Long-term Effects of a Perennial Forage Grass in a Peanut-Cotton Rotation on Soil Properties

by

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Abstract

Peanut (*Arachis hypogeae*) and cotton (*Gossypium hirsutum*) are traditionally rotated together in southern Georgia and Alabama, and in northern Florida. Maintaining crop yields and long-term economic sustainability with this rotation is difficult. Inversion of peanuts for harvest and fallow soil in the winter causes fields to be prone to water and wind erosion. This is exacerbated by the fact that neither cotton nor peanut contribute greatly to soil organic carbon (SOC), which is known to improve soil structure and drainage and reduce erosion. Conservation practices such as reduced tillage aid in soil conservation, but may not be sufficient in these highly carbon-depleted soils. The addition of bahiagrass (*Paspalum notatum*) to the traditional peanut-cotton rotation is a potential cropping strategy that may improve sustainability and profitability of traditional crops. It has shown to lower the inputs of fertilizers, fuel, and pesticides; reduce pest and disease pressure; and increase productivity. However, the effect of the perennial forage grass on soil organic carbon and soil quality has not been adequately quantified. The objective of this research is to determine the effect of bahiagrass incorporated into the cotton-peanut rotation (i.e., sod-based rotation) on soil organic carbon and associated physical and chemical properties.

Traditional and sod-based rotation systems that have been established for more than 8 years were evaluated at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and the North Florida Research and Education Center (NFREC) in Quincy and Marianna, FL. The WREC and NFREC (Marianna) sites have large-scale plots that are in all phases of the sod-based rotation (bahiagrass-bahiagrass-peanut-cotton) with cattle grazing on the 2nd year of bahiagrass and on winter oat/rye cover crops. The WREC and NFREC (Quincy) sites have small-scale plots that have all phases of the sod-based and traditional rotations without grazing. For general comparisons of the rotations, all plots are irrigated under strip tillage, but additional treatments in the small plot experiments allow comparison of moldboard plow and strip tillage (WREC), as well as irrigation and non-irrigation (NFREC Quincy). The large-scale plots have cattle exclusion cages (15x15 m) that allows for the comparison of grazed and non-grazed conditions. Soil organic carbon (SOC) was assessed with depth, and the $^{13}C/^{12}C$ isotopic ratio of the SOC was assessed at 0-5 cm to assess the contribution of bahiagrass to the system. The effects of bahiagrass on water relationships were assessed by examining the infiltration rate, bulk density, macroporosity, and the saturated hydraulic conductivity of the soil in the crop management systems. In addition to carbon analysis, nutrient assessments included available Ca, Mg, K, P and Na, as well as nitrate-N and ammonium-N.

Overall, there were few differences between the sod-based and conventional rotations. Soil organic C was found to range from 1.20-19.00 g kg^{-1} and decrease with depth. No difference was found between the cropping sequences or the rotation; however, SOC was typically higher following the bahiagrass sequences. Secondary treatment, plow vs strip-tillage, in the small plot experiment at the WREC location was also found to differ by tillage treatment, with the strip-tilled plots usually having a higher amount of SOC than the plowed plots. Using $\delta^{13}C$ values, it was determined that 19.0 to

37.5% of the SOC was contributed by the bahiagrass. Macroporosity ranged from 0 to 1.1% and was generally highest after the peanut and cotton of the traditional rotation and after the cotton of the sod-based rotation. Cropping sequence, secondary treatment, and rotation provided no difference in macroporosity. Bulk density was not found to differ by cropping sequence or rotation at any location, but was generally higher in the 5-10 cm depth than in the 0-5 cm depth. No difference in saturated hydraulic conductivity or infiltration was found between the cropping sequences or by rotation at any location. Calcium, K, Mg, Na, and P at all locations differed by depth, but there was no effect of cropping sequence, except with Mg (WREC small plot experiment) and P (WREC and NFREC large experiments), or secondary treatment in any of the experiments. At both the small plot experiments, a difference in the amount of NO_3-N and NH_4-N was found between the different cropping sequences. All benefits previously found were following the first few years of the sod-based rotation, while this study evaluated the system after 10 years. This suggests that over time the benefits of the sod-based rotation when compared to the traditional rotation, both using conservation practices, are lost. This is likely due to the accumulation of organic C by cover crops. However, when grazing was allowed on the 2nd year of bahiagrass, there was generally less organic C than in the non-grazed portion. More research is needed to complete the assessment of why the benefits of the sod-based rotation equal those of the traditional rotation when both in conservation systems.

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I. Literature Review

Introduction

The current world population is 6.9 billion (U.S. Census Bureau, 2010), and it is expected to rise to approximately 10 billion by the year 2050 (Worldwatch Institute, 2011). As the world population increases, the demand for food and plant-based products will continue to rise. Long-term, sustainable agricultural practices that are capable of maintaining high yield are necessary to keep pace with the rising demand.

The traditional crop rotation in the southeastern U.S. is peanut (*Arachis hypogaea*) followed by one to two years of cotton (*Gossypium hirsutum*). This rotation is consistently plagued with disease, pests, and weeds (Crookston, 1995; Tanaka et al., 2002) that require high levels of management inputs. Furthermore, the rotation is typically managed by conventional agronomic management practices involving inversion tillage and fallow periods during the winter months. These practices decrease residues on the soil surface, which contributes to erosion and soil loss reducing long-term sustainability (Reeves, 1997; Reddy et al., 2004). Because of these factors, conventional management of the traditional peanut-cotton rotation is difficult to sustain economically and environmentally.

Conservation practices, such as reduced tillage and cover cropping, are an alternative to conventional management practices. These practices improve environmental sustainability by reducing erosion and soil loss through preservation of plant residues on the soil surface. Reduced tillage has shown to increase crop production (Reeves, 1994), but long-term benefits to the soil from conservation practices can also improve sustainability due to changes in soil organic matter, nutrients, water retention, and soil structure (Reeves, 1994; Ess et al., 1998; Raper et al., 2000).

In addition to conservation practices, adding a perennial grass to the traditional peanut-cotton rotation (i.e., sod-based rotation) improves profitability and environmental sustainability (Norden et al., 1977; Wiatrak et al., 2007). Perennial grasses, such as bahiagrass (*Paspalum notatum*), have a large root biomass that contributes to soil organic carbon (SOC), which is known to provide numerous benefits to agronomic systems (e.g., infiltration, water and nutrient retention, and pH buffering). Furthermore, sod-based rotations have demonstrated high yields with reduced fertilizer, pesticide, herbicide, and irrigation inputs (Norden et al., 1977; Wright et al., 2005; Wiatrak et al., 2007).

The overall effects of sod-based rotation combined with conservation management on soil physical and chemical properties are poorly understood, especially in established systems (i.e., >8 years). Understanding the impact of perennial grasses under hay and grazing management on soil properties may lead to improvements in management practices and sustainability for cotton and peanut producers in the southeastern U.S.

Peanut-cotton Producing Region of the Southeastern Coastal Plain

Geography

The peanut-cotton producing region of the southeastern Coastal Plain lies in the southern portion of Alabama and Georgia and the northern portion of Florida. This region is located on the East Gulf Coastal Plain and the Atlantic Coastal Plain. The northern portion of the peanut-cotton producing region rests on sedimentary bedrock. Topography drastically changes from flat areas to steep slopes ranging from 40 to 180 m above sea level. Steeper areas tend to be prone to runoff and erosion, while flatter areas accumulate water and are susceptible to leaching (USDA, 2012). The southern portion of the peanut-cotton producing region is formed from beds of sandy and clayey marine sediments deposited by ocean currents and has a consistent elevation of 30-40 m. The soils are formed from deltaic or shallow marine sediments with hills carved into the land by flowing water (USDA, 2012).

Climate

The climate of the southeastern U.S. peanut-cotton region is warm and relatively humid. The air temperature typically follows a positive gradient from the north to the south, and there is a pronounced seasonal cycle (Mearns et al., 2003). The temperature ranges from a daily average maximum of 33ºC in the summer to a low of 3ºC in the winter in southern Alabama and northern Florida (USDA, 2002).

Average annual rainfall ranges from 1,040 to 1,525 mm in southern Alabama and northern Florida (USDA, 2002). Short-term droughts lasting from 14 to 21 days are common during the peanut-cotton growing season (Simoes et al., 2009). Minimum monthly rainfall is typically in October near peanut and cotton harvest times (Mearns et al., 2003).

Soils

The soils in the peanut-cotton producing region tend to be very similar. They are typically coarse-textured, highly weathered, erodible, carbon-depleted, and have poor water and nutrient retention (Simoes et al., 2009). Soils also tend to be weak structured, single-grained or massive, low in soil organic carbon (SOC), and high in bulk density (Campbell et al., 1974). These factors cause conditions in the soil that can physically impede root growth (Barley et al., 1965; Doty et al., 1975; Trouse and Reaves, 1980). With the weak soil structure in the peanut-cotton producing region, soils tend to be highly weathered and leached of plant available nutrients (USDA, 2012). These factors also contribute to the inherently acidic soils of the peanut-cotton producing region (USDA, 2012).

Agronomic Practices

Conventional Agronomic Management Practices

Cultivation of cotton and peanut are common in the rural parts of southern Alabama and Georgia and in northern Florida in the Coastal Plain region of the Southeast. The traditional agronomic practice in this region is to rotate one year of peanut with one to two years of cotton using conventional tillage practices involving plowing in the fall followed by a winter fallow and spring disking to break the surface prior to planting (Brown et al., 1985). Short two-year rotations can become susceptible to classic problems, such as stagnant yields, soil degradation, and survival and adaptation of pests (e.g., nematodes) and disease (Tomato Spotted Wilt Virus; Cox and Sholar, 1995; Crookston, 1995; Tanaka et al., 2002).

Stagnate yields are likely linked to soil degradation. Peanut and cotton provide little residue and do not contribute to organic carbon in the soil (Reeves, 1997; Reddy et al., 2004). Furthermore, plowing and disking reduces surface residue and increases SOC degradation. This leaves the system in a highly erodible condition during the fallow period (Brown et al., 1985). The erosion and depletion of SOC under conventional agronomic practices are primary processes that contribute to the degradation of the soil (Bruce et al., 1995). In the sandy soils of the Southeast, SOC plays a major role in nutrient retention in soils (Wilson et al., 1982). To maintain production yields, growers supplement soil with fertilizers for nutrients that are lost due to leaching and residue removal (Katsvario et al., 2007). However, fertilization costs reduce profitability and can be a source of environmental pollution.

Shallow rooting depth is also a problem with the traditional peanut-cotton rotation. Cotton and peanut roots cannot penetrate the compaction zone that commonly exists in the region at the 15-cm soil depth (Kashirad et al., 1967; Campbell et al., 1974). This can cause crops to reach drought stress in as little as three days (Elkins et al., 1977). After decades of farming in this manner, yields have grown stagnant due to erosion, poor nutrient retention, and increased susceptibility to droughts, while the prices of fuel, fertilizer, seed, pesticides and herbicides have increased (USDA-Economic Research Service, 2011). This limits profitability and leads to farm failure.

Soil Physical Properties under Conventional Agronomic Practices

Management is known to directly affect soil physical properties including structure, bulk density, compaction, infiltration, saturated hydraulic conductivity, and porosity. These properties influence productivity by limiting the amount of water crops are able to obtain (Benjamin et al., 2003). Not only is water availability reduced in the soil, but there is a greater chance that rainfall and irrigation will runoff potentially taking soil with it.

Soils under conventional agronomic management practices tend to be weak structured, single-grained or massive (Campbell et al., 1974). Soil organic carbon is known to be a natural binding agent for soil aggregation (Tisdall and Oades, 1982), but under conventional agronomic practices, decreases in SOC reduce the amount of water-stable aggregates (Causarano et al., 2008). The decrease in aggregation and overall soil structure increases soil bulk density due to loss of micro- and macropore space (Causarano et al., 2006).

Bulk density is defined as the mass of dry soil per unit bulk volume (Soil Science Society of America, 2001). Bulk densities associated with the conventional agronomic system, range from 1.5 to 1.6 g cm^{-3} (Benjamin et al., 2010). High bulk densities such as these can be an indicator of soil compaction (Arshad et al., 1996), which is important when considering root growth and water movement through the soil. Simoes et al. (2009) noted that a mixture of coarse particles (sand) from the surface and fine particles (clay) from the subsurface tends to fill most of the void spaces at the horizon interface. This potentially creates a root restricting layer (Kashirad et al., 1967; Campbell et al., 1974) that prevents crops from reaching the nutrients and water beneath it. High bulk density also contributes to water accumulation and runoff from the surface of the soil without infiltration resulting in sheet, rill, and gully erosion (Campbell et al., 1974). Thus, maintaining or improving bulk density and reducing compaction can reduce losses in productivity and environmental pollution.

Soils with lower bulk density typically have higher infiltration and less erosion (Paxton et al., 1993). Soils under conventional agronomic management practices in the Southeast have been measured to have infiltration rates of 0.31 cm min^{-1} (Katsvairo et al. 2007). This is largely due to the low saturated hydraulic conductivity (e.g., 6×10^{-5} cm s^{-1}) of soils with low organic matter and poor structure (Benjamin et al., 2010). Low infiltration and poor saturated hydraulic conductivity contribute to erosion as rainfall and irrigation practices are likely to exceed infiltration and downward movement of water.

Macropores are the pathways for preferential flow of water, air, and nutrients in soils (Beven and Germann, 1982; Lin et al., 2005; Jarvis, 2007). Soil type and land management are among the most important factors in determining macropore characteristics (Gantzer and Anderson, 2002; Mooney and Morris, 2008). Macropores formed by roots are highly continuous and round, and decrease in size with depth (Luo et al., 2010). Cropped management systems typically have few macropores (0.024 m^3 m^{-3}), which are smaller and less frequent near the compaction zone.

Soil Chemical Properties under Traditional Management

Chemical characteristics of the soil, such as pH, salinity, organic matter, nutrient content, and cation and anion exchange capacity, affect both sustainability and productivity of row crop production systems. Production costs in the peanut-cotton producing region of the Southeast are increasing due to limitations caused by chemical properties associated with infertile soils (Marois et al., 2002). Conventional management practices decrease the ability of the soil to recycle nutrients, lower its cation exchange capacity (CEC), and lower the pH of the soil.

Cation exchange capacity indicates the capacity of a soil to hold cationic nutrients such as Ca, Mg, K, and Na. In acid soils, this also includes proton and Al and its associated hydrolysis products (Essington, 2004b). Cation exchange capacity is influenced by several factors including management practices (Hussain et al., 1999), amount of SOC (Fesha, 2004), and pH (Bohn et al., 1985). Low CEC is associated with the conventional management practices due to their effect on reduction of SOC (Fesha,

2004) and pH (Katsvairo et al., 2007). In general, about 45% of CEC is due to SOM with the remaining 55% attributed to clay (Foth and Ellis, 1997b). Mahboubi et al. (1993) showed a significant increase in CEC in the 0 to15 cm depth range of a sandy clay loam layer when a no-till system was adopted that increased soil organic matter over 28 years.

The pH of soil is an indicator as of nutrient availability to plants. In addition, each crop requires a certain pH range to be able to grow. Management practices have a tendency to change pH quickly in the surface horizon of the soil (Smith and Doran, 1996). Soils that have a pH lower than 4.0 to 4.5 or greater than 8.5 have usually been influenced by human activity (Essington, 2004a). The pH of the soil affects the charge, both negative and positive, of mineral and organic particles, and thus the cation and anion exchange capacities of a soil (Foth and Ellis, 1997a). The CEC of a soil will increase with increasing pH, thus a decreasing soil pH indicates reduced cation retention (Katsvairo et al., 2007). Low pH is commonly corrected through the application lime, which increases pH and provides cations to the soil. It will also help alleviate any aluminum toxicity associated with the soil. Traditional management practices typically reduce soil organic matter, which is a natural buffer against changes in pH. Thus, long-term traditional management practices may result in more rapid pH decline than systems that promote higher SOC levels.

Nutrients are highly influenced by their forms, concentrations, and ability to be retained by the soil and organic particles. Loss of basic cationic nutrients, such as K, Ca, and Mg, under the traditional management practices is high, and it often outweighs the removal of crops, livestock and livestock products (Tivy, 1987). The root-impeding compaction zone that is common in the Coastal Plain region prevents roots from reaching nutrients found up to 170 cm beneath the soil surface (Long and Elkins, 1983). Potassium is typically unavailable and tends to be bound within rock or within specific clay minerals (Tivy, 1987).

Nitrogen, which is crucial to plant growth, does not stay in the soil for long-periods of time when applied as fertilizer. Approximately 30-50% of applied nitrogen is taken up by crops (Tivy, 1987). The remaining nitrogen is either immobilized by soil microorganisms or lost through leaching, volatilization, and denitrification (Cassman et al., 2002). In particular, nitrate is susceptible to loss with drainage water due to repulsion of the anion by negatively charged soil colloids. In areas with poor aeration and drainage, denitrification may occur (Tivy, 1987). Denitrification is the bacterial reduction of nitrate to gaseous nitrogen (Tivy, 1987). Ammonium compounds tend to volatilize when added near or on the soil surface (Smilde, 1972). Under traditional agronomic practices, the majority of plant biomass is removed from the surface of the field taking with it organic N that could be mineralized and subsequently available to future crops. Even when some residues remain, fields can lose up to 60% more N than if the field was under a winter cover crop (Wagger, 1989).

Phosphorus is the most ‘temperamental’ of the nutrients (Tivy, 1987). It has low mobility and low efficiency of use. It is less susceptible to leaching than N or K, but is more easily fixed and rendered unavailable (Tivy, 1987). The optimum pH range for P is much smaller than that of other macronutrients. In acidic environments, such as the peanut-cotton producing region of the southeastern U.S., P is likely to form insoluble compounds with Fe, Al, and Mn (Tivy, 1987). Conventional agronomic practices typically apply excess P to overcome immobilization issues (Wilson, 1982); however, this can result in contamination of water due to loss of in runoff, leachate, and eroded particles.

Conservation Management

Conservation agronomic practices are becoming more prevalent in the Coastal Plain region. By definition, it is any tillage or seeding system that maintains a minimum of 30% residue on the soil surface (ASABE Standards, 2005). Reduced tillage, strip tillage, no tillage, and cover cropping are the most common techniques used alone or in combination; however, strip tillage is the most common technique used in this region (Wiatrak et al., 2007). Strip tillage removes residue from the seeding area of the row allowing sunlight to reach the soil and warm it without disturbing most of the residue adjacent to the row (Johnson et al., 2001). Unlike conventional agronomic systems, which may require multiple passes through a field to prepare a seedbed, only one pass through the field is needed saving time and fuel.

In the peanut-cotton producing region of the Southeast, about 50% of the 2.9 million ha of cotton and 55% of the 525,000 ha were in some type of conservation tillage system (CTIC, 2005). Conservation systems in this region have demonstrated increased water retention and SOC levels, as well as improved soil structure (Reeves, 1994; Ess et al., 1998; Raper et al., 2000). Because water retention increases, the number of days before a crop reaches drought stress increases reducing irrigation needs (Elkins et al., 1977). Furthermore, the increase in SOC reduces erosion by increasing aggregation and improving soil structure (Paxton et al., 1993).

Another common conservation management practice in this region is planting a cover crop during the winter after row crops have been harvested. The potential for winter annual cover crops to conserve soil and water resources in conservation tillage production systems is well documented over diverse cropping environments (Blevins et al., 1971; Sojka et al., 1984). Cover crops contribute to nutrient cycling and decrease the amount of erosion in comparison with a fallow field (Wagger, 1989). In a study conducted by Wilson et al. (1982), cover cropping during the winter improved SOC content, total organic nitrogen, water retention and transmission properties, and decreased bulk density in the top 10 cm of soil.

Sod-based Rotation

The sod-based rotation adds two years of a perennial forage grass into the traditional peanut-cotton rotation, thus extending a two year peanut-cotton rotation into a four year sequence of peanut, cotton, perennial grass, and perennial grass (Katsvairo et al., 2007). Numerous benefits of this rotation system have been identified including reducing of pressure from disease and pests by breaking their life cycles (Cox and Sholar, 1995), improved water relationships (Benjamin et al., 2008), and enhanced nutrient retention (Wilson et al., 1982).

Bahiagrass is a good perennial forage grass for the Southeastern Coastal Plain because it is suited for soils with low fertility (Magness et al., 1971). It is traditionally grown in pastures in this region. It is drought tolerant and able to grow in sandy soils (Field and Taylor, 2002). The extensive root system exhibited by bahiagrass (Blue and Graetz, 1977; Impithuksa and Blue, 1978) increases porosity, which lowers bulk density allowing for greater water movement, and greater growth for subsequent crops (Simoes et al., 2009). It has been shown that roots from crops following bahiagrass were able to reach below the compaction zone (Katsvairo et al., 2007). Katsvario et al. (2007) found that compared to cotton in the traditional rotation, cotton in sod-based rotation had larger root crown diameters, larger total root area, longer total root lengths, and a larger root biomass allowing the roots to explore a larger soil volume for nutrients and moisture. This could lead to a decrease in the amount of fertilizer and water needed for crops to be grown. Elkins et al. (1977) noted that the sod-based rotation was able to resist water stress up to ten times longer than the peanut-cotton rotation under conventional agronomic management practices. The perennial grass contributes to SOC through its remaining above-ground biomass and decay of below-ground biomass (Wright et al., 2006). Devane et al. (1952) reported greater soil N and SOC under bahiagrass than in the adjacent cultivated fields.

A decrease in the amount of weeds (Wiatrak et al., 2007), diseases (Cox and Sholar, 1995; Jordan et al., 2002; Lamb et al., 1993), and pests (Cox and Sholar, 1995; Dickson and Hewlett, 1989; Jordan et al., 2002; Lamb et al., 1993; Wright et al., 2005) has also been observed in the sod-based rotation system. This reduces the amount of herbicide and pesticide needed for maximum crop production and increases profitability of the crop by reducing the expense associated with maximum crop production.

With these improved conditions, productivity would be expected to increase (Norden et al., 1977; Wiatrak et al., 2007). Wiatrak et al. (2007) observed a decrease in the number of plants, but more cotton bolls per plant under strip-tillage. Also, the yield and quality of peanuts were significantly better following bahiagrass sod than under the traditional peanut-cotton rotation (Norden et al., 1977).

Grazing vs. Non-grazing of the Sod-based Rotation

Bahiagrass in the sod-based rotation can be managed for hay or grazing. By including livestock and allowing it to graze on the bahiagrass in the sod-based rotation, producers extend the period of productivity, improve economic returns, and reduce risk by diversification of their products available for sale. Broadening the range of products for sale alleviates stress associated with fluctuations in climate and price by efficient utilization of resources (Tanaka et al., 2002; Zentner et al., 2002).

Grazing cattle return nutrients to the surface horizon of the soil (Sigua and Coleman, 2010). Grazing also partially controls the amount and composition of SOC and distribution of N in the soil profile (Rosswall, 1976; Smoliak et al., 1972). White et al. (2001) suggested that the longer durations of cattle grazing in one area increases defecation, and thus nutrient cycling. Therefore, grazing pastures can help lower fertilizer input.

Soil Organic Carbon

Following addition of a perennial grass to the peanut-cotton rotation, SOC increased (Wright et al., 2006). This has also been demonstrated with the adoption of conservation tillage practices (Reeves, 1994). Soil organic carbon influences the ability of the soil to aggregate, retain water, erode, sequester carbon, and cycle nutrients (Katsvairo et al., 2007). Most short-term changes in SOC result from changes in management (Bowman et al., 1999; Mikha et al., 2006; McVay et al., 2006). Carbon sequestration is the removal and storage of carbon from the atmosphere in carbon sinks (i.e., oceans, forests or soils) through physical or biological processes. Agricultural soil is a potential sink for reducing the amount of carbon dioxide in the atmosphere (Sperow et al., 2003). Sequestering carbon in the soil may decrease the amount of carbon dioxide in the atmosphere, and thus impact global warming by decreasing greenhouse gases (Rosenzweig and Hillel, 2000; Izaurralde et al., 2001; Metting et al., 2001; Lal, 2004). Switching from annual crops to perennial crops and using of specialized management practices such as the use of improved grasses and rotated grazing (Conant et al., 2001) may improve soil carbon sequestration by increasing residues and plant roots and decreasing disturbances in the soil (Paustian et al., 1997).

Influence of Soil Organic Carbon on Soil Physical Properties

Soil organic carbon is known to be a natural binding agent for soil aggregation (Tisdall and Oades, 1982). Under conservation tillage practices, increases in SOC have improved water stable macroaggregation in wheat/grass plots compared to wheat/fallow rotations (Causarano et al., 2008). Macroaggregates are associated with the slowly decomposable or stabilized fraction of SOC (Cambardella and Elliot, 1992).

Typically, increases in SOC result in decreases in soil bulk density (Wilson et al., 1982). Soil organic matter is a key in aggregation (Causarano et al., 2006) and combined with conservation management techniques improve soil structure, which decreases bulk density. This is due to the lower bulk density of SOC itself, but also to the increased soil structure. Reeves (1994) found that the average bulk density in fields under conservation tillage were lower than conventionally tilled fields. Franzluebbers and Struedemann (2010) found a difference in bulk density in the top 6 cm of soil when grazing was allowed on the sod portion of the rotation (1.46 vs. 1.42 Mg m^{-3}, grazed vs. ungrazed, respectively). The improved structure and decreased bulk density can lessen the degree of erosion seen in southeastern fields (Causarano et al., 2006). Also, with a decrease in erosion, the amount of nutrients that are carried away with the soil is lessened (Paxton et al., 1993).

Water retention in Southeast soils tends to be minimal due to the coarse soil textures and lack of SOC (USDA, 2007). This causes crops to enter water stress quickly (Elkins et al., 1977) following several days without rain (Simoes et al., 2009). Irrigation to supplement rainfall is costly to rural growers. The sod-based rotation with bahiagrass and other conservation methods have demonstrated increased soil water retention due to increases in SOC compared to traditional rotation and management practices (Reeves, 1994; Ess et al., 1998; Raper et al., 2000). The increased SOC would increase the water holding capacity of the soil (Reeves, 1994; Ess et al., 1998; Raper et al., 2000) by absorbing the moisture and releasing it slowly. Studies conducted in Texas show that using strip-tillage and cover cropping reduced the amount of evapotranspiration in soil and from the following cotton crop (Lascano et al., 1994). This could reduce the need to supplement rainfall with irrigation (Lascano et al., 1994).

Influence of Soil Organic Carbon on Soil Chemical Properties

The increase in SOC increases the CEC of a soil (Fesha, 2004). Wilson et al. (1982) showed that the increase in SOC after 2 years in bahiagrass increased the mean SOC by 0.35% *(w/w)*, exchangeable Ca by 490 mg kg^{-1}, and exchangeable Mg by 79 mg kg^{-1}. An increase in K status occurs because forage grasses, such as bahiagrass, are able to extract non-exchangeable K and recycle it from sub-surface horizons (Juo and Lal, 1977).

Nitrogen availability and quantity are important factors in cotton development and yield (Doss and Scarsbrook, 1969; Oosterhuis et al., 1983). Numerous studies have shown that legumes, such as peanuts, can immediately increase available N in soils, when left as residue, due to their rapid breakdown and release of N (McVay et al., 1989; Holderbaum et al., 1990; and Vyn et al., 2000). Newman et al. (2006) found that soil organic N increased by 5.7% per year and SOC increased by 26% over six years by leaving residue in the field. The use of crop rotation may reduce the potential of nitrogen to leach and degrade into groundwater (Touchton et al., 1995). However, it is important to keep in mind that high C:N and C:P ratios can lead to immobilization of nutrients making them unavailable for plant uptake (Dubeux et al., 2007).

Summary

The traditional peanut-cotton rotation under conventional tillage management practices has limited sustainability environmentally and economically. Both the rotation and the tillage management contribute to decreasing SOC (Katsvario et al., 2007), which affects soil structure and stability, nutrient and water retention, infiltration, and ultimately leads to erosion and soil loss (Paxton et al., 1993). In addition, the peanut-cotton rotation does not sufficiently break disease and pest cycles. Over time, inputs such as fertilizer, fungicides, pesticides, herbicides, and irrigation become more and more necessary as soils degrade, retain less nutrients and water, and disease and pest cycles are not interrupted. Fuel required to apply agrochemicals and operate irrigation systems further decreases the profit margin for producers.

Conservation management is becoming more widely adopted in the peanut-cotton producing region of the Southeast in place of conventional management (Johnson et al., 2001). These management practices have been proven to increase SOC and reduce erosion. Coupling sod-based rotation with conservation management has the potential to further increase SOC and all of its associated benefits. For the producer, this should equate to increased profitability and sustainability, as well as increased commodity diversity that will protect against unstable economic markets.

Following implementation, the sod-based rotation has shown that it can improve physical and chemical aspects of the soil to further increase the yields of the crops following bahiagrass. Bahiagrass returned organic residue to the soil, while simultaneously improving water- and nutrient-holding capacity, increasing crop rooting depth, improving soil structure, and reducing erosion (Reeves, 1994; Ess et al., 1998; Raper et al., 2000). However, previous studies have not evaluated whether the sod-based rotation can improve SOC and its associated benefits to soil physical and chemical properties after more than a couple of years. More research is needed to evaluate the potential benefits of the sod-based rotation in the long-term.

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II. Soil Physical Effects of Perennial Grasses Included in a Peanut-Cotton Rotation on Coastal Plain Soils

ABSTRACT

Peanut and cotton crops have traditionally been grown under conventional tillage systems that decrease the already low amount of soil organic carbon (SOC) in the soil. Conservation tillage systems along with the addition of a forage crop, such as bahiagrass, into the peanut (*Arachis hypogaea*) -cotton (*Gossypium hirsutum*) rotation (bahia-bahia-peanut-cotton or sod-based rotation) have been suggested to help increase SOC, which has been demonstrated to improve soil structure, reduce erosion, and improve water- and nutrient-holding capacities. The objective of this study was to compare macroporosity, SOC, bulk density, saturated hydraulic conductivity of the soil, and infiltration rates in sod-based and traditional rotation systems that have been established for 8 to 10 years. Additional effects of tillage method, irrigation, and grazing were also investigated. Studies were conducted at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and at the North Florida Research and Education Center (NFREC) in Quincy, FL, (small plot experiment) and Marianna, FL (large experiment). Soil organic C ranged from 7.87 to 17.32 g kg^{-1}. Macroporosity, evaluated by computerized tomography from 0-60 cm and defined as pore sizes $\geq$ 1.1 mm in diameter, ranged from not detectable to 1.14% over all depths evaluated. Bulk density ranged from 1.37 to 2.27 g cm^{-3}. Infiltration rate ranged from 1.49x10^{-3} to 6.43x10^{-4} cm s^{-1}. Values for hydraulic conductivity of saturated soil had a similar range. None of the parameters tested was

affected by rotation system, tillage, irrigation, or grazing treatment. However, most were affected by depth, and macroporosity was affected by crop sequence in the NFREC small plot experiment where the peanut phase had the highest porosity. Results indicate SOC and physical properties are not improved with the addition of bahiagrass to the peanut-cotton rotation when conservation practices (e.g., strip-tillage and cover crops) are performed. Lack of differences among treatments suggest that conservation practices, especially cover cropping which was used in all treatments, contribute significantly to the relatively high SOC levels and similar physical properties exhibited in these soils.

Introduction

Row-crop production in southern Alabama and Georgia and northern Florida is dominated by peanuts and cotton. These crops are typically grown in rotation using conventional tillage practices. Soils tend to be coarse-textured with weak structure, highly weathered, erodible, carbon-depleted, and have poor water retention (Simoes et al., 2009; Campbell et al., 1974). In addition, soils in this region are commonly plagued with a root restricting layer near 15 cm depth (Barley et al., 1965; Doty et al., 1975; Trouse and Reaves, 1980) preventing crop roots from reaching water and nutrients in the sub-surface soil, making crops more susceptible to the effects of short-term droughts (Simoes et al., 2009). The inherent soil properties in this region combined with conventional tillage practices (e.g., disking, soil inversion, winter fallow fields) have led to enhanced erosion and loss of water and nutrient-holding capacity over time resulting in a loss of economic and environmental sustainability. In addition, repeated cropping of peanut and cotton have led to increased soil loss resulting in infertile fields and environmental contamination (Katsvairo et al., 2006).

In order to alleviate long-term soil degradation and high water demand from crops managed with conventional tillage, conservation management practices are becoming more common in this peanut-cotton growing region. Common practices include reduced and no tillage practices and winter cover crops. These practices can decrease the amount of evapotranspiration (Lascano et al., 1994), increase nutrient- and water-holding capacity (Reeves, 1994; Raper et al., 2000; Fesha, 2004), and reduce erosion through beneficial properties associated with increased soil organic carbon (SOC) (Causarano et al., 2006; Wright et al., 2006).

In addition to conservation practices to improve soil quality, the addition of a perennial forage grass into the peanut-cotton rotation (i.e., sod-based rotation) has improved yield, soil carbon, nutrient cycling, hydraulic properties, and reduced pests and diseases, irrigation, fuel consumption, use of fertilizers and chemicals (Dickson and Hewlett, 1989; Lamb et al., 1993; Jordan et al., 2002; Wright et al., 2005; Wiatrak et al., 2007) in the short-term (one complete rotation). To fully understand the benefits of a sod-based rotation in the Southeast, it is necessary to evaluate the system with at least two complete rotation cycles (i.e., 8 years).

Conservation practices and the sod-based rotation are designed primarily to improve soil through increases in SOC. Soil organic carbon contributes to the stabilization of soil aggregates (Benjamin et al., 2008). Tisdall and Oades (1982) found that organic bonding agents were the main binding agent for aggregates > 250 μm in diameter. Maintaining adequate SOC is crucial to improving soil physical properties (Reeves, 1994). Reduced tillage, strip tillage, no tillage, and cover cropping are the most common techniques used alone or in combination to improve SOC; however, strip-tillage is the most common technique used in this region (Wiatrak et al., 2007). Residue management systems that increase soil coverage by plants and reduce incorporation of residues have the greatest impact on SOC (Havlin et al., 1990; Wood et al., 1991; Edwards et al., 1992).

Typically, increases in SOC result in decreases in soil bulk density (Wilson et al., 1982). This is due to the lower bulk density of SOC itself, but also improved soil structure. Reeves (1994) found that the average bulk density in fields under conservation tillage were lower than conventionally tilled fields. While the sod-based rotation has the potential to improve SOC, grazing of perennial grasses may reduce the effectiveness of SOC to reduce bulk density. Franzluebbers and Struedemann (2010) found that grazing increased bulk density (1.46 vs. 1.42 g cm^{-3}, grazed vs. ungrazed, respectively) in the top 6 cm of soil.

With a natural lack of SOC, coarse-textured surface soils do not retain water, and water stress for crops is reached within a few days (Elkins et al., 1977). Irrigation to supplement rainfall is costly to rural growers. The sod-based rotation with bahiagrass and other conservation methods have demonstrated increased soil water retention due to increases in SOC compared to traditional rotation and management practices (Reeves, 1994; Ess et al., 1998; Raper et al., 2000). Sigua et al. (2009) noted that rainfall on SOC promoted plant growth. Studies in Texas show that using strip tillage and cover cropping reduced the amount of evapotranspiration in soil from the following cotton crop reducing the need to supplement rainfall with irrigation (Lascano et al., 1994).

Increases in SOC can improve infiltration rates (Wright et al., 2006) due to the role of SOC in soil structure and aggregation (Causarano et al., 2006). Practices that increase SOC result in more stable aggregation, improved soil structure, and lower bulk density. This structural benefit usually increases the porosity, especially macroporosity, of the soil resulting in greater infiltration (Causarano et al., 2006). Macropores are important as preferential pathways of water, air, and chemicals in the soil (Beven and Germann, 1982; Lin et al., 2005; Jarvis, 2007). Also, with a decrease in erosion, the amount of nutrients that are carried away with the soil is lessened (Paxton et al., 1993).

The overall objective of this study was to determine the effect of the sod-based rotation on soil physical properties, including infiltration, saturated hydraulic conductivity, bulk density, and porosity on Coastal Plain soils after two complete rotation cycles. In addition, factors such as tillage, irrigation, and grazing were also evaluated.

Methods and Materials

Site Description

The study was conducted using four separate established experiments. Two experiments utilized small 0.1 to 0.25 ha plots in a randomized block design and two experiments were large 20.2 to 60.1 ha fields divided into sections representing each phase of the rotation. One of each type was located at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and at the North Florida Research and Education Center (NFREC) in Quincy, FL, (small plot experiment) and Marianna, FL (large experiment). All experiments had been established for approximately 8-10 years. All experiments were managed using irrigation, strip tillage, winter oat/rye cover cropping, unless otherwise noted as an additional secondary treatment in small plot experiments.

The small plot experiment at WREC included all phases of the sod-based rotation (bahia1-bahia2-peanut-cotton) and the traditional rotation (peanut-cotton) under irrigation. In addition to the various rotation treatments, a secondary treatment of strip tillage or moldboard plow was also included. Each phase of the rotation with tillage treatment was replicated 5 times; however, 3 of the 5 replications were randomly selected for sampling.

The small plot experiment at NFREC also included all phases of the sod-based rotation, but the traditional rotation included two years of cotton instead of one (peanut-cotton1-cotton2) under strip tillage. In addition to the rotation treatments, a secondary treatment of irrigation or non-irrigation was also included. Plots were arranged in a randomized complete block split plot design with irrigation treatment split in the plots. All plots were sampled, but the 2nd year of cotton (cotton 2) treatment was excluded from data analysis to simplify statistical analysis with experiments without this treatment.

The large experiment at WREC was a 20.2 ha field divided into 5 sections with each phase of the sod-based rotation and one section that alternated peanut and cotton as a control representative of the traditional rotation. Cattle were allowed to graze the 2nd year of bahiagrass during the summer, and they were rotated in all sections during the winter as forage was available. Within each section there were three sampling locations identified using Global Positioning Systems (GPS; MiTAC Digital Corp., Santa Clara, CA). At each sampling location, the site was split into a caged area to assess soil properties not affected by cattle grazing and an adjacent grazed area to assess soil properties affected by cattle grazing. Cattle exclusion cages were approximately 15 × 15 m and the grazed sampling area was approximately the same dimensions located 3 m to the side of the caged area. All sampling locations were under the irrigation pivot. Cattle density was maintained at approximately 5.0 head ha^{-1} between 2008 and 2011.

The large experiment at NFREC was a 60.1 ha field divided into 4 quadrants representing each phase of the sod-based rotation. Cattle were allowed to graze on the 2nd year of bahiagrass during the summer, and were rotated during the winter as forage was available. Within each section there were three sampling locations identified using GPS. Similarly to the large experiment at WREC, at each sampling location, the site was split into a caged area to assess soil properties not affected by cattle grazing and an adjacent grazed area to assess the soil properties affected by cattle grazing. Cages were approximately 15 × 15 m and the grazed area was approximately the same dimensions and located 3 m to the side of the caged area. All locations were under the irrigation pivot. Cattle density was maintained at approximately 3.7 head ha^{-1} between 2008 and present.

Sampling

For determination of macroporosity, soil cores were collected in triplicate in April and May 2010 before planting from selected plots and sampling locations described above for all experiments to a 60-cm depth using a 7.5 cm diameter Giddings Probe® (Giddings Machine Company, Windsor, CO) equipped with plastic liners. Specific sampling locations were recorded using GPS. A general horizon description (master horizon, subordinate, depth to boundary) was determined for each horizon in every core. Following horizonation and macropore analysis, composite samples were made from the triplicate cores taken from each plot or sampling location. Samples were air dried and sieved through a 2-mm mesh screen for analysis of the 0-5, 5-10, 10-15, 15-30, and 30-60 cm depth increments. These composite samples were used for pH, and SOC analyses. Separate sampling was performed for bulk density and SOC, which is described below.

General Soil Characteristics

Two composite samples were randomly selected from the small plot experiment at the WREC location and one from the small plot experiment at NFREC (i.e., Quincy) for texture and cation exchange capacity (CEC) determination. Texture was determined using particle size fractionation as outlined by the Soil Survey Investigation Staff (2004). Cation exchange capacity was determined using the ammonium acetate at pH 7 method (Soil Survey Investigation Staff, 2004). Soil series were identified using CEC, texture, and horizonation of the selected soil profiles from the small plot experiments at WREC and NFREC. Identified soil series were consistent with those reported in the USDA-NRCS Soil Survey Division, Web Soil Survey (Soil Survey Division, 2012) for these sites. The predominate soil series at WREC is a Dothan loamy-sand (Appendix 1), while the soil at NFREC is an Orangeburg loamy-sand (Appendix 2).

The pH was evaluated on all composite samples from each depth increment using a 2:1 water:soil ratio as outlined by the Soil Survey Investigation Staff (2004). Data was averaged by depth and experiment. General soil characteristics are reported in Table 1.

Macroporosity

Computerized tomography (CT) was used to evaluate macroporosity in collected soil cores, but before application to field samples, calibration cores were prepared to determine the effectiveness of the methodology and establish the grayscale values representing macropores on an area basis. Triplicate artificial soil cores were prepared using the same plastic liners as the soil cores (7.5 cm diameter) to 35 cm length and filled with either loam, loam mixed with 5% (v/v) peat, and 100% peat. Artificial macropores were made using drinking straws (5.33 mm inner diameter), coffee stirrers (3.34 mm inner diameter), laboratory tubing (2 mm inner diameter), and capillary tubing (~1 mm inner diameter) with the ends sealed to prevent clogging. Actual artificial macropore space was approximately 28.23 m^2 in each scan and calculated using only the tubing with >1 mm diameter as this was the pixel size and detection limit of the scan. The actual macroporosity is defined as the percentage of macropore area in the area of the scan.

Calculated macroporosity of calibration cores was determined using computerized tomography (CT). The CT scan was performed on 10 cores simultaneously using a GE Highspeed CT/i (GE, Cincinnati, OH) using a contrast of 2500 × -125 cd m^{-2} at 120 kV and 120 mA. Each CT scan was composed of individual scans taken 10 mm apart in an axial program with scanning every 2 seconds with a 46 cm field of view. Scans were cropped by individual core. From the 35 individual scans per calibration core, 5 scans were selected per core that displayed clear artificial macropores that were not distorted due to angles. This was done to improve correlation between actual macroporosity and calculated macroporosity.

A 0 to 255 grayscale was used to evaluate scans for macropore space using ERDAS Imagine® (Intergraph Corp., Cobham, UK), which ranges from black to white, respectively. In order to differentiate organic material from macropores, the 100% peat treatment was used to identify the grayscale range for organic matter and macropores. Artificial macropores appearing in the 100% peat samples had values < 72 (Figure 1). Thus, macropores were defined as pixels with values < 72 with a minimum size of 1.1 mm diameter, which was based on pixel size. Other studies have used similar size parameters for macropores stating that the size for a macropore is > 1 mm in diameter (Kim et al., 2010). Macroporosity was defined as the percentage of pixels attributable to macropores (i.e., < 72) from the total pixel count of the image. Macroporosity from the five selected scans was averaged for the three replicate cores from each core media treatment (e.g., loam, loam + 5% peat, and 100% peat) for a final macroporosity per soil treatment and final correction factor in macropore determination.

For field soil core analysis of macroporosity by volume, two of three cores were randomly selected from each plot in each experiment for CT analysis, excluding damaged cores. Tomographic analysis was similar to that performed on calibration cores. Individual CT scans (~60 per field core) were analyzed digitally from the surface to 60 cm and analyzed for grayscale values < 72. Percent macroporosity was averaged for all scans within a depth increment (e.g., 0-5, 5-10, 10-15, 15-30, 30-60 cm).

Bulk Density and Soil Organic Carbon

Sampling for bulk density and SOC measurements was performed in August 2010 in the small plot experiments at WREC and NFREC that were strip-tilled and irrigated. Two samples per plot were taken at 0-5 and 5-10 cm depth increments using 7.5 cm rings with a known volume. Samples were weighed then dried at 105°C. Soil dry weight was determined, and the sample was ground and passed through a 2-mm sieve to determine coarse fragment weight. Bulk density was determined by dividing the air-dried mass minus the coarse fragment mass from the soil volume (Soil Survey Investigation Staff, 2004). Composite samples were prepared from replicate bulk density samples and analyzed for SOC using a LECO-TruSpec (LECO Corp., St. Joseph, MI). Using the same methodology, SOC was determined at each depth interval for soil cores collected for macropore analysis. The 0-5 and 5-10 cm depth increments for SOC analysis from August 2011 was compared with the values found in the macropore cores from April and May 2010. No difference was found in the SOC values; therefore, only SOC collected in April and May 2010 are reported.

Saturated Hydraulic Conductivity and Infiltration

Hydraulic conductivity of saturated soil was determined in the field using a constant head procedure (Amoozegar and Wilson, 1999). Briefly, this method determines saturated soil hydraulic conductivity by inserting a constant-head soil permeameter into a borehole at a test depth. The borehole was dug to a depth of 15 cm using a bucket auger. The 15 cm test depth was used because that is the average depth of the compaction zone in the soil (Barley et al., 1965; Doty et al., 1975; Trouse and Reaves, 1980). This test evaluated the hydraulic conductivity of saturated soil at the compaction zone interface. Water was added to a calibrated reservoir and allowed to flow freely into the borehole until an equilibrium level was reached. Water flowing into the permeameter was throttled by an “adjustable bubble tube”. Hydraulic conductivity of saturated soil is determined mathematically using the equilibrium height of water, rate of water flow, and dimension of the borehole. Determination of saturated hydraulic conductivity was done by multiplying the A-coefficient (Equation 1)

Equation 1 $$A = \sinh^{-1}(H/r) - (r/H^2) + (r/H)/2\pi H^2$$

by the steady-state rate of water flow from the permeameter into the auger hole. Where H is the change in water height and r is the radius of the borehole. The A-coefficient is unique to the size of the bore hole and the depth at which saturated hydraulic conductivity is being evaluated.

Infiltration rates were determined in the field using a sprinkle infiltrometer (Cornell University, Ithaca, NY) from the irrigated and strip-tilled treatments of the small plot experiments at WREC and NFREC. Infiltration rates were measured by simulating rainfall in a single, 24-cm inner diameter ring. This allows for a wide range of predetermined rainfall rates to be assessed; for this project, 0.007 cm s^{-1} was used. The volume of water that was released and the time required for water to accumulate on the surface of the soil were recorded. The runoff was then collected over 3 minute intervals until measurements were equilibrated. Measurements were taken in the row and conducted in duplicate in each selected plot. Infiltration rate was determined by subtracting the runoff volume from the total amount of water released by the reservoir. Due to weather constraints, infiltration was only assessed in the small plot experiment at WREC.

Data Analysis

Data was analyzed using the SAS® program (SAS Institute Inc., Cary, NC). The data was processed through statistical analysis tests using the GLIMMIX procedure as outlined in *SAS® for Mixed Models, Second Edition* (2006). These analyses allow for comparison of the strip-tilled and plowed plots, irrigated and dry land plots, grazed and non-grazed, as well as the sod-based and traditional rotations using the cotton cropping sequences for analysis. Differences among treatment groups were evaluated at $\alpha = 0.05$ level.

Results

Soil Organic Carbon

Soil organic carbon from all experiments ranged from 1.2 to 19.0 g kg^{-1} and decreased with increasing depth at all locations as expected (Table 2; $P < 0.0001$). Within the 0-5 cm depth increment, average SOC was 8.4, 15.6, 17.4, and 9.1 g kg^{-1} in the WREC small plot, NFREC small plot, WREC large, and NFREC large experiments, respectively. There were no differences due to cropping sequence or rotation within any experiment at this depth. However, within a specific depth increment, SOC following bahiagrass was generally greater than from other crop sequences at all depths although crop sequence was rarely significant. This trend was most pronounced in the large experiments, where the greatest SOC occurred following bahiagrass and the least SOC occurred following peanuts and cotton. However, results were significant only in the WREC (large) experiment in the 10-15 ($P = 0.0010$) and 15-30 ($P = 0.0033$) cm depth increments; and only at the 30-60 cm depth at the WREC (small) were differences among cropping sequence observed ($P = 0.0067$), where SOC following bahiagrass and peanuts were greater than SOC following cotton.

When cotton and peanut were compared by rotation in the small plot experiments, there was no difference in SOC due to the rotation at any depth increment (Table 3). There was also no difference between the overall sod-based rotation and the overall traditional rotation in the small plot experiments.

Tillage method affected SOC in the small plot experiment at WREC. Strip tillage yielded 5.82 g kg^{-1} greater SOC at 0-5 cm depth than the moldboard plow treatment (Table 4). While the treatments were similar at 5-10 cm, the moldboard plow treatments were 0.5 and 0.75 g kg^{-1} greater in SOC than strip-tilled treatments at the 10-15 and 15-30 cm depth increments, respectively. No interaction was observed between the tillage treatment and the cropping sequence.

The secondary treatments of irrigation (NFREC small plot experiment) and grazing (WREC and NFREC large experiments) were not significant. However, it is interesting to note that the non-grazed treatments were slightly higher in SOC than the grazed treatments at all depths, except 30-60 cm, in both large experiments.

Macroporosity

Percent macroporosity evaluated using CT scans of artificial soil cores with constructed macropores was 0.4 and 0.5% of the total scan area for the loam and loam with 5% peat cores, respectively (Table 5). This is 64 and 72% of the actual macroporosity determined using combined area of the artificial macropores > 1 mm in diameter. While the loam with 5% had slightly greater calculated macroporosity, it did not differ from the loam without peat. The 100% peat soil reported nearly 100% macroporosity. Calculated macroporosity was relatively consistent with coefficient of variations, ranging from 0.0 in the OM soil to 0.2 in the loam with 5% OM.

Macroporosity in field cores ranged from none to 1.1% over all experiments and depths evaluated (Table 6). In the small plot experiment at WREC, macro-porosity decreased with depth. At the surface (0-5 cm) macro-porosity ranged from 0.6 to 0.1%, while the 30-60 cm depth ranged from 0.0 to 0.1%. Although cropping sequence and secondary treatment were not significant within a depth, the peanut and cotton cropping sequences of the traditional rotation and the cotton cropping sequence of the sod-based rotation had generally higher macroporosity than other cropping sequences in the 0-30 cm depth increments. No difference between sod-based and traditional rotation was found.

It the NFREC small plot experiment, macroporosity ranged from 0.02 to 1.14%, and there was an effect of the cropping sequence of the rotation at each depth increment. Macroporosity following peanuts in the sod-based rotation had the highest percentage of macropore space at each depth increment. In particular, macroporosity was greater in peanut in the sod-based rotation than in the traditional rotation; however, there was no difference in the cotton cropping sequence of the different rotations.

In the large experiments at WREC and NFREC, macroporosity ranged from 0.0 to 1.1% and 0.0 to 0.3%, respectively. No difference in macroporosity was found due to depth, secondary treatment, or cropping sequence of the rotation (Table 5).

Bulk Density

Within the small plot experiment at the WREC, bulk density at the surface 0-5 cm depth ranged between 1.01 g cm^{-3} in the 2nd year of bahiagrass and 1.46 g cm^{-3} in the 1st year of bahiagrass (Table 7); however, there was no difference among the cropping sequences ($P = 0.2195$). Bulk density in the 5-10 cm depth increment was greater than that at the surface ($P < 0.0001$). Bulk density ranged from 1.65 g cm^{-3} in the peanut phase of the sod-based rotation to 1.76 g cm^{-3} in the peanut phase of the traditional rotation at this depth, but it did not differ by cropping sequence ($P = 0.6018$).

In the small plot experiment at the NFREC, bulk density at the surface 0-5 cm depth ranged between 1.17 g cm^{-3} in the 1st year of bahiagrass to 1.50 g cm^{-3} in the peanut cropping sequence of the traditional rotation (Table 7). Bulk density did not differ among cropping sequence ($P = 0.9906$). Bulk density was generally greater in the 5-10 cm depth increment than in the 0-5 cm depth (P = 0.0002), but did not differ with depth. Within the 5-10 cm depth increment, bulk density did not differ among the cropping sequences (P = 0.4308).

Comparing the overall rotation systems, bulk density did not differ among the rotations in the 0-5 or 5-10 cm depth increments at either location.

Hydraulic Conductivity of Saturated Soil and Infiltration

For the small plot experiment at WREC, the hydraulic conductivity of saturated soil at 15 cm below the soil surface ranged from 1.49×10^{-3} cm s^{-1} in the peanuts of the traditional rotation to 6.43×10^{-4} cm s^{-1} in the 2nd year of bahiagrass in the sod-based rotation, but differences among cropping sequence were not significant (P = 0.2722) (Figure 2A). In the small plot experiment at NFREC, the highest saturated hydraulic conductivity was found in the cotton cropping sequence of the traditional rotation (9.19×10^{-4} cm s^{-1}), and the lowest was found in the peanut cropping sequence of the sod-based rotation (4.28×10^{-4} cm s^{-1}) (Figure 2B). Differences at this location were also not significant (P = 0.1609). In addition, there was also no difference between the overall rotation schemes at either location (P = 0.2947 at WREC and P = 0.1808 at NFREC).

Infiltration rates ranged from 7.27×10^{-3} cm s^{-1} in the cotton cropping sequence in the traditional rotation to 4.31×10^{-3} cm s^{-1} in the peanut cropping sequence for the sod-based rotation in the small plot experiment at WREC (data not shown). The phase of the rotation was not significant (P = 0.2225) nor was the overall rotational scheme (P = 0.9810).

Discussion

Soil Organic Carbon

The average SOC from all experiments was 12.5 g kg^{-1} and 8.1 g kg^{-1} at the 0-5 and 5-10 cm depths, respectively. Values are slightly higher than those found under conservation management practices at these depths (Terra et al., 2005; Siri-Pierto et al., 2007; Causarano et al., 2008); however, slightly larger depth increments (Causarano et al., 2008; Terra et al., 2005) could account for lower SOC. Lower SOC due to intensive tillage practices at 0-5 cm is consistent with other studies in this region (Terra et al., 2005; Siri-Pierto et al., 2007; Causarano et al., 2008).

The lack of effect from the crop rotation system on SOC was also noted by Katsvairo et al. (2009), who reported data from the NFREC small plot experiment 4 years following its establishment. They reported an average of 9.8 g C kg^{-1} (1.56% soil organic matter) in the 0-15 cm depth increment. Because this average is most similar to the 10-15 cm depth increment in the current study, results suggest that SOC has increased over the last 6 years regardless of the rotation or irrigation treatments.

Intensive tillage with the moldboard plow reduced SOC by approximately 50% (11.32 to 5.5 g kg^{-1}) in the 0-5 cm depth increment. Causarano et al. (2008) also found reduced SOC due to intensive tillage practices. They found that SOC increased from 6.0 g kg^{-1} under conventional tillage to 8.0 g kg^{-1} using minimal tillage conservation practices. Concentration of SOC was relatively similar to the current study although cropping systems in the Causarano et al. (2008) study did not include a perennial grass, whereas this study did, but their study did include corn, soybean, cotton, peanut, and tobacco that had been under the management practices for well over 10 years.

Also, cover crops increase C inputs into agricultural systems (Reeves, 1997; Kuo et al., 1997). They would have contributed small but significant amounts of organic C to the soil which will improve soil quality. In a study conducted by Kuo et al. (1997), rye contributed approximately 1 g kg^{-1} organic C to the surface (0-15 cm) soil over 10 years. Rye was able to produce between 144 and 248 g kg^{-1} of above ground biomass (Dabney et al., 2001). Combinations of increased carbon inputs together with reductions in tillage are needed to maximize increases in soil organic carbon (Roberson et al., 1991; Wright et al., 1999).

Macroporosity

Macroporosity assessed using CT scans of the calibration cores of loam and loam with 5% peat was 64-72% of the actual macroporosity. However, analysis of the 100% peat treatments greatly overestimated macroporosity. Macroporosity in this sample was nearly 100% of the total scan area. This indicates that the grayscale criterion for macropores was not effective at separating organic material from macropore space because the density of the organic material is not high enough to lighten the background color above the 72 grayscale value assigned to the macropores. While addition of 5% peat to the loam sample slightly increased the macroporosity, it was not a significant difference. Thus, even though organic materials can interfere with macroporosity analysis as performed, it was not a factor for soils with less than 5% organic matter, which is < 2% SOC assuming 60% C in soil organic matter (Edwards et al., 1999). Analysis of macroporosity using CT of the field soils in this study is acceptable due to the < 2% SOC found in these soils. For the loam samples, macroporosity measured by CT was approximately 30% by area less than the actual macropore content. This is likely due to the pixels at the edge of the macropores that are not sufficiently dark to be classified as macropores. However, this difference was consistent among analyses and should be used as a correction factor.

In the field soils, macroporosity (pore size ≥ 1.1 mm diameter) ranged from 0.0 to 1.1% by area over all experiments and depths evaluated. The small plot experiment at NFREC was the only location where differences between the various cropping sequences were found. In this study, macroporosity following peanut was greater throughout the soil profile than following other crop phases. In a study conducted by Kim et al. (2010), macroporosity between treatments was most pronounced in the surface 10 cm of soil, and differences dissipated by 20 cm. Using CT scans and grayscale analysis, Kim et al. (2007) found 0.03% macroporosity in the surface to 10 cm of soil, 0.01% in the 10-20 cm depth increment, and none in the 20-30 cm depth increment. These findings include the range found in this study; however, maximum macroporosity observed was up to 30x greater in the current study. Several factors could account for these differences. Differences in cropping system and soil type are likely to impact macroporosity. In the study by Kim et al. (2007), corn was planted for two years prior to sampling on a silt loam soil in Missouri. Given poor structure of the soils, coarse textured soils, such as those in Alabama and Florida, have a larger number of macropores compared to the smaller particles in a finer soil. Unfortunately, courser textured soils are less likely to hold together during sampling and transportation of soil cores. Although care was taken to minimize core damage, the irregularly high macroporosity may be an artifact from handling. However, it could also be due to irregularly distributed zones of macropores created by biota (e.g., root zones, earthworm burrows).

The lack of difference in macroporosity between cropping sequence, rotation, and secondary treatment was unexpected. Peanuts must be inverted at harvest and may have increased the amount of porosity at the surface of the soil at the time of sampling. However, much of the added porosity could have dissipated during the 6-7 months between peanut harvest and sample collection. Differences between strip tillage and moldboard plow and grazed and non-grazed were expected. The lack of difference among treatments could be explained by the consistent use of winter cover cropping. After 10 years in rotation, the SOC levels had few differences among the treatments, except for tillage. Because SOC is likely the main factor driving differences in macroporosity, it is then not surprising that differences were not observed. However, SOC under strip tillage was greater than moldboard plow treatments at the 0-5 depth and less at 10-15 and 15-10 cm depths. Differences in macroporosity would be expected, but were not observed. However, differences in SOC were rather small and may not be sufficient to see differences in macroporosity.

Bulk Density

Bulk density in both small plot experiments differed by depth, but was not affected by phase of the rotation or overall rotation scheme. Bulk density averaged 1.19 and 1.33 g cm^{-3} in the 0-5 cm depth of the sod-based rotation at WREC and NFREC, respectively. These values are below the 1.6 g cm^{-3} bulk density where root penetration, depending on the plant species and soil type, begins to be impacted (C.A.R.E.S., 2012). These values are lower, even considering the differences in depth increments, than those reported by Wilson et al. (1982), who found that bulk density for the 0-10 cm depth was 1.49 g cm^{-3} when bahiagrass was used as a cover crop. Bulk density in the traditional rotation (1.24 and 1.44 g cm^{-3} in the 0-5 cm depth at WREC and NFREC, respectively) was the less than the 1.65 g cm^{-3} reported by Siri-Prieto et al. (2007) under a no-till peanut-cotton cropping system. Franzluebbers and Stuedemann (2010) found the bulk density for the top 20 cm of a soil in Georgia to be 1.44 g cm^{-3} under pasture management, which is lower than that of the sod-based rotation. This is not surprising as traffic from row crop production would be expected to increase bulk density.

Saturated Hydraulic Conductivity and Infiltration

Saturated hydraulic conductivities were not found to differ in the small plot experiments at WREC and NFREC. Benjamin et al. (2003) showed that the soil physical environment can influence crop productivity in a semiarid environment by influencing hydraulic properties of the soil. He found saturated hydraulic conductivities of $3.00\text{x}10^{-4}$ cm s^{-1} for conservation systems. These values are similar to the values that were found in the strip-tilled plots at both small plot experiments at WREC and NFREC. While the data from this study is consistent with Benjamin et al. (2003), the expected difference between sod-based and traditional rotations or the cropping sequences within the rotations was not found. However, the lack of difference in hydraulic properties is supported by the lack of difference in SOC, macroporosity, and bulk density. Each of these parameters has a strong influence on saturated hydraulic conductivity (Benjamin et al., 2008).

In this study, cropping sequence and rotation were all expected to differ in infiltration, and neither did. Katsvairo et al. (2007) measured the infiltration rate at $3.05\text{x}10^{-2}$ cm s^{-1} in the sod-based rotation, while the traditional rotation had an infiltration of $5.17\text{x}10^{-3}$ cm s^{-1}. The data from the small plot experiment at WREC is consistent with the traditional rotation measurements found by Katsvairo et al. (2007), but are much lower than the values they found for the sod-based rotation. Differences in infiltration rates for sod-based and traditional rotations in the small plot experiment at WREC and those found by Katsvairo et al. (2007) were likely due to the amount of time the crops have been in rotation. At the WREC small plots have been in rotation for approximately 10 years, while those studied by Katsvairo et al. (2007) were within the first 4 years of the rotation. The lack of difference in infiltration rates between the cropping sequences could be due to lack of differences in SOC. Typically infiltration rates increase when SOC increases; this is to be expected through increased aggregation and improved soil structure (Benjamin et al., 2008).

Conclusion

Initial studies in the sod-based rotation suggested that it may have the potential to increase SOC and its associated soil benefits beyond what traditional and conservation practices can achieve. After 10 years in the sod-based rotation, SOC, macroporosity, bulk density, saturated hydraulic conductivity, and infiltration were evaluated and compared to the traditional peanut-cotton rotation managed with conservation practices. However, few differences were found. The use of conservation management practices in both the traditional and sod-based rotations may have, over time, equalized with respect to SOC accumulation. Because it is a key factor in forming aggregates and improving soil structure, it is not surprising that soil physical properties do not differ when SOC concentrations are similar among rotation systems studied. While there are numerous benefits to the sod-based rotation, including disruption of disease and pest cycles and economic diversity, the benefits to SOC and its associated role in the physical properties of soil were not evident when both systems were managed using strip tillage and cover cropping.

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Table 1. Soil particle size distribution, texture, and mean pH for the small plot experiments at the Wiregrass Research and Extension Center (WREC) and the North Florida Research and Extension Center (NFREC). The soil series at WREC was Dothan (Fine-loamy, kaolinitic, thermic Plinthic Kandiudult) and at NFREC was Orangeburg (Fine-loamy, kaolinitic, thermic Typic Kandiudult).

Location	**Depth**	**Sand†**	**Silt**	**Clay**	**Texture**	**pH**
	cm		%			
WREC	0 – 5	83.15	11.48	5.37	Loamy Sand	5.3
	5 – 10	83.58	8.96	7.46	Loamy Sand	5.2
	10 – 15	83.32	11.31	5.37	Loamy Sand	5.1
	15 – 30	77.12	11.25	11.64	Sandy Loam	5.3
	30 – 60	66.06	11.83	22.12	Sandy Loam	5.2

Location	**Depth**	**Sand**	**Silt + Clay**	**Texture**	**pH**
	cm	%			
NFREC	0 – 5	91.29	8.71	Loamy Sand	5.7
	5 – 10	91.99	8.01	Loamy Sand	5.8
	10 – 15	90.16	9.84	Loamy Sand	5.8
	15 – 30	75.74	24.26	Sandy Clay Loam	5.6
	30 – 60	63.43	36.57	Sandy Clay Loam	5.5

†Sand, Silt and Clay = 0.5-2.0, 0.002-0.5, <0.002 mm particle size separates, respectively

Table 2. Soil organic carbon (SOC) by cropping sequence in the small plot and large experiments at the Wiregrass Research and Extension Center (WREC) and at the North Florida Research and Education Center (NFREC).

Location	Depth	Bahia 1 SBR†	Bahia 2 SBR	Peanut SBR	Cotton SBR	Peanut TR	Cotton TR§	P-value
	cm	g SOC kg^{-1}						
WREC (small)	0-5	9.23	9.02	7.61	7.90	8.59	8.13	0.3428
	5-10	4.68	4.95	5.33	4.80	5.04	4.90	0.5441
	10-15	4.86	4.83	4.49	4.46	4.12	4.46	0.4713
	15-30	3.79	3.73	4.10	3.53	3.73	3.37	0.5933
	30-60	1.50 ab‡	1.81 a	1.80 a	1.30 b	1.80 a	1.43 b	0.0067
NFREC (small)	0-5	17.43	13.98	16.14	16.03	14.93	14.99	0.5781
	5-10	12.14	11.05	11.48	11.34	11.00	10.83	0.7153
	10-15	9.46	8.67	8.90	9.53	9.23	9.40	0.9306
	15-30	6.57	5.47	5.32	5.53	5.29	5.72	0.2368
	30-60	2.11	2.15	1.78	2.00	2.05	1.74	0.5630
NFREC (large)	0-5	10.24	12.61	5.10	8.64	-	-	0.0791
	5-10	9.41	12.92	4.91	6.71	-	-	0.0633
	10-15	8.01	9.55	3.96	4.33	-	-	0.1227
	15-30	6.69	7.83	2.85	3.29	-	-	0.0580
	30-60	1.20	2.73	1.23	0.88	-	-	0.2447
WREC (large)	0-5	19.00	18.76	16.66	15.18	-	-	0.1592
	5-10	11.15	9.43	9.32	8.55	-	-	0.1659
	10-15	7.47 b	9.50 a	6.10 c	6.14 bc	-	-	0.0010
	15-30	5.47 a	6.11 a	5.11 a	3.60 b	-	-	0.0033
	30-60	2.58	2.29	2.43	1.60	-	-	0.2522

† All crop sequence labels are for the 2009 growing season with sample collection prior to 2010 growing season; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton), TR = traditional rotation (peanut-cotton, except in small plot experiment at NFREC which as peanut-cotton1-cotton2)

‡ Letters denote significance at the $\alpha = 0.05$ level; significance calculated across crop sequence, each depth increment analyzed individually

§ The second year of cotton in the traditional rotation was omitted at the NFREC for statistical analysis

Table 3. Soil organic carbon and bulk density in the 0-5 and 5-10 cm depth increments for each of the rotations in the small plot experiments at the Wiregrass Research and Extension Center (WREC) and the North Florida Research and Extension Center (NFREC).

Location	Depth	Rotation	SOC	Bulk Density
	cm		g kg^{-1}	g cm^{-3}
WREC	0-5	SBR†	10.81	1.18
	0-5	TR	12.35	1.23
	P-value		0.6822	0.9500
	5-10	SBR	6.50	1.68
	5-10	TR	5.74	1.74
	P-value		0.6822	0.9471
NFREC	0-5	SBR	15.56	1.27
	0-5	TR	14.35	1.45
	P-value		0.7315	0.6094
	5-10	SBR	12.25	1.64
	5-10	TR	11.10	1.66
	P-value		0.7530	0.9894

† SBR = sod-based rotation (bahia1-bahia2-peanut-cotton); TR = traditional rotation (peanut-cotton or peanut-cotton1-cotton2). Cotton2 was omitted from NFREC data.

Table 4. Soil organic carbon (SOC) by secondary treatment and combined crop sequences in the small plot and large experiments conducted at the Wiregrass Research and Extension Center (WREC) and at the North Florida Research and Education Center (NFREC).

Location	**Depth**	**Moldboard Plow**	**Strip Tillage**	**Irrigated**	**Non-Irrigated**	**Grazed**	**Non-grazed**	**P-value**
	cm	g SOC kg^{-1}						
WREC (Small)	0-5	5.50 b†	11.32 a	-	-	-	-	<0.0001
	5-10	4.94	4.97	-	-	-	-	0.8206
	10-15	4.91 a	4.16 b	-	-	-	-	0.0028
	15-30	3.96 a	3.45 b	-	-	-	-	0.0434
	30-60	1.60	1.62	-	-	-	-	0.6003
NFREC (Small)	0-5	-	-	14.84	16.32	-	-	0.1990
	5-10	-	-	11.28	11.33	-	-	0.9006
	10-15	-	-	9.21	9.18	-	-	0.9439
	15-30	-	-	5.53	5.77	-	-	0.4577
	30-60	-	-	1.83	2.07	-	-	0.3459
NFREC (Large)	0-5	-	-	-	-	8.10	10.20	0.2784
	5-10	-	-	-	-	7.86	9.12	0.5300
	10-15	-	-	-	-	5.35	7.58	0.2365
	15-30	-	-	-	-	4.49	5.84	0.3392
	30-60	-	-	-	-	1.54	1.48	0.9242
WREC (Large)	0-5	-	-	-	-	16.60	18.20	0.2423
	5-10	-	-	-	-	8.96	10.26	0.1381
	10-15	-	-	-	-	7.00	7.60	0.2288
	15-30	-	-	-	-	4.97	5.18	0.6079
	30-60	-	-	-	-	2.19	2.26	0.8475

† Letters denote significance at the $\alpha = 0.05$ level; significance calculated across secondary treatments, each depth increment analyzed individually, and all crop sequences were combined.

Table 5. Calculated macroporosity (pore size ≥ 1.1 mm diameter) by area in calibration cores determined by gray-scale analysis of computerized tomographic scans of a loam, loam with 5% added peat, and 100% peat with three added macropores.

Soil Type	**Macro-pores**	**Macroporosity**			**Accuracy†**
		Calculated		**Actual**	**Mean**
	No. pixels	%	**CV‡**		%
Loam	24.2	0.44 ± 0.05 b§	0.11	0.69	64.2 ± 6.7 b
Loam+5% peat	27.2	0.52 ± 0.11 b	0.21	0.69	75.8 ± 14.2 b
100% peat	5333.8	98.74 ± 1.39 a	0.01	0.69	14309 ± 685 a

† Accuracy is defined as the ratio of calculated to actual macroporosity x 100.

‡ CV is the coefficient of variation, which is the ratio of the standard deviation to the mean.

§ Values are mean ± standard deviation. Dissimilar letters within a column indicated significant differences at the $\alpha = 0.05$ level.

Table 6. Calculated macroporosity by area (pore size ≥ 1.1 mm diameter) in field cores by cropping sequence and depth in the small plot and large experiments at the Wiregrass Research and Extension Center (WREC) and the North Florida Research and Extension Center (NFREC) using computerized tomography (CT) scans. Calibration of the CT scan method for determination of macroporosity indicated approximately 30% less macropores than actually present. Data has not been corrected to reflect this loss.

Location	**Depth**	**Bahia 1 SBR†**	**Bahia 2 SBR**	**Peanut SBR**	**Cotton SBR**	**Peanut TR**	**Cotton TR¶**	**P-value**
	cm	%						
WREC (small)	0-5	0.50‡	0.09	0.21	0.56	0.43	0.58	0.5404
	5-10	0.10	0.05	0.33	0.37	0.44	0.38	0.7550
	10-15	0.02	0.00	0.10	0.07	0.30	0.25	0.5920
	15-30	0.01	0.01	0.06	0.01	0.09	0.09	0.5818
	30-60	0.11	0.01	0.07	0.04	0.04	0.03	0.5235
NFREC (small)	0-5	0.14 b§	0.02 b	0.89 a	0.02 b	0.12 b	0.06 b	0.0201
	5-10	0.16 b	0.02 b	0.88 a	0.02 b	0.12 b	0.05 b	0.0141
	10-15	0.17 b	0.02 b	0.84 a	0.02 b	0.07 b	0.05 b	0.0226
	15-30	0.11 b	0.04 b	1.01 a	0.04 b	0.39 b	0.03 b	0.0060
	30-60	0.08 b	0.05 b	1.14 a	0.12 b	0.45 b	0.05 b	0.0019
WREC (large)	0-5	0.03	0.15	0.03	0.37	-	-	0.2940
	5-10	0.32	0.17	0.01	0.54	-	-	0.3419
	10-15	0.06	0.10	0.00	0.50	-	-	0.2125
	15-30	0.04	0.09	0.01	0.59	-	-	0.1619
	30-60	0.16	0.03	0.00	0.26	-	-	0.0780
NFREC (large)	0-5	0.00	0.05	0.26	0.06	-	-	0.5404
	5-10	0.04	0.00	0.09	0.03	-	-	0.7576
	10-15	0.07	0.00	0.04	0.05	-	-	0.8001
	15-30	0.07	0.00	0.00	0.04	-	-	0.1095
	30-60	0.17	0.07	0.00	0.05	-	-	0.4613

† All crop sequence labels are for the 2009 growing season; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton), TR = traditional rotation (peanut-cotton, except in small plot experiment at NFREC which as peanut-cotton1-cotton2)

‡ Values are a mean of macropore area through the depth increment

§ Letters denote significance at the $\alpha = 0.05$ level; significance calculated across crop sequence, each depth increment analyzed individually

¶The second year of cotton in the traditional rotation was omitted at the NFREC for statistical analysis

Table 7. Bulk density in the 0-5 and 5-10 cm depth increments for each of the crop sequence for the irrigated strip-tilled treatments in the small plot experiments at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and the North Florida Research and Extension Center (NFREC) in Quincy, FL.

Location	**Crop in 2010**	**Rotation**	**Depth**	**Bulk Density**
			cm	g cm^{-3}
WREC	Bahia 1†	SBR‡	0-5	1.46
	Bahia 2	SBR	0-5	1.01
	Peanut	SBR	0-5	1.12
	Cotton	SBR	0-5	1.13
	Peanut	TR	0-5	1.17
	Cotton	TR	0-5	1.30
	P-value			0.9737
	Bahia 1	SBR	5-10	1.69
	Bahia 2	SBR	5-10	1.69
	Peanut	SBR	5-10	1.65
	Cotton	SBR	5-10	1.69
	Peanut	TR	5-10	1.76
	Cotton	TR	5-10	1.72
	P-value			0.3138
NFREC	Bahia 1	SBR	0-5	1.17
	Bahia 2	SBR	0-5	1.21
	Peanut	SBR	0-5	1.26
	Cotton	SBR	0-5	1.46
	Peanut	TR	0-5	1.49
	Cotton	TR	0-5	1.39
	P-value			0.7807
	Bahia 1	SBR	5-10	1.67
	Bahia 2	SBR	5-10	1.66
	Peanut	SBR	5-10	1.71
	Cotton	SBR	5-10	1.51
	Peanut	TR	5-10	1.62
	Cotton	TR	5-10	1.70
	P-value			0.6158

† Bahia 1 is the 1st year of bahiagrass in the crop rotation and Bahia 2 is the 2nd year of bahiagrass in the rotation

‡ SBR = sod-based rotation (bahia1-bahia2-peanut-cotton); TR = traditional rotation (peanut-cotton or peanut-cotton1-cotton2). Cotton2 data was omitted.

Figure 1. Example grayscale computerized tomography (CT) scans of calibration cores constructed with A) loam soil, B) loam soil with 5% peat, and C) 100% peat that were used to compare macroporosity calculated using CT analysis with actual macroposity. Arrows indicate constructed macropores with grayscale values < 72. Macroporosity is defined as pore sizes ≥1.1 mm in diameter.

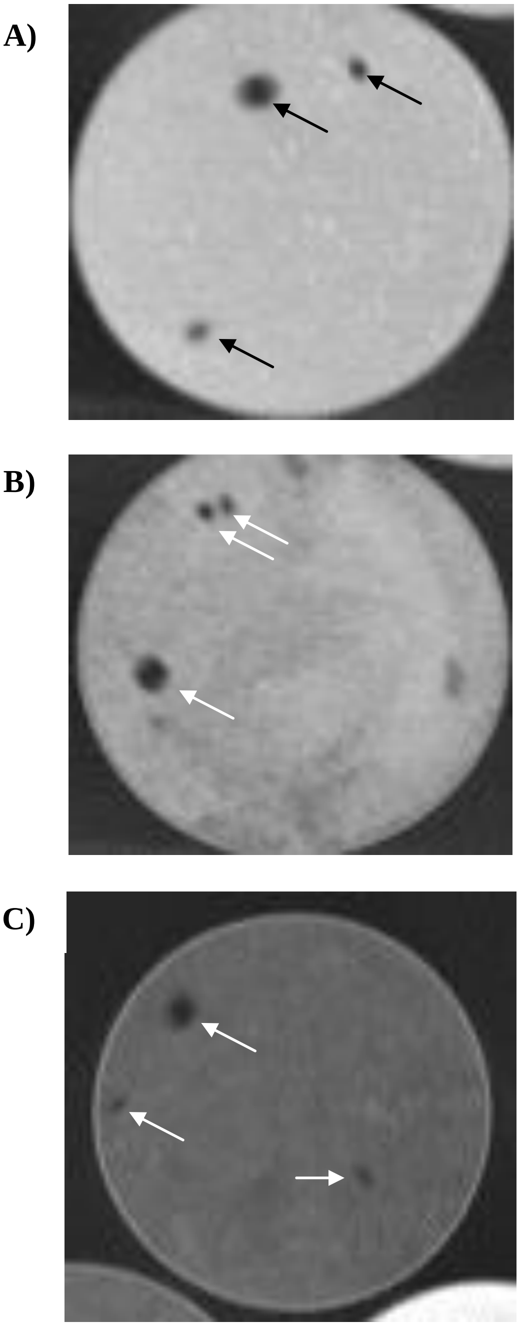
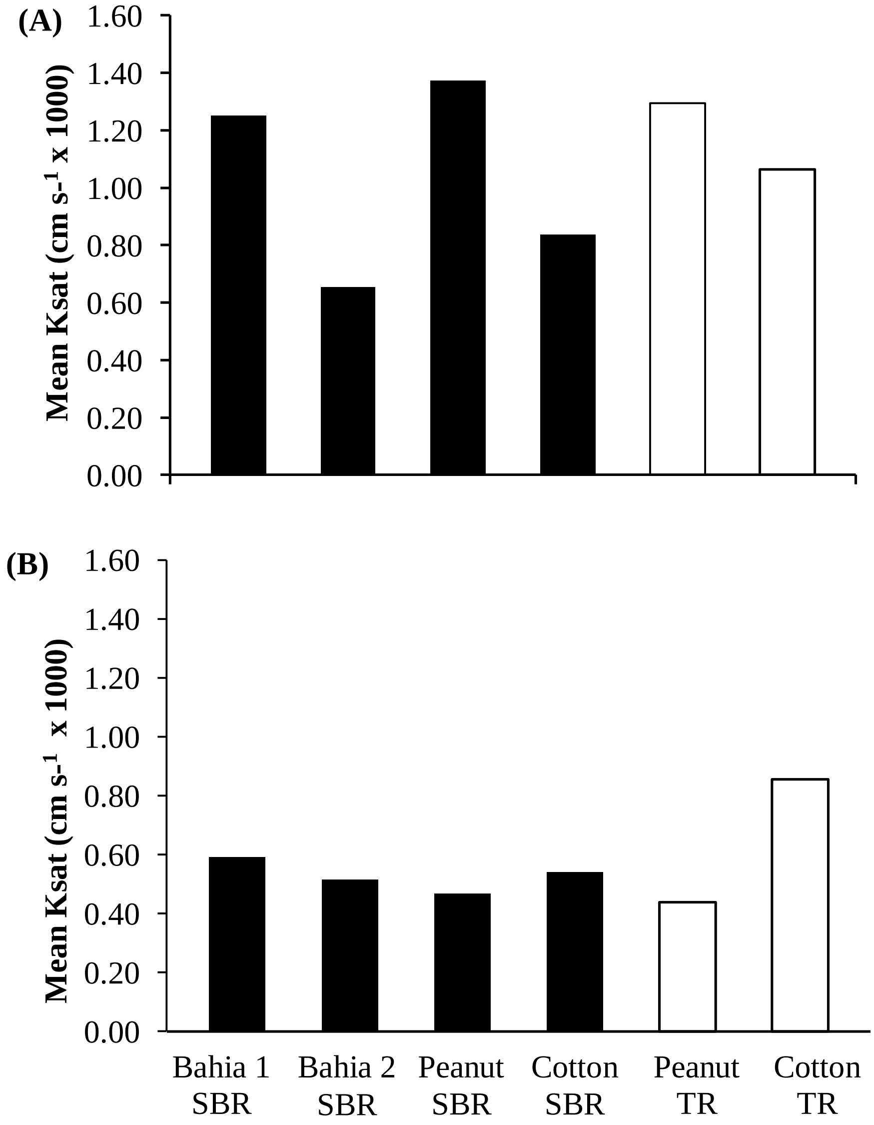


Figure 2. Mean hydraulic conductivity of saturated soil (Ksat) at 15 cm below soil surface for each of the cropping sequences that were strip-tilled and irrigated in the small plot experiments at A) the Wiregrass Research and Extension Center (WREC) and B) the North Florida Research and Extension Center (NFREC). Significance letters indicate differences by cropping sequence at α=0.05; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton); TR = traditional rotation (peanut-cotton or peanut-cotton1-cotton2). Cotton2 data is not shown. Black bars indicate crop sequences in the SBR and white bars indicate crop sequences in the TR.



III. Effects of Perennial Grasses Added to a Peanut-Cotton Rotation on Soil Chemical Properties

ABSTRACT

The conventional tillage systems that have been traditionally applied to the commonly used peanut-cotton rotation have degraded the soil organic carbon (SOC) contents leaving the soils with a low cation exchange capacity (CEC) and thus a low concentration of nutrients being retained in the soil. To help alleviate these problems associated with the traditional rotation and conventional tillage systems, along with conservation tillage methods, implementing a forage grass, such as bahiagrass, into the rotation (sod-based rotation) has been suggested. The objective of this study was to evaluate the effect of the sod-based rotation on SOC and nutrient concentrations as compared with the traditional rotation under multiple different treatments. Long-term (~10 years) sod-based rotations were sampled to a depth of 60 cm and divided into 5 depth increments for analysis. Analysis was performed to compare effects of management systems, irrigation, grazing, and the sod-based vs traditional rotations at the Wiregrass Research and Extension Center (WREC) in Headland, AL (small plot and large plot experiments), and the North Florida Research and Education Center (NFREC) in Quincy, FL (small plot experiment) and Marianna, FL (large plot experiment). Soil organic C ranged from 0.88 to 19.00 g kg^{-1} in all samples. Soil organic C decreased with increasing depth at all locations and differed by cropping sequence at the 30-60 cm depth at the small plot experiment at the WREC location with the 2nd year of bahiagrass having

the highest amount of SOC. At the WREC small plot experiment, SOC in the 0-5 cm depth was greater in conservation tillage systems than the conventional tillage systems regardless of the whether the rotation was sod-based or traditional. Carbon isotopic analysis showed two years of bahiagrass contributed 36.5% of the SOC, but after a year of peanut and a year of cotton the contribution of bahiagrass dropped to 16.5% indicating that this pool of carbon was relatively labile. Nutrients were largely unaffected by rotation and tillage management, except for phosphorus and nitrogen which differed among the crop phases due to fertilization of cotton and cover crops. Consistency in SOC between the sod-based rotation and traditional rotation under conservation practices after ~10 years suggests that perennial grasses do not increase the carbon sequestration potential in Coastal Plain soils beyond the ability of conservation practices after 10 years.

Introduction

The agriculture in southern Alabama and Georgia and northern Florida is dominated by peanut and cotton production. These crops are traditionally rotated year-to-year. The soils in this area tend to be coarse-textured, weakly structured, highly weathered, erodible, and carbon-depleted with poor water retention (Simoes et al., 2009; Campbell et al., 1974). In addition, the soils typically have a root restricting zone at the 15 cm depth (Barley et al., 1965; Doty et al., 1975; Trouse and Reaves, 1980). While the soil structure is ideal for peanut production, the conventional tillage methods typically used in these sandy soils contribute to erosion (Reeves, 1994) and decrease nutrient cycling (Tivy, 1987), cation exchange capacity (CEC) (Fesha, 2004), and soil pH (Katsvairo et al., 2007) resulting in a loss of economic and environmental sustainability.

Much of the decline in soil quality is due to the loss of soil organic matter from the intensive cotton-peanut production systems. Soil organic carbon (SOC) has high nutrient- and water-holding capacities and reduces erosion by improving aggregation and soil structure (Reeves, 1997). Conservation tillage practices, such as cover cropping, no tillage, and strip tillage, are designed to increase organic residues at the surface and organic carbon in the soil. In this region, conventional tillage methods are slowly being replaced by conservation practices in order to capitalize on the benefits of added carbon (Johnson et al., 2001). Currently, more than 50% of the cotton and peanut production in this region utilize one or more conservation tillage practice (CTIC, 2005), primarily cover cropping and strip-tillage (Wiatrak et al., 2007). However, conservation practices may not be sufficient to maximize SOC to levels that provide the greatest benefit to production and environmental sustainability.

Incorporating perennial grasses into the traditional peanut-cotton rotation has been suggested as another mechanism to improve SOC and thus the economic and environmental sustainability of peanut and cotton production. Many perennial grasses are well known for their ability to contribute to SOC due to their high above- and below-ground biomass that increases surface residue, reduces soil disturbance, and improves SOC (Paustian et al., 1997). Specialized management practices such as rotated grazing (Conant et al., 2001) have also shown to improve SOC (Paustian et al., 1997).

In the southeastern Coastal Plain, bahiagrass is a perennial forage grass that is suited for soils with low fertility (Magness et al., 1971). Addition of two years of bahiagrass into the peanut-cotton rotation has shown to increase SOC (Wright et al., 2006), especially with the use of conservation practices (Reeves, 1994). This rotation is sometimes called the sod-based rotation (Katsvairo et al., 2007). The extensive root system of bahiagrass (Blue and Graetz, 1977; Impithuksa and Blue, 1978) has been shown to reach below the compaction zone allowing the roots of subsequent crops to explore a larger soil volume for nutrients and moisture (Katsvairo et al., 2007). Wilson et al. (1982) showed that 2 years in bahiagrass increased residue at the surface and increased mean SOC by 0.35% *(w/w)*.

Soil organic carbon influences chemical properties associated with the soil. Due to the numerous functional groups found in organic matter, increases in SOC increase CEC of a soil (Fesha, 2004). The increase in SOC after 2 years in bahiagrass resulted in increased exchangeable Ca by 490 mg kg^{-1} and exchangeable Mg by 79 mg kg^{-1} within two years (Wilson et al., 1982). Potassium status following perennial grass production has also been seen to improve (Wilson et al., 1982) because many grasses are able to extract K from sub-surface horizons and recycle it to the surface (Juo and Lal, 1977) thus improving nutrient cycling in excess of fallow fields (Wagger, 1989).

Nitrogen is also influenced by SOC. Numerous studies have shown that legumes, such as clover, can immediately increase available N in soils when left as residue, due to their rapid breakdown and release of N (McVay et al., 1989; Holderbaum et al., 1990; and Vyn et al., 2000). Allen et al. (2006) found that soil organic N increased by 5.7% per year and SOC increased by 26% over six years due to legume residue left in the field. However, a study conducted by Meso et al. (2010) showed that there was not a significant increase in N when peanut residue was left in the field.

Stable C isotopic ratios have been used in SOC studies to trace the source of vegetative components in SOC (Flessa et al., 2000; Bronson et al., 2005; Haile et al., 2010). Carbon from plants using the C_4 carbon fixation mechanism can be distinguished from carbon from plants using the C_3 carbon fixation mechanism due to the greater discrimination against ^{13}C by C_3 plants. The delta ^{13}C ($\delta^{13}C$) values typically range from -9 to -19‰ for C_4 plants and from -20 to -35‰ for C_3 plants (Haile et al., 2010). In a 37-year rye-maize rotation system, maize, which is a C_4 plant, contributed to SOC up to 20 cm depth and accounted for 15% of the SOC in the A_p horizon (Flessa et al., 2000). Bronson et al. (2005) found that the contribution of carbon from C_4 species in particulate organic matter (0-30 cm depth) was 59% in native grasslands and conservation reserve program lands (predominantly C_4 species) compared to 35% in cropland soils dominated by cotton, rye, and wheat (predominantly C_3 species).

The sod-based rotation, coupled with conservation management practices, has the potential to improve carbon sequestration, which can improve SOC; however, the effects of the rotation more than a few years following establishment are not demonstrated. The objective of this study was to evaluate the long-term effect (> 10 years) of the sod-based rotation on SOC and nutrient distributions in the soil profile. Management effects of irrigation, grazing, and tillage (i.e., strip-tillage vs conventional moldboard plowing) were also evaluated.

Materials and Methods

Site Description

The study was conducted using four separate established experiments. Two experiments utilized small 0.1 to 0.25 ha plots in a randomized block design and two were large experiments of 20.2 and 60.1 ha that are divided into sections representing each phase of the rotation. Both small plot and large experiments were located at the

Wiregrass Research and Extension Center (WREC) in Headland, AL, and at the North Florida Research and Education Center (NFREC) in Quincy, FL, (small plot experiment) and Marianna, FL (large experiment). All experiments had been established for 8-10 years. All experiments were managed using irrigation and strip tillage with a winter oat/rye cover crop, unless otherwise noted as an additional secondary treatment.

The small plot experiment at WREC included all phases of the sod-based rotation (bahia1-bahia2-peanut-cotton) and the traditional rotation (peanut-cotton) under irrigation. In addition to the various rotation treatments, a secondary treatment of strip tillage or moldboard plow was also included. Each phase of the rotation with tillage treatment was replicated 5 times; however, only 3 of the 5 replications were randomly selected for sampling.

The small plot experiment at NFREC also included all phases of the sod-based rotation, but the traditional rotation included two years of cotton instead of one (peanut-cotton1-cotton2) under strip tillage. In addition to the rotation treatments, a secondary treatment of irrigation or non-irrigation was also included. Each phase of the rotations were arranged in a randomized complete block split plot design with irrigation treatment split in the plots. All plots were sampled, but the 2nd year cotton treatment was excluded from data analysis to make statistical analysis similar.

The 20.2 ha large experiment at WREC was divided into 5 sections with each phase of the sod-based rotation and one section that represented the traditional rotation, which alternated peanut and cotton. Cattle were allowed to graze the 2nd year of bahiagrass during the summer, and they were rotated in all sections during the winter as forage was available. Within each section there were three sampling locations identified using Global Positioning Systems (GPS; MiTAC Digital Corp., Santa Clara, CA). At each sampling location, the site was divided into grazed and non-grazed sampling locations. Cattle exclusion cages were approximately 15 × 15 m and located within 3 m of the adjacent grazed sampling area (15 × 15 m). All sampling locations were under the irrigation pivot. Cattle density was maintained at approximately 5.0 head ha^{-1} between 2008 and 2010.

The 60.1 ha large experiment at NFREC was divided into 4 quadrants representing each phase of the sod-based rotation. Cattle were allowed to graze on the 2nd year of bahiagrass during the summer and were rotated during the winter in all quadrants as forage was available. Similar to the large experiment at WREC, there were three sampling locations per quadrant identified using GPS. Unlike WREC, one sampling location per quadrant was located outside the irrigation pivot. This sampling location was omitted due to possible confounding effect of irrigation practice. To supplement the two sampling locations per quadrant, an additional grazed sampling location was selected inside the irrigation pivot. The corners and sampling locations within this 15 x 15 m area were recorded to ensure reproducibility. Thus, there were three grazed sampling locations per quadrant and two non-grazed sampling locations. Cattle density was maintained at approximately 3.7 head ha^{-1} from 2008 to the present.

Sampling

Soil cores were collected in triplicate during April and May 2010 before planting from selected plots and sampling locations described above for all experiments to a 60-cm depth using a 7.5 cm diameter Giddings Probe® (Giddings Machine Company, Windsor, CO) equipped with plastic liners. Specific sampling locations were recorded using GPS. Following horizonation, composite samples were prepared by combining the triplicate cores taken from each plot or sampling location at 0-5, 5-10, 10-15, 15-30, and 30-60 cm depth increments. Samples were air dried and sieved through a 2-mm mesh screen for analysis.

General Soil Characteristics

A general horizon description (master horizon, subordinate, depth to boundary) was determined for each horizon in every core. Two sets of composite samples, all depth increments for selected samples, were randomly selected from the small plot experiment at the WREC location and one from the small plot experiment at NFREC (i.e., Quincy) to have texture and CEC determined. Texture was determined using established procedures as outlined by the Soil Survey Investigation Staff (2004). Cation exchange capacity was determined using the ammonium acetate at pH 7 method (Soil Survey Investigation Staff, 2004). Predominate soil series were determined using CEC, texture, horizonation, and the USDA-NRCS Soil Survey Division, Official Soil Series Descriptions (USDA-NRCS Soil Survey Division, 2011) for the WREC and NFREC locations and were in agreement with the findings of the USDA-NRCS Web Soil Survey (Soil Survey Staff, 2012). The predominate soil series at WREC is a Dothan loamy-sand (Appendix 1) and the predominate soil series at NFREC is an Orangeburg loamy-sand (Appendix 2). The pH was evaluated on all composite samples from each depth increment using a 2:1 water:soil ratio as outlined by the Soil Survey Investigation Staff (2004). Data was averaged by depth and experiment. General soil characteristics are reported in Table 8.

Soil Organic Carbon and Carbon Isotopic Analysis

Soil organic carbon (SOC) analysis of composite samples from each depth increment was determined using a LECO-TruSpec® (LECO Corp., St. Joseph, MI). Analysis of δ^{13}C of samples from the WREC and NFREC small plot experiments at the 0-5 cm depth (only strip-tilled and irrigated plots) was performed by the Stable Isotope Facility at the University of California at Davis using a PDZ Europa ANCA-GSL elemental analyzer interfaced with a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK).

The δ^{13}C value represents the isotopic signature and is reported as the parts per thousand (per mil, ‰). It reflects the difference between the ratio of ^{13}C/^{12}C of the sample of interest and an internationally accepted standard (Equation 1).

Equation 1

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C} \right)_{sample}}{\left(\frac{^{13}C}{^{12}C} \right)_{standard}} - 1 \right) \times 1000 \permil$$

The standard for δ^{13}C is Pee Dee Belemnite (or PDB), which is a carbonite fossil from South Carolina. The δ^{13}C value is higher for C_4 plants compared to C_3 plants due to the difference in carbon assimilation pathways. Plants with the C_3 pathway (e.g., cotton, peanut, oat, and rye) discriminate against ^{13}C more than C_4 plants (e.g., bahiagrass). The δ^{13}C value can then be used to calculate the contribution of carbon by C_4 and C_3 plants (Equation 2 and 3). Reference δ^{13}C values of -25.8‰ for peanut (Hubick et al., 1986; 1988), -26.4‰ for cotton (Tsialtas et al., 2008), and -27.2‰ for rye (Nii-Annang et al., 2009) were averaged to represent the C_3 plants yielding -26.5‰ for $\delta^{13}C_3$. The reference δ^{13}C value for bahiagrass was -13.1‰ for $\delta^{13}C_4$ (Haile et al., 2010).

Equation 2 $$\%C_4 = \frac{\delta^{13}C_{sample} - \delta^{13}C_3}{\delta^{13}C_4 - \delta^{13}C_3} \times 100\%$$

Equation 3 $$\%C_3 = 100\% - \%C_4$$

Nutrient Analysis

Calcium, K, Mg, Na, and P were extracted from each composite sample using the Mehlich-I or double acid extract, which is a mixture of 0.05 N hydrochloric acid and 0.025 N sulfuric acid (Mehlich, 1953). Extracted nutrients were quantified using inductively coupled plasma (ICP) spectroscopy (Spectro Ciros ICP, SPECTRO Analytical Instruments, Kleve, Deutschland).

NO_3-N and NH_4-N Analysis

Nitrogen from nitrate (NO_3^-) and ammonium (NH_4^+) was determined in composite samples from 0-5 and 5-10 cm depths using the method of Sims et al. (1995). In this procedure, the sample is prepared by shaking 5 g of soil and 25 mL of 2 M KCl for 30 min followed by filtering through Whatman #42 filter paper. Filtrate is then placed into a microplate, and a mixture of citrate (5 g L^{-1} of trisodium citrate with 2 g L^{-1} of sodium hydroxide), salicylate-nitroprusside (7.813 g L^{-1} of sodium salicylate and 0.126 g L^{-1} of sodium nitroprusside), hypochlorite (1 g L^{-1} of sodium (tribasic) phosphate, 2 mL of 2 M sodium hydroxide, and 10 mL of commercial bleach), and 2 M KCl is added and allowed to develop for 30 min. The NH_4^+-N is analyzed using a spectrophotometer equipped with a microplate reader (Bio Tek FLx800, Bio Tek Instruments Inc., Winooski, VT) at 695 nm. The NO_3^- is then converted to NH_4^+ in the microplate with Devarda's alloy and reanalyzed for total organic nitrogen (TON) (i.e., NO_3^--N plus NH_4^+-N). The NO_3-N concentration was determined by difference.

Data Analysis

Data was analyzed using SAS$^{®}$ (SAS Institute Inc., Cary, NC). The data was processed using the GLIMMIX procedure in reference to Littell et al. (2006). Analyses allowed for comparison of the strip tilled and plowed, irrigated and non-irrigated, grazed and non-grazed, and the sod-based and traditional rotation treatments with the cropping sequence. Differences among treatment groups were evaluated at $\alpha = 0.05$ level.

Results

Soil Organic Carbon and Carbon Isotopic Analysis

Soil organic carbon from all experiments ranged from 1.20 to 19.00 g kg^{-1} and decreased with increasing depth at all locations as expected ($P < 0.0001$). Within the 0-5 cm depth increment, average SOC was 8.4, 15.6, 17.4, and 9.1 g kg^{-1} in the WREC small plot, NFREC small plot, WREC large, and NFREC large experiments, respectively. There were no differences due to cropping sequence or rotation within any experiment at this depth. However, within a specific depth increment, SOC following bahiagrass was generally greater than from other crop sequences at all depths although crop sequence was rarely significant (Table 9). This trend was most pronounced in the large experiments, where the greatest SOC occurred following bahiagrass and the least SOC occurred following peanuts and cotton. However, results were significant only in the WREC (large) experiment in the 10-15 ($P = 0.0010$) and 15-30 ($P = 0.0033$) cm depth increments; and only at the 30-60 cm depth at the WREC (small) were differences among cropping sequence observed ($P = 0.0067$), where SOC following bahiagrass and peanuts were greater than SOC following cotton.

When cotton and peanut were compared by rotation in the small plot experiments, there was no difference in SOC due to the rotation at any depth increment. There was also no difference between the overall sod-based rotation and the overall traditional rotation in the small plot experiments.

Tillage method affected SOC in the small plot experiment at WREC. Strip tillage yielded 2x greater SOC at 0-5 cm depth than the moldboard plow treatment (Table 10). While the treatments were similar at 5-10 cm, the moldboard plow treatments were greater in SOC than strip-tilled treatments at the 10-15 and 15-30 cm depth increments, but overall differences were < 20%. No interaction was observed between the tillage treatment and the cropping sequence.

The secondary treatments of irrigation (NFREC small plot experiment) and grazing (WREC and NFREC large experiments) were not significant. However, it is interesting to note that the non-grazed treatments were slightly higher in SOC than the grazed treatments at all depths, except 30-60 cm, in both large experiments.

Delta ^{13}C values differed by cropping sequence in the 0-5 cm depth ($P < 0.0001$) (Table 11). The δ^{13}C for cotton and peanuts in the traditional rotation were 2.6 to 5.3‰ lower than all sequences of the sod-based rotation. Cotton in both rotation systems had the lowest δ^{13}C values in their respective rotations. The C_4 bahiagrass in the sod-based rotation contributed 19.0-37.5% of the SOC found in the soil, which was maximized following the 2nd year of bahiagrass and minimized following cotton.

Nutrient Analysis

Calcium, K, Mg, Na, and P at all locations differed by depth, but there was no effect of cropping sequence, except with Mg (WREC small plot experiment) and P

(WREC and NFREC large experiments), or secondary treatment in any of the experiments. Typically, concentrations of Ca, K, Mg, and P were highest at the surface decreasing with depth, while Na appeared to be slightly irregular at 10-15 cm depth (Table 12).

Magnesium in the small plot experiment at the WREC location differed by cropping sequence at the 30-60 cm depth increment (Table 13). The cotton grown in the traditional rotation was higher in Mg than all other cropping sequences except cotton grown in the sod-based rotation at this depth. Magnesium concentrations also differed by the secondary tillage treatment at this location. The strip-tilled treatment had higher Mg concentrations (43.60 mg kg^{-1}) than the moldboard plowed treatment (36.26 mg kg^{-1}). There was also an interaction of depth with the tillage secondary treatment and depth with cropping sequence.

At both large plot experiments, P differed by cropping sequence within the sod-based rotation (Table 13). The highest concentration of Mehlich-I extractable soil P in the NFREC large experiment was following cotton with 67.55 mg kg^{-1} at the 0-5 cm depth. Significantly greater P in cotton was also measured in the 15-30 cm depth increment. While cropping sequence did not differ significantly in the other depth increments, P concentrations following cotton were slightly higher than following other crops. At the WREC large plot experiment, a similar trend was observed. Cropping sequence affected P concentration in all depths, except the 30-60 cm depth increment. Phosphorus concentrations following cotton were generally higher than other crops at the top three surface depths. The P concentrations following the 1st year of bahiagrass were lower than cotton in all depth increments to 30 cm, and they were lower than all other cropping sequences except at the 5-10 cm depth increment.

Nitrate-N and Ammonium-N Analysis

Both NO_3-N and NH_4-N differed by cropping sequence and by depth. In the small plot experiment at the WREC location, the highest concentration of NO_3-N and NH_4-N was in the 0-5 cm depth increment from the cotton phase of the traditional rotation (Table 14). At this depth, the 1st year of bahiagrass had generally the lowest NO_3-N and NH_4-N, although they did not differ significantly from other cropping sequences, except cotton from the traditional rotation.

In the small plot experiment at NFREC, the highest concentration of NO_3-N was in the 2nd year of bahiagrass in the sod-based rotation at 0-5 and 5-10 cm depths (Table 14). The lowest concentrations of NO_3-N were in the peanut and cotton phases of the traditional rotation. These values were 4 to 9 times lower than those following the 2nd year of bahiagrass. Concentrations of NH_4-N did not differ by cropping sequence at either depth.

In both large experiments, there was no difference in NO_3-N concentration among the bahiagrass and peanut phases of the sod-based rotation at 0-5 and 5-10 cm depths (Table 14). However, at the 0-5 cm depth, the NO_3-N concentration was greater following the cotton phase than all other phases at NFREC and following the 1st year of bahiagrass at WREC. At NFREC, the same differences among cropping sequence were also seen at the 5-10 cm depth. There was no difference in NH_4-N due to cropping sequence in either experiment.

In all experiments, NO_3-N and NH_4-N differed by depth. Both NO_3-N and NH_4-N concentrations were, typically, higher in the 0-5 cm depth than in the 5-10 cm depth. The WREC large plot experiment had the highest NO_3-N concentration at 72.59 mg kg^{-1} in the 0-5cm depth and 27.34 mg kg^{-1} in the 5-10 cm depth.

Discussion

Soil Organic Carbon and Carbon Isotopic Analysis

The average SOC from all experiments was 12.5 and 8.1 g kg^{-1} at the 0-5 and 5-10 cm depths, respectively. Values are slightly higher than those found under conservation management practices at these depths (Terra et al., 2005; Siri-Pierto et al., 2007; Causarano et al., 2008); however, slightly larger depth increments (Causarano et al., 2008; Terra et al., 2005) could account for lower SOC. Lower SOC due to intensive tillage practices at 0-5 cm is consistent with other studies in this region (Terra et al., 2005; Siri-Pierto et al., 2007; Causarano et al., 2008).

The lack of effect from the crop rotation system on SOC was also noted by Katsvairo et al. (2009), who reported data from the NFREC small plot experiment 4 years following its establishment. They reported an average of 9.8 g C kg^{-1} (1.56% soil organic matter) in the 0-15 cm depth increment. Because this average is most similar to the 10-15 cm depth increment in the current study, results suggest that SOC has increased over the last 6 years regardless of the rotation or irrigation treatments.

Intensive tillage with the moldboard plow reduced SOC by approximately 50% (11.32 to 5.5 g kg^{-1}) in the 0-5 cm depth increment as compared to the strip-tilled treatment. Causarano et al. (2008) also found reduced SOC due to intensive tillage practices. They found that SOC increased from 6.0 g kg^{-1} under conventional tillage to

8.0 g kg^{-1} using minimal tillage conservation practices. Concentration of SOC was relatively similar to the current study although cropping systems in the Causarano et al. (2008) study did not include a perennial grass, but did include corn, soybean, cotton, peanut, and tobacco that had been under the management practices for well over 10 years.

Bahiagrass was able to contribute up to 37.5% of the SOC after two years; however, in subsequent years under peanut and cotton its contribution declined. After the cotton phase, or 2 years following bahiagrass, only 19% of SOC was attributable to bahiagrass. Haile et al. (2010) was also able to distinguish carbon attributed to bahiagrass from that supplied by trees in a silvopasture system. The contribution of SOC contributed by C_4 plants in the silvopasture system was found to be between 25 and 32% (Haile et al., 2010). This value is slightly lower than the percentage found in this study; however, most silvopasture systems include both C_3 and C_4 plants simultaneously, which may reduce the impact of the C_4 contribution. Studies conducted by Puget et al. (1995), Flessa et al. (2000), and Christensen et al. (2011) evaluated the percent carbon due to maize under long-term cultivation. The contribution of maize to SOC was 11 and 44% after 6 and 23 years in a silty soil (Puget et al., 1995), while it was only 15% after 37 years in a very sandy soil (Flessa et al., 2000) and 14-16 years in a clayey soil (Christensen et al., 2011). However, inputs of maize-derived carbon were likely much lower than that attributable by perennial bahiagrass due to shorter growth cycle and harvesting of maize in these studies. In addition, maize stubble was plowed to a 25 cm depth each year (Flessa et al., 2000; Christensen et al., 2011), which would likely encourage SOC decomposition.

Also, cover crops increase C inputs into agricultural systems (Reeves, 1997; Kuo et al., 1997). They would have contributed small but significant amounts of organic C to the soil which will improve soil quality. In a study conducted by Kuo et al. (1997), rye contributed approximately 1 g kg^{-1} organic C to the surface (0-15 cm) soil over 10 years. Rye was able to produce between 144 and 248 g kg^{-1} of above ground biomass (Dabney et al., 2001). Combinations of increased carbon inputs together with reductions in tillage are needed to maximize increases in soil organic carbon (Roberson et al., 1991; Wright et al., 1999).

The 18.5% decrease in the contribution of C_4-carbon to the pool of SOC between the 2nd year of bahiagrass and the cotton phases of the rotation indicates that this portion of C_4-carbon has been mineralized. Because SOC concentrations did not differ significantly, additional SOC was supplied by subsequent C_3 crops (i.e., peanut, cotton, oat, rye). Loss of nearly 20% C_4 carbon from maize decomposition is consistent with measured CO_2 fluxes of 25% attributable to maize residue that was measured in the fall in a no-till study in Canada (Drewitt et al., 2009).

Overall the lack of difference in SOC among the crop phases and between rotations suggests that the conservation practices are responsible for the relatively high carbon levels in these Southeast Ultisols. While the bahiagrass does contribute to SOC pools, half of this carbon is rapidly mineralized within the next couple of years.

Nutrient Analysis

Soil organic carbon plays an important role in nutrient retention, especially in sandy soils. Neither the rotation system nor the crop phase had a large impact on Ca, K, Mg, and Na. Because changes in SOC were not observed due to rotation, crop sequence, grazing, tillage, and irrigation, it is not unexpected that there were few changes in nutrient cycling. The highest amount of P at the WREC and NFREC large plot experiments was found in the cotton cropping sequence of the sod-based rotation and were likely due to fertilization, which was applied to both cotton and cover crops each year.

Nitrogen from nitrate and ammonium were higher in the surface 0-5 cm than in the 5-10 cm depth. Total organic N in this study ranged between 0.053 and 0.034 g kg^{-1} in the 0-5 cm depth. In similar soils, total organic N (NO_3 and NH_4) ranged between 0.3 and 0.4 g kg^{-1} in the surface soil (Hubbard et al., 2008), which is 10x higher. However, total organic nitrogen is slightly higher than the 0.01 to 0.02 g kg^{-1} measured by Allen et al. (2006) in an experiment conducted in Minnesota. Fertilization practices and reduced tillage practices that maintain residue at the surface are likely responsible for higher nitrogen at the surface. Nitrate-N was higher than NH_4-N in both depths at all locations. This is as expected as nitrate fertilizers were typically used. Cotton sequences, typically, had the highest concentration of NO_3-N due to fertilization. Lack of differences among the rotations indicates that the contribution of nitrogen from peanut is not affected by addition of perennial grasses into peanut-cotton rotation when conservation practices are used.

Conclusion

The peanut-cotton rotation in southern Alabama and Georgia and in northern Florida has been troubled with low sustainability and productivity due to conventional management practices. Conservation management practices seek to improve sustainability and productivity through improving SOC. In order to further improve

SOC, addition of a perennial grass to the traditional peanut-cotton rotation has been suggested. Together and over time, the conservation management system and forage grass were expected to increase the amounts of SOC, increase nutrients, and increase the amounts of organic N in the soil.

Initial studies of the sod-based rotation expected to find increases in SOC, but now after 10 years in the system few differences are found. However, the long-term use of conservation practices in both the traditional and sod-based rotation may account for this lack of difference. Relatively high levels of SOC were found in these soils, which may indicate that build-up of SOC through conservation practices has matched what the sod-based rotation achieved earlier. The contribution of bahiagrass to overall SOC through each phase of the sod-based rotation supports this concept as SOC contributed by bahiagrass is fairly rapidly mineralized over the peanut and cotton phases of the rotation. Differences in SOC due to intensive tillage were still observed, even though the conservation practice of cover cropping was practiced. Due to lack of differences in SOC, differences in nutrient cycling would not be expected and were not found. Differences in nutrient distributions that were observed were largely attributable to fertilization practices for individual crop phases.

This research shows that after 10 years, there is little difference between the sod-based rotation and the traditional rotation when conservation practices such as strip tillage and cover cropping are used. However, SOC levels were relatively high for the region and evidence supports that conservation practices, as well as the sod-based rotation, have the ability to improve SOC, which should lead to reduced erosion, improved water management, and improved nutrient cycling.

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Table 8. Soil textural class, mean pH, and cation exchange capacity (CEC) for Dothan soil series (Fine-loamy, kaolinitic, ,thermic Plinthic Kandiudult) at the Wiregrass Research and Extension Center (WREC) in Headland, AL, and for the Orangeburg soil series (Fine-loamy, kaolinitic, thermic Typic Kandiudult) at the North Florida Research and Extension Center (NFREC) in Quincy, FL.

Location	**Depth**	**Texture**	**Soil Series**	**pH**	**CEC**
	cm				cmol$_c$ kg^{-1}
WREC (small)	0-5	Loamy Sand	Dothan	5.3	3.51
	5-10	Loamy Sand		5.2	2.21
	10-15	Loamy Sand		5.1	2.03
	15-30	Loamy Sand		5.3	2.86
	30-60	Sandy Loam		5.2	2.91
NFREC (small)	0-5	Loamy Sand	Orangeburg	5.7	3.64
	5-10	Loamy Sand		5.8	4.36
	10-15	Loamy Sand		5.8	4.36
	15-30	Sandy Loam		5.6	3.49
	30-60	Sandy Loam		5.5	3.41

Table 9. Soil organic carbon (SOC) by cropping sequence in the small plot and large experiments at the Wiregrass Research and Extension Center (WREC) and the North Florida Research and Education Center (NFREC).

Location	Depth	Bahia 1 SBR†	Bahia 2 SBR	Peanut SBR	Cotton SBR	Peanut TR	Cotton TR§	P-value
	cm	g SOC kg^{-1}						
WREC (small)	0-5	9.23	9.02	7.61	7.90	8.59	8.13	0.3428
	5-10	4.68	4.95	5.33	4.80	5.04	4.90	0.5441
	10-15	4.86	4.83	4.49	4.46	4.12	4.46	0.4713
	15-30	3.79	3.73	4.10	3.53	3.73	3.37	0.5933
	30-60	1.50 ab‡	1.81 a	1.80 a	1.30 b	1.80 a	1.43 b	0.0067
NFREC (small)	0-5	17.43	13.98	16.14	16.03	14.93	14.99	0.5781
	5-10	12.14	11.05	11.48	11.34	11.00	10.83	0.7153
	10-15	9.46	8.67	8.90	9.53	9.23	9.40	0.9306
	15-30	6.57	5.47	5.32	5.53	5.29	5.72	0.2368
	30-60	2.11	2.15	1.78	2.00	2.05	1.74	0.5630
NFREC (large)	0-5	10.24	12.61	5.10	8.64	-	-	0.0791
	5-10	9.41	12.92	4.91	6.71	-	-	0.0633
	10-15	8.01	9.55	3.96	4.33	-	-	0.1227
	15-30	6.69	7.83	2.85	3.29	-	-	0.0580
	30-60	1.20	2.73	1.23	0.88	-	-	0.2447
WREC (large)	0-5	19.00	18.76	16.66	15.18	-	-	0.1592
	5-10	11.15	9.43	9.32	8.55	-	-	0.1659
	10-15	7.47 b	9.50 a	6.10 c	6.14 bc	-	-	0.0010
	15-30	5.47 a	6.11 a	5.11 a	3.60 b	-	-	0.0033
	30-60	2.58	2.29	2.43	1.60	-	-	0.2522

† All crop sequence labels are for the 2009 growing season with sample collection prior to 2010 growing season; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton), TR = traditional rotation (peanut-cotton, except in small plot experiment at NFREC which as peanut-cotton1-cotton2)

‡ Letters denote significance at the $\alpha = 0.05$ level; significance calculated across crop sequence, each depth increment analyzed individually

§ The second year of cotton in the traditional rotation from NFREC (small) and the traditional rotation from WREC (large) was omitted

Table 10. Soil organic carbon (SOC) by secondary treatment (tillage, irrigation, grazing) in the small plot and large experiments conducted at the Wiregrass Research and Extension Center (WREC) and at the North Florida Research and Education Center (NFREC).

Location	**Depth**	**Moldboard Plow**	**Strip Tillage**	**Irrigated**	**Non-Irrigated**	**Grazed**	**Non-grazed**	**P-value**
	cm	g SOC kg^{-1}						
WREC (Small)	0-5	5.50 b†	11.32 a	-	-	-	-	<0.0001
	5-10	4.94	4.97	-	-	-	-	0.8206
	10-15	4.91 a	4.16 b	-	-	-	-	0.0028
	15-30	3.96 a	3.45 b	-	-	-	-	0.0434
	30-60	1.60	1.62	-	-	-	-	0.6003
NFREC (Small)	0-5	-	-	14.84	16.32	-	-	0.1990
	5-10	-	-	11.28	11.33	-	-	0.9006
	10-15	-	-	9.21	9.18	-	-	0.9439
	15-30	-	-	5.53	5.77	-	-	0.4577
	30-60	-	-	1.83	2.07	-	-	0.3459
NFREC (Large)	0-5	-	-	-	-	8.10	10.20	0.2784
	5-10	-	-	-	-	7.86	9.12	0.5300
	10-15	-	-	-	-	5.35	7.58	0.2365
	15-30	-	-	-	-	4.49	5.84	0.3392
	30-60	-	-	-	-	1.54	1.48	0.9242
WREC (Large)	0-5	-	-	-	-	16.60	18.20	0.2423
	5-10	-	-	-	-	8.96	10.26	0.1381
	10-15	-	-	-	-	7.00	7.60	0.2288
	15-30	-	-	-	-	4.97	5.18	0.6079
	30-60	-	-	-	-	2.19	2.26	0.8475

† Letters denote significance at the $\alpha = 0.05$ level; significance calculated across secondary treatments, each depth increment analyzed individually all crop sequences were combined

Table 11. Delta ^{13}C values and contributions SOC by C_3 and C_4 plants in 0-5 cm depth increment in the small plot experiments at Wiregrass Research and Extension Center (WREC) and the North Florida Research and Extension Center (NFREC).

Crop Sequence	**δ^{13}C Values**	**C_4-Carbon**	**C_3-Carbon**
	‰	——— % SOC ———	
Bahia1 SBR†	-22.55 c‡	29.5	70.5
Bahia2 SBR	-21.48 d	37.5	62.5
Peanut SBR	-22.40 c	30.6	69.4
Cotton SBR	-24.12 b	19.0	81.0
Peanut TR	-26.74 a	ND¶	100
Cotton TR§	-27.13 a	ND	100
P-value	<0.0001		

† All crop sequence labels are for the 2009 growing season; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton), TR = traditional rotation (peanut-cotton, except in small plot experiment at NFREC which as peanut-cotton1-cotton2)

‡ Letters denote significance at the $\alpha = 0.05$ level. Because there was no difference between locations, data were combined.

§ The second year of cotton in the traditional rotation was omitted at the NFREC for statistical analysis

¶ ND = Not Detectable

Table 12. Concentrations of Ca, K, Mg, Na, and P by depth at the small plot and large experiments at Wiregrass Research and Extension Center (WREC) and the North Florida Research and Extension Center (NFREC).

Location	**Depth**	**Ca**	**K**	**Mg**	**Na**	**P**
	cm	mg/kg				
WREC						
(Small)	0-5	529.34 a†	61.20 a	38.90 b	41.25 ab	10.31 a
	5-10	307.54 b	40.64 c	23.54 c	40.54 b	7.46 b
	10-15	273.06 b	41.43 c	23.60 c	39.21 b	7.45 b
	15-30	307.74 b	46.92 b	39.02 b	42.54 ab	5.81 c
	30-60	305.47 b	30.71 d	79.58 a	44.99 a	0.93 d
P-value		<0.0001	<0.0001	<0.0001	0.0435	<0.0001
NFREC						
(Small)	0-5	891.85 a	147.72 a	135.14 a	41.67 b	57.52 a
	5-10	745.55 b	96.19 b	118.14 b	40.81 b	39.62 b
	10-15	618.65 c	90.51 b	105.87 c	39.58 b	27.56 c
	15-30	397.83 d	87.68 b	115.59 b	42.75 ab	7.22 d
	30-60	315.39 e	42.92 c	109.84 bc	44.94 a	0.70 e
P-value		<0.0001	<0.0001	<0.0001	0.0129	<0.0001
NFREC						
(Large)	0-5	611.33 a	113.66 a	60.06 a	32.91	50.84 a
	5-10	628.07 a	63.96 b	52.69 b	31.29	46.42 ab
	10-15	558.48 a	58.72 bc	46.21 c	31.76	42.51 b
	15-30	410.82 b	52.76 bc	37.73 d	32.00	28.60 c
	30-60	249.82 c	42.17 c	30.73 e	31.83	4.66 d
P-value		<0.0001	<0.0001	<0.0001	0.5792	<0.0001
WREC						
(Large)	0-5	789.44 a	112.62 a	205.27 a	38.01 ab	25.17 a
	5-10	571.90 b	52.28 b	151.43 b	36.73 bc	11.26 b
	10-15	487.40 c	41.14 bc	133.64 bc	35.02 c	6.79 c
	15-30	445.14 c	30.14 cd	131.18 c	37.80 ab	3.61 d
	30-60	343.16 d	20.17 d	120.07 bc	40.13 a	0.26 e
P-value		<0.0001	<0.0001	<0.0001	0.0102	<0.0001

† Letters denote significance at the $\alpha = 0.05$ level by depth increment for each nutrient in each experiment; all crop sequences were combined.

Table 13. Magnesium and P concentrations in soil by cropping sequence and depth in the small plot experiment at Wiregrass Research and Extension Center (WREC) and the large experiments at WREC and North Florida Research and Education Center (NFREC).

Location	**Nutrient**	**Depth**	**Bahia 1 SBR†**	**Bahia 2 SBR**	**Peanut SBR**	**Cotton SBR**	**Peanut TR**	**Cotton TR**	**P-value**
		cm	mg/kg						
WREC (Small)	Mg	0 – 5	43.30	49.44	47.11	42.98	28.72	36.20	0.7419
		5 – 10	27.64	25.26	24.03	29.69	16.75	24.70	0.3488
		10 – 15	26.98	24.85	28.64	22.56	15.22	28.51	0.1395
		15 – 30	41.22	33.94	30.12	45.08	27.05	54.21	0.0737
		30 – 60	76.80 bc‡	66.14 bc	75.74 bc	91.77 ab	53.07 c	107.89 a	0.0500
NFREC (Large)	P	0 – 5	38.75 b	55.14 ab	41.60 b	67.55 a	-	-	0.0381
		5 – 10	36.14	51.07	38.93	57.17	-	-	0.1102
		10 – 15	33.93	47.21	29.45	54.82	-	-	0.1121
		15 – 30	26.53 b	19.89 b	26.77 b	42.02 a	-	-	0.0308
		30 – 60	3.39	1.87	3.69	10.90	-	-	0.1588
WREC (Large)	P	0 – 5	10.39 b	30.06 a	26.67 a	33.27 a	-	-	0.0024
		5 – 10	3.87 b	11.26 ab	11.67 ab	18.51 a	-	-	0.0082
		10 – 15	2.18 b	7.56 a	8.53 a	8.92 a	-	-	0.0013
		15 – 30	1.06 b	4.55 a	6.09 a	4.35 a	-	-	0.0022
		30 – 60	0.47	0.71	0.59	0.89	-	-	0.1077

† All crop sequence labels are for the 2009 growing season; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton), TR = traditional rotation (peanut-cotton)

‡ Letters denote significance at the $\alpha = 0.05$ level when compared within a depth increment across crop sequence

Table 14. Nitrate-nitrogen (NO_3^--N) and ammonium-N (NH_4^+-N) concentrations at 0-5 and 5-10 cm depths by cropping sequence in the small plot and large experiments at the Wiregrass Research and Extension Center (WREC) and the North Florida Research and Extension Center (NFREC).

Location	**N Form**	**Depth**	**Bahia 1 SBR†**	**Bahia 2 SBR**	**Peanut SBR**	**Cotton SBR**	**Peanut TR**	**Cotton TR§**	**P-value**
			mg N/kg						
WREC (Small)	NO_3^--N	0 – 5	15.32 b	18.09 b	19.08 b	15.82 b	25.42 b	47.99 a	0.0002
	NH_4^+-N		6.76 b	8.07 ab	17.51 ab	7.83 ab	8.57 ab	17.51 a	0.0382
	NO_3^--N	5 – 10	7.56	6.68	9.95	7.75	10.79	13.89	0.1039
	NH_4^+-N		5.63	5.00	5.90	5.37	5.96	6.15	0.9508
NFREC (Small)	NO_3^--N	0 – 5	17.31 bc	39.47 a	11.66 bc	30.30 ab	4.30 c	9.10 c	0.0148
	NH_4^+-N		16.52	18.23	9.90	17.84	10.92	16.04	0.7233
	NO_3^--N	5 – 10	5.63 bc	18.25 a	8.78 bc	14.27 ab	2.99 c	4.93 c	0.0124
	NH_4^+-N		8.66	7.87	6.76	11.50	7.38	8.14	0.4902
NFREC (Large)	NO_3^--N	0 – 5	32.37 b	31.28 b	24.56 b	64.89 a	-	-	0.0087
	NH_4^+-N		5.75	10.90	10.09	15.31	-	-	0.2429
	NO_3^--N	5 – 10	23.48 b	17.82 b	14.84 b	36.32 a	-	-	0.0057
	NH_4^+-N		4.99	5.39	8.14	8.42	-	-	0.1114
WREC (Large)	NO_3^--N	0 – 5	16.58 b	32.70 ab	33.23 ab	72.59 a	-	-	0.0003
	NH_4^+-N		26.84	17.61	16.30	15.74	-	-	0.6915
	NO_3^--N	5 – 10	11.73	14.38	27.34	19.46	-	-	0.2912
	NH_4^+-N		11.64	8.14	7.70	8.40	-	-	0.3466

† All crop sequence labels are for the 2009 growing season; SBR = sod-based rotation (bahia1-bahia2-peanut-cotton), TR = traditional rotation (peanut-cotton, except in small plot experiment at NFREC which was peanut-cotton1-cotton2)

‡ Letters denote significance at the $\alpha = 0.05$ level when compared within a depth increment across crop sequence.

§ The second year of cotton in the traditional rotation was omitted at the NFREC for statistical analysis

Appendix 1. Official series description of the Dothan soil series as described by the USDA-NRCS Soil Survey Division.

DOTHAN SERIES

The Dothan series consists of very deep, well drained, moderately slowly to slowly permeable soils on broad uplands. They formed in thick beds of unconsolidated, medium to fine-textured marine sediments of the Coastal Plain. Slopes range from 0 to 12 percent. Near the type location, the average annual precipitation is about 53 inches and the average annual air temperature is about 65 degrees F.

TAXONOMIC CLASS: Fine-loamy, kaolinitic, thermic Plinthic Kandiudults

TYPICAL PEDON: Dothan sandy loam--cultivated field. (Colors are for moist soil.)

Ap--0 to 13 inches; brown (10YR 4/3) sandy loam; weak fine granular structure; very friable; about 2 percent, by volume, ironstone; many fine roots; strongly acid; abrupt smooth boundary. (6 to 12 inches thick)

Bt1--13 to 22 inches; yellowish brown (10YR 5/8) sandy clay loam; weak medium subangular blocky structure; friable; about 2 percent, by volume, ironstone; many fine roots; common faint clay films on ped faces; strongly acid; diffuse smooth boundary.

Bt2--22 to 36 inches; yellowish brown (10YR 5/8) sandy clay loam; weak medium subangular blocky structure; friable; common fine roots; common faint clay films on ped faces; about 1 percent, by volume, plinthite nodules; common medium distinct strong brown (7.5YR 5/8) masses of iron accumulation; strongly acid; clear wavy boundary. (Combined thickness of the Bt horizons ranges from 15 to 36 inches.)

Btv1--36 to 52 inches; yellowish brown (10YR 5/8) sandy clay loam; weak medium subangular blocky structure; friable; common fine roots; common faint clay films on ped faces; about 10 percent by volume, plinthite nodules; common medium distinct strong brown (7.5YR 5/8), red (2.5YR 4/8), yellow (10YR 7/8) masses of iron accumulation and common medium distinct light brownish gray (10YR 6/2) areas of iron depletions; very strongly acid.

Btv2--52 to 80 inches; 20 percent yellowish brown (10YR 5/8), 20 percent strong brown (7.5YR 5/8), 20 percent red (2.5YR 4/8), 20 percent yellow (10YR 7/8) and 20 percent very pale brown (10YR 8/2) sandy clay loam in a variegated pattern; weak medium subangular blocky structure; firm; compact in place; many fine roots; common faint clay films on ped faces; about 20 percent by volume, plinthite nodules; the areas of yellowish brown, strong brown, red, and yellow are iron accumulations; the areas of very pale brown are iron depletions; very strongly acid.

TYPE LOCATION: Henry County, Alabama; Wiregrass Agricultural Experiment Station; south side of Alabama Highway 134; NE 1/4, NW 1/4, Section 3, R. 27 E., T. 4 N.; latitude 31 degrees, 21 minutes, 17.2 seconds N; longitude 85 degrees, 19 minutes, 30.4 seconds W.

RANGE IN CHARACTERISTICS: Solum thickness ranges from 60 to more than 80 inches. Depth to horizons that contain 5 percent or more plinthite ranges from 24 to 60 inches. Content of ironstone pebbles range from 0 to 5 percent, by volume in the A horizon and upper part of the B horizon. Content of quartzite pebbles range from 0 to 5 percent throughout the profile. Soil reaction ranges from very strongly acid to moderately acid throughout except where the surface has been limed.

The A or Ap horizon has hue of 10YR or 2.5Y, value of 3 to 7, and chroma of 2 to 4. Texture is sand, loamy fine sand, loamy sand, fine sandy loam, or sandy loam.

The E horizon, where present, has hue of 10YR or 2.5Y, value of 5 to 7, and chroma of 3 to 6. Textures are the same as the Ap horizon.

The BE or BA horizon, where present, has hue of 10YR or 2.5Y, value of 5 or 6, and chroma of 3 to 8. Texture is fine sandy loam or sandy loam.

The Bt horizon has hue of 7.5YR to 2.5Y, value of 5 to 8, and chroma of 4 to 8. The upper 20 inches of the Bt horizon contains 18 to 35 percent clay and less than 20 percent silt. Redoximorphic features in shades of brown or red range from none to common. Content of nodular plinthite ranges from 0 to 3 percent, by volume. Texture is fine sandy loam, sandy loam, or sandy clay loam.

The Btc horizon, where present, has the same colors and textures as the Bt horizon.

The Btv horizon has hue of 10YR or 2.5Y, value of 3 to 8, and chroma of 4 to 8; or it has no dominant matrix color and is variegated in shades of red, yellow, brown, and gray. A matrix hue of 2.5YR, 5YR, or 7.5YR is allowed below a depth of 40 inches. Content of nodular or platy plinthite ranges from 5 to 35 percent, by volume. Texture is commonly sandy clay loam or sandy clay but includes clay loam.

Appendix 2. Official series description of the Orangeburg soil series as described by the USDA-NRCS Soil Survey Division.

ORANGEBURG SERIES

The Orangeburg series consists of very deep, well drained, moderately permeable soils that formed in loamy and clayey sediments of the Coastal Plain. Slopes range from 0 to 25 percent.

TAXONOMIC CLASS: Fine-loamy, kaolinitic, thermic Typic Kandiudults

TYPICAL PEDON: Orangeburg loamy sand--cultivated. (Colors are for moist soil unless otherwise stated.)

Ap--0 to 7 inches; dark grayish brown (10YR 4/2) loamy sand; weak fine granular structure; very friable; many fine and medium roots; strongly acid; clear smooth boundary. (3 to 10 inches thick)

BA--7 to 12 inches; strong brown (7.5YR 5/6) sandy loam; weak fine subangular blocky structure; very friable; many fine roots; sand grains bridged and coated with clay; very strongly acid; clear smooth boundary. (0 to 12 inches thick)

Bt1--12 to 54 inches; yellowish red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable; many fine roots; many fine pores; common distinct clay films on faces of peds; very strongly acid; gradual smooth boundary.

Bt2--54 to 72 inches; yellowish red (5YR 5/8) sandy clay loam; moderate medium subangular blocky structure; friable; few fine roots; few faint clay films on faces of peds; few fine distinct yellowish brown (10YR 5/6) masses of relic iron accumulation; very strongly acid. (Combined thickness of the Bt horizons is 52 to 70 inches or more)

TYPE LOCATION: Dougherty County, Georgia; 0.6 mile west on Antioch Road from intersection with Gravel Hill Road; 660 yards north in cultivated field. (USGS Quadrangle, Putney, GA. (1974); lat. 31 degrees 29 minutes 07 seconds N., long. 84 degrees 04 minutes 20 seconds W.)

RANGE IN CHARACTERISTICS: Solum thickness typically is 72 to 96 inches and ranges from 70 to 120 inches. Ironstone nodules range from 0 to 10 percent throughout the solum. Reaction of the A and Bt1 horizons is very strongly acid to moderately acid, and the Bt2 and underlying horizons are very strongly acid or strongly acid.

The A or Ap horizon has hue of 5YR, 7.5YR, or 10YR, value of 3 through 5, and chroma of 2 through 6. Texture is sand, loamy sand, loamy fine sand, sandy loam, fine sandy loam, or sandy clay loam.

The E horizon, where present, has hue of 7.5YR or 10YR, value of 5 or 6, and chroma of 3 through 6. It is loamy sand or sand.

The BA or BE horizon, where present, has hue of 2.5YR, 5YR, 7.5YR, or 10YR, value of 4 through 6 and chroma of 4 through 8. Texture is sandy loam or fine sandy loam.

The Bt horizon has hue of 5YR or 2.5YR, value of 4 or 5, and chroma of 6 or 8, however, hues of 7.5YR are allowed within the upper 10 inches, and 10R hues are allowed in the lower Bt. The upper part of the Bt horizon is sandy clay loam and the lower part is sandy clay loam or sandy clay with less than 45 percent clay.
The lower Bt horizon has none to common brownish masses of iron accumulation which are relic redoximorphic features. Clay content of the upper 20 inches of the Bt horizon ranges from 20 to 35 percent and silt content is less than 20 percent.