter et al. (2004) found that higher soil organic matter resulted in increased site quality for most soils. Saxton and Rawls (2006) also found that soil texture was not the only parameter affecting water holding capacity: other factors included OM and soil bulk density along with gravel content and salinity, which also affected water availability.

<u>Soil Chemical Variable Ordination</u>

Using principal components analysis with randomization, four significant variables were chosen that account for approximately 63% of the variation among the 69 new soil chemical related variables (Table 11). The factors driving principal component one (24% of variance) were: concentrations of K, Ca, Mg, and boron in the B horizon, as well as total Mg and boron weighted by depth of the B horizon, and total K, Ca, Mg, and S weighted by depth of the 150 cm soil profiles. Principal component two (17% of the variance) was driven by concentration of K, Ca, Mg, S, and boron in the E horizon, total K, Ca, Mg, S, and B weighted by depth in the E horizon. Principal component three (14% of the variance) was driven by total C, P, K, Ca, and Mg weighted by depth in the A horizon, as well as total grams of P weighted by depth of E horizon and total NH_4^+ and total N weighted by depth of the B horizon. Principal component four (8% of the variance) was driven by total C and P within the profile, and total N, P, and C in the B horizon. In essence, each component was driven by chemical variables within a specific horizon.

Table 11. Randomization results displaying the P-values from each of the first 10 principal components from 999 randomizations produced from PC-ORD to determine significant components based on relationship to the maximum theoretical eigenvalue versus the true eigenvalue of all chemical variables with associated variation.

Axis	Eigenvalue	Maximum Eigenvalue	% of Variance	Cumulative Variance	P value
1	16.216	7.439	23.501	23.501	0.001
2	11.56	5.986	16.753	40.254	0.001
3	9.757	5.488	14.14	54.394	0.001
4	5.822	5.112	8.438	62.832	0.001
5	4.248	4.73	6.156	68.988	0.292
6	3.269	4.378	4.738	73.726	1
7	2.649	4.074	3.838	77.564	1
8	2.45	3.739	3.551	81.115	1
9	1.89	3.5	2.739	83.854	1
10	1.732	3.401	2.51	86.364	1

Site Index Regression of Ordinations for Soil Chemical Variables

Principal component one, as determined by multiple regression, was the only axis that was considered significant to site index with a positive correlation. Driving component one included total K, Ca, Mg and B of the B horizon as well as total K, Ca, Mg, and S in the 150 cm profile. In essence, nutrients in the B horizon and total profile were driving factors in longleaf pine site index. The following regression equation had an R^2 value of 0.1459:

Site Index = 21.61416 + (Principal Component 1 * 0.79316**)**.

Principal component one was primarily a factor of nutrients within the B horizon and total profile. Growth is often limited in many forests in the southern United States by nutrient availability, promoting fertilization in silvicultural practices for managed forest. Nitrogen and phosphorous are often considered the most common nutrients that limit growth in southern pine forests (Fox et al. 2007). Similarly, Hunter and Gibson (1984) found nutrients had a positive correlation with site index in radiata pine, but they did not specify a given depth at which the nutrients were most effective. Our study found that nutrient levels in the B horizon, which Hunter and Gibson (1984) did not specify, had a strong correlation with site index increase in longleaf pine as did total amounts of nutrients in the profile, which were usually correlated to soils with higher silt and clay concentrations and shallower B horizons. Boron has been shown to positively correlate with growth in pine (Mead and Gadgil 1978). Our study also showed boron being positively correlated to longleaf pine site index, but did not differ between soils. This study did not confirm that any of the available or total nutrients in the soil were significant in predicting site index for longleaf pine ecosystems located on these soils. However, in contrast to Mead and Gadgil, Klinka and Carter (1990) found for Douglas-fir, soil nutrients were found to be a good predictor of site index over a large area. Hunter and Gibson 1984 also found that a pH of 6 was optimal for radiata pine, however, this study did not find a significant difference between pH and site index as the range in pH in the soils of this study were small.

Combined Soil Chemical and Physical Variables Ordination

Using principal component analysis with randomization, seven uncorrelated variables that accounted for 67% of the variation of the 132 new variables developed by ordinations (Table 12). Principal component one (19% of the variance) was driven by depth to B, thickness of E and B, wilting coefficient of the B horizon, percentage of silt and clay in the B, total potential wilting point of the B, total wilting point in the profile, organic matter in the E horizon, Mg in the B, total N, K, Ca, Mg, S, and B in the B horizon, and total K, Ca, Mg, and S in the profile. Principal component two (12% of the variance) was driven by field capacity and available water capacity in the A horizon, field capacity and total field capacity of the B horizon, total field capacity in the profile, P, K, Ca, and Mg in the A horizon, NH_4^+ in the E horizon, NH_4^+ in the B horizon, total P, K, Ca, Mg and S in the A horizon, and total NH_4^+ in the profile. Principal component three (10% of the variance) was driven by Ca, Mg, and B in the E horizon, Mg, S, and B in the B horizon, total grams of P in the A horizon, and total Mg in the E, and total B in the B horizon. Principal component four (9% of the variance) was driven by percent coarse sand, very fine sand, silt and clay, and total sand in the A horizon, percent coarse sand, fine sand, very fine sand, total sand, and total silt in the E horizon, total organic matter in the profile, P in the B horizon, and total C, P, and B in the profile. Principal component five (6% of the variance) was driven by concentration of K, Ca, Mg, S, and B of the E horizon and concentration of C in the B horizon. Principal component six (6% of the variance) was driven by bulk density and organic matter in the E and B horizons, concentration of B in the A horizon, concentration of C in the E horizon, concentration of P and C in the B horizon, and total grams of NH_4^+, P, and B within the profile. Principal component seven (5% of the variance) was driven by clay, wilting point, and total potential wilting point of the E horizon, concentration of Ca in the A horizon, and total Ca in the A horizon.

Table 12. Randomization results displaying the p-values from each of the first 10 principal components from 999 randomizations produced from PC-ORD to determine significant components based on relationship to the maximum theoretical eigenvalue versus the true eigenvalue for all physical and chemical variables with associated variance.

Axis	Eigenvalue	Maximum Eigenvalue	% of Variance	Cumulative Variance	P value
1	25.104	10.939	19.018	19.018	0.001
2	15.501	9.352	11.743	30.762	0.001
3	13.821	8.668	10.47	41.232	0.001
4	11.791	8.197	8.933	50.165	0.001
5	8.031	7.667	6.084	56.249	0.001
6	7.595	7.286	5.754	62.003	0.001
7	6.989	6.832	5.295	67.298	0.001
8	5.684	6.471	4.306	71.604	0.983
9	5.09	6.2	3.856	75.46	1
10	4.086	5.933	3.096	78.556	1

Regression of the Combined Soil Physical and Chemical Ordination Values

Of the seven principal components created through ordinations, only principal component one (P=0.0186) and five (P=0.0010) were found to be significant to site index in longleaf pine. Principal component one is primarily a factor of the depth to each horizon as well as certain nutrients within the B horizon, while principal component five is a factor of nutrients within the E horizon. The following regression equation generated had an R^2 value of 0.4249:

Site Index = 21.61416 - (Principal Component 1 * 0.95211) – (Principal Component 5 * 1.12095).

Principal component one was driven by concentration of nutrients in the B horizon and principal component five was driven by total nutrients within the 150 cm profile, which correlates directly to thicker B horizons, had a positive correlation to site index. Hunter and Gibson (1984) found that higher nutrient levels correlated positively with site index, but did not specify if this relationship was by horizon or total in the profile. They suggest that soils low in macronutrients showed an increase in growth with the application of fertilizer with the limiting nutrients. Our study showed low total nutrients within all three soils; however, as depth to the first argillic B horizon increased, nutrients available decreased. Stringtown appeared to have greater amounts of nutrients within the B than the Tehran in most situations with Letney soils intermediate in nutrient availability.

Corona et al. (1998) found that clay content was among the environmental factors that accounted for 58% of the variation explained for site index while Hunter and Gibson (1984) found that nutrients and soil penetrability positively correlated to site index.

Regression of Measured Parameters

Regression for Soil Chemical Variables

Using the results from the principal component analysis, 10 variables from the original 69 variables were chosen to use for regression that correlated most with site index of longleaf pine in east Texas on Stringtown, Letney, and Tehran soils: total K, Ca, Mg, and S in the profile, total Mg and B in the B horizon, and concentration of K, Ca, Mg S, and B in the B horizon. Of these 10 variables, only a one variable model best fit the site index with an R^2 of 0.2026:

Site Index = 66.93652 + (Total Ca in the Profile * 0.05947).

Woollons and Will (1975) found that Ca, N, P, K, and Mg did not affect site index when added to radiata pine on the Pumice Plateau. This conflicts with our data, as Ca was the only nutrient that was found to be significant.

Regression for Soil Physical Variables

Of the 63 physical variables evaluated, seven variables were chosen as the most significant physical factors affecting longleaf pine on the Stringtown, Letney, and Tehran soils: Depth to B, thickness of the E and B horizons, percent silt and clay in the B horizon, wilting coefficient of for the B horizon, wilting coefficient of the profile, and percent organic matter in the E horizon. The best two variable model included depth to the B horizon and total wilting coefficient of the B, horizon with an R^2 of 0.3984:

Site index = 88.71063 – (Depth to the B horizon * 0.19074) – (Total B horizon wilting potential * 0.26955).

As depth to the B horizon increased, clay content greatly decreased. As clay content decreases, so does water holding capacity along with available water capacity and wilting coefficient. Texture is inherently related to the amount of water a soil can hold. All three of the soil series in this study had A, E, and B horizons. The A horizon is characterized by the amount of organic matter mixed into the matrix of the inorganic soil. Within the E horizon, leaching of the nutrients occurs along with leaching of smaller size particles. The B horizon is the zone of illuviation, or where the smaller size particles, along with nutrients, tend to accumulate. This can be seen within this study, however texture did not prove to be as important as expected.

Regression of Combined Soil Chemical and Physical Variables

Of the 132 variables evaluated in this study, principal components analysis reduced that number to variables to the top 17 variables that are most correlated to site index: Depth to the B horizon, wilting coefficient of the B horizon, percent silt and clay and depth weight wilting coefficient of the B horizon, the profile weight wilting point of the whole profile, organic matter of the E horizon, concentration of Mg in the B horizon, total N, K, Ca, Mg, S, and boron in the B horizon, and total K, Ca, Mg, and S in the B horizon. After using step-wise regression, the top variables that affect longleaf pine site index in the Stringtown, Letney and Tehran soils were total N and S in the B horizon, concentration of Mg in the B horizon, total Mg and S in the profile, and wilting coefficient weighted by horizon thickness in the B horizon. These six-variables proved to be the best six variable model and had an R^2 of 0.6668. Therefore, the regression equation for site index using all variables was:

Site Index = 64.98 + (Total N in the B * 0.05119) + (Total Mg in the Profile * 1.66002) + (Total S in the B horizon * 5.87648) – (concentration of Mg in the B horizon * 0.22445) – (Total S in the profile * 5.25599) – (Total wilting potential in the B horizon * 0.53062).

Total N, Mg, and Sulfur in the B horizon had a positive effect on longleaf pine site index, while concentrations of Mg and S had a negative impact with site index. Indirectly, depth to the B horizon had a correlation to these values as the thickness of the B impacts total available nutrients in that horizon. In addition, it was found that as the B horizon depth increased, the percent clay within the horizon decreased. The presence of sand in the A and E horizon resulted in a lower cation exchange capacity, allowing for nutrients to leach through these horizons while the B horizon had an increase in clay content allowing for a higher cation exchange capacity allowing for more nutrients.

CONCLUSIONS

The soil depth of 150 cm was arbitrarily determined to be the depth at which sampling should ceases, not necessarily consistent with rooting depth of longleaf pine. Soil physical parameters in the A and E horizons did not appear to greatly influence site index for longleaf pine on Stringtown, Letney and Tehran soils in east Texas. However, soil physical parameters involving the first argillic B horizon, including depth to B and wilting coefficient of the B influenced site index of longleaf pine on these three soils, which suggest that water availability may play the largest role in affecting site index on these deep, coarse textured soils.

Soil chemical parameters in the A and E horizons did not appear to significantly influence site index for longleaf pine on the study soils; however, soil chemical parameters in the first argillic B horizon, as well as nutrient availability in the whole profile, appeared to influence site index on these soils. This may suggest that these deep coarse textured soils may also be nutrient deficient.

Soil physical and chemical variables were combined in order to build a model that reflects the most variables and, once again, it did not appear that soil chemical and physical parameters in the A and E horizons significantly affected site index in longleaf pine; however, it did appear that soil chemical and physical parameters in the B horizon did influences site index on these soils in east Texas.

Six regression models were created explaining the influence of chemical and physical variables in multiple ways. Ordination grouped like variables into categories to explain site index for longleaf pine and revealed that soil variables in the B horizon affect site index for longleaf pine the most, while some variables within the whole 150 cm profile also had an effect on site index for longleaf pine. This is likely due to the effect of the weighted by horizon thickness of the B horizon had on the total profile because of clay content of the horizon providing for higher available water content, and nutrient storage. Some A horizon parameters showed some slight effect on longleaf pine site index, but this could possibly due to the amount of organic matter within the A horizon. While each model may highlight different variables, this could be caused by the true complexity of the interaction of soil variables with site index. Productive forests tend to have soils with favorable physical properties that enhance biological functions. Separating and choosing the most significant of these soil variables can be challenging due to the inherent complexity and interactions among many of them.

Future studies should look at rooting depth within each of these three soils as well as the effect of soils with drainage classes that are known to hold have more water. Studies should also consider planting on these three soil series using the same treatments to reduce competition to determine survivability on these soils to determine how these soil variables affect longleaf pine regeneration.

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Appendix

Table A. 1. GPS plot center locations for the 30 study sites.

ID	Latitude	Longitude	y_proj	x_proj	altitude
Bh1	31.04786	-94.3636	31.04786	-94.3636	115.4833
Bh2	31.04945	-94.3629	31.04945	-94.3629	
Bs1	31.05747	-94.2643	31.05747	-94.2643	60.68848
Bs10	31.06039	-94.2845	31.06039	-94.2845	95.53601
Bs11	31.07132	-94.2658	31.07132	-94.2658	99.14087
Bs3	31.07881	-94.277	31.07881	-94.277	115.4833
Bs4	31.07615	-94.2799	31.07615	-94.2799	102.7459
Bs5	31.07769	-94.2703	31.07769	-94.2703	113.08
Bs6	31.07579	-94.2702	31.07579	-94.2702	114.2816
Bs7	31.07152	-94.2714	31.07152	-94.2714	107.7927
Bs8	31.06781	-94.2716	31.06781	-94.2716	100.5829
Bs9	31.0643	-94.2628	31.0643	-94.2628	110.4364
Fh3	31.18228	-93.7261	31.18228	-93.7261	132.0658
Fh4	31.17034	-93.7085	31.17034	-93.7085	132.5465
Str4	31.05933	-94.3452	31.05933	-94.3452	89.04712
Str5	31.06009	-94.3466	31.06009	-94.3466	
Str6	31.05558	-94.3439	31.05558	-94.3439	84.96155
Str7	31.09024	-94.1895	31.09024	-94.1895	85.6825
Str8	31.07415	-94.249	31.07415	-94.249	87.36487
Trn1	31.07229	-94.2421	31.07229	-94.2421	115.2429
Trn11	31.07006	-94.2734	31.07006	-94.2734	89.76807
Trn12	31.06844	-94.2726	31.06844	-94.2726	84.72131
Trn2	31.08321	-94.2379	31.08321	-94.2379	114.5219
Trn3	31.08437	-94.2388	31.08437	-94.2388	116.9252
Trn4	31.08447	-94.241	31.08447	-94.241	121.2511
Trn6	31.05559	-94.2705	31.05559	-94.2705	41.70252
Trn7	31.08289	-94.2057	31.08289	-94.2057	107.0717
Trn8	31.08396	-94.2067	31.08396	-94.2067	99.38123
Trn9	31.0882	-94.1987	31.0882	-94.1987	90.72937
L1	31.07673	-94.2399	31.07673	-94.2399	118.8478

Table A. 2. Tree GPS points for the 30 study sites used for this study.

ID	Latitude	Longitude	y_projection	x_projection	altitude
Bh1T1	31.04777	-94.3635	31.04777	-94.3635	76.55017
Bh1T2	31.04776	-94.3635	31.04776	-94.3635	76.06946
Bh1T3	31.04776	-94.3635	31.04776	-94.3635	75.8291
Bh1T4	31.04773	-94.3635	31.04773	-94.3635	70.78223
Bh1T5	31.04773	-94.3635	31.04773	-94.3635	70.54187
Bh1T6	31.04776	-94.3636	31.04776	-94.3636	70.54187
Bh2T1	31.04932	-94.363	31.04932	-94.363	88.32617
Bh2T2	31.04932	-94.363	31.04932	-94.363	88.08582
Bh2T3	31.04933	-94.363	31.04933	-94.363	88.08582
Bh2T4	31.04941	-94.3629	31.04941	-94.3629	91.69067
Bh2T5	31.04938	-94.3629	31.04938	-94.3629	94.09412
Bh2T6	31.04938	-94.3629	31.04938	-94.3629	93.6134
Bs1T1	31.05743	-94.2642	31.05743	-94.2642	75.8291
Bs1T2	31.05728	-94.2642	31.05728	-94.2642	81.83728
Bs1T3	31.05743	-94.2643	31.05743	-94.2643	64.0531
Bs1T4	31.0575	-94.2643	31.0575	-94.2643	80.63574
Bs1T5	31.05753	-94.2644	31.05753	-94.2644	80.39539
Bs1T6	31.0576	-94.2644	31.0576	-94.2644	84.48096
Bs3T1	31.07873	-94.2769	31.07873	-94.2769	134.9497
Bs3T2	31.07884	-94.2767	31.07884	-94.2767	141.9193
Bs3T3	31.0788	-94.2768	31.0788	-94.2768	152.9742
Bs3T4	31.07873	-94.2769	31.07873	-94.2769	132.7869
BS3T5	31.07876	-94.2769	31.07876	-94.2769	137.353
Bs3T6	31.07882	-94.277	31.07882	-94.277	130.1432
Bs4T1	31.07618	-94.2799	31.07618	-94.2799	109.7155
Bs4T2	31.07617	-94.2799	31.07617	-94.2799	108.5138
Bs4T3	31.07612	-94.2798	31.07612	-94.2798	102.5055
Bs4T4	31.07605	-94.2798	31.07605	-94.2798	99.86194
BS4T5	31.07597	-94.2799	31.07597	-94.2799	95.53601
Bs4T6	31.07604	-94.2799	31.07604	-94.2799	100.8232
Bs5T1	31.07764	-94.2704	31.07764	-94.2704	108.5138
Bs5T2	31.07783	-94.2703	31.07783	-94.2703	108.2734
Bs5T3	31.07783	-94.2702	31.07783	-94.2702	108.2734
Bs5T4	31.07777	-94.2702	31.07777	-94.2702	105.3894
Bs5T5	31.07772	-94.2701	31.07772	-94.2701	105.8701
Bs5T6	31.07767	-94.2701	31.07767	-94.2701	105.8701
Bs6T1	31.07577	-94.2703	31.07577	-94.2703	100.8232
Bs6T2	31.07586	-94.2702	31.07586	-94.2702	104.9087
BS6T3	31.07589	-94.2701	31.07589	-94.2701	106.8313

BS6T4	31.07582	-94.2701	31.07582	-94.2701	105.3894
BS6T5	31.07571	-94.2702	31.07571	-94.2702	103.4668
BS6T6	31.07583	-94.2704	31.07583	-94.2704	100.3425
Bs7T1	31.07146	-94.2714	31.07146	-94.2714	98.41992
Bs7T2	31.07141	-94.2713	31.07141	-94.2713	98.66028
Bs7T3	31.07152	-94.2715	31.07152	-94.2715	99.62158
Bs7T4	31.07156	-94.2715	31.07156	-94.2715	103.2264
Bs7T5	31.07156	-94.2714	31.07156	-94.2714	102.9861
Bs7T6	31.07157	-94.2714	31.07157	-94.2714	102.5055
Bs8t1	31.06775	-94.2717	31.06775	-94.2717	92.17151
Bs8t2	31.06772	-94.2717	31.06772	-94.2717	91.45032
Bs8t3	31.06772	-94.2718	31.06772	-94.2718	91.45032
Bs8t4	31.06773	-94.2718	31.06773	-94.2718	91.21008
Bs8t5	31.06776	-94.2718	31.06776	-94.2718	91.69067
Bs8T6	31.06779	-94.2718	31.06779	-94.2718	91.45032
BS9T1	31.06426	-94.2628	31.06426	-94.2628	103.7072
BS9T2	31.06429	-94.2628	31.06429	-94.2628	102.0249
BS9T3	31.06432	-94.2628	31.06432	-94.2628	100.3425
BS9T4	31.06432	-94.2628	31.06432	-94.2628	100.8232
BS9T5	31.06432	-94.2627	31.06432	-94.2627	100.3425
BS9T6	31.06426	-94.2627	31.06426	-94.2627	98.17969
Bs10T1	31.06041	-94.2846	31.06041	-94.2846	97.45862
Bs10T2	31.06042	-94.2846	31.06042	-94.2846	95.77637
Bs10T3	31.06037	-94.2846	31.06037	-94.2846	97.93933
Bs10T4	31.06036	-94.2845	31.06036	-94.2845	101.0635
Bs10T5	31.06028	-94.2847	31.06028	-94.2847	95.29565
Bs10T6	31.0604	-94.2847	31.0604	-94.2847	103.4668
Bs11T1	31.07136	-94.2658	31.07136	-94.2658	94.33447
Bs11T2	31.07137	-94.2658	31.07137	-94.2658	93.85376
Bs11T3	31.07141	-94.2658	31.07141	-94.2658	90.72937
Bs11T4	31.07139	-94.2658	31.07139	-94.2658	90.00842
Bs11T5	31.07133	-94.2657	31.07133	-94.2657	89.76807
Bs11T6	31.0713	-94.2658	31.0713	-94.2658	92.17151
F3T1	31.18225	-93.7261	31.18225	-93.7261	106.8313
F3T2	31.18226	-93.7263	31.18226	-93.7263	108.5138
F3T3	31.18228	-93.7263	31.18228	-93.7263	107.5524
F3T4	31.18234	-93.7262	31.18234	-93.7262	105.3894
F3T5	31.18231	-93.7261	31.18231	-93.7261	105.149
F3T6	31.1823	-93.726	31.1823	-93.726	104.6685
F4T1	31.17037	-93.7085	31.17037	-93.7085	138.7949
F4T2	31.17038	-93.7085	31.17038	-93.7085	138.7949
F4T3	31.17037	-93.7085	31.17037	-93.7085	138.7949
F4T4	31.17037	-93.7085	31.17037	-93.7085	138.7949

F4T5	31.17037	-93.7085	31.17037	-93.7085	138.074
F4T6	31.17039	-93.7085	31.17039	-93.7085	132.7869
F5T1	31.18282	-93.7278	31.18282	-93.7278	114.0413
F5T2	31.18283	-93.7278	31.18283	-93.7278	116.6848
F5T3	31.18276	-93.7278	31.18276	-93.7278	114.5219
F5T4	31.18275	-93.7278	31.18275	-93.7278	114.5219
F5T5	31.1828	-93.7278	31.1828	-93.7278	118.1268
F5T6	31.18285	-93.7278	31.18285	-93.7278	118.1268
L1T1	31.07673	-94.2399	31.07673	-94.2399	118.8478
L1T2	31.07671	-94.2399	31.07671	-94.2399	121.7317
L1T3	31.07671	-94.2399	31.07671	-94.2399	120.2897
L1T4	31.07682	-94.2399	31.07682	-94.2399	121.4913
L1T5	31.07687	-94.2398	31.07687	-94.2398	126.0576
L1T6	31.07691	-94.2398	31.07691	-94.2398	122.9334
S4T1	31.05952	-94.3453	31.05952	-94.3453	90.48914
S4T2	31.05956	-94.3453	31.05956	-94.3453	90.48914
S4T3	31.05942	-94.3452	31.05942	-94.3452	90.72937
S4T4	31.05941	-94.3452	31.05941	-94.3452	89.76807
S4T5	31.05942	-94.3452	31.05942	-94.3452	90.96973
S4T6	31.05941	-94.3453	31.05941	-94.3453	87.6051
S5T1	31.06001	-94.3464	31.06001	-94.3464	97.45862
S5T2	31.06	-94.3464	31.06	-94.3464	94.57471
S5T3	31.05999	-94.3464	31.05999	-94.3464	92.17151
S5T4	31.06001	-94.3464	31.06001	-94.3464	90.24878
S5T5	31.06002	-94.3464	31.06002	-94.3464	90.24878
S5T6	31.06	-94.3465	31.06	-94.3465	91.21008
S6T1	31.05573	-94.3439	31.05573	-94.3439	85.44226
S6T2	31.05573	-94.3439	31.05573	-94.3439	85.44226
S6T3	31.05571	-94.344	31.05571	-94.344	85.44226
S6T4	31.05569	-94.344	31.05569	-94.344	86.40356
S6T5	31.05571	-94.344	31.05571	-94.344	86.40356
S6T6	31.05571	-94.344	31.05571	-94.344	87.12451
STR7T1	31.09016	-94.1896	31.09016	-94.1896	93.85376
STR7T2	31.09013	-94.1897	31.09013	-94.1897	92.17151
STR7T3	31.09017	-94.1897	31.09017	-94.1897	92.6521
STR7T4	31.09021	-94.1897	31.09021	-94.1897	96.97803
STR7T5	31.09035	-94.1897	31.09035	-94.1897	103.2264
STR7T6	31.09029	-94.1895	31.09029	-94.1895	96.49731
STR8T1	31.07408	-94.2489	31.07408	-94.2489	94.33447
STR8T2	31.07409	-94.2489	31.07409	-94.2489	94.33447
STR8T3	31.07424	-94.2489	31.07424	-94.2489	86.88416
STR8T4	31.07425	-94.2489	31.07425	-94.2489	85.6825
STR8T5	31.0742	-94.249	31.0742	-94.249	86.64392

STR8T6	31.07408	-94.249	31.07408	-94.249	89.04712
Tr1T1	31.07225	-94.2419	31.07225	-94.2419	93.85376
Tr1T2	31.07224	-94.2419	31.07224	-94.2419	89.04712
Tr1T3	31.07222	-94.2419	31.07222	-94.2419	92.6521
Tr1T4	31.07222	-94.2418	31.07222	-94.2418	99.62158
Tr1T5	31.07223	-94.2419	31.07223	-94.2419	97.93933
Tr1T6	31.07225	-94.2419	31.07225	-94.2419	94.33447
TR2T1	31.08323	-94.2379	31.08323	-94.2379	108.0331
TR2T2	31.08327	-94.2379	31.08327	-94.2379	107.5524
TR2T3	31.08327	-94.2379	31.08327	-94.2379	107.0717
TR2T4	31.08327	-94.2378	31.08327	-94.2378	106.8313
TR2T5	31.0832	-94.2379	31.0832	-94.2379	109.9557
TR2T6	31.08321	-94.2379	31.08321	-94.2379	108.2734
TR3T1	31.08435	-94.2388	31.08435	-94.2388	112.359
TR3T2	31.08437	-94.2387	31.08437	-94.2387	110.917
TR3T3	31.08427	-94.2388	31.08427	-94.2388	105.8701
TR3T4	31.08436	-94.2387	31.08436	-94.2387	104.6685
TR3T5	31.08441	-94.2387	31.08441	-94.2387	111.6381
TR3T6	31.08443	-94.2387	31.08443	-94.2387	107.0717
Tr4T1	31.08434	-94.2411	31.08434	-94.2411	110.6766
Tr4T2	31.08427	-94.2411	31.08427	-94.2411	109.7155
Tr4T3	31.08436	-94.2412	31.08436	-94.2412	107.312
Tr4T4	31.08441	-94.2411	31.08441	-94.2411	107.312
Tr4T5	31.08442	-94.2411	31.08442	-94.2411	107.312
Tr4T6	31.08439	-94.2411	31.08439	-94.2411	106.5911
TR6T1	31.05563	-94.2705	31.05563	-94.2705	72.70483
TR6T2	31.05564	-94.2706	31.05564	-94.2706	72.94519
TR6T3	31.0556	-94.2706	31.0556	-94.2706	73.18555
TR6T4	31.05561	-94.2706	31.05561	-94.2706	72.94519
TR6T5	31.05564	-94.2706	31.05564	-94.2706	70.30151
TR6T6	31.05571	-94.2706	31.05571	-94.2706	71.02258
Tr7T1	31.08281	-94.2056	31.08281	-94.2056	108.5138
Tr7T2	31.08279	-94.2057	31.08279	-94.2057	111.6381
Tr7T3	31.083	-94.2059	31.083	-94.2059	113.8009
Tr7T4	31.08298	-94.2055	31.08298	-94.2055	109.2347
Tr7T5	31.08288	-94.2055	31.08288	-94.2055	110.917
Tr7T6	31.08289	-94.2055	31.08289	-94.2055	109.2347
Tr8T1	31.08373	-94.2065	31.08373	-94.2065	103.7072
Tr8T2	31.08369	-94.2065	31.08369	-94.2065	102.7459
Tr8T3	31.08367	-94.2066	31.08367	-94.2066	97.21826
Tr8T4	31.08377	-94.2067	31.08377	-94.2067	97.93933
Tr8T5	31.08387	-94.2066	31.08387	-94.2066	97.69898
Tr8T6	31.08385	-94.2065	31.08385	-94.2065	99.62158

Tr9T1	31.0882	-94.1987	31.0882	-94.1987	101.5442
Tr9T2	31.0882	-94.1987	31.0882	-94.1987	101.5442
TR9T3	31.0882	-94.1987	31.0882	-94.1987	101.3038
Tr9T4	31.08812	-94.1988	31.08812	-94.1988	100.5829
Tr9T5	31.08813	-94.1988	31.08813	-94.1988	100.5829
Tr9T6	31.08804	-94.1987	31.08804	-94.1987	99.14087
TRN11T1	31.07009	-94.2735	31.07009	-94.2735	99.86194
TRN11T2	31.07008	-94.2735	31.07008	-94.2735	99.38123
TRN11T3	31.0701	-94.2735	31.0701	-94.2735	94.33447
TRN11T4	31.07012	-94.2735	31.07012	-94.2735	92.6521
TRN11T5	31.07015	-94.2735	31.07015	-94.2735	91.93103
TRN11T6	31.07017	-94.2735	31.07017	-94.2735	91.69067

LOCATION STRINGTOWN TX

Established Series
CLN:LCB; Rev.JDS
07/2000

STRINGTOWN SERIES

The Stringtown series consists of deep, well drained, moderately permeable soils that formed in weakly consolidated loamy sediments on the Western Coastal Plain. These soils are on sloping to steep uplands. Slopes range from 5 to 35 percent.

TAXONOMIC CLASS: Fine-loamy, siliceous, semiactive, thermic Typic Hapludults

TYPICAL PEDON: Stringtown fine sandy loam, on convex slope of 10 percent in forest. (Colors are for moist soil unless otherwise stated.)

A--0 to 5 inches; dark grayish brown (10YR 4/2) fine sandy loam; few stains of very dark grayish brown (10YR 3/2) organic accumulation; weak fine granular structure; soft, very friable, nonsticky and nonplastic; many fine, medium, and coarse roots; few ironstone gravel up to 1/2 inch in diameter; strongly acid; clear smooth boundary. (2 to 6 inches thick)

E--5 to 11 inches; light yellowish brown (10YR 6/4) fine sandy loam; few pockets of dark grayish brown (10YR 4/2) material; weak fine granular structure; soft, very friable, nonsticky and nonplastic; few fine medium and coarse roots; about 10 percent by volume of ironstone gravel up to 1/2 inch in diameter; strongly acid; clear smooth boundary. (4 to 6 inches thick)

Bt1--11 to 26 inches; strong brown (7.5YR 5/8) sandy clay loam; moderate medium subangular blocky structure; hard, friable, slightly sticky and slightly plastic; few medium and coarse roots; about 10 percent by volume of ironstone gravel; clay films on faces of peds; very strongly acid; gradual wavy boundary. (12 to 27 inches thick)

Bt2--26 to 34 inches; reddish yellow (7.5YR 6/8) sandy clay loam; moderate medium subangular blocky structure; hard, firm, slightly sticky and slightly plastic; few coarse tree roots; few ironstone gravel up to 1/2 inch in diameter; clay films on faces of peds;

common medium prominent red (2.5YR 5/8) masses of iron accumulation; very strongly acid; gradual wavy boundary. (6 to 10 inches thick)

Bt3--34 to 45 inches; reddish yellow (7.5YR 6/8) sandy clay loam; moderate medium subangular blocky structure; hard, firm, slightly sticky and slightly plastic; few fine prominent light gray (10YR 6/1) lithochromic mottles; about 4 percent by volume of plinthite; few clay films on faces of peds; common medium prominent red (2.5YR 4/8) masses of iron accumulation; very strongly acid; gradual wavy boundary. (8 to 12 inches thick)

BC--45 to 54 inches; variegated reddish yellow (7.5YR 6/8), red (2.5YR 4/8) and light gray (10YR 7/1) sandy clay loam; weak medium subangular blocky structure; very hard, firm, slightly sticky and slightly plastic; few fragments of purple and white shale; extremely acid; diffuse irregular boundary. (6 to 10 inches thick)

C--54 to 80 inches; thinly bedded light gray (10YR 7/1), reddish yellow (7.5YR 6/8) and red (2.5YR 4/8, 2.5YR 3/6, and 10R 4/8) sandy clay loam, shale and soft sandstone; stratified with shale beds 1/4 inch to 2 inches thick; sandstone parts are weakly cemented; extremely acid.

TYPE LOCATION: Newton County, Texas; from Newton 4.1 miles northeast on Texas Highway 87, 4.6 miles east on Farm Road 1414, 2.15 miles southeast on county road, 120 feet north in forest.

RANGE IN CHARACTERISTICS: Solum thickness ranges from 40 to 60 inches. Ironstone pebbles and angular fragments make up 1 to 20 percent by volume of the A and E horizons. A few ironstone cobbles up to 6 inches across occur in some pedons. Plinthite makes up 1 to 4 percent by volume of the lower Bt horizons. Base saturation ranges from 25 to 35 percent.

The A horizon has hue of 10YR, value of 3 through 5, and chroma of 2 to 4. Texture is fine sandy loam, loamy fine sand, gravelly fine sandy loam, or gravelly loamy fine sand. Reaction ranges from slightly acid through very strongly acid.

The E horizon has hue of 10YR, value of 5 or 6, and chroma of 3 or 4. Texture is fine sandy loam, loamy fine sand, gravelly fine sandy loam, or gravelly loamy fine sand. Reaction ranges from slightly acid through very strongly acid.

The Bt horizon has hue of 7.5YR or 10YR, value of 5 or 6, and chroma of 6 or 8. Iron accumulations in shades of red, yellow, and brown, and lithochromic mottles in shades of gray are in the Bt1 and Bt2 horizon. Gray lithochromic mottles are due to weathered shale fragments. Texture is sandy clay loam or clay loam with clay content of the upper 20 inches of the Bt horizon ranging from 18 to 35 percent. The Bt horizon generally contains 1 to 15 percent by volume of pebbles and flattened fragments of ironstone. Reaction is medium acid to very strongly acid.

The BC horizon is variegated in shades of yellow, red, and gray. It commonly contains fragments of shale and sandstone. Reaction ranges from strongly acid through extremely acid.

The C horizon is sandy clay loam with strata of soft shale and sandstone in colors of gray, red, and brown. The strata of sandstone can be cut with a spade. Reaction ranges from strongly acid through extremely acid.

COMPETING SERIES: These are the Apison, Biffle, Cahaba, Durham, Euharlee, Granville, Hartsells, Linker, Nauvoo, Oktaha, Olla, Pirum, Sipsey, Spadra, and Suffolk series in the same family, and the Emporia, Kempsville, Smithdale, and Wickham series in closely related families. Apison and Sipsey soils have soft shale or shale interbedded with thin layers of siltstone or fine-grained sandstone at a depth of 20 to 40 inches. Hartsells, Linker, Oktaha, and Pirum soils have hard acid sandstone bedrock at 20 to 40 inches deep. Biffle soils formed in residuum from cherty limestone and have a solum that is 20 to 40 inches thick. Cahaba soils have a redder argillic horizon and developed in very deep loamy and sandy alluvium on stream terraces. Durham soils formed in residuum weathered from acid crystalline rocks, chiefly granite and gneiss. Granville soils formed in residuum weathered from Triassic sandstone and shale and do not have plinthite segregations in the solum. Emporia, Kempsville, and Smithdale soils do not have weathered sandstone or shale within a depth of 6 feet and have a subactive activity class. Euharlee soils contain more silt and developed from cherty limestone. Nauvoo soils have a redder argillic horizon and do not have plinthite in the solum. Olla, Spadra, Suffolk, and Wickham soils do not have weathered shale or sandstone within a depth of 80 inches. In addition, Wickham soils have mixed mineralogy.

GEOGRAPHIC SETTING: Stringtown soils are on sloping to steep uplands. They usually occur on narrow ridgetops and side slopes. Slopes range from 5 to 35 percent. The soil formed in weakly consolidated loamy sediments of late Tertiary or early

Pleistocene age. The climate is humid; mean annual precipitation ranges from 46 to 58 inches and the mean annual temperature ranges from 66 to 70 degrees F. The Thornthwaite annual P-E index exceeds 72.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Bonwier, Boykin, Doucette, Letney, Newco, Pinetucky, Tehran, and Urland series. Bonwier soils are on similar positions and more than 35 percent clay in the control section. Urland soils are on adjacent smoother areas and more than 35 percent clay in the control section. Boykin and Doucette soils have a sandy epipedon more than 20 inches thick, and are on lsee sloping sideslope positions. Letney and Tehran soils have a sandy epipedon more than 20 inches thick, and are on slightly higher ridgetop and shoulder positions. Newco soils have redox depletions and aquic conditions in the upper 24 inches of the argillic horizon. Pinetucky soils are on gently sloping areas, are more deeply developed, and contain more than 5 percent plinthite.

DRAINAGE AND PERMEABILITY: Stringtown soils are well drained; medium rate of runoff on slopes from 5 to 20 percent, and high rate of runoff on slopes more than 20 percent. Permeability is moderate.

USE AND VEGETATION: Stringtown soils are used mainly for woodland and pastureland. The principal trees are loblolly and shortleaf pines, and sweetgum, red oak, hickory, and other hardwoods. Pastures are of common and improved bermudagrass and bahiagrass.

DISTRIBUTION AND EXTENT: Western coastal plain (MLRA 133B) in southeast Texas and Louisiana. The series is of moderate extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Temple, Texas

SERIES ESTABLISHED: Newton County, Texas; 1980.

REMARKS: The Stringtown series was assigned to a semiactive actiity class in 1999.
Diagnostic horizons and features recognized in the type location pedon include:
Ochric epipedon --- 0 to 11 inches (A and E horizons).
Argillic Horizon -- 11 to 45 inches (Bt horizons).
Plinthite segregations -- 34 to 45 inches (Bt3 horizon).

LOCATION LETNEY TX+LA

Established Series
Rev. KG:CLN:LCB
03/1999

LETNEY SERIES

The Letney series consists of deep, well drained, moderately rapidly permeable, upland soils. They formed in thick sandy and loamy sediments of the coastal plains. These soils are on gently sloping to moderately steep uplands with slopes ranging from 1 to 20 percent.

TAXONOMIC CLASS: Loamy, siliceous, semiactive, thermic Arenic Paleudults

TYPICAL PEDON: Letney loamy sand on smooth 10 percent slope in forest. (Colors are for moist soils unless otherwise stated.)

A--0 to 7 inches; dark grayish brown (10YR 4/2) loamy sand; common stains of brown (10YR 5/3); single grained; loose, nonsticky and nonplastic; few medium and coarse roots; very strongly acid; clear smooth boundary. (3 to 10 inches thick)

E--7 to 34 inches; pale brown (10YR 6/3) loamy sand; single grained; loose, nonsticky and nonplastic; few medium and coarse roots; 5 to 10 percent siliceous gravel; few krotovinas; very strongly acid; clear smooth boundary. (11 to 32 inches thick)

Bt1--34 to 62 inches; strong brown (7.5YR 5/6) sandy clay loam; common medium faint reddish yellow (7.5YR 6/8) and few medium distinct yellowish red (5YR 5/8) mottles; moderate medium subangular blocky structure; very hard, friable; slightly sticky and slightly plastic; few medium and coarse roots; 5 to 10 percent siliceous gravel; sand grains coated and bridged with clay; very strongly acid; diffuse smooth boundary. (20 to 45 inches thick)

Bt2--62 to 75 inches; reddish yellow (7.5YR 6/8) sandy clay loam; few medium prominent red (2.5YR 4/6) mottles; weak medium subangular blocky structure; hard, friable; slightly sticky and slightly plastic; many small white and purple shale fragments and masses of clay; very strongly acid.

TYPE LOCATION: Newton County, Texas; from the intersection of Farm Road 692 and Texas Highway 63 at Burkeville, Texas, 10.2 miles north along Farm Road 692; 1.8 miles northwest on forest road; 0.6 mile northeast on forest trail; 150 feet north in forest.

RANGE IN CHARACTERISTICS: Solum thickness ranges from 60 to more than 80 inches thick. Reaction ranges from very strongly acid through medium acid. Clay content of the upper 20 inches of the argillic horizon ranges from 18 to 32 percent with a silt content 5 to 10 percent. Base saturation ranges from 15 to 30 percent. Coarse and very coarse sand comprises 10 to 25 percent of the sand fraction. The combined A and E horizon range in thickness from 20 to 40 inches.

The A horizon has hue of 10YR, value of 3 to 5, and chroma of 2 or 3. When values are less than 3.5, the thickness of the horizon is less than 7 inches.

The E horizon has hue of 10YR, value of 5 to 7, and chroma of 3 or 4. Some pedons contain up to 10 percent siliceous gravel.

The upper part of the Bt horizon has hue of 7.5YR and 10YR, value of 5 and 6, and chroma of 4 through 6. Mottles are in shades of yellowish red, brown, and gray. Mottles with chroma 2 or less are 60 inches of more below the surface. The texture of the Bt commonly is sandy clay loam, but ranges to sandy loam in some places. In some pedons, the Bt horizon contains up to 5 percent plinthite by volume, and some pedons contain up to 10 percent by volume siliceous gravel.

The lower part of the Bt horizon and the BC horizon, when present, have hue of 7.5YR and 10YR, value of 5 and 6, and chroma of 6 or 8. Some pedons have many small white and purple shale fragments and masses of clay.

COMPETING SERIES: These are Autryville, Bonneau, Boykin, Briley, Lowndes, Lucy, Rosalie, Trip, and Wagram soils in the same family and the similar Doucette, Larue, Lilbert, Tehran, and Tenaha series. Autryville and Lowndes soils have bisequel profiles. Bonneau soils have gray mottles between 30 and 60 inches of the surface and have a water table nearer the surface during the spring. Boykin, Briley, and Lucy soils have hue of 5YR and redder in the upper Bt horizon and contain more fine sand. Rosalie and Trip soils have common or many gray mottles in the lower B horizon, and in addition Rosalie soils have sand and silt coated peds in the lower Bt horizon and Trip soils have clay increasing with depth. Wagram soils have clays with lower cation exchange activity in the argillic and contain less coarse and very coarse sand. Doucette and Lilbert soils contain more than 5 percent plinthite. Larue soils have base saturation greater than 35 percent. Tehran soils have sandy A and E horizons more than 40 inches thick. Tenaha soils have sola 20 to 40 inches thick over weathered sandstone.

GEOGRAPHIC SETTING: Letney soils are on broad ridgetops and upper parts of side slopes on uplands. Slope ranges from 1 to 20 percent. They formed in marine-deposited sandy and loamy sediments of the coastal plains. Mean annual rainfall ranges from 46 to 54 inches. Mean annual temperature ranges from 65 to 70 degrees F., and the Thornthwaite annual P-E indices exceed 64.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the competing Doucette and Tehran series and the Corrigan, Melhomes, Newco, and Rayburn series. Corrigan and Rayburn soils occur as ridges and steep side slopes above drainageways and have fine textured control sections. Doucette soils occur on the ridgetops. Melhomes soils occur in the drainageways and have an aquic moisture regime. Newco soils occur as heads of drainageways and sloping to moderately steep side slopes, and have clayey control sections. Tehran soils occur as broad ridgetops and the foot slopes of steep side slopes.

DRAINAGE AND PERMEABILITY: Letney soils are well drained. Runoff is slow and permeability is moderately rapid.

USE AND VEGETATION: Used mainly for timber or pasture. Loblolly, longleaf, and shortleaf pine are predominant. Understory is mostly longleaf uniola, broomsedge bluestem, beaked panicum, and a few bluejack oak.

DISTRIBUTION AND EXTENT: Eastern Texas and Louisiana. The series is of moderate extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Temple, Texas

SERIES ESTABLISHED: Newton County, Texas; 1980.

REMARKS: These soils were formerly included in the Wagram series.

ADDITIONAL DATA: Base saturation at type location was 28 percent at 72 inches. Data by Hach Field Kit.

LOCATION TEHRAN TX

Established Series
KG:CLN:LCB; Rev. JDS
07/2000

TEHRAN SERIES

The Tehran series consists of deep, somewhat excessively drained, moderately rapidly permeable soils on uplands. They formed in thick loamy and sandy sediments on the Western Coastal Plain. These soils are on gently sloping to moderately steep uplands with slopes ranging from 1 to 20 percent.

TAXONOMIC CLASS: Loamy, siliceous, semiactive, thermic Grossarenic Paleudults

TYPICAL PEDON: Tehran loamy sand on smooth 7 percent slope, in forest. (Colors are for moist soil unless otherwise stated.)

A--0 to 5 inches; dark grayish brown (10YR 4/2) loamy sand; weak fine granular structure; loose, nonsticky and nonplastic; many fine and common medium and coarse roots; strongly acid; clear smooth boundary. (3 to 6 inches thick)

E1--5 to 13 inches; brown (10YR 5/3) loamy sand; few pockets of dark grayish brown (10YR 4/2) organic accumulation; single grained; loose, nonsticky and nonplastic; few medium and coarse roots; strongly acid; clear smooth boundary. (4 to 8 inches thick)

E2--13 to 36 inches; light yellowish brown (10YR 6/4) loamy sand; single grained; loose, nonsticky and nonplastic; few coarse roots; strongly acid; diffuse smooth boundary. (5 to 39 inches thick)

E3--36 to 51 inches; light yellowish brown (10YR 6/4) loamy sand; single grained; loose, nonsticky and nonplastic; 8 percent quartzite gravel; many fine faint light brown (7.5YR 6/4) masses of iron accumulation; very strongly acid; clear smooth boundary. (8 to 21 inches thick)

Bt1--51 to 62 inches; reddish yellow (7.5YR 6/6) sandy clay loam; weak medium subangular blocky structure; hard, friable, slightly sticky and slightly plastic; thin patchy clay films on faces of peds; 8 percent quartzite gravel; common coarse distinct brownish yellow (10YR 6/6) and few medium faint strong brown (7.5YR 5/6) masses of iron accumulation; very strongly acid; diffuse smooth boundary. (10 to 23 inches thick)

Bt2--62 to 75 inches; variegated strong brown (7.5YR 5/6), red (2.5YR 5/8), yellowish red (5YR 5/6), and light gray (10YR 7/2) sandy clay loam; weak medium subangular blocky structure; hard, friable, slightly sticky and slightly plastic; thin patchy clay films on faces of peds; very strongly acid.

TYPE LOCATION: Newton County, Texas; from the intersection of Farm Road 692 and Texas Highway 63 at Burkeville, Texas; 10.2 miles north along Farm Road 692; 1.8 miles northwest on forest road; 0.7 mile northeast on forest trail; 100 feet south, in forest.

RANGE IN CHARACTERISTICS: Solum thickness is more than 60 inches. Clay content in the upper 20 inches of the argillic horizon ranges from 18 to 32 percent. Base saturation at 72 inches below the surface ranges from 15 to 30 percent. Coarse and very coarse sand make up 10 to 25 percent of the sand fraction. The thickness of the epipedon (A and E horizons) ranges from 40 to 72 inches thick. Reaction ranges from very strongly acid to medium acid throughout the profile.

The A horizon has hue of 10YR, value of 4 or 5, and chroma of 2 to 4. Texture is loamy sand or sand. Quartzite gravel ranges from 0 to 10 percent by volume.

The E horizon has hue of 10YR, value of 5 to 7, and chroma of 3 or 4. Iron accumulations are in shades of yellow and brown. Texture is loamy sand or sand. Quartzite gravel ranges from 0 to 10 percent by volume.

The Bt horizon has hue of 5YR to 10YR, value of 5 to 7, and chroma of 4 through 6; or hue of 2.5YR, value of 4 and chroma of 8. Iron accumulations in shades of yellow, red, and brown are common. Iron depletions with chroma of two or less are at 60 inches or more below the surface. Texture commonly is sandy clay loam, but ranges to sandy loam in some pedons. Quartzite gravel ranges from 0 to 10 percent and plinthite segregations range from 0 to 5 percent by volume.

COMPETING SERIES: These are the Blanton, Darco, Eddings, Murad, and Shankler series in the same family, and the Albany, Boykin, Gunter, Landman, Letney, Pickton, Troup, and Wadley series in closely related families. Albany and Murad soils contain gray iron depletions in the upper part of the argillic horizon. Blanton and Eddings soils have redox depletions within a depth of 72 inches. In addition, Eddings soils have saturated layers below 3.5 to 4.5 feet deep. Darco and Shankler soils contain less than 10 percent coarse or very coarse sands. Boykin and Letney soils have a sandy epipedon 20 to 40 inches thick. Gunter soils contain more than 5 percent plinthite. Landman and Pickton soils have more than 35 percent base saturation at a depth of 72 inches. Troup soils have a kandic horizon.

GEOGRAPHIC SETTING: Tehran soils are on broad ridgetops, side slopes, and foot slopes of steep uplands. Slope ranges from 1 to 20 percent. They formed in marine deposited sandy and loamy sediments on the Western Coastal Plains. Mean annual precipitation ranges from 46 to 54 inches. Mean annual temperature ranges from 65 to 70 degrees F., and the Thornthwaite annual P-E indices exceed 64.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the competing Letney series and the Betis, Corrigan, Lilbert, Osier, Rayburn, Sacul, and Tenaha series. Betis soils are on similar positions but have a Bt horizon consisting of lamellae. Corrigan and Rayburn soils are on ridges and steep side slopes on nearby areas, and have a clayey control section. Letney soils are in close association and occur on broad ridgetops and on the upper parts of side slopes. Lilbert and Tenaha soils are on ridgetops and have a sandy epipedon 20 to 40 inches thick. Osier soils have a depleted matrix and aquic conditions within a depth of 20 inches and are on drainageways. Sacul soils have a fine textured control section and are at the heads of drainageways or on sloping to moderately steep side slopes.

DRAINAGE AND PERMEABILITY: Tehran soils are somewhat excessively drained. Runoff is negligible on slopes less than 5 percent, and very low on slopes of 5 percent or more; permeability is moderately rapid.

USE AND VEGETATION: Used mainly for timber or pasture. Loblolly, longleaf, and shortleaf pine are predominant. Understory is mostly longleaf uniola, broomsedge blusetem, beaked panicum, and a few bluejack oak.

DISTRIBUTION AND EXTENT: Western Coastal Plain (MLRA 133B) in eastern Texas and Louisiana. The series is of moderate extent.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: Temple, Texas

SERIES ESTABLISHED: Newton County, Texas; 1980.

REMARKS: The Tehran series was assigned to a semiactive activity class in 1999.
Diagnostic horizons and features recognized in the type location pedon include:
Ochric epipedon --- 0 to 51 inches (A and E horizons)
Argillic horizon -- 51 to 75 inches (Bt horizons)

ADDITIONAL DATA: Base saturation at type location is 28 percent at a depth of 72 inches. Data are by Hach Field Kit. Engineering test data also are available for the E2 and Bt1 horizons from the type location pedon (S76TX-351-002). Texture data by Field Hydrometer at 2 other sites near the type location are as follows:
Sand Fractions
Clay Silt Sand VC&C Med Fine V. Fine
Pit #2
A 0-5" 3 7 90 23 39 22 6
E3 22-45" 2 6 92 20 42 24 6
Bt 48-63" 26 4 70 14 26 20 10

Pit #11
A 0-6" 5 9 86 15 38 25 8
E3 30-48" 5 9 86 18 39 23 6
Bt 51-57" 21 8 71 6 32 27 6

VITA

After graduating from Nacogdoches High School, Nacogdoches, Texas, in 2011, Ryan Svehla began his studies in Forest Wildlife Management at Stephen F. Austin State University where he graduated in December 2015. While obtaining his undergraduate degree, he worked at Cherries Tree Farm where he maintained the farm until graduation. While interning at Plum Creek, he found what he wanted to focus on. In January of 2017, he began his graduate research to obtain his Master of Science in Environmental Science, while working as a graduate assistant. Ryan received his degree of Master of Science in December of 2017.

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Style Manual Designation:
Soil Science Society of America

This thesis was typed by Ryan A. Svehla.