Carbon and Nitrogen Cycling in a Peanut-Cotton-Bahiagrass Rotation

by

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Abstract

Restoration of soil fertility is important in the peanut-producing portion of the Coastal Plain, where many soils are highly weathered, structurally weak, and low in fertility as a result of intense row cropping. A frequently used cropping system in this region is an annual rotation of cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) under conventional tillage (CT). This traditional peanut-cotton rotation (TR) often results in erosion and loss of soil organic carbon (SOC). Incorporation of perennial grasses into the peanut-cotton rotation for 2 years (also called the sod-based rotation or SBR) has been suggested for improving SOC in the Coastal Plain, particularly in conjunction with conservation tillage practices. Perennial grasses such as bahiagrass (*Paspalum notatum* Fluegge) produce a high biomass that may increase SOC and prevent soil erosion, leading to increased nutrient-holding capacity. Incorporating cattle grazing may further enhance SOC storage if managed properly. Greenhouse gases (GHG) occur naturally in the atmosphere and contribute to global climate change by entrapping infrared heat. By incorporating high-biomass crops and conservation tillage in a cropping rotation, the net emission of GHG from agricultural soils may be mitigated through SOC storage. Unfortunately, grazing may increase the emission of GHG from the soil. To determine the environmental effect of perennial grasses and grazing on carbon sequestration in the peanut-cotton rotation, SOC, soil N, and GHG emissions were assessed on established (>10 years) crop rotation systems. Bahiagrass contribution to SOC was derived using stable C isotopic analysis. Systems evaluated in this study included 1) TR under CT, 2) TR under strip tillage (ST), 3) SBR under CT, 4) SBR under ST and 5) SBR under ST with cattle grazing. Total SOC, soil N, bahiagrass-derived SOC, and potential C mineralization increased in the top 10 cm of soil and were stratified with depth under ST in the SBR, indicating the potential for ST to improve soil fertility in the SBR. Grazing bahiagrass decreased SOC in the 5- to 10-cm depth, but this effect was not observed for the subsequent peanut crop and did not appear to have a long-term negative effect on SOC storage. A moderate stocking rate of 2.5 cattle ha^{-1} appeared to reduce soil emissions of CO_2 and N_2O, dependent upon season and crop. Flux of CH_4 was often negligible; however, grazing resulted in increased soil uptake of CH_4 in some instances. For moderate cattle stocking rates used in this study, grazing did not appear to have a negative effect on SOC storage or GHG emissions in SBR systems. The SBR did not show consistent improvements in total SOC compared to the TR. Isotopic analysis of mineralized CO_2 indicated SOC with a higher $^{13}C/^{12}C$ ratio (e.g., bahiagrass-derived SOC) may be preferred over SOC with a lower ratio (e.g., C_3 crop-derived SOC) for degradation by microorganisms. Concentration of SOC increased from 2009 to 2012 in many instances, indicating that other conservation practices (e.g., winter cover cropping) maximized SOC storage for Coastal Plain soils evaluated in this study.

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List of Abbreviations

Bahia1	1st year bahiagrass
Bahia2	2nd year bahiagrass
CT	Conventional Tillage
GHG	Greenhouse Gases
NFREC-LP	North Florida Research and Education Center-Large Plots
TR	Traditional Rotation
SBR	Sod-Based Rotation
SOC	Soil Organic Carbon
SOC_4-C	C_4-derived Soil Organic Carbon
ST	Strip-tillage
WREC-LP	Wiregrass Research and Extension Center-Large Plots
WREC-SP	Wiregrass Research and Extension Center-Small Plots

I. LITERATURE REVIEW

INTRODUCTION

A traditional cropping system in the Coastal Plain region of southeast U.S. is a rotation of cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) under conventional tillage. This type of system often leads to loss of soil organic carbon (SOC) and increased soil erosion (Campbell et al., 1991; Katsvairo et al., 2006). Storage of SOC is important for increasing nutrient- and water-holding capacities, as well as improving soil aggregation and structure. The humid climate and sandy soils of the Coastal Plain region create an environment favorable for SOC degradation (USDA-NRCS, 2013). Conservation practices such as cover cropping and reduced tillage are often employed in this region to improve SOC (Prior et al., 2010). As a method for further improvement, perennial grasses such as bahiagrass (*Paspalum notatum* Fluegge) may be incorporated into a cropping system (Causarano et al., 2008). Addition of 2 yr of bahiagrass into the peanut-cotton rotation (also called the sod-based rotation or SBR) is being evaluated as a method to increase SOC storage in the Coastal Plain. Incorporation of cattle grazing into the SBR can improve the economic efficiency of this type of system by providing an alternative income for producers when row crops are not being produced. Grazing management may also affect SOC storage.

Increasing storage of SOC in the SBR has potential not only to increase soil fertility, but also to mitigate the emission of greenhouse gases (GHG) into the atmosphere. Greenhouse gas emissions are of concern because of their ability to contribute to global climate change. It has been estimated that agriculture is the source of 7% of CO_2 emissions (Morgan et al., 2010), 50% of CH_4 emissions (Smith et al., 2007), and 60% of N_2O emissions (Smith et al., 2007).

Agricultural soils have lost 30 to 70% of their initial SOC as a result of increased cultivation (Eve et al., 2002; Lee et al., 2006). Mitigation of GHG is important in agricultural soils because they are large contributors to emissions and have the potential to mitigate global climate change by sequestering CO_2 (Morgan et al., 2010). By incorporating high-biomass crops and conservation tillage in a cropping rotation, more CO_2 can be allocated to the soil by increasing the amount of crop residue stored as SOC. Unfortunately, grazing practices in the SBR may increase the emission of CO_2, N_2O, and CH_4 from the soil; however, this effect may be partially mitigated through enhanced C sequestration. Assessment of SOC storage in conjunction with emissions of GHG is useful for determining the environmental impact of a SBR and cattle grazing practices.

THE SOD-BASED ROTATION

The SBR has the potential to increase SOC, particularly in conjunction with conservation tillage practices (Wilson et al., 1982; Reeves, 1994; Wright et al., 2005). In addition, yield improvements for cotton (George et al., 2013) and peanut (Katsvairo et al., 2006) have been observed in the SBR. Bahiagrass produces a high biomass above and below ground that promotes SOC sequestration, improves soil structure, and lessens soil erosion (Katsvairo et al., 2006). Soils the southeastern U.S. tend to be coarse-textured, highly weathered, and structurally weak (Doty et al., 1975; Simoes et al., 2009) with a root restricting zone at 15 cm depth that limits water and nutrient availability to row crops (Barley et al., 1965; Doty et al., 1975; Trouse and Reaves, 1980). The large root biomass of bahiagrass (Blue and Graetz, 1977; Impithuksa and Blue, 1978) demonstrated the ability of the grass to reach below the compaction zone, which allows roots of subsequent crops to explore a larger soil volume and add nutrient- and moisture-holding capacity (Katsvairo et al., 2007). Bahiagrass can also improve row crops by breaking disease (Cox and Sholar, 1995; Jordan et al., 2002; Lamb et al., 1993), weed (Wiatrak et al., 2007), and pest cycles (Cox and Sholar, 1995; Jordan et al., 2002; Lamb et al., 1993; Wright et al., 2005) that often hinder production. Because the addition of bahiagrass into a crop rotation would reduce row crop acreage, the economic benefits may not outweigh the environmental benefits. Cattle grazing in the SBR provides a source of income when row crops are not in rotation. In addition to supplying income, moderate cattle grazing can enhance agricultural productivity by improving SOC content and adding nutrients back to the soil (Franzluebbers and Stuedemann, 2008). The SBR can be used under conservation or conventional tillage practices but may be more efficient at storing SOC under conservation tillage.

MANAGEMENT EFFECTS ON SOIL CARBON

Carbon sequestration can be defined as long-term storage of C that results in a reduced CO_2 concentration in the atmosphere (Johnson et al., 2007). Carbon dioxide from the atmosphere is assimilated into stable forms of C in plant material during photosynthesis. Once the plant dies, the carbon-based plant materials are degraded. Some C is released back into the atmosphere, while other is stored in the soil as SOC (Hernandez-Ramirez et al., 2009). Increasing storage of C is important in agricultural soils because SOC can increase soil fertility, prevent soil degradation, and mitigate climate change (Smith et al., 2007). Growing crops with high biomass have the potential to increase the retention of C within the soil, particularly under conservation tillage (Cole et al., 1997; Morgan et al., 2010; Prior et al., 2010).

Perennial Grass Effect on Soil Carbon

Wood et al. (1991) observed increases in C storage in soils of continuous perennial grasses without residue removal. Eve et al. (2002) predicted that the conversion of cropland to pastureland could result in a 0.56 Mg ha^{-1} yr^{-1} increase in C storage for soils in southeastern U.S.

Similarly, in a review by Franzluebbers (2010), it was estimated that converting land from row crops to pastureland could increase SOC by 0.84 Mg C ha^{-1} yr^{-1}. Although it is well-established that conversion to pastureland can increase SOC storage, research is necessary to investigate the effects of incorporating 2 yr of pastureland in a 4 yr SBR.

Tillage Effect on Soil Carbon

Increased SOC sequestration often results from reduced tillage systems as a result of decreasing soil disturbance (Alluvione, 2009; Bono et al., 2007; Morell et al., 2011), particularly in the top layers of the soil (Watts et al., 2010; Wood and Edwards, 1992). Disturbance of soil aggregates and aeration of a soil are maximized with increased tillage, leading to an increase microbial activity and release of CO_2 to the atmosphere (Sainju et al., 2010b). Increases in SOC of 3.9 Mg C ha^{-1} were observed by Morell et al. (2011) when conventional tillage was replaced with no tillage. Increasing SOC in the top layers of soil is important because it protects against leaching and runoff by collecting pesticides and fertilizers. Additionally, it protects the soil from the impact of rainfall to prevent erosion and creates an environment in which soil microorganisms thrive, promoting soil health (Franzluebbers, 2010). Soils under conservation tillage often store more SOC than those under conventional tillage in the top layers of soil. Wood and Edwards (1992) observed a 67% increase in SOC in the top 10 cm of soil using conservation tillage compared to conventional tillage. Franzluebbers and Stuedemann (2008) obtained increases of 4.8 Mg C ha^{-1} in the top 30 cm of soil by replacing tillage with a moldboard plow with no-tillage after 3 yr of tillage treatment.

Increases in potential C mineralization rates are an additional result of conservation tillage practices. Potentially mineralizable C is a good indicator of soil health (Sainju et al., 2007; Wood and Edwards, 1992). An understanding of decomposition rates can lead to a better understanding of C and nutrient cycling. Potential C mineralization observed by Franzluebbers and Stuedemann (2008) was greater under no-tillage (1371 kg C ha^{-1} d^{-1}) management than conventional disk tillage (1240 kg C ha^{-1} d^{-1}) when cover crops of treatments were grazed with cattle. Wood and Edwards (1992) detected increased C mineralization rates in the top 5 cm of soil by substituting conservation for conventional tillage. Watts et al. (2010) found that C mineralization in the top 5 cm of soil was 14 and 28% higher under no-tillage compared to conventional tillage in soybean and corn cropping systems, respectively. The opposite was true at the 5- to 10-cm layer, with C mineralization being higher under conventional tillage. When examining the C turnover, Watts et al. (2010) found that conventional tillage methods resulted in 41 and 20% greater C turnover at the 0- to 5-cm depth when compared to no-tillage treatments on soybean and corn systems, respectively. They observed a similar trend at lower depths as well, indicating that although C mineralizes faster in the top layers of soil when using conservation tillage, it is often more labile under conventional tillage methods.

As a result of adding residue to a soil with conservation tillage, there is an increased amount of substrates available for soil respiration (Morell et al., 2011). Heller et al. (2010) observed that tillage increased loss of SOC through CO_2 emissions by 1.8 Mg CO_2–C ha^{-1} yr^{-1} compared with no-tillage practices. Measurements of short-term CO_2 emissions were evaluated by Omonode et al. (2007) for approximately 168 h after tillage treatments with a moldboard plow, chisel plow, and no-tillage. Greater CO_2 flux was measured for tillage with a chisel plow (6.2 Mg CO_2–C ha^{-1} yr^{-1}) than with a moldboard plow (5.9 Mg CO_2–C ha^{-1} yr^{-1}) or no-tillage (5.7 Mg CO_2–C ha^{-1} yr^{-1}). However, effects of tillage on CO_2 flux have been variable. Sainju et al. (2010a) did not detect differences in CO_2 emission or C storage after 3 yr of no-tillage treatment when compared with conventional tillage. Increased C storage with conservation tillage may mitigate loss of C from CO_2 emissions (Liebig et al., 2010; Robertson et al., 2000).

Grazing Effect on Soil Carbon

Pastureland contains approximately 10-30% of the world SOC stock (Schuman et al., 2002). Moderate cattle grazing of perennial grasses can enhance agricultural productivity by improving SOC content and providing nutrients to soil (Franzluebbers and Stuedemann, 2008). Proper grazing management has potential to increase global C stock by 0.1 – 0.3 Mg ha^{-1} yr^{-1} for pastures in the U.S. (Morgan et al., 2010). Schuman et al. (1999) found increases of 0.5 – 0.75 Mg C ha^{-1} yr^{-1} in the top 30 cm of soil for grazed treatments compared with ungrazed over a 12 yr period in the Great Plains. Liebig et al. (2010) also observed SOC accumulation of 0.39 – 0.46 Mg C ha^{-1} yr^{-1} in pasture land that had been moderately or heavily grazed by cattle after examining changes in SOC for a 44 yr period with archived soil samples from the Great Plains. Li et al. (2007) observed increases in SOC as well as C mineralization rates in pastures that were grazed by cattle compared to land of the same soil type that was cultivated for grain production. Franzluebbers and Stuedemann (2008) observed maintained levels of SOC and decreased potential for C mineralization after a 3 yr of grazing by livestock in the Southeast. They determined that grazing did not have a damaging effect on soil C pools.

Changes in stocking density and duration of livestock grazing also affect the composition of soil organic matter and cycling of SOC (Hart et al., 1995; Reeder et al., 2001; Schönbach et al., 2012). In a short-term 2 yr study, Silveira et al. (2013) evaluated SOC at 3 grazing densities. Although they found no significant differences in SOC, they observed a linear increase in SOC with decreased grazing intensity. Ingram et al. (2007) found that pastures with no grazing or light grazing resulted in no changes in SOC at the 0- to 60-cm depth after a 10 yr period, compared with a 30% loss in SOC when pastures were heavily grazed. They reported that depths of 0- to 5- and 15- to 30-cm with light grazing and no grazing resulted in higher SOC accumulation than heavy grazing. Schönbach et al. (2012) found that pastures ungrazed by sheep accumulated SOC, pastures lightly grazed remained balanced in SOC, and pastures moderately or heavily grazed decreased SOC in the top 0- to 5-cm of soil, compared with pasture being cut for hay. Conversely, Hart et al. (1995) observed increases in SOC storage in treatments that were lightly or heavily grazed by cattle, compared to ungrazed treatments in the top 7.6 cm of soil for pastures that had been grazed for >10 yr. They also found that at depths from 7.6- to 30-cm, SOC in all lightly and heavily grazed treatments remained greater than or equal to that of ungrazed enclosures.

MANAGEMENT EFFECTS ON SOIL NITROGEN

Increasing SOC with proper residue management has potential to increase N use efficiency and reduce leaching and runoff of N (Cole et al., 1997; Venterea et al., 2005). The majority of N losses from agriculture occur as the result of inefficient N fertilization (Jarecki et al., 2008; Venterea et al., 2005). Loss of N can be reduced by properly managing substrates in the soil such as crop residue, organic amendments, and fertilizers (Beauchamp, 1997). Conservation practices, such as decreased tillage and use of manure as a fertilizer, have shown to increase long-term storage of soil N in cropping systems (Mikha et al., 2006).

Tillage Effect on Soil Nitrogen

Conservation tillage practices have exhibited potential to increase storage of soil N, particularly in the top layers of soil. Wood et al. (1991) found increased accumulation of N pools 4 yr after conversion to no-tillage management in cropland that had been previously under tillage management for >50 yr. Franzluebbers and Stuedemann (2008) also found greater amounts of total soil organic N in the top 6 cm of soil with no-tillage (1.59 g N kg^{-1} soil) when compared with conventional tillage with a moldboard plow (0.7 g N kg^{-1} soil). At a 6- to 12-cm depth, they observed no differences in tillage treatment, and at a depth of 12- to 30-cm, conventional tillage treatments stored greater amounts of soil organic N. When examining potential N mineralization, Franzluebbers and Stuedemann (2008) observed a similar trend to that of total organic N. No-tillage was greater than conservation tillage at 0- to 3- and 3- to 6-cm, while conservation tillage was greater at 6- to 12-, 12- to 20-, and 20- to 30-cm depths. In a study by Watts et al. (2010), a >75% increase in soil N and a 15% increase in soil N mineralization in the top 5 cm of soil was observed for a soybean cropping system under conservation tillage, when compared to the same crop under conventional tillage. The opposite was true for the 5- to 10-cm depth, where N mineralization was 64% higher with conventional tillage.

Several studies have reported a reduction in N loss as N_2O with conservation tillage (Heller et al., 2010; Lee et al., 2006; Ussiri et al., 2009). Nitrous oxide emissions of 0.94 kg N_2O–N ha^{-1} yr^{-1} were obtained by Ussiri et al. (2009) with no-tillage management, which was almost half of the amount emitted when using a moldboard plow (1.82 kg N_2O–N ha^{-1} yr^{-1}). Heller et al. (2010) observed an annual increase of 8.1 kg N_2O–N ha^{-1} emissions when using shallow tillage instead of no-tillage. Robertson et al. (2000) did not observe variations among N_2O emission between no-tillage and conventional tillage systems.

Grazing Effect on Soil Nitrogen

In grazed pastures, manure and urine deposits may provide readily-decomposable organic C and N compounds that can be utilized by soil microorganisms (Oenema et al., 1997). Over a 12 yr period, Schuman et al. (1999) found increases of 450-700 kg N ha^{-1} in grazing treatments compared with ungrazed treatments in the top 30 cm of soil. They also found increased N storage in moderately-grazed pastures compared with pastures that had been over-grazed, indicating that appropriate management of livestock, as opposed to overgrazing, can more efficiently retain soil N. Comparable results were found by Hart et al. (1995); an increase in soil N content in the top 7.6 cm of soil occurred over an 11 yr period with light and heavy grazing compared to non-grazing treatment with enclosures that prevented cattle from entering. They also observed that soil N remained higher or equal to that of the enclosures in all treatments that had been lightly grazed by cattle at depths from 7.6- to 30-cm. Franzluebbers and Stuedemann (2008) did not observe increases in soil N levels with grazing but did find that soil N was maintained after 3 yr of grazing in the southeast U.S.

NATURAL ABUNDANCE OF ISOTOPIC CARBON

Stable C isotopic-ratio analysis has been used to quantitatively trace the source of carbon from C_3 and C_4 plants (Balesdent and Balabane, 1992; Flessa et al., 2000; Bronson et al., 2004; Haile et al., 2010) and to identify distribution and relative losses of SOC under agricultural production (Cambardella and Elliott, 1992; Conteh and Blair, 1998). It is useful in field experiments where a shift is being made from C_3 to C_4 crop production, or vice versa. This technique is based on the difference in anatomy and carbon fixation of C_3 and C_4 plants. Plants with the C_4 photosynthetic system (e.g., bahiagrass) have a specific leaf anatomy that concentrates CO_2 in the bundle sheath cells and increases the efficiency of ribulose-1,5-bisphosphate carboxylase oxygenase (RuBisCO), which is a key CO_2 fixation enzyme with a known discrimination of $^{12}CO_2$ in preference to $^{13}CO_2$. Therefore, C_4 plants have a greater $^{13}C/^{12}C$ ratio than C_3 plants. The difference in $^{13}C/^{12}C$ ratio between plants occurs at a much larger scale than changes that occur during SOC degradation processes (Balesdent and

Mariotti, 1996). The delta (δ) notation is commonly used to report carbon isotopic ratios near natural abundance levels and is defined in Equation 1, where R = $^{13}C/^{12}C$ and the standard for C is the internationally accepted Vienna Pee Dee Belemnite (VPDB; $^{13}C/^{12}C$ = 0.112372; Coplen, 1996). Thus, C_4 plants have higher $\delta^{13}C$-values (-19 to -9‰) than C_3 plants (-35 to -20‰) (Haile et al., 2010).

$$\partial^{13}C = \frac{R_{sample} - R_{standard}}{R_{standard}} x1000 \qquad \text{Equation 1}$$

By measuring changes in $\delta^{13}C$-values over time, it is possible to quantify the amount of SOC being stored from C_3 or C_4 plants (Balesdent and Mariotti, 1996). Carbon isotopic analysis is well-suited for comparing the SBR system with the conventional peanut-cotton rotation when bahiagrass is the only C_4 plant and other crops (i.e., peanut and cotton) are C_3 plants. Isotopic analysis of SOC can evaluate the specific contribution of bahiagrass to SOC storage and the effect of management practices on bahiagrass-derived SOC contribution. Isotopic composition has been used to determine the impacts of grazing intensities on SOC retention in a pastureland in the southeastern U.S. (Silveira et al., 2013). However, no previous study has shown other effects of management (e.g., tillage and grazing) on changes in isotopic composition of SOC in the SBR.

Isotopic analysis of $\delta^{13}C$ of CO_2 formed during soil respiration has been used to determine mineralization rates of C_4–SOC relative to C_3–SOC (Flessa et al., 2000). There are two processes which affect the isotopic ratio of $^{13}C/^{12}C$ during mineralization, the preference of microorganisms for new, easily degradable SOC inputs and discrimination of ^{13}C in preference to lighter ^{12}C of soil microorganisms (Flessa et al., 2000; Kristiansen et al., 2004). However, discrimination by microorganisms is often negligible when compared to the preference of microorganisms for new, more labile SOC inputs available for degradation (Blagodatskaya et al., 2011). Whether bahiagrass-derived SOC is more or less labile than C_3-plant derived SOC can be investigated by examining the $\delta^{13}C$ of CO_2 mineralized in a laboratory incubation study.

THE GREENHOUSE EFFECT

In order for earth's climate to remain balanced, a radiative equilibrium of incoming solar radiation and outgoing infrared radiation must take place. As solar radiation reaches earth's surface, it is used to warm the earth. Earth returns heat to the atmosphere by emitting infrared radiation. As infrared radiation travels through the atmosphere, some is trapped in gas molecules. Gases that absorb radiation within the wavelength range of 5-50 µm are known as GHG (Jacob, 1999). Gas molecules will only absorb radiation if the energy from the radiation causes transition to a higher energy level, and if charge asymmetry is possible. Greenhouse gases contribute to global climate change by returning some of the radiation to earth's surface. They include CO_2, N_2O, and CH_4 and occur both naturally and from anthropogenic sources (IPCC, 2001). Increasing abundance of GHG in the atmosphere may be a contributor to global climate change (IPCC, 2001). Mitigation of greenhouse gases is important in agricultural soils since they are large contributors to GHG emission, and have potential to sequester CO_2 as SOC (Morgan et al., 2010). Incorporating perennial grasses and conservation tillage has potential to mitigate CO_2 flux in soils of the Coastal Plain region by storing SOC.

Contribution of Agriculture to Greenhouse Gas Emissions

Global atmospheric CO_2 concentration is increasing at a rate of 1.4 ppm yr^{-1} (Solomon et al., 2007). The world's soils hold approximately 2000 Gt C, making it the largest component of the global terrestrial C stock (Turcu et al., 2005). Sources of CO_2 in the atmosphere include fossil fuel combustion, deforestation and decomposition of plant matter (Solomon et al., 2007). Agricultural soils have lost 30 to 70% of their initial amount SOC as a result of increased cultivation (Eve et al., 2002; Lee et al., 2006), and it has been projected that 80 Pg C-CO_2 is emitted into the atmosphere from the soil-atmosphere interface each year (Raich et al., 2002). The production of CO_2 in the soil comes primarily from respiration of soil microorganisms (Solomon et al., 2007).

Methane is 25 times more potent than CO_2 at trapping infrared heat (Weihermüller, 2011), and approximately 50% of CH_4 emissions result from agriculture (Smith et al., 2007). The production of CH_4 primarily occurs under anaerobic conditions. Sources of CH_4 include wetlands, landfills, rice production, and livestock production sites (Solomon et al., 2007). Soil may be a source of CH_4 when oxygen is limiting through process of methanogenesis but can also be consumed by the soil by methanotrophic bacteria (Ussiri et al., 2009). While agricultural soils act as either producers or consumers of CH_4, which is dependent upon moisture and land-management practices (Chan and Parkin, 2001; Hernandez-Ramirez et al., 2009; Venterea et al., 2005), the production of CH_4 is often negligible (Flessa et al., 2002; Ginting et al., 2003).

The International Panel on Climate Change (Solomon et al., 2007) reported that atmospheric N_2O concentration has risen from 314 ppb in 1998 to 319 ppb in 2005. The average rate of increase in N_2O concentration in the atmosphere has been estimated at 0.2 – 0.3% yr^{-1}. Although the rate of increase may seem small, N_2O is 300 times more effective at trapping infrared heat than CO_2 (Beauchamp,1997; Weihermüller et al., 2011). Production of N_2O is primarily carried out by soil microorganisms during nitrification and denitrification processes. It has been estimated that agriculture is the source 60% of global N_2O emissions (Smith et al., 2007), of which 15% is contributed from livestock farming (Oenema et al., 2008). There are three primary sources for N_2O production: mineralization of organic N, decomposition of organic additions such as manure, and inorganic N fertilizer (Mikha et al., 2006). The majority of N_2O released from agriculture is the result of N fertilization, which increases substrate availability for nitrification and denitrification processes (Jarecki et al., 2008; Venterea et al., 2005). Loss of N_2O to nitrification and denitrification processes can be managed by altering substrates in the soil that contribute to these processes, such as crop residue, organic amendments, and fertilizers (Beauchamp, 1997). The most efficient way to mitigate N_2O emissions is to promote N use efficiency.

Perennial Grass Effect on Greenhouse Gas Emissions

Studies comparing CO_2 emissions in cropland with grasslands have been variable. Raich and Schlesinger (1992) reviewed global studies on soil respiration rates and determined that the average respiration rate for cropland is 544±80 g C m^{-2} yr^{-1}, while grasslands only produce 442±78 g C m^{-2} yr^{-1}. Reducing cropping intensity with the use of perennial grasses has potential to decrease losses of SOC as CO_2. However, some studies have reported higher CO_2 emission in grassland systems compared with cropland due to increased C storage from their large root systems (Sainju et al., 2010b).

While agricultural soils act as either producers or consumers of CH_4, dependent upon moisture and land-management practices (Chan and Parkin, 2001; Hernandez-Ramirez et al., 2009; Venterea et al., 2005), undisturbed soils are often sinks for CH_4 (Ussiri et al., 2009; Venterea et al., 2005). It has been estimated that 0.5 – 5.6 Tg of CH_4 is taken up by grassland systems each year globally (Mosier et al., 1991). Mosier et al. (1991) observed uptake of 2.6, 1.8 and 6.3 g CH_4 ha^{-1} d^{-1} on native grassland, fallow, and cultivated wheat, respectively, indicating that increased biomass production can decrease net uptake of CH_4.

Grazing Effect on Carbon Dioxide and Methane Flux

Livestock production is expected to increase in the coming years due to high population growth rates as well as increasing meat consumption in developing countries (Oenema et al., 2008). Increased livestock production will result in more land being put into grazing management. Grazing has the potential to increase emission rates of GHG (Schönbach et al., 2012) by providing soluble forms of C that are available for respiration. However, increases in SOC storage may mitigate a portion of the increase in GHG flux (Ginting et al., 2003). Livestock production contributes to atmospheric CH_4 primarily through enteric formation (i.e., formed during digestion and released through the nose and mouth) and through the release of manure. Enteric formation releases 80 Tg CH_4 yr^{-1}, accounting for about 20-25% of the global rise of atmospheric CH_4 (Lassey, 2007). When compared with enteric formation, CH_4 emissions from manure are minor. Soils typically act as a sink for CH_4 instead of a source of CH_4.

Following the release of manure from livestock, Flessa et al. (1996) observed that soils became a net sink for CH_4, after 20 d had passed. Liebig et al. (2010) also found that pasture land grazed by cattle acted as a sink for CH_4. When land was moderately or heavily grazed by cattle, approximately 1.9 kg CH_4–C ha^{-1} yr^{-1} was taken up by the soil. Schönbach et al. (2012) observed uptake of CH_4 in treatments that were ungrazed, lightly grazed, moderately grazed, or heavily grazed by sheep. Highest uptake of CH_4 took place with lightly grazed treatments, while lowest uptake was in heavily grazed treatments compared with ungrazed and moderately grazed treatments. Under light grazing, CH_4 uptake was sufficient to offset enteric formation. In a study by Johnson and Matchett (2001), respiration rates for land ungrazed and grazed by bison were 76.1 and 40.6 kg CO_2–C ha^{-1} d^{-1}, respectively. Land grazed by bison resulted in significantly lower CO_2 flux than ungrazed.

Grazing Effect on Nitrous Oxide Flux

Approximately 15% of N_2O released in agriculture is contributed by livestock farming (Oenema et al., 2008). Cattle excretions are the source of an estimated 1.18 Tg of N_2O–N (Flessa et al., 1996). However, organic wastes released during grazing are often considered more efficient fertilizer than inorganic fertilizers since they must be mineralized prior to plant uptake. Nitrogen from excretions must be must be converted to ammonium before it can be further used by nitrifying and denitrifying microorganisms (Oenema et al., 1997).

Several studies have reported increased N_2O emissions in pastures grazed by livestock compared to those left fallow (Chroňáková et al., 2009; Oenema et al., 1997). However, N_2O measurement in pasture systems is often highly variable due to unequal distribution of animal waste (Liebig et al., 2010). Flessa et al. (1996) reported that 3.2% of excreted N from livestock is released as N_2O. Similarly, Oenema et al. (1997) reported that 2% of N in excrements is released as N_2O. They found that N_2O emissions in 4 soil types were consistently higher in grazed land compared to grassland that was mowed, except in winter months when grazed and ungrazed treatment did not differ. In contrast, Liebig et al. (2010) did not observe differences in N_2O flux when comparing moderately (1.1±0.2 kg N_2O–N) and heavily (1.0±0.1 kg N_2O–N ha^{-1} yr^{-1}) grazed pastures. Some studies have even shown decreases in N_2O flux with grazing. Schönbach et al. (2012) found that as grazing intensity increased, emission of N_2O from the soil decreased in pastures grazed by sheep. Studies that examine N_2O flux from soil have been highly variable when comparing grazing systems. Although studies involving flux of N_2O with grazing have been variable, many studies report increased levels of soil N with grazing. Although N_2O emissions are often higher in grazed pastureland, a portion of these emissions can be mitigated by increased storage of N.

Wastes produced during grazing may increase the emission of CO_2, N_2O, and CH_4 from the soil. However, incorporating high-biomass crops and no- or reduced-tillage practices in a cropping rotation may help mitigate the net emission of GHG from agricultural soils through sequestration of SOC. While it is well established that pastures can increase SOC storage compared to row cropping, it is necessary to determine implications of short-term (2 yr) incorporation of pastureland in a crop rotation on SOC storage and GHG emissions with and without grazing.

OBJECTIVES

The traditional peanut-cotton rotation in the Coastal Plain decreases soil fertility, increases susceptibility to erosion, and limits the soils ability to sequester SOC. Lack of crop diversity in this system can potentially increase occurrence of pests and decrease yields in peanut and cotton. A more sustainable cropping system is needed in the peanut-producing portion of the Coastal Plain. One method for improving productivity and sustainability of these soils is to increase the amount of biomass produced. It has been demonstrated that incorporation of bahiagrass into a cropping system has potential to improve yields and break pest cycles in crop rotations in the southeastern Coastal Plain (Hagan et al., 2003). However, there is a need to estimate the impact of the SBR on the environment.

The first objective of this study was to measure storage and mineralization rates of SOC and soil N in a long-term (>10 yr) SBR compared with a traditional peanut-cotton rotation (TR). Dry combustion was used to measure total SOC and soil N, and a laboratory incubation study was used to evaluate potential mineralization of SOC and soil N. Natural isotopic abundance of ^{13}C was used to determine the amount of SOC derived from bahiagrass compared to SOC derived from other crops in the SBR. Isotopic analysis of CO_2 mineralized in a laboratory incubation study was used to compare mineralization rates of bahiagrass-derived SOC with C3-derived SOC. The SBR and TR were examined under two tillage (i.e., conventional tillage, strip-tillage) and two grazing (i.e., grazed, ungrazed) treatments for this objective. The second objective was to assess emissions of CO_2, CH_4, and N_2O in the SBR and TR. Greenhouse gases were seasonally measured using a closed chamber method to determine the effect of grazing on emissions. This complete study will evaluate SOC and soil N cycling to determine the effectiveness of the SBR as an environmentally sustainable cropping system.

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II. IMPACT OF A PEANUT-COTTON-BAHIAGRASS ROTATION ON SOIL ORGANIC CARBON AND NITROGEN STORAGE IN THE SOUTHEASTERN COASTAL PLAIN

ABSTRACT

Restoration of soil fertility is important in the peanut-producing region of the Coastal Plain, where many soils are highly weathered, structurally weak, and low in fertility as a result of intense row cropping. A common cropping system in the Coastal Plain is an annual peanut (*Arachis hypogaea* L.) and cotton (*Gossypium hirsutum* L.) rotation under conventional tillage (CT). This type of system often results in loss of soil organic carbon (SOC) and susceptibility to erosion. Incorporation of perennial grasses such as bahiagrass (*Paspalum notatum* Fluegge) to the peanut-cotton rotation has been suggested for improving SOC. To determine the effect of a 2 yr incorporation of bahiagrass into the peanut-cotton rotation (also called a sod-based rotation or SBR) on carbon sequestration, SOC and its isotopic composition were evaluated on established (>10 years) crop rotation systems. Mineralization of SOC and isotopic composition of CO_2 mineralized were used to assess the recalcitrance of bahiagrass-derived SOC. Soil N and mineralization were also determined. Effects of tillage and grazing on SOC storage were assessed in the SBR. The SBR did show consistent improvements in SOC compared to the TR. Total SOC, soil N, bahiagrass-derived SOC, and potential C mineralization increased in the top 10 cm of soil and were stratified with depth under ST in the SBR, indicating the potential of the ST to increase soil fertility. Although grazing of bahiagrass decreased SOC in the 5- to 10-cm depth, this effect was not observed for the subsequent peanut crop and did not appear to have a long-term effect on SOC storage. Isotopic analysis of mineralized CO_2 was slightly higher in ^{13}C than the SOC from which it was derived, indicating that SOC with a higher $^{13}C/^{12}C$ ratio (e.g.,

bahiagrass-derived SOC) may be preferred over SOC with a lower ratio (e.g., C_3 crop-derived SOC) for degradation by microorganisms. The preference for ^{13}C for mineralization may explain why 2 yr of bahiagrass did not reliably increase SOC. Because SOC increased from 2009 to 2012, other conservation practices (e.g., winter cover cropping) are likely to have contributed to SOC storage in the Coastal Plain soils in this study.

Abbreviations: CT, conventional tillage; SBR, sod-based rotation; SOC, soil organic carbon; ST, strip-tillage; TR, traditional peanut-cotton rotation

INTRODUCTION

Although the Coastal Plain in the southeastern U.S. has favorable climate for crop production (Causarano et al., 2008), soils in this area have a low nutrient-holding capacity that can be limiting for plant growth (Franzluebbers, 2010). Much of the decline in soil fertility in this region is due to the loss of SOC, which is known for its high nutrient- and water-holding capacities, as well as its ability to contribute to soil aggregation and improve soil structure. Producers in the peanut-producing portion of the southeastern Coastal Plain often rotate peanuts annually with cotton. This type of system often leads to loss of SOC due to soil erosion (Campbell et al., 1991; Katsvairo et al., 2006), particularly when operated under CT management (Tivy, 1987). Because the southeastern U.S. produces approximately 50% of U.S. cotton and 80% of U.S. peanut (Franzluebbers, 2007), it is necessary to identify management practices that can restore fertility to these soils. Conservation practices (e.g., winter cover cropping, conservation tillage) are known for their ability to increase soil fertility (Prior et al., 2010; Simoes et al., 2009; Watts et al., 2010b), improve soil aggregation (Reeves et al., 1994), and offset the emission of greenhouse gases (Liebig et al., 2010; Robertson et al., 2000). It has been estimated that for soils in the Southeast, conservation tillage has the ability to sequester 0.45 Mg ha^{-1} yr^{-1} compared to soils under CT (Franzluebbers, 2010). However, previous research has shown that even under conservation tillage, SOC storage may not be adequate to maintain SOC levels when land is used for annual crop production (Huggins et al., 2007). Incorporation of perennial grass pastures (e.g., bahiagrass) may have potential to further promote SOC sequestration in the Southeast (Causarano et al., 2008).

Incorporation of 2 yr of bahiagrass to the peanut-cotton rotation (also called a sod-based rotation or SBR) has been suggested as a method for improving soil fertility in the Southeast. Perennial grasses produce a large biomass above and below ground that increases SOC, improves soil structure, and lessens soil erosion (Katsvairo et al., 2006). Bahiagrass is a perennial forage grass that is suited to low fertility soils (Magness et al., 1971). Often, soils in the Southeast have a root restricting zone at the 15-cm depth that limits water and nutrient availability to row crops (Barley et al., 1965; Doty et al., 1975; Trouse and Reaves, 1980). The large root biomass of bahiagrass (Blue and Graetz, 1977; Impithuksa and Blue, 1978) has demonstrated the ability to reach below this root restricting zone, which allows roots of subsequent crops to explore a larger soil volume and add nutrient- and moisture-holding capacity (Katsvairo et al., 2007). Rotations that incorporate perennial grasses have shown to increase SOC, particularly in conjunction with conservation tillage practices (Wilson et al., 1982; Reeves, 1994; Wright et al., 2005). Strip-tillage (ST) has been identified as a practical conservation tillage method for peanut and cotton production in the Southeast (Katsvairo et al., 2006) and has been shown to improve SOC levels in the Coastal Plain (Balkcom et al., 2013).

Because the addition of bahiagrass into a crop rotation would reduce row crop acreage, the economic benefits may not outweigh the environmental benefits. Cattle grazing of perennial grasses and winter cover crops would allow a source of income when row crops are not in rotation. In addition to providing income, moderate cattle grazing can enhance agricultural productivity by improving SOC content and providing nutrients to a soil (Franzluebbers and Stuedemann, 2008). Proper grazing-land management has the potential to increase global C stock by 0.1 to 0.3 Mg ha^{-1} yr^{-1} for pastures in the U.S. (Morgan et al., 2010), as a result of increasing decomposition rates and redistribution of plant material (Reeder et al., 2001). Although it is well-established that conversion to conservation tillage or pastureland can increase SOC storage, research is necessary to determine the impact of a short-term (2 yr) pastureland in a crop rotation to SOC. Comparing SOC storage in a SBR and a traditional peanut-cotton rotation (TR) may provide an indication of the potential of the SBR to increase nutrient-holding capacity, improve soil structure, and mitigate CO_2 emissions.

To further examine SOC storage in the SBR, it is useful to compare amounts of SOC contributed by bahiagrass to SOC contributed by row crops. Stable C isotopic-ratio analysis has been used to quantitatively trace the source of carbon from C_3 and C_4 plants (Balesdent and Balabane, 1992; Flessa et al., 2000; Bronson et al., 2004; Haile et al., 2010) and to identify distribution and relative losses of SOC under agricultural production (Cambardella and Elliott, 1992; Conteh and Blair, 1998; Silveira et al., 2013). It is useful in field experiments where a shift is being made from C_3 to C_4 crop production, or vice versa. This technique is based on the difference in anatomy and carbon fixation of C_3 and C_4 plants. Plants with the C_4 photosynthetic system (e.g., bahiagrass) have a specific leaf anatomy that concentrates CO_2 in the bundle sheath cells and increases the efficiency of ribulose-1,5-bisphosphate carboxylase oxygenase

(RuBisCO), which is the key CO_2 fixation enzyme with a known discrimination of $^{12}CO_2$ in preference to $^{13}CO_2$. Thus, C_4 plants are known to have a greater $^{13}C/^{12}C$ ratio and higher $\delta^{13}C$-values (–19 to –9‰) than C_3 plants (–35 to –20‰) (Haile et al., 2010). The difference in $^{13}C/^{12}C$ ratio between C_3 and C_4 plants occurs at a much larger scale than changes that occur during SOC degradation processes (Balesdent and Mariotti, 1996).

Carbon isotopic analysis is well-suited for comparing the SBR system with the conventional peanut-cotton rotation when bahiagrass is the only C_4 plant and other crops (i.e., peanut and cotton) are C_3 plants. By measuring changes in $\delta^{13}C$ values between rotations, it is possible to quantify the contribution and distribution of bahiagrass-derived SOC (SOC_4–C) storage compared to C_3 plant-derived SOC (SOC_3–C) in the SBR (Balesdent and Mariotti, 1996).

In addition to SOC analysis, potential C and N mineralization are good indicators of soil health (Sainju et al., 2007; Wood and Edwards, 1992). Doran (1980) found that increases in potentially mineralizable N are associated with increasing populations of soil microorganisms. Laboratory incubation studies are highly correlated with mineralization under field studies and are often carried out to examine potential mineralization rates in a controlled environment (Mikha et al., 2006). Potential mineralization is largely dependent on soil texture, temperature, moisture, and agricultural management practices (Watts et al., 2010a). By holding temperature and moisture constant in a laboratory incubation study, the effects of management practices on mineralization rates can be more closely examined for a particular soil type. Incubation studies can be used to determine the amount of CO_2 from C_3-derived or C_4-derived SOC by measuring the $\delta^{13}C$ of mineralized CO_2 (Flessa et al., 2000). Although microorganisms have shown a preference of ^{12}C compared to ^{13}C (Flessa et al., 2000; Kristiansen et al., 2004), discrimination against ^{13}C is typically negligible when compared to the preference of microorganisms for new, more labile SOC inputs available for degradation (Blagodatskaya et al., 2011). Determining rates of mineralization of C_3-derived compared to C_4-derived SOC can estimate the lability of bahiagrass-derived SOC in the SBR. Studies that evaluate retention and degradation of SOC are becoming increasingly important as CO_2 concentrations in the atmosphere continue to rise (Balesdent and Mariotti, 1996).

Data supporting the long-term efficacy of the SBR for C sequestration and the contribution of bahiagrass to long-term C pools is not well-documented. Evaluation of SOC and mineralization rates in the SBR is important to provide preliminary assessment of soil health. Isotopic analysis of SOC is useful to determine the contribution and depth distribution of bahiagrass-derived SOC compared to C_3 crops. Incubation studies that analyze the $\delta^{13}C$ ratio of CO_2 produced during mineralization may elucidate factors affecting SOC storage and degradation. The objective of this study was to evaluate SOC storage and degradation in the SBR and compare to the TR on Coastal Plain soils.

MATERIALS AND METHODS

Site Description

Three established (>10 years) SBR systems were evaluated for this study, one at the North Florida Research and Education Center (NFREC) in Marianna, FL and two at the Wiregrass Research and Extension Center (WREC) in Headland, AL. At NFREC, a farm-scale large plot system was evaluated (NFREC-LP). Soils at the NFREC-LP site are primarily (>70%) classified as loamy, kaolinitic, thermic Arenic Plinthic Kandiudults of the Fuquay series. At WREC, a small-plot experiment (WREC-SP) was tested in addition to a farm-scale large plot experiment (WREC-LP). Soils at the WREC site are classified as fine-loamy, kaolinitic, thermic Plinthic Kandiudults of the Dothan series.

Experimental Design

At NFREC-LP, a 61 ha field was divided equally into quadrants rotating all phases of the SBR (Figure 2-1). Phases included a sequential rotation of peanut (Peanut-SBR), cotton (Cotton-SBR), bahiagrass in its first year (Bahia1-SBR), and bahiagrass in its second year (Bahia2-SBR). Pensacola bahiagrass was used at NFREC-LP. The winter cover crop of oat (*Avena sativa* L.) and rye (*Secale cereale* L.) or annual ryegrass (*Lolium multiflorum* L.) followed Peanut-SBR, Cotton-SBR, and Bahia2-SBR each winter at NFREC-LP. Two cattle exclusion cages (15 x 15 m) were placed into each quadrant >5 yr prior to sampling using GPS coordinates during each grazing period. This area was established as the ungrazed sampling area. A similarly sized area was identified 3 m to the side of each cage as a grazed sampling area. Soil samples were taken near the middle of each ungrazed and grazed sampling area to assess the effect of grazing on SOC and soil N storage in all phases of the SBR. An additional grazed sampling area within each quadrant was established to increase sampling replications at NFREC-LP. Therefore, two ungrazed and three grazed areas were sampled for each phase of the SBR at NFREC-LP.

At WREC-LP, a field of 20.2 ha was divided into six sections (Figure 2-2). Four of the six sections rotated all phases of the SBR in a sequential rotation of Peanut-SBR, Cotton-SBR, Bahia1-SBR, and Bahia2-SBR. Three fenced cages (15 x 15 m) were placed into each section during grazing to exclude cattle and provide an ungrazed sampling area. A similarly sized area was identified 3 m to the side of each cage as a grazed sampling area. The additional two sections were established in a traditional rotation of peanut (Peanut-TR) and cotton (Cotton-TR) for comparison to the SBR. These sections each contained two cattle exclusion cages for ungrazed sampling areas and two non-caged grazed sampling areas. Soil samples were taken near the middle of each ungrazed and grazed sampling area to assess the effect of grazing on SOC storage. Cattle exclusion cages had been used for >5 yr and placed prior to each grazing event using GPS coordinates. Tifton 9 bahiagrass was used at WREC-LP and WREC-SP. A winter cover crop of oat and rye mixture followed Peanut-TR, Cotton-TR, Peanut-SBR, Cotton-SBR, and Bahia2-SBR crops each winter at WREC-LP.

Management factors were identical in caged and non-caged areas of large plot experiments with the exception of bahiagrass being periodically cut for hay in caged areas. All large plots in the SBR were managed under pivot irrigation and ST. Large plots in the TR were managed with ST before planting Peanut-TR and Cotton-TR, but disked before planting the winter cover crop at WREC-LP. At NFREC-LP, cotton stalks were pulled after harvest, which had an effect of turning the soil. At WREC-LP, cotton stalks were mowed after harvest.

Each crop phase is classified as the summer phase of the rotation and includes the subsequent winter cover crop. For example, Peanut-SBR indicates peanut in the summer followed by the winter cover crop, and changes to Cotton-SBR when cotton is planted the following summer. Cattle grazed Bahia2-SBR during summer and early fall. During winter and spring, cattle grazed cover crop as forage was available. At WREC-LP, a stocking rate of approximately 2.5 cattle ha^{-1} was employed during summer grazing of Bahia2-SBR and during winter grazing of cover crops following Peanut-SBR, Cotton-SBR, Peanut-TR, and Cotton-TR. Bahia1-SBR was grazed from the end of September until the beginning of December at a stocking rate of 2.5 cattle ha^{-1}, while winter cover crops were being established in other blocks. A rate of 1.2 cattle ha^{-1} was used for grazing the winter cover crop that followed Bahia2-SBR.

Bahia1-SBR was only grazed from the end of September until the beginning of December at a stocking rate of 2.5 cattle ha^{-1}, while winter cover crops were being established in other blocks. Fertilizer and herbicide at WREC-LP and WREC-SP were applied according to Alabama Cooperative Extension System recommendations. At NFREC, a stocking rate of approximately 3.4 cattle ha^{-1} was used for grazing of all winter cover crops, and 2.5 cattle ha^{-1} was used for summer grazing of bahiagrass (Bahia2-SBR). Fertilizer and herbicide at NFREC-LP were applied according to University of Florida Extension recommendations.

At WREC-SP, all crops in the SBR (i.e., Peanut-SBR, Cotton-SBR, Bahia1-SBR, Bahia2-SBR) and the TR (i.e., Peanut-TR, Cotton-TR) were included in the experiment. Each crop phase was replicated five times under two tillage treatments (i.e., ST and CT). Small plots were organized in an incomplete randomized block design. Three of the five replications for each treatment were randomly chosen for this study. Small plots were managed under pivot irrigation with an oat/rye cover crop following Peanut-TR, Cotton-TR, Peanut-SBR, Cotton-SBR, and Bahia2-SBR crops each winter. Winter cover crops and bahiagrass were cut and left on top of the soil as residue instead of being cut for hay at WREC-SP. No grazing treatments were included in the small plot study.

Soil Sample and Plant Material Collection

Soil samples were collected using a truck-mounted Giddings probe (Giddings Machine Company, Windsor, CO) in December 2012, after harvest of summer crops. For each plot, three cores of approximately 4 cm in diameter were taken to a depth of 60 cm and divided into 0- to 5-, 5- to 10-, 10- to 15-, 15- to 30- and 30- to 60- cm increments while in the field. Upon return, soils were stored at room temperature for <2 wk, until drying for bulk density.

An additional core was taken in each plot and divided into of 0- to 5-, 5- to 10- and 10- to 15- cm increments in the field and refrigerated at 4ºC prior to use in incubation studies. Samples were placed in the refrigerator within 5 d of retrieval. Soils were refrigerated for approximately 8 wk until the incubation was begun.

Leaf samples for cotton, peanut, bahiagrass, and winter cover crop were taken by selecting three leaves from 10 randomly selected plants for each crop. Plant samples were dried at 60ºC, ground, and stored at room temperature until weighing for isotope analysis.

Laboratory Analysis

To determine bulk density, soils were oven dried at 60ºC for 48 hr. After drying, oven-dry weight (ODW) and core volume (CV) of the soil sample were recorded. Samples were ground with a mortar and pestle and sieved through a 2-mm sieve to remove rocks. Rock weight (RW) and rock volume (RV) were recorded. Bulk density was determined according to the formula:

$$Bulk\ Density = \frac{(ODW - RW)}{(CV - RV)}$$

After measuring bulk density, the three samples for each plot were mixed to form a composite sample. Soils were then ground with a coffee grinder to obtain fine particles (<1 mm) that could be used to determine total C and N. Dry combustion with a CN LECO 2000 analyzer (LECO Corp., St. Joseph, MI) was used to measure total C and N. To ensure that all C present in soils was part of the organic fraction, a simple titrimetric procedure to determine carbonate content was followed according to a method by Loeppert and Suarez (1996). None of the samples contained inorganic C. To convert SOC and soil N from g C kg^{-1} to Mg C ha^{-1} or g N kg^{-1} to Mg N ha^{-1}, the appropriate bulk density and volume of soil was multiplied by SOC or total N concentration.

To measure changes in SOC over a three year period, SOC measurements in December 2012 were compared to SOC measurements taken in March 2010 using the same methods and equipment as described for the current study. Changes in SOC over time were reported as a concentration instead of total SOC, because bulk densities were not recorded for soil samples from March 2010.

Soil samples of approximately 75 mg were weighed and sent to the Stable Isotope Facility at the University of California Davis. At the isotope facility, soil samples were analyzed using a PDZ Europa ANCA-GSL elemental analyzer paired with a PDZ Europa 20-20 isotope ratio mass spectrometer (Sercon Ltd., Cheshire, UK). Results were reported using the delta (δ) notation, which is the common reporting unit for carbon isotopic ratios near natural abundance levels and is defined in Equation 1, where R = $^{13}C/^{12}C$ and the standard for C is the internationally accepted Vienna Pee Dee Belemnite (VPDB; $^{13}C/^{12}C$ = 0.112372; Coplen, 1996).

$$\partial^{13}C = \frac{R_{sample} - R_{standard}}{R_{standard}} x1000 \qquad \text{Equation 1}$$

The percentage of carbon derived from bahiagrass was determined using Equation 2 (Balesdent and Mariotti, 1996), where δ is the $\delta^{13}C$ of a given sample, δ_3 represents the $\delta^{13}C$ value for the C_3 plants (i.e., peanut, cotton, oat, rye) and δ_4 represents the $\delta^{13}C$ value for the C_4 plant (i.e., bahiagrass).

$$\%C_4\text{-derived SOC} = \frac{(\partial - \partial_3)}{(\partial_4 - \partial_3)} \text{x}100 \qquad \text{Equation 2}$$

The $\delta^{13}C$ value for the C_3 plants was determined by taking the average $\delta^{13}C$ for peanut, cotton, oat, and rye, which were −28.21‰, −28.82‰, −29.19‰, and −30.41‰, respectively. These were similar to literature values of −25.8‰ for peanut (Hubick et al., 1986), −26.4‰ for cotton (Tsialtas et al., 2008), and –27.2‰ for rye (Nii-Annang et al., 2009). The $\delta^{13}C$ value for bahiagrass, the only C_4 plant, was −12.38‰, which was similar to that obtained by Haile et al. (2010). The total contribution of SOC from bahiagrass was determined by multiplying the %C_4-derived SOC by the total SOC content. Isotopic C was measured at WREC-SP and NFREC-LP and not at WREC-LP, due to previous long-term management under switchgrass that may have confounded results.

Incubation Study

To prepare soils for the incubation study, oven-dry weight was determined on a subsample of the refrigerated soil samples. Approximately 5 g of each sample was weighed, dried in a 105ºC oven for at least 48 hours, and reweighed. Dry weight was divided by wet weight to obtain percent moisture. Web soil survey (USDA-NRCS, 2013) was used to approximate water content at −33 kPa (i.e., field capacity). Field capacity was 15.08% (w/w) for soils at WREC and 4.00% (w/w) at NFREC.

Laboratory incubations followed the procedure outlined by Torbert et al. (1999). Moist, sieved (2 mm) soil samples of 25 g (oven-dried weight basis) were measured into labeled 118 mL plastic cups. Deionized water was used to bring soils to 85% of field capacity moisture. Plastic cups were lightly shaken to ensure that water was evenly distributed through the soil. Containers were then placed in 1 L jars. Ten milliliters of water was added to the bottom of each jar to control humidity. Tops of jars were fitted for butyl septa so that gas samples could be withdrawn. Jars were immediately sealed and placed into an incubator at 25ºC in the dark for 28

d. Eight blank jars, only containing 10 mL of water and an empty plastic container were used as control samples.

Headspace samples were taken from quart jars to determine C mineralized. The average CO_2 concentration from eight blank samples was determined at the beginning of the incubation to obtain an initial CO_2 concentration. At the end of the 28 d incubation, headspace samples were taken from each jar to determine final concentrations of CO_2. Samples were run on a Shimadzu GC-2014 gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD) equipped with a flame ionization detector and methanizer to detect CO_2 concentration. Standard pressure and temperature were assumed when determining mass of CO_2–C mineralized. Soil extractions to determine inorganic N were done both prior to and after the incubation study with 2 M KCl according to the procedure by Mulvaney (1996). The extractant was analyzed for inorganic N colorimetrically using a Bran+Luebbe Auto Analyzer 3 (Bran+Luebbe, Norderstedt, Germany).

Gas samples were analyzed at the University of California Davis Stable Isotope Facility to determine isotopic composition of CO_2 in the headspace samples. A ThermoScientific PreCon-GasBench system interfaced to a ThermoScientific Delta V Plus isotope ratio mass spectrometer (ThermoScientific, Bremen, DE) was used to determine $\delta^{13}C$ values.

Potential C mineralized was calculated as the difference between final (day 28) and initial (day 1) CO_2–C mass for each sample divided by the mass of soil. Soil N mineralized was calculated as the difference between final (day 28) and initial (day 1) soil inorganic N content divided by mass of soil. Because the difference between final (day 28) and initial (day 1) soil inorganic N content was negative in some cases, C/N mineralized ratio could not be calculated.

Data Analysis

Data were analyzed using mixed models methodology as implemented in SAS® PROC GLIMMIX. The analyses were conducted separately for each location, where block and its interactions with other effects were considered to be random effects. For the small plot experiment at WREC, fixed effects included crop, tillage, and depth as well as all two-way and the single three-way interactions. For the large plot experiments at WREC and NFREC, fixed effects included crop, grazing, and depth as well as all two-way and the single three-way interactions. The non-random nature of the depth factor imposes a repeated measures structure on to the depth stratum; the residual variances were modeled using a number of covariance structures implemented in the above named procedure. The best-fitting model was chosen based on Akaike's Information Criterion Corrected (AICC); the best model differed among response variables. Because two-way interactions were often significant ($P \leq 0.10$), crops and or grazing were compared (α=0.05) at each depth using a simulation approach implemented in SAS to account for the inflation in the Type I error rate due to multiple comparison.

RESULTS AND DISCUSSION

Bulk Density

Bulk density was evaluated at each depth increment at WREC-SP, WREC-LP, and NFREC-LP. At WREC-SP, bulk density was affected by tillage at the 0-5 cm depth (data not shown) and was higher for CT (1.29 g cm^{-3}) treatments than for ST (1.16 g cm^{-3}) treatments (P = 0.001). An increase in bulk density with depth was observed until reaching the 15- to 30-cm depth (1.55 g cm^{-3}), whether under CT or ST at WREC-SP. At the 30- to 60-cm depth, bulk density decreased to approximately 1.45 g cm^{-3} similar to that of 5- to 10- and 10- to 15-cm depths. The increase observed for bulk density at the 15- to 30-cm depth may be the result of a plow pan present from previous land management. This effect was only seen at WREC-SP. For WREC-LP and NFREC-LP, bulk density consistently increased with depth, but was not affected by grazing. Bulk densities were comparable to those in Balkcom et al. (2013), where an average bulk density of 1.31 g cm^{-3} at the 0- to 5-cm depth, and 1.51 g cm^{-3} at depths from 5- to 45-cm was observed across four types of tillage treatments for a fine sandy loam in the southeast Coastal Plain region.

Crop had an effect on bulk density at WREC-SP in the top 5 cm ($P = 0.001$). At this depth, soil from the Cotton-TR and Bahia2-SBR crop phases had higher bulk density than that from Peanut-SBR; this is most likely due to recent inversion of soil during peanut harvest. Other studies in the Coastal Plain region have reported lower bulk density under perennial grass compared to cropland under conservation tillage (Causanaro et al., 2008). This effect was not seen for the SBR under short-term (2 yr) bahiagrass incorporation.

Soil Organic Carbon

When examining the effect of tillage on SOC storage at WREC-SP, SOC was stratified under ST but uniform under CT for the top 30 cm of soil averaged across crop treatments (Figure 2-3). Differences for SOC according to tillage treatment were affected by depth. Higher SOC was observed under ST at the 0- to 5-cm ($P < 0.001$) and 5- to 10-cm depth ($P = 0.002$) compared with CT. In the top 5 cm, SOC averaged 4.3 Mg ha^{-1} cm^{-1} for CT and 6.8 Mg ha^{-1} cm^{-1} for ST. Increased SOC in the top layers of soil is commonly observed in the southeast U.S. as a result of conservation tillage management (Balkcom et al., 2013; Watts et al., 2010b; Wood and Edwards, 1992) as a result of less soil disturbance. It is important to increase SOC in the top layers of soil to prevent erosion, promote soil health, and protect against leaching and runoff of fertilizers (Franzluebbers, 2010). The opposite was true at the 10- to 15- and 15- to 30-cm depths, where

SOC was higher under CT ($P \leq 0.010$). At the 30- to 60-cm depth, no differences were observed between tillage treatments. For the 0- to 15-cm depth, total SOC accumulation was approximately 25% higher under ST than CT. Similarly, Causarano et al. (2008) found that SOC storage was 25% higher in the top 20 cm of soil under conservation tillage practices compared to conventional tillage in the southern Piedmont and Coastal Plain regions of the southeast U.S.

A crop × depth interaction for SOC storage occurred at WREC-SP ($P < 0.001$; Table 2-1). In general, SOC storage decreased with depth when adjusted to a uniform depth increment. No differences due to cropping phase occurred in the top 15 cm of soil at WREC-SP. In the 15- to 30-cm layer, Peanut-SBR had higher SOC than Bahia2-SBR, and in the 30- to 60-cm layer, Bahia2-SBR had higher SOC than Peanut-TR. Higher SOC in Peanut-SBR may be a result of a buildup in SOC during the previous bahiagrass crop, which may have been incorporated into the 15- to 30-cm depth during soil inversion during plowing and peanut harvest. It is unclear why Peanut-TR has a low SOC at the 30- to 60-cm depth. It is important to note that Peanut-SBR did not have higher SOC than Peanut-TR and Cotton-SBR did not have higher SOC than Cotton-TR at any depth, indicating that the SBR did not increase SOC compared to the TR at WREC-SP.

At WREC-LP, SOC was higher for all phases of the SBR (Bahia1-SBR, Bahia2-SBR, Peanut-SBR, and Cotton-SBR) compared to phases the TR (Peanut-TR, Cotton-TR) in the top 5 cm of soil ($P < 0.001$; Table 2-1). However, it should be taken into account that the TR in this system was managed with plowing before the planting of winter cover crop and may have caused faster decomposition of SOC. At the 10- to 15-cm depth, Bahia1-SBR had higher SOC than Peanut-SBR. At NFREC-LP, there were no differences in SOC due to cropping phase.

A depth × grazing × crop interaction was observed for WREC-LP (P=0.026; Table 2-2). At the 5- to 10-cm level, both Bahia1-SBR and Bahia2-SBR had higher SOC in ungrazed treatments, likely caused by decreased root biomass under grazing. Grazing did not have an effect in the subsequent peanut crop. Other studies in the Southeast have reported decreased SOC for pasture when grazed (Franzluebbers and Stuedemann, 2008; Silveira et al., 2013). Although there was no interaction for depth x grazing x crop at NFREC-LP (0.538), ungrazed treatments were consistently higher in SOC than grazed treatments for all depths from 0- to 30-cm. This may be due to an alteration in the distribution of photosynthates under grazing to shoot production away from root growth, thus reducing root biomass and SOC inputs; a decrease in root growth is commonly observed as grazing intensity increases (Schuster, 1964). However, by the next crop phase (Peanut-SBR), ungrazed treatments did not differ from grazed indicating this is a temporal process that is reversed when shoot biomass carbon returns to the soil. Previous studies have shown that grazing did not have an effect on SOC in the top 15 cm of soil in the SBR (George et al., 2013).

The SBR was expected to increase SOC storage compared to the TR due to increased biomass produced with short-term (2 yr) rotational incorporation of bahiagrass. Previous evidence suggests that SOC storage may increase in the southern Piedmont and Coastal Plain regions for established (>5 yr) perennial pastureland compared to cropland under CT (Causarano et al., 2008). Although some increases in SOC occurred when bahiagrass was in rotation, these changes were not consistent and did not often carry over to the subsequent crop (Peanut-SBR) in this study. Peanut and cotton in the SBR did not accumulate more SOC than the same crop in TR after >10 years in the SBR at WREC-SP, indicating that increases in SOC with bahiagrass are relatively labile. Increases in SOC across all SBR crops only occurred in the top 5 cm at one location (WREC-LP); however, different tillage practices were used before planting of winter cover crops. It is likely that disking before planting the winter cover crop at WREC-LP increased SOC degradation and confounded the results. However, it may also be a better comparison to traditional practices in the area where disking may be used to improve cover crop establishment.

One explanation for the lack of differences between SBR and TR is that SOC storage had already been maximized. Balkcom et al. (2013) reported increases in SOC of 926 ± 344 kg C ha^{-1} yr^{-1} after 6 years in conservation management for a factorial experiment of various winter cover crops and tillage treatments. All conservation management strategies that were evaluated were equally efficient at increasing SOC in this study conducted in a Coastal Plain soil in the Southeast. Sandy soils in the Southeast often promote SOC degradation and are less efficient at storing SOC (Silveira et al., 2013). Soils in the SBR may have reached equilibrium for SOC accumulation as a result of other conservation practices that were used in both SBR and TR (e.g., winter cover cropping). Additionally, peanut digging and cotton stalk removal practices may negate some of the benefit of incorporating 2 yr of bahiagrass. Grazing did not appear to have a long-term negative effect on SOC storage in the SBR.

Soil Nitrogen

Distribution of soil N according to tillage practice was similar to that of SOC; soil N was stratified with ST, but uniform under CT until reaching a depth of 30 cm (Figure 2-3). Stratification of soil N is common in conservation-tilled land in the Southeast (Franzluebbers and Stuedemann, 2008). Treatments under ST had higher total N than CT in the 0- to 5- and 5- to 10-cm depths ($P < 0.001$; $P = 0.001$). Conventional tillage treatments had higher soil N at the 10- to 15- and 15- to 30-cm depths (P = 0.003; P <0.001). For the total sampling depth (60 cm), soil N averaged 2.57 Mg ha^{-1} for ST and 2.47 Mg ha^{-1} for CT.

Soil N differed by depth and cropping phase at WREC-SP (P <0.001) and WREC-LP (P <0.001). In the top 5 cm depth at WREC-SP, Bahia1-SBR (0.463 Mg ha^{-1}) had higher total N than all peanut and cotton crops (Peanut-SBR, Cotton-SBR, Peanut-TR, and Cotton-TR), and Bahia2-SBR had higher soil N than all peanut and cotton crops with the exception of Cotton-SBR (Table 2-3). No differences were observed between crops in the 5- to 10-, 10- to 15-, or 15- to 30-cm layers. However, at the 30- to 60-cm depth, Bahia2-SBR had higher soil N than Cotton-SBR and Peanut-TR. At WREC-LP, all phases of the SBR (Bahia1-SBR, Bahia2-SBR, Peanut-SBR, and Cotton-SBR) had higher soil N than phases of the TR (Peanut-TR, Cotton-TR) in the top 5 cm of soil (Table 2-3). These results are similar to those obtained for SOC and suggest that the SBR is more efficient at storing N in the top 5 cm of soil at WREC-LP. Again, it should be taken into account that the TR was managed with disking before the planting of winter cover crop at this location and may have increased decomposition rates, causing a decrease in soil N. For 0- to 5-cm, total soil N ranged from 0.798– 0.841 Mg ha^{-1} for crops in the SBR and 0.478–0.487 Mg ha^{-1} for crops in the TR at WREC-LP. It is unclear why Bahia1-SBR had higher total N than Bahia2-SBR at the 15- to 30-cm depth. At NFREC-LP, soil total N did not differ for any crop treatments. However, Bahia2-SBR consistently had the highest soil N at all depths. Overall, bahiagrass consistently increased soil N in the top soil 5 cm. Increases were not always apparent for the subsequent Peanut-SBR and Cotton-SBR crops and may have been lost to crop uptake.

Soil N did not differ with grazing treatment according to depth at WREC-LP (P = 0.065) or NFREC-LP (P = 0.561; data not shown), but decreased consistently with depth whether grazed or ungrazed. Silveira et al. (2013) also observed that soil N did not change in the top 20 cm due to grazing treatment for a short-term (2 yr) grazing study in the Southeast. Other studies have measured a decrease in total soil N with grazing under conservation tillage for the top 3 cm of soil when pasture was mowed or rolled instead of being cut for hay (Franzluebbers and Stuedemann, 2008). In this study, ungrazed treatments were cut and removed for hay, which may explain why no differences were observed for grazed versus ungrazed treatments.

Results suggests that bahiagrass may contribute to soil N at the surface. At two locations bahiagrass phases were higher than any TR phase. At one location, bahiagrass was higher than subsequent SBR peanut and cotton phases. Thus, results suggest that while bahiagrass may contribute to soil N, it may be transitory. Based on the similarly between SOC and soil N, it is likely that SOC and soil N are contributed from the same source.

Potential Carbon Mineralization

Incubation studies were performed to determine the effect of management practices on potential C mineralization. Results indicated that potential C mineralization was higher under ST than CT in the top 10 cm of soil ($P \leq 0.019$), but not in the 10- to 15-cm depth Figure 2-4). Potential C mineralization was 2.6 times higher under ST compared to CT at the 0- to 5-cm depth and 1.6 times higher at the 5- to 10-cm depth. This is consistent with a study by Franzluebbers and Stuedemann (2008), which found potential C mineralization was 2.2 times greater under no-tillage than conventional tillage for a 0- to 3-cm depth and that tillage had no effect on C mineralization at the 10- to 15-cm depth.

In the current study, the depths with increased potential C mineralization under ST corresponded with depths that had increasing amounts SOC under ST. It can be assumed that increased potential C mineralization was the result larger amounts of SOC available for degradation. Wood and Edwards (1992) also observed increased potential C mineralization in the top 5 cm of soil when substituting conservation for conventional tillage. Increasing potential C mineralization indicates increased soil fertility in the top 10 cm of soil under ST.

An effect of cropping phase on potential C mineralization was found at WREC-SP and WREC-LP for the 0- to 5-cm depth and at NFREC-LP for the 10- to 15-cm depth. At WREC-SP, the potential C mineralization was higher for Bahia1-SBR and Bahia2-SBR compared to Cotton-TR in the top 5 cm (Table 2-4). Bahia2-SBR was also higher than Cotton-SBR at the 0- to 5-cm depth. Results indicate that mineralization of SOC may occur faster at the soil surface when planted in bahiagrass compared to cotton. At WREC-LP, potential C mineralization was higher for Bahia2-SBR than Peanut-TR in the top 5 cm. Causarano et al. (2008) measured potential C mineralization that was nearly 2 times higher in long-term (>10 yr) pastureland than in cropland under conservation tillage and approximately four times higher than land under CT. At WREC-SP and WREC-LP, there are indications that incorporation of short-term (2 yr) of pastureland may increase potential C mineralization as well, but subsequent cropping reduces the differences established by the grass. To achieve a more permanent increase in SOC, it may take longer than 2 yr of establishment. At NFREC-LP, Cotton-SBR showed increased potential C mineralization compared to Peanut-SBR and Bahia2-SBR at the 10- to 15-cm depth. However, two samples (Bahia2-SBR at 5- to 10-cm and Cotton-SBR at 10- to 15-cm) in the incubation study at Marianna were affected by refrigerator moisture, which resulted in false differences between crops.

No differences in potential C mineralization were seen between treatments at WREC-LP or NFREC-LP for grazing according to depth. Potential C mineralization consistently decreased with depth at all locations. Although some studies have shown increases in potential C mineralization with grazing (Li et al., 2007), grazing did not appear to have an effect on potential C mineralization observed in this study.

Potential Nitrogen Mineralization

Potential N mineralization rates were highly variable in this study and ranged from 8.48 to 33.09 for WREC-SP, 9.21 to 45.94 for WREC-LP, and 4.3 to 11.9 mg kg^{-1} for NFREC-LP. Due to the high variability in the data, there were no differences due to depth, crop, or tillage. Previous studies have shown changes in N mineralization with tillage (Franzluebbers and Stuedemann, 2008; Watts et al., 2010b) and with grazing (Dubeux et al., 2006).

Soil C_4- derived Carbon

Isotopic analysis of SOC_4–C allowed for a more in-depth analysis of SOC at WREC-SP and NFREC-LP. Under CT, crops in the SBR were more uniform with depth compared to ST (Figure 2-5a and b); however, in both there is a decrease in SOC_4-C with depth. Peanut-SBR under CT was an exception. It tended to increase with depth to the 15- to 30-cm depth then decrease. This is consistent with SOC data for Peanut-SBR treatment that was discussed previously. It is hypothesized that CT treatments had incorporated SOC from the previous bahiagrass crop into the deeper soil layers. Isotopic analysis of SOC supports this hypothesis by indicating that the source of C was derived from SOC_4–C. Stratification with depth was observed for each crop in the SBR (Bahia1-SBR, Bahia2-SBR, Peanut-SBR, Cotton-SBR) under ST (Figure 2-5b). Stratification of SOC_4–C has been previously observed for soils planted in C_4 crops under conservation tillage when measured using isotopic analysis (Huggins et al., 2007). Because no C_4 crops were planted in the TR, Peanut-TR and Cotton-TR did not exhibit stratification under CT or ST.

Crops in the SBR at WREC-SP exhibited higher SOC_4–C than crops in the TR in the top soil depths. Under CT, all SBR crops had higher SOC_4–C to a depth of 30 cm, with the exception of Peanut-SBR at the 0- to 5-cm depth (Figure 2-5a). For ST treatments, SOC_4–C remained higher for all SBR crops than for TR crops throughout the top 15 cm of soil ($P = <0.001$; Figure 2-5b). A crop × tillage × depth interaction was observed for SOC_4–C ($P <0.001$). When operated under ST, approximately 32% of SOC was C_4-derived at the 0- to 5-cm depth for Bahia1-SBR (Figure 2-5d). As the SBR phases rotated, SOC_4–C increased to approximately 50% SOC_4-C in the second yr of bahiagrass (Bahia2-SBR), but decreased to 35% after rotating through Cotton-SBR. Even at the 15- to 30-cm depth, SOC_4–C was higher during Bahia2-SBR and lower while rotating through Peanut-SBR and Cotton-SBR. Results suggest that although bahiagrass-derived SOC builds up under the bahiagrass crops under ST, approximately 40% is lost by the end of the peanut phase of the rotation. At the 30- to 60-cm depth, Bahia2-SBR had higher SOC_4–C than all crops except Bahia1-SBR and Cotton-TR, suggesting that bahiagrass roots were able to penetrate below the soil compaction zone. No other crops differed at the 30- to 60-cm depth, each maintaining approximately 35-50% SOC_4–C. While total SOC_4–C remained constant with depth for TR crops, percentage of SOC_4–C for TR crops increased consistently with depth for ST and is uniform with depth under CT between 0 and 30 cm (Figure 2-5 c and d). It is typical for $\delta^{13}C$ to increase with depth as a result of enrichment in ^{13}C with age of the soil (Balesdent and Mariotti, 1996). Another possible reason for increased percentage at the 30- to 60-cm depth is previous land management under C_4 grasses that accumulated SOC_4–C. Huggins et al. (2007) also observed an increase in SOC_4–C at a 30- to 45-cm depth after a C_4 crop had been in production for 12 years, although SOC only increased until reaching 30 cm.

When examining differences between tillage for each crop at a certain depth, all crops in the SBR (Bahia1-SBR, Bahia2-SBR, Peanut-SBR, Cotton-SBR) had higher SOC_4–C stored under ST compared to CT in the top 5-cm depth (Figure 2-5a). Bahia2-SBR and Peanut-SBR were higher under ST than CT at the 5- to 10-cm depth (P = 0.019, 0.047, respectively). At deeper depths, some crops in the SBR exhibited higher amounts of SOC_4–C under CT due to mixing of the soil. Bahia1-SBR and Peanut-SBR crops had higher SOC_4–C under CT at the 15- to 30-cm depth (P = 0.035, 0.024; respectively). The Peanut-SBR crop had higher SOC_4–C under CT at the 10- to 15- and 15- to 30-cm depths (P = 0.024, 0.001, respectively). No differences were observed for Peanut-TR and Cotton-TR for amounts of SOC_4–C in the soil. This was expected since no C_4 crops are grown in the TR rotation.

At NFREC-LP, depth × crop interaction was observed (P = 0.007) that was similar to WREC-SP (Figure 2-6). The SOC_4–C was consistently higher in Bahia2-SBR, suggesting that bahiagrass was able to reach below the compaction zone and increase SOC at the 30- to 60-cm depth. Approximately 29% of SOC was C_4-derived at the 0- to 5-cm depth for Bahia1-SBR. As the SBR rotated, SOC_4-C increased to approximately 36% for Bahia2-SBR, and decreased to approximately 33% in Cotton-SBR. At NFREC-LP, Peanut-SBR and Cotton-SBR were not stratified with depth, although both were operated under strip-tillage. This is most likely due to the mixing of the soil that occurs during peanut harvest and cotton stalk removal. Grazing did not have an effect on SOC_4–C at NFREC-LP.

Isotopic Composition of Mineralized Carbon

When measuring the isotopic composition of CO_2 mineralized in the incubation study, $\delta^{13}C$ values for CO_2 ($\delta^{13}C$–CO_2) differed according to a crop × depth interaction (P = 0.020). The highest $\delta^{13}C$–CO_2 values were observed in Bahia2-SBR at each depth, indicating that soils under bahiagrass production had the most SOC_4–C being respired (Figure 2-7). This was expected, as bahiagrass contained the newest SOC_4–C inputs. Blagodatskaya et al. (2011) found that after 33 d incubation, 60% of respired C was contributed from new SOC_4–C inputs. It is well-established that new inputs are concentrated near the surface and are most likely to be degraded first by microorganisms. All crop phases of the SBR had higher $\delta^{13}C$ values for CO_2 than all of the crop phases of the TR at each depth, since no C_4 crops were grown in the TR.

The $\delta^{13}C$ values for SOC ($\delta^{13}C$–SOC) were compared with $\delta^{13}C$–CO_2 to determine the recalcitrance of bahiagrass-derived SOC compared to C_3 crop-derived SOC (Figure 2-7). At WREC-SP, approximately 93% of all data points had higher $\delta^{13}C$–CO_2 values than corresponding $\delta^{13}C$–SOC values, indicating that SOC_4-C was preferred over SOC_3-C for degradation (Figure 2-7). The difference between $\delta^{13}C$-SOC and $\delta^{13}C$-CO_2 ($\Delta\delta^{13}C$) was analyzed to determine which crops resulted in the quickest degradation of SOC_4–C; a crop × depth interaction was observed at WREC-SP (P = 006). The $\Delta\delta^{13}C$ for Bahia2-SBR was higher for all crops with the exception of Bahia1-SBR and Peanut-TR in the 0- to 5-cm depth (Figure 2-7a), Bahia1-SBR in the 5- to 10-cm depth (Figure 2-7b), and Bahia1-SBR and Peanut-SBR in the 10- to 15-cm depth (Figure 2-7c). This indicates that microorganisms prefer the bahiagrass-derived SOC over that of peanut- and cotton-derived SOC, which is likely explained by preference of microorganisms to respire the newest SOC inputs. Because Bahia2-SBR had the newest SOC contributions, it is not surprising that microorganisms prefer this SOC_4–C for degradation. However, even when Peanut-SBR and Cotton-SBR were in rotation, $\delta^{13}C$–CO_2 values tended to be 2–3‰ higher than the corresponding $\delta^{13}C$–SOC in the 5- to 10- and 10- to 15-cm depths. Although the newest SOC inputs were from crops with a lower $^{13}C/^{12}C$ ratio (e.g., C_3 crops), SOC with a higher $^{13}C/^{12}C$ ratio appeared to be preferred for degradation.

The $\Delta\delta^{13}C$ for Peanut-TR and Cotton-TR were not statistically different from Peanut-SBR and Cotton-SBR, but the $\delta^{13}C$–CO_2 was an average of 1‰ higher than corresponding $\delta^{13}C$–SOC, indicating that ^{13}C may be preferred by microorganisms during degradation. Although some studies have observed discrimination against ^{13}C, the opposite affect was observed in this study. For instance, Blagodatskaya et al. (2011) found that differences between $\delta^{13}C$–SOC and $\delta^{13}C$–CO_2 were <1‰ for reference soils, but had higher $\delta^{13}C$–SOC compared to $\delta^{13}C$–CO_2. Data in this study suggests that ^{13}C was preferred over ^{12}C for degradation. It is interesting that ^{13}C appeared to mineralize faster than ^{12}C, since the percentage of SOC_4–C from the 15- to 30- to the 30- to 60-cm depth. Again, perhaps the reason for this increase is previous management in C_4 grasses. The least labile forms of C may have built up in the soil over long periods of time, resulting in a stable amount of SOC_4 in the 30- to 60-cm depth.

At NFREC-LP, the $\Delta\delta^{13}C$ differed only with crop at NFREC-LP ($P < 0.001$). Bahia1-SBR was higher than other SBR crops across all depths (Figure 2-8). Again, bahiagrass-derived inputs were degraded more quickly when they were the newest inputs, although at this location the increases were with Bahia1-SBR instead of Bahia2-SBR. This is perhaps because bahiagrass established more quickly at NFREC-LP compared to WREC-SP. The $\delta^{13}C$–CO_2 averaged approximately 4‰ higher than $\delta^{13}C$–SOC for Bahia1-SBR, 2‰ higher for Bahia2-SBR, and 1‰ higher for Peanut-SBR and Cotton-SBR. Approximately 83% of data points had higher $\delta^{13}C$–CO_2 values than $\delta^{13}C$–SOC (data not shown). This corresponds with data at WREC-SP that indicates SOC_4–C was preferred for degradation, even when the newest SOC inputs were from cotton and peanut.

Changes in Soil Organic Carbon over a Three-Year Interval

Changes in SOC concentration from 2009 to 2012 were evaluated to determine changes in SOC with time for the SBR and TR. At WREC-SP, there was an interaction for year × crop × depth for SOC concentration ($P = 0.036$). Concentration of SOC increased from 2009 to 2012 for Bahia2-SBR and Peanut-SBR in the 0- to 5-cm depth, all crops with the exception of Peanut-SBR in the 5- to 10-cm depth, and Peanut-SBR, Cotton-SBR, and Peanut-TR in the 10- to 15-cm depth. In the 15- to 30- and 30- to 60-cm depths, SOC increased from 2009 to 2012 for all crop phases of the SBR and TR (Figure 2-9). Results indicate that SOC is increasing over time for both the SBR and the TR, suggesting that other conservation practices (e.g., winter cover cropping) are contributing to SOC storage, even at relatively deep soil layers. Clay and Fe oxide content is typically higher between 15- to 60-cm when compared to 0- to 15-cm depths. Increased SOC in the deeper soil layers could be the result of increased retention of C by clay and Fe oxides as SOC leaches through the soil profile.

CONCLUSION

Indicators of soil fertility (i.e., SOC, soil total N, and potential C mineralization) increased under ST in the top soil layers, demonstrating that ST is beneficial for restoring soil health in the SBR and TR. Strip-tillage is likely to be beneficial for farmers in the Southeast incorporating the SBR. There are indications that the SBR has the potential to increase SOC in the top layers of soil. However, results were not consistent in all locations. Isotopic analysis revealed contribution of C_4-derived carbon below the compaction zone suggesting that bahiagrass roots are able to extend below this zone and may allow roots of subsequent crops to reach deeper in the soil profile to obtain water and nutrients. Grazed treatments of bahiagrass had less SOC compared to non-grazed treatments, indicating less root growth due to a lack of photosynthates from the shoots to the roots under grazing management. Although SOC storage may be reduced under grazing of bahiagrass, grazing did not appear to have a long-term effect on SOC pools. Nitrogen storage and mineralization did not differ with grazing.

Cycling of SOC from bahiagrass was clearly seen in isotopic analysis of SOC and demonstrated that bahiagrass resulted in up to 50% SOC, but decreased to as low as 30% SOC after the last cotton phase of the SBR. The majority of inputs of SOC from bahiagrass (observed to 30 cm depth) were reduced in the subsequent Peanut-SBR crop, suggesting that bahiagrass-derived SOC is recalcitrant and does not further improve SOC storage. Additionally, peanut harvesting and cotton stalk removal practices may negate some of the benefit of incorporating bahiagrass into the peanut-cotton rotation. Mineralization studies suggested that bahiagrass-derived SOC is more likely to be mineralized than SOC contributed by other C_3-crops in the SBR. Concentration of SOC consistently increased from 2009 to 2012, indicating that soils in the SBR may have reached equilibrium for SOC accumulation as a result of other conservation practices (e.g., winter cover cropping). Although the SBR did not improve SOC compared to the TR, results indicate that conservation management practices are able to improve SOC storage in the southeast Coastal Plain. Identifying management practices that increase SOC storage are essential for improving soil fertility for crop production in the Southeast. Furthermore, it is important for the Southeast to increase SOC storage for the offset of CO_2 emissions. Results demonstrate that agricultural management practices such as conservation tillage and winter cover crop incorporation are able to improve soil and environmental health, whether used in a row crop system or an integrated crop-livestock system.

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Table 2-1. Soil organic carbon (SOC) for all crop phases of the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center small plots (WREC-SP), Wiregrass Research and Extension Center large plots (WREC-LP) and North Florida Research and Education Center large plots (NFREC-LP) at 0-5, 5-10, 10-15, 15-30, and 30-60 cm depths in 2012.

Location	**Depth**	**Soil Organic Carbon†**					
		Bahia1-SBR	**Bahia2-SBR**	**Peanut-SBR**	**Cotton-SBR**	**Peanut-TR**	**Cotton-TR**
	cm	Mg ha^{-1}					
WREC-SP	0-5	6.49	6.29	5.12	5.18	4.96	5.28
	5-10	4.71	4.87	4.17	4.50	4.73	4.41
	10-15	3.75	3.53	4.15	4.14	4.19	3.85
	15-30	11.79 ab‡	11.03 b	14.14 a	13.32 ab	12.38 ab	11.82 ab
	30-60	12.24 ab	13.80 a	11.77 ab	10.53 ab	8.83 b	11.45 ab
WREC-LP	0-5	12.59 a	11.48 a	11.90 a	12.29 a	6.00 b	7.77 b
	5-10	8.69	8.93	6.63	7.46	7.28	8.01
	10-15	7.38 a	5.82 ab	5.49 b	5.77 ab	6.18 ab	5.85 ab
	15-30	18.35	14.56	12.57	13.46	12.36	13.83
	30-60	18.53	16.12	10.69	13.04	12.90	9.34
NFREC-LP	0-5	7.27	9.44	4.20	4.79	–	–
	5-10	6.42	8.95	4.18	5.01	–	–
	10-15	5.66	7.50	3.73	4.54	–	–
	15-30	14.76	19.88	11.53	10.37	–	–
	30-60	14.27	22.51	11.56	7.18	–	–

† SOC is based on total amount of C at a specific depth increment. Depth increments vary in magnitude.

‡ Means within a row followed by a different lowercase letter differ significantly for comparisons within a depth (0.05 level).

Table 2-2. Soil organic carbon (SOC) for all crop phases of the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center large plots (WREC-LP) and North Florida Research and Education Center large plots (NFREC-LP) at 0-5, 5-10, and 10-15 cm depths separated based on grazed and non-grazed treatments in 2012.

Location	**Crop**	**Soil Organic Carbon**					
		0-5 cm		**5-10 cm**		**10-15 cm**	
		Grazed	Ungrazed	Grazed	Ungrazed	Grazed	Ungrazed
		Mg ha^{-1}					
WREC-LP	Bahia1-SBR	12.62	12.55	7.43	9.95*	7.52	7.25
	Bahia2-SBR	11.70	11.26	6.79	11.06*	6.01	5.64
	Peanut-SBR	12.31	11.50	7.01	6.25	5.01	5.98
	Cotton-SBR	13.76	10.83	8.42	6.51	5.98	5.56
	Peanut-TR	5.25	6.76	6.48	8.07	6.35	6.00
	Peanut-TR	7.68	7.85	8.35	7.67	6.15	5.55
NFREC-LP	Bahia1-SBR	5.63	8.90	5.73	7.11	4.49	6.83
	Bahia2-SBR	7.56	11.32	7.48	10.43	6.15	8.86
	Peanut-SBR	4.64	3.76	4.58	3.78	3.97	3.50
	Cotton-SBR	5.07	4.51	5.56	4.45	4.85	4.22
	Peanut-TR	–	–	–	–	–	–
	Peanut-TR	–	–	–	–	–	–

* Difference between grazed and ungrazed treatments is significant at $P \leq 0.05$.

Table 2-3. Soil nitrogen for all crop phases of the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center small plots (WREC-SP), Wiregrass Research and Extension Center large plots (WREC-LP) and North Florida Research and Education Center large plots (NFREC-LP) at 0-5, 5-10, 10-15, 15-30, and 30-60 cm depths in 2012.

Location	**Depth**	**Soil Nitrogen†**					
		Bahia1-SBR	**Bahia2-SBR**	**Peanut-SBR**	**Cotton-SBR**	**Peanut-TR**	**Cotton-TR**
	cm	Mg ha^{-1}					
WREC-SP	0-5	0.463 a‡	0.460 ab	0.321 c	0.347 bc	0.329 c	0.332 c
	5-10	0.331	0.338	0.269	0.300	0.321	0.272
	10-15	0.239	0.250	0.256	0.263	0.273	0.252
	15-30	0.716	0.667	0.838	0.783	0.715	0.726
	30-60	0.865 ab	1.037 a	0.872 ab	0.796 bc	0.642 c	0.873 ab
WREC-LP	0-5	0.841 a	0.798 a	0.831 a	0.837 a	0.487 b	0.478 b
	5-10	0.636	0.677	0.537	0.621	0.587	0.630
	10-15	0.581	0.458	0.459	0.451	0.566	0.480
	15-30	1.669 a	1.071 b	1.294 ab	1.405 ab	1.311 ab	1.463 ab
	30-60	2.196	2.063	2.085	1.863	1.626	1.884
NFREC	0-5	0.528	0.634	0.309	0.374	–	–
	5-10	0.444	0.617	0.295	0.373	–	–
	10-15	0.360	0.501	0.260	0.310	–	–
	15-30	0.309	0.388	0.249	0.177	–	–
	30-60	0.161	0.246	0.155	0.090	–	–

† Soil N is based on total amount of N at a specific depth increment. Depth increments vary in magnitude.

‡ Means within a row followed by a different lowercase letter differ significantly for comparisons within a depth (0.05 level).

Table 2-4. Potential carbon mineralization for all crop phases of the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center small plots (WREC-SP), Wiregrass Research and Extension Center large plots (WREC-LP) and North Florida Research and Education Center large plots (NFREC-LP) at 0-5, 5-10, and 10-15 cm depths in 2012.

Location	**Depth**	**Potential Carbon Mineralization**					
		Bahia1-SBR	**Bahia2-SBR**	**Peanut-SBR**	**Cotton-SBR**	**Peanut-TR**	**Cotton-TR**
	cm	mg kg^{-1}					
WREC-SP	0-5	559 ab†	641 a	421 abc	331 bc	430 abc	170 c
	5-10	170	189	134	126	171	83
	10-15	85	109	87	92	96	92
WREC-LP	0-5	355 b	997 a	702 ab	482 ab	244 b	648 ab
	5-10	206	271	251	183	199	148
	10-15	128	168	157	113	142	203
NFREC	0-5	255	273	119	122	–	–
	5-10	99	219	106	102	–	–
	10-15	103 ab	81 b	67 b	133 a	–	–

† Means within a row followed by a different lowercase letter differ significantly for comparisons within a depth (0.05 level).

Figure 2-1. The 61 ha large plot experiment at the North Florida Research and Education Center in Marianna, FL was divided into four blocks. Blocks rotate crop phases of the sod-based rotation (SBR).

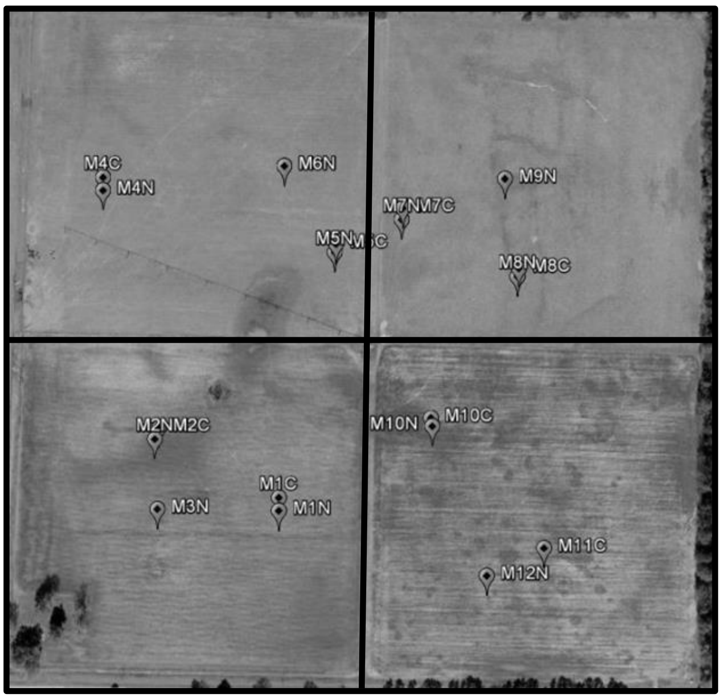


Figure 2-2. The 20.2 ha large plot experiment at the Wiregrass Research and Extension Center (WREC-LP) was divided into six blocks. Blocks A, B, C, and D rotate crop phases of the sod-based rotation (SBR). Blocks F and G rotate phases of the traditional rotation (TR).

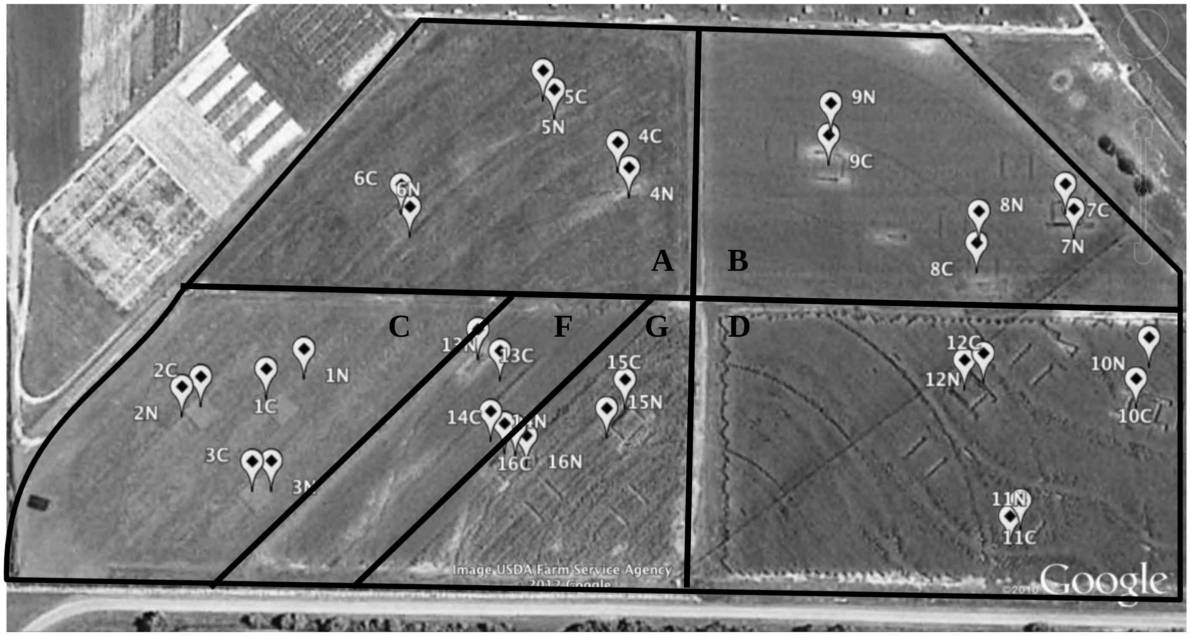


Figure 2-3. Soil organic carbon and soil nitrogen for Wiregrass Research and Extension Center small plots (WREC-SP) measured across conventional tillage (CT) or strip-tillage (ST) crop phases at 0-5, 5-10, 10-15, 15-30, and 30-60 cm depth increments. Bars represent a 95% confidence interval for the population mean (depth × tillage; P <0.001). For comparison purposes, all data is adjusted to a 5 cm depth increment and reported for the median depth.

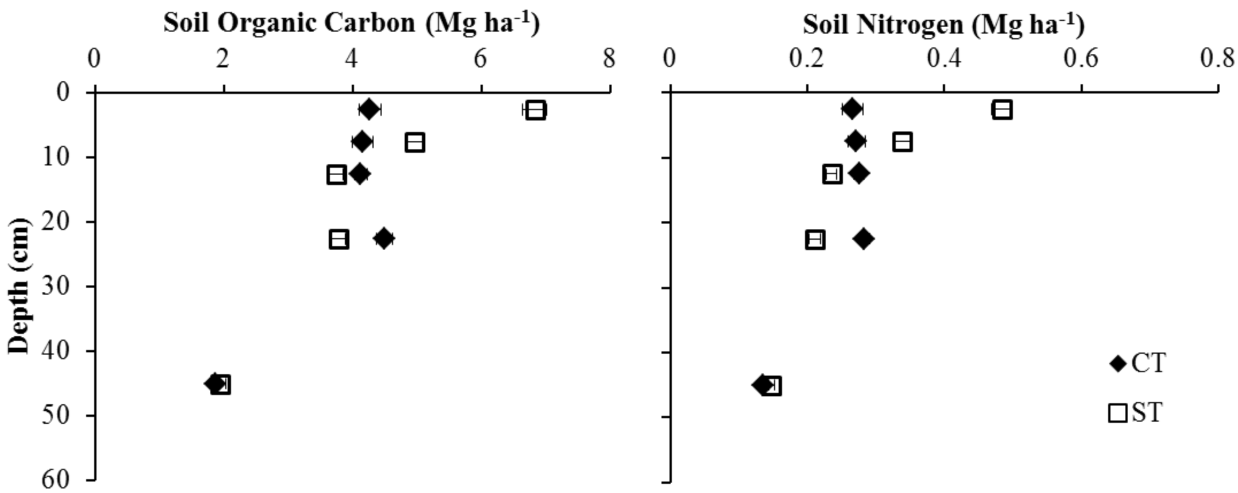


Figure 2-4. Potential C and N mineralization in Wiregrass Research and Extension Center small plots (WREC-SP) measured across conventional tillage (CT) or strip-tillage (ST) crop phases at 0-5, 5-10, and 10-15 cm depth increments. Bars represent a 95% confidence interval for the population mean (depth × tillage; P <0.001 for potential C mineralization; P = 0.145 for potential N mineralization).

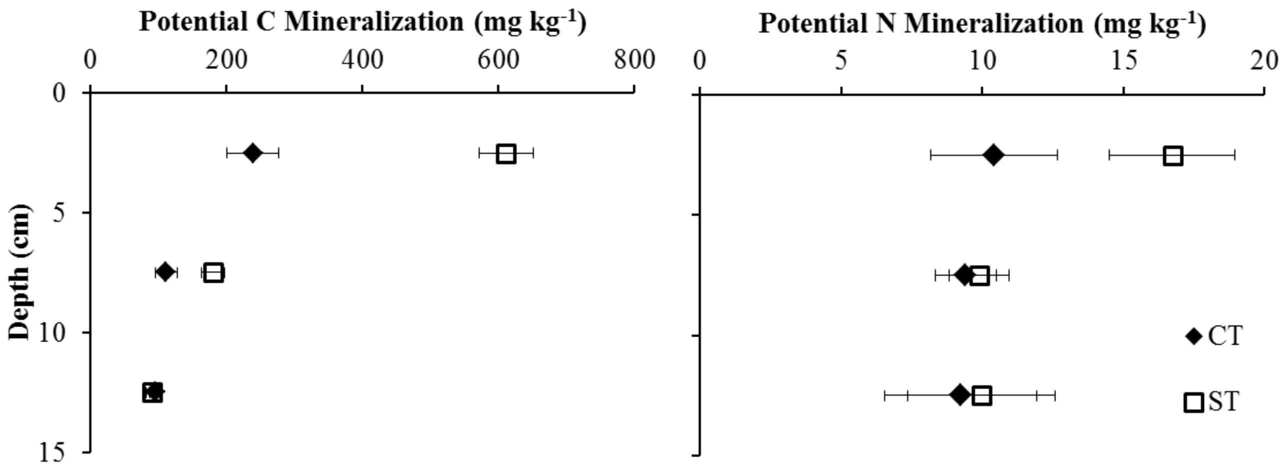


Figure 2-5. Total and percentage soil organic C_4-carbon (SOC_4-C) at WREC-SP at 5 depths (0-5, 5-10, 10-15, 15-30, 30-60 cm) for all crop phases of the sod-based rotation (SBR) and traditional rotation (TR) separated into (a) total SOC_4-C under conventional tillage (CT), (b) total SOC_4-C under strip-tillage (ST), (c) percent SOC_4-C under CT, and (d) percent SOC_4-C under ST. For comparison purposes, all values are adjusted to a 5 cm depth increment.

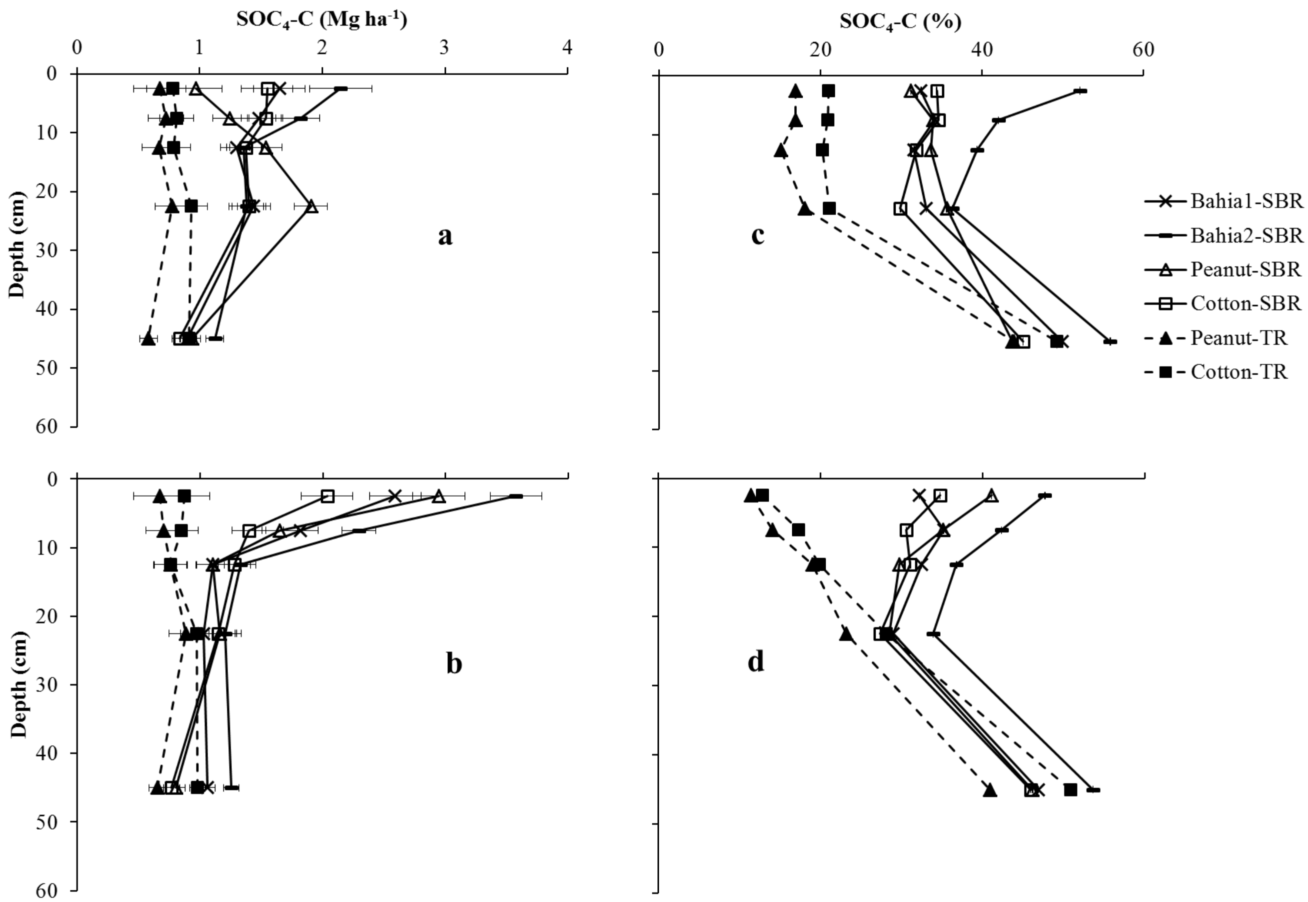


Figure 2-6. Total soil organic C_4-carbon (SOC_4-C) at NFREC-LP for 5 depths (0-5, 5-10, 10-15, 15-30, 30-60 cm) for all crop phases of the sod-based rotation (SBR). For comparison purposes, all values are adjusted to a 5 cm depth increment.

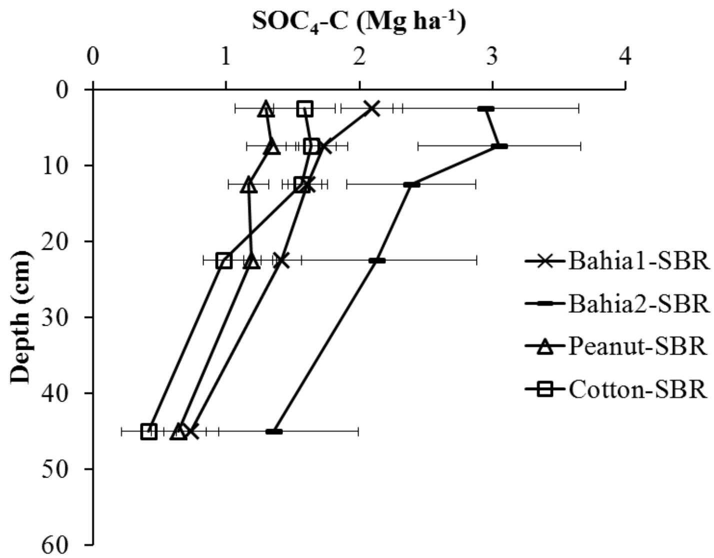


Figure 2-7. The $\delta^{13}C$ values for CO_2 produced during incubation ($\delta^{13}C$ –CO_2) plotted against the respective $\delta^{13}C$ values for soil organic C ($\delta^{13}C$ -SOC) used during the incubation at the Wiregrass Research and Extension Center small plots (WREC-SP). Data includes conventional tillage and strip-tillage treatments separated into (a) 0-5 cm, (b) 5-10 cm, and (c) 10-15 cm depth increments.

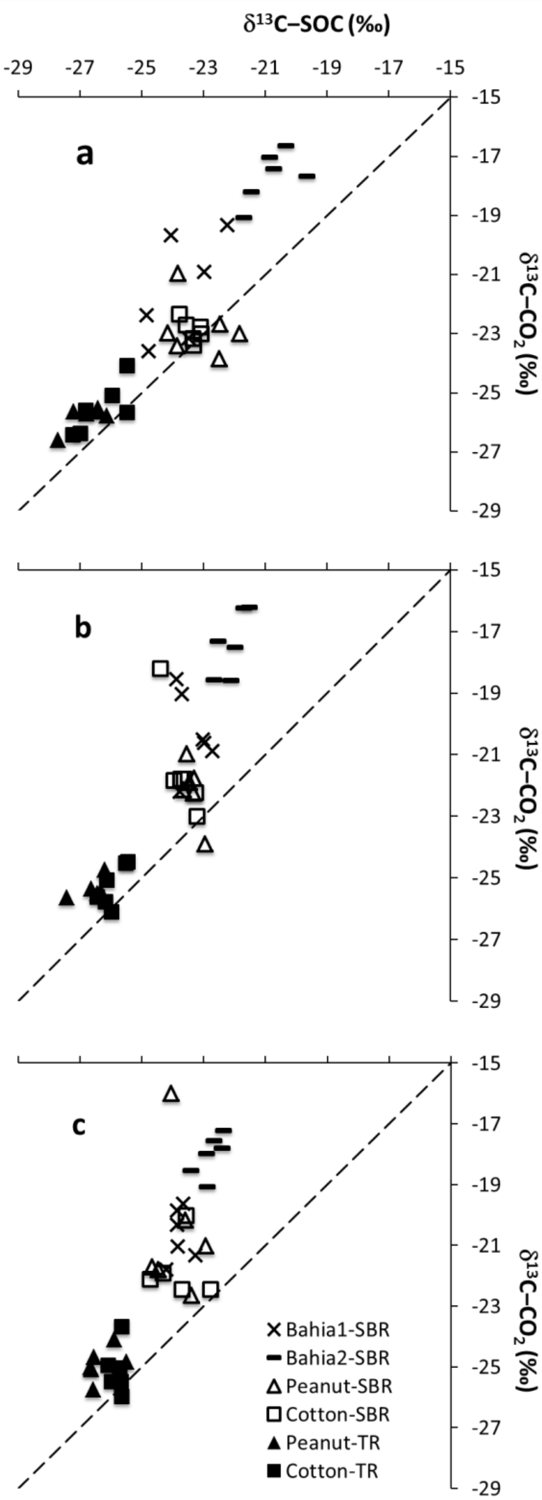


Figure 2-8. The $\delta^{13}C$ values for CO_2 produced during incubation ($\delta^{13}C$ –CO_2) plotted against the respective $\delta^{13}C$ values for soil organic C ($\delta^{13}C$ -SOC) used during the incubation at the North Florida Research and Education Center large plots (NFREC-LP). Data includes grazed and ungrazed treatments across all depths.

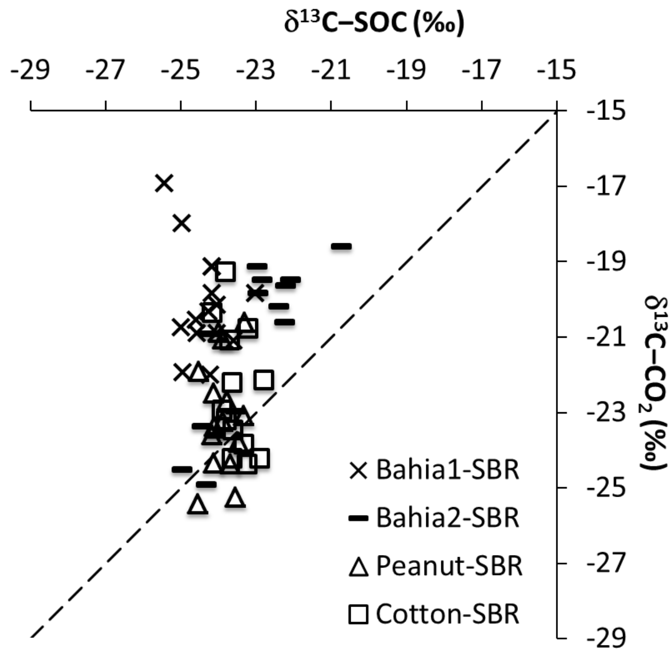
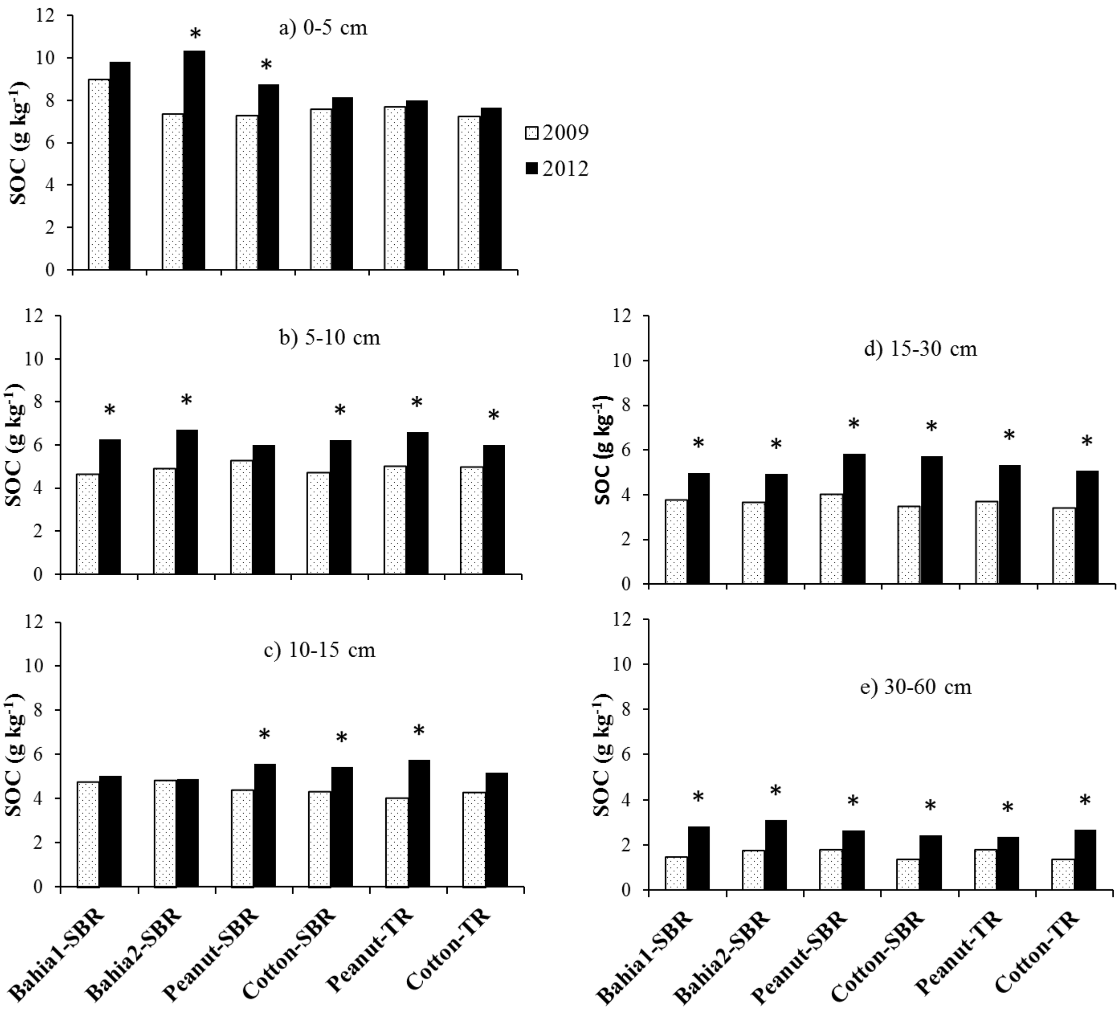


Figure 2-9. Soil organic carbon (SOC) concentration for Wiregrass Research and Extension Center small plots (WREC-SP) measured across conventional tillage (CT) and strip-tillage (ST) treatments for (a) 0-5 cm, (b) 5-10 cm, (c) 10-15 cm, (d) 15-30 cm, and (e) 30-60 cm depth increments for years 2009 and 2012. Asterisks represent significant differences (α = 0.05) between year 2009 and 2012.



III. EFFECT OF GRAZING ON GREENHOUSE GAS EMISSIONS IN A SOD-BASED ROTATION

ABSTRACT

A frequently used cropping system in the Southeast U.S. is an annual rotation of cotton (*Gossypium hirsutum* L.) and peanut (*Arachis hypogaea* L.) under conventional tillage (CT). This type of system often leads to loss of soil organic carbon (SOC) due to soil erosion and increased decomposition rates. Incorporation of 2 yr of perennial grasses such as bahiagrass (*Paspalum notatum* Fluegge) into the peanut-cotton crop rotation (also called a sod-based rotation or SBR) has been shown to improve soil quality, relieve environmental stress, and increase resistance to disease and pests. By incorporating cattle grazing on bahiagrass and winter cover crops, the productivity of the SBR can be increased. Greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) occur naturally in the atmosphere, but are of concern as they contribute to global climate change. Agricultural soils contribute to GHG emissions primarily through decomposition of SOC into CO_2. Thus, it is necessary to evaluate SOC storage in conjunction with GHG emissions to assess the environmental impact of the SBR in the Coastal Plain. In addition, grazing animals contribute nitrogen to soil that can be lost to the atmosphere through denitrification processes, and compaction created from grazing can contribute to poor soil aeration that can lead to anaerobic conditions favorable to CH_4 production. A closed chamber method was used to examine emissions of CO_2, CH_4, and N_2O for grazed and ungrazed treatments in a SBR. Storage of SOC was evaluated for SBR soils. Results indicated that the SBR has potential to increase SOC storage in the top 5 cm of soil. Grazing of bahiagrass reduced SOC in the 5- to 10-cm depth, but this effect was not observed in the subsequent peanut crop. A moderate stocking rate of 2.5

cattle ha^{-1} appeared to result in fewer emissions of CO_2 and N_2O compared to ungrazed management, dependent upon season and crop. Flux of CH_4 was often negligible; however, grazing increased uptake of CH_4 in some instances. For the moderate cattle stocking rates used in this study, grazing did not appear to negatively affect SOC storage or GHG emissions in SBR systems.

Abbreviations: CT, conventional tillage; ST, strip-tillage; GHG, greenhouse gases; SOC, soil organic carbon; SBR, sod-based rotation; TR, traditional peanut-cotton rotation.

INTRODUCTION

Soils hold approximately 2000 Gt C, making it the largest component of the global terrestrial C stock (Turcu et al., 2005). It has been projected that 80 Pg C–CO_2 is emitted into the atmosphere from the soil-atmosphere interface each year (Raich et al., 2002). Increasing concentrations of CO_2 and other greenhouse gases (GHG) in the atmosphere is a concern due to their role in global climate change (IPCC, 2001). Agriculture is the source of an estimated 20% of global CO_2 emissions (Hernandez-Ramirez et al., 2009), 50% of global CH_4 emissions, and 60% of global N_2O emissions (IPCC, 2007b). However, soils have potential to mitigate GHG emissions by sequestering CO_2 as SOC (Morgan et al., 2010).

Storage of SOC is not only important for mitigation of GHG emissions but is also essential for restoration of soil fertility. Agricultural soils occupy between 40-50% of global land surfaces (IPCC, 2007b) and have lost 30-70% of SOC due to cultivation (Eve et al., 2002; Lee et al., 2006). Soils in the southeastern Coastal Plain are often depleted in SOC as a result of intense row cropping systems (Franzluebbers, 2010). Decomposition of soil organic matter is accelerated in the warm, humid climate of the Southeast. A traditional crop rotation (TR) in the peanut-producing portion of the Coastal Plain is an alternating rotation of peanut and cotton managed using conventional tillage practices, which can lead to loss of SOC due to soil disturbance. Because the Southeast produces approximately 50% of U.S. cotton and 80% of U.S. peanut (Franzluebbers, 2007), it is necessary to identify management practices that can restore fertility in soils. Conservation practices (e.g., winter cover cropping, conservation tillage) are known for their ability to increase soil fertility (Prior et al., 2010; Watts et al., 2010), improve soil aggregation (Reeves et al., 1994), and offset the emission of greenhouse gases (Liebig et al., 2010; Robertson et al., 2000) by increasing SOC storage. The southeastern Coastal Plain has potential for increased biomass production and SOC sequestration when operated under conservation management due to favorable climate and long growing seasons. Practices that implement perennial grass further promote SOC sequestration (Causarano et al., 2008).

Perennial grasses produce a large biomass above and below ground that increases SOC, improves soil structure, and lessens soil erosion (Katsvairo et al., 2006). In the Southeast, bahiagrass is a perennial forage grass that is suited to low fertility soils (Magness et al., 1971). A crop rotation that incorporates 2 yr of bahiagrass into a peanut-cotton rotation has been suggested to promote C sequestration in the Southeast. Because the addition of bahiagrass into a crop rotation would reduce row crop acreage, the economic benefits may not outweigh the environmental benefits. Cattle production from grazing of bahiagrass and winter cover would allow a source of income when row crops are not in rotation. Additionally, moderate cattle grazing can enhance agricultural productivity by improving SOC content and providing nutrients to the soil (Franzluebbers and Stuedemann, 2008; Hart et al., 1995; Liebig et al., 2010). Proper grazing land management has the potential to increase global C stock by 0.1-0.3 Mg ha^{-1} yr^{-1} for pastures in the U.S. (Morgan et al., 2010), as a result of increasing decomposition rates and redistribution of plant material (Reeder et al., 2001). However, grazing may also contribute to GHG emissions (Flessa et al., 1996; Oenema et al., 1997).

Carbon dioxide is produced in the soil through respiration of microorganisms, roots, and mycorrhizae (Raich and Schlesinger, 1992). Respiration is largely effected by the amount and type of plant residue available for decomposition. Grazing has the potential to increase emission rates of CO_2 (Schönbach et al., 2012) by providing soluble forms of C that are available for soil respiration. However, some reports have observed decreases in CO_2 emissions with livestock grazing (Johnson and Matchett, 2001). Increases in SOC storage may also occur under grazing treatment (Ginting et al., 2003). Schuman et al. (1999) found increases of 0.5-0.75 Mg C ha^{-1} yr^{-1} in the top 30 cm of soil for grazing treatments compared with non-grazing over a 12 yr period in the Great Plains. However, several grazing studies in the Southeast have reported no differences in SOC with grazing (Franzluebbers and Stuedemann, 2008; Silveira et al., 2013). Franzluebbers and Stuedemann (2008) observed maintained levels of SOC and decreased potential for C mineralization after a 3 yr of grazing by livestock in the Southeast.

Methane is 25 times more potent than CO_2 at trapping infrared heat (Weihermüller, 2011) and is typically produced in soils under anaerobic conditions. Sources of CH_4 include wetlands, landfills, rice production and livestock production sites (IPCC, 2007a). Livestock production contributes to atmospheric CH_4 primarily through enteric formation (i.e., formed during digestion and released through the nose and mouth) and through the release of manure. Enteric formation releases 80 Tg CH_4 yr^{-1}, accounting for about 20-25% of the global rise of atmospheric CH_4 (Lassey, 2007). When compared with enteric formation, CH_4 emissions from manure are minor. While soils used in crop production can act as either producers or consumers of CH_4, dependent upon moisture and land-management practices (Chan and Parkin, 2001; Hernandez-Ramirez et al., 2009; Venterea et al., 2005), the production of CH_4 is often negligible (Flessa et al., 2002; Ginting et al., 2003).

Nitrous oxide is produced during soil nitrification and denitrification processes and is largely affected by amount and source of N fertilizer (Jarecki et al, 2008; Venterea et al., 2005) Loss of N_2O via nitrification and denitrification can be managed by altering substrates in the soil that contribute to these processes, such as crop residue, organic amendments, and fertilizers (Beauchamp, 1997). The most efficient way to mitigate N_2O emissions is to promote N use efficiency. The average rate of increase in N_2O concentration in the atmosphere has been estimated at 0.2-0.3% yr^{-1}. Although the rate of increase for atmospheric N_2O may seem small, N_2O is 300 times more effective at trapping infrared heat than CO_2 (Beauchamp,1997; Weihermüller et al., 2011). Approximately 15% of agricultural N_2O emissions are contributed from livestock farming (Oenema et al., 2008). Cattle excretions are the source of an estimated 1.18 Tg of N_2O–N (Flessa et al., 1996). Nitrous oxide measurements in pasture systems are often highly variable due to unequal distribution of animal waste (Liebig et al., 2010).

Wastes produced during grazing may increase the emission of CO_2, N_2O, and CH_4 from the soil. However, incorporating high-biomass crops and no- or reduced-tillage practices in a cropping rotation may help mitigate the net emission of GHG from agricultural soils through sequestration of SOC. While it is well established that pastures can increase SOC storage compared to row cropping, it is necessary to determine implications of short-term (2 yr) incorporation of pastureland in a crop rotation on SOC storage and GHG emissions with and without grazing.

MATERIALS AND METHODS

Site Description

Two farm-scale large plot systems were evaluated for this study, one at the Wiregrass Research and Extension Center (WREC-LP) in Headland, AL and one at the North Florida Research and Education Center (NFREC-LP) in Marianna, FL. Each SBR had been established for >10 years. Soils at the WREC-LP site are classified as fine-loamy, kaolinitic, thermic Plinthic Kandiudults of the Dothan series. Soils at the NFREC-LP site are primarily (>70%) classified as loamy, kaolinitic, thermic Arenic Plinthic Kandiudults of the Fuquay series.

Experimental Design

At WREC-LP, a field of 20.2 ha was divided into six blocks (Figure 3-1). Four of the six blocks rotated all phases of the sod-based rotation: peanut (Peanut-SBR), cotton (Cotton-SBR), bahiagrass in its first year (Bahia1-SBR), and bahiagrass in its second year (Bahia2-SBR) during the summer, which will be used to define the treatment for the year. Tifton 9 bahiagrass was used at WREC-LP and WREC-SP. A winter cover crop of oat (*Avena sativa* L.) and rye (*Secale cereale* L.) followed Peanut-TR, Cotton-TR, Peanut-SBR, Cotton-SBR, and Bahia2-SBR each winter and was actively grazed from mid-December until late-April. Bahia1-SBR, which is actually the transition between Bahia1-SBR and Bahia2-SBR, was actively grazed from late-September to mid-December, while winter cover crops were being established. In spring, crops were transitioning from winter cover crop to summer crop, and only Bahia2-SBR was actively being grazed.

Three fenced cattle-exclusion cages (15 x 15 m) were placed in each SBR block during the grazing period at established locations designated using GPS coordinates. The additional two blocks were established as a traditional rotation (TR) of peanut (Peanut-TR) and cotton (Cotton-TR) for comparison to the SBR. There are only two cattle-exclusion cages in these blocks. An area of similar size to the cattle exclusion cage was designated 3 m adjacent to one side of each of the cattle exclusion cages as the grazed area to be sampled. Samples were taken from the middle of each cattle exclusion cage and adjacent grazed area to assess the grazing effects on SOC storage and GHG emissions.

At NFREC-LP, a 61 ha field was divided equally into four blocks rotating all phases of the sod-based rotation (SBR). These included Peanut-SBR, Cotton-SBR, Bahia1-SBR, and Bahia2-SBR (Figure 3-2). Pensacola bahiagrass was used at NFREC-LP. A winter cover crop of oat and rye or annual ryegrass (*Lolium multiflorum* L.) followed Peanut-SBR, Cotton-SBR, and Bahia2-SBR crops each winter at NFREC-LP. Two fenced cages (15 x 15 m) were placed into each quadrant during grazing periods to prevent cattle from entering. Similar to WREC-LP, an adjacent location of similar size to the cage was designated 3 m adjacent to the cage as a grazing sampling area. Samples were taken from each cattle exclusion cage and adjacent grazed area to assess the effect of grazing on SOC storage and GHG emissions. Due the lack of exclusion cages at this site, an additional grazed sampling area was established within each quadrant at NFREC-LP.

Management factors within a location were identical in caged and grazed areas of large plot experiments with the exception of bahiagrass, which was periodically cut for hay in caged areas. Cages were removed for crop management (e.g., planting, harvest, hay cutting), but were re-installed at any time when cattle were actively grazing. All sampling locations were located under an irrigation pivot. All SBR treatments were under strip tillage (ST). The TR treatments at WREC-LP were managed with strip-tillage before planting Peanut-TR and Cotton-TR, but were disked before planting winter cover crop to mimic practices typical of farmers in the area. At WREC-LP, cotton stalks were mowed after harvest. At NFREC-LP, cotton stalks were pulled after harvest, which had the effect of turning the soil.

Cattle were allowed to graze Bahia2-SBR during summer and fall. During winter and spring, cattle grazed Bahia2-SBR or oat/rye cover crop as forage was available. At WREC-LP, a stocking rate of approximately 2.5 cattle ha^{-1} was employed during summer grazing of Bahia2-SBR and winter grazing of cover crops following Peanut-SBR, Cotton-SBR, Peanut-TR, and Cotton-TR. A rate of 1.2 cattle ha^{-1} was used for the winter cover crop that followed Bahia2-SBR. Bahia1-SBR (i.e., transition from Bahia1-SBR to Bahia2-SBR) was grazed from the end of September until the beginning of December at a stocking rate of 2.5 cattle ha^{-1}, while winter cover crops were being established in other blocks. Fertilizer and herbicide at WREC-LP were applied according to Alabama Cooperative Extension System recommendations. At NFREC-LP, a stocking rate of approximately 3.4 cattle ha^{-1} was used for grazing of all winter cover crops, and a rate of 2.5 cattle ha^{-1} was used for summer grazing of bahiagrass.

Soil samples from each location were collected using a truck-mounted Giddings probe (Giddings Machine Company, Windsor, CO) in December 2012 after harvest of summer crops. Cores of approximately 4 cm in diameter were taken to a depth of 60 cm from grazed and ungrazed treatments in the SBR and TR. Three cores were taken for each cattle-exclusion cage and adjacent sampling point. Cores were divided into 0- to 5-, 5- to 10-, 10- to 15-, 15- to 30-, and 30- to 60- cm increments while in the field. Soils were stored at room temperature until drying for bulk density analysis. Soils were not stored for longer than two weeks before drying.

Laboratory Analysis

To determine bulk density, soils were oven dried at 60ºC. After drying, oven-dry weight (ODW) and core volume (CV) of the soil sample were recorded. Samples were ground with a mortar and pestle and sieved through a 2-mm sieve to remove any rocks. Rock weight (RW) and rock volume (RV) were recorded. Bulk density (BD) was determined according to the formula:

$$BD = \frac{(ODW - RW)}{(CV - RV)}$$

After measuring bulk density, soils were ground with a coffee grinder to obtain fine particles (<1 mm) that could be used to determine total C and N. Dry combustion with a CN LECO 2000 analyzer (LECO Corp., St. Joseph, MI) was used to measure total C and N. To ensure that all C present in soils was part of the organic fraction, a simple titrimetric procedure to determine carbonate content was followed according to a method by Loeppert and Suarez (1996). None of the samples contained inorganic C.

Gas Measurement

Gas samples of CO_2, N_2O and CH_4 were taken seasonally for two years using the closed chamber method according to Hutchinson and Mosier (1981). Dates of closed chamber gas measurements at the WREC-LP site were 21 Nov. 2011, 20 Feb. 2012, 23 May 2012, 16 Aug. 2012, 16 Nov. 2012, 20 Feb. 2013, 21 May 2013, and 28 Aug. 2013. Dates of closed chamber gas measurements at NFREC-LP were 13 Dec. 2011, 12 Mar. 2012, 18 June 2012, 11 Sept. 2012, 14 Dec. 2012, 6 Mar. 2013, 12 June 2013, and 09 Sept. 2013.

Chambers were constructed of PVC pipe (20 cm diameter x 16 cm height), and were made of a base and detachable top containing a sampling port and a 5 mm gas vent to prevent changes in pressure. Bases were inserted 3 cm into the soil profile in each plot the day prior to sampling so that the top of the base was above the soil surface and open to the atmosphere. Plots were irrigated uniformly 2-3 d prior to sampling (unless sampling followed a rain event) to ensure rings could be inserted into the ground. To obtain a representative sample, bases were placed between the row and inter-row area. Any plant material present was clipped to 2.5 cm above soil to ensure a constant volume within the chamber. Tops of chambers were covered with reflective material to prevent absorption of sunlight and maintain ambient temperature within the chamber.

Gas samples were taken between 12:00 and 16:00 on each sampling day. Gas measurements were taken at during the hottest time of day in fields that had recently been irrigated, creating a favorable environment in which to observe differences in CO_2 flux. Flux readings are not representative of season or daily averages.

For each block of the SBR or TR, one person was present to take samples for each plot. This ensured that all samples were taken at approximately the same time of day for accurate comparison between treatments. At the start of gas sampling, tops to the chambers were fitted onto each base and secured with a rubber elastic band. Removable butyl rubber septa were inserted into the sampling port. Air was mixed within the chamber by pumping air through 60 mL syringe into the septa 3 times before taking the sample. Using a 10 mL syringe, gas samples were taken and inserted into a 5 mL pre-evacuated headspace vial, except for the first two sampling dates where vials were not pre-evacuated and were 2 mL in size. Each sample was taken in duplicate. Vials were over-pressurized to ensure adequate sample for gas analysis. This process was repeated at 30 and 60 min. Exact times for each sample were recorded. Field standards were prepared prior to sampling and taken to the field. Four blank samples were taken for each sampling date.

Vials containing the gas samples were stored at 5°C prior to analysis. Samples were analyzed using a Shimadzu GC-2014 gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD), which was equipped with a flame ionization detector and methanizer to detect CO_2 and CH_4 concentrations and an electron capture detector to determine N_2O concentrations for each time interval. Samples were arranged on the GC according to time sequence for each plot to avoid drift errors of the instrument.

Gas flux was determined linearly by regressing time against change in mass per unit area. Mass of CO_2–C, CH_4–C, and N_2O–N were determined based on area, temperature, and pressure in the chamber. Ambient pressure was assumed. Temperature data was collected for WREC-LP from Alabama Mesonet Agricultural Weather Information Services (AWIS, 2013) and for NFREC-LP from the Florida Automated Weather Network (FAWN, 2013).

Data Analysis

Data were generalized mixed models procedures as implemented in SAS PROC GLIMMIX using a lognormal distribution function. Year, block(year x cropping sequence) and season*block(year x cropping sequence) were treated as random effects in the model. Because this was a repeated measures design with multiple observations taken over eight seasons on each experimental unit, the residual covariance structure was modeled. None of the models resulted in an improvement over the default compound symmetry structure base on Akaike's Information Criterion Corrected (AICC). All other source of variation (i.e., cropping sequence, grazing, and season) and their two- and three-way interactions were treated as fixed effects. The P-values from multiple comparisons among means were adjusted using the simulation option implemented in the above named procedure. Means and 95% confidence limits are reported as back-transformed to the original scale.

RESULTS AND DISCUSSION

Soil Organic Carbon

Grazing had an effect on SOC storage at WREC-LP, but was affected by season and crop (P=0.026). Grazing decreased SOC by 25% and 40% for Bahia1-SBR and Bahia2-SBR compared to ungrazed treatments at the 5- to 10-cm depth (Table 3-1). However, the next crop phase (Peanut-SBR) reflected no differences between grazed and ungrazed treatments. Losses of SOC were likely caused by a decrease in root biomass attributed to reduced photosynthetic biomass under grazing treatment. Grazing may have caused the photosynthates to be allocated to shoot growth as opposed to root growth, especially in the 5- to 10-cm depth. Franzluebbers and Stuedemann (2008) observed that grazing of cover crops decreased SOC in the 0- to 3- and 3- to 6-cm layer after 2 yr of grazing treatment. Although grazing decreased SOC in the 5- to 10-cm layer for bahiagrass, it is unlikely that grazing had a long-term effect on SOC storage since no differences were observed for the subsequent peanut crop. Although there was no interaction for depth × grazing × crop at Marianna (0.538), ungrazed treatments consistently had higher SOC than grazed treatments for all depths from 0- to 30-cm.

Soil organic C was higher for all crop phases of the SBR (Bahia1-SBR, Bahia2-SBR, Peanut-SBR, and Cotton-SBR) compared to crop phases the TR (Peanut-TR, Cotton-TR) in the top 5 cm of soil at WREC-LP (P <0.001). However, it should be taken into account that the TR was managed with disking before the planting of winter cover crop, which may have increased decomposition of SOC. Similar results were seen by Causarano et al. (2008), who found higher

SOC storage in perennial pastureland compared to cropland managed under conservation tillage in the Coastal Plain. Tracy and Zhang (2008) observed higher SOC concentration in integrated crop-pasture systems than a continuous corn system in Illinois. At the 10- to 15-cm depth, Bahia1-SBR had higher SOC than Peanut-SBR. The SBR appeared to increase SOC compared to the TR in the top 5 cm. Results indicate bahiagrass has the potential to increase SOC, particularly at the surface when operated under ST.

Carbon Dioxide Flux

Flux of CO_2 ranged from 8.2 to 15.0 kg CO_2–C ha^{-1} d^{-1} during the fall season, 8.8 to 30.5 kg CO_2–C ha^{-1} d^{-1} during the winter season, 17.6 to 48.4 kg CO_2–C ha^{-1} d^{-1} during the spring season, and 26.7 to 53.1 kg CO_2–C ha^{-1} d^{-1} during the summer season at WREC-LP (Table 3-2). Flux of CO_2 tended to be greater during warmer seasons. Increasing CO_2 flux in spring and summer seasons is a common observation (Omonode et al., 2007; Tracy et al., 2008). A season × grazing × crop interaction was observed for CO_2 flux at WREC-LP (Table 3-3). When examining differences between grazed and ungrazed treatments for the interaction, no differences were observed during the fall season for any crop at WREC-LP. For Bahia1-SBR and Bahia2-SBR in the winter, Cotton-TR in the spring, and Peanut-SBR in the summer, CO_2 flux was higher in ungrazed plots compared to grazed plots (Table 3-2). Increases in CO_2 flux in ungrazed Bahia1-SBR and Bahia2-SBR in the winter are likely due to the increased amount of residue left in the soil when left ungrazed. It is possible that excess SOC in the surface layers of ungrazed bahiagrass, as previously discussed in SOC results, provides increased substrates for soil microorganisms to respire. Bremer et al. (1998) observed higher CO_2 flux in ungrazed pastures compared to those that had been clipped to simulate grazing for a tallgrass prairie in Kansas. Increased CO_2 in Cotton-TR during the spring could also be caused by increased residue left for respiration immediately after winter cover crop grazing. Although Cotton-TR was the only crop that was statistically higher when ungrazed in spring, most other crops were consistently higher after coming out of the winter cover crop when ungrazed (i.e., Bahia2-SBR, Cotton-SBR, Peanut-TR). Johnson and Matchett (2001) observed that livestock grazing resulted in significantly lower CO_2 flux than ungrazed pasture. They observed respiration rates of 76.1 and 40.6 kg CO_2-C ha^{-1} d^{-1} for land ungrazed and grazed by bison, respectively. The only crop × season combination that resulted in higher CO_2 with grazing at WREC-LP occurred during summer in the Cotton-SBR treatment. In the summer, higher CO_2 production in grazed compared to ungrazed Cotton-SBR could have resulted from labile C left during previous grazing of winter crop, although this does not coincide with other differences in between grazing treatments. Grazing had an effect on CO_2 production at WREC-LP, but not at NFREC-LP; differences in management between the two locations are likely responsible. In particular, differences in cattle stocking rate may have affected the results, although other management practices (e.g., timing of fertilizer application, cotton stalk removal practices) varied between locations as well. Increasing cattle stocking rate can provide more easily decomposable substrates that are available for respiration. At NFREC-LP, CO_2 emissions resulting from higher stocking rate may have offset CO_2 emissions resulting from increased SOC in ungrazed treatments.

When examining differences between crops at WREC-LP for the season × grazing × crop interaction, no differences were observed in fall (Figure 3-3). During the winter season, Bahia1-SBR had a lower CO_2 flux than all other crops, whether grazed or ungrazed with the exception of ungrazed Peanut-TR. Lower CO_2 flux in Bahia1-SBR was most likely caused by dormancy of bahiagrass during the winter season, while winter cover crops were actively growing and promoting biological respiration of CO_2. During the winter, all crops were planted in winter cover with the exception of Bahia1-SBR. A reverse effect was seen in the spring season, when winter cover crop had been killed in order to plant the subsequent summer crop. Bahia1-SBR had higher CO_2 flux than all other crops for grazed treatments (Figure 3-3a). For ungrazed treatments, Bahia1-SBR was significantly higher than Peanut-TR, but consistently higher than all other crops (Figure 3-3b). Since Bahia1-SBR was the only actively growing crop at this time, an increase in CO_2 flux was probably caused by increased soil and plant respiration while bahiagrass was actively growing. In the summer, Peanut-TR was lower than Bahia1-SBR, Bahia2-SBR, and Cotton-SBR than for grazed treatments, but was consistently lower than all other crops (Figure 3-3a). It should also be noted that although not statistically different, Peanut-SBR was lower than Cotton-SBR, and Peanut-TR was lower than Cotton-TR. Under grazing treatment, soil may be more compacted in peanut than other crops, because of the weak soil structure after peanut harvest. During the peanut harvest, peanuts are turned from underneath the soil, having a similar effect to plowing. Soil that has recently been mixed is more susceptible to compaction. Increased compaction from cattle grazing would have reduced aeration, therefore preventing CO_2 production. In the ungrazed treatments, Peanut-SBR was higher than Cotton-SBR during summer for WREC-LP (Figure 3-3b). The reason for higher CO_2 flux in ungrazed Peanut-SBR compared to Cotton-SBR in the summer is unclear, but may be related to the type of residual carbon available for mineralization.

At NFREC-LP, crop differences for CO_2 production were affected by season, but not grazing (Table 2-3). In the spring, Bahia1-SBR (50.3 kg CO_2–C ha^{-1} d^{-1}) and Cotton-SBR (48.2 kg CO_2–C ha^{-1} d^{-1}) had higher CO_2 flux than Peanut-SBR (25.8 kg CO_2–C ha^{-1} d^{-1}). It is unclear why Peanut-SBR would have lower CO_2 production than Bahia1-SBR and Cotton-SBR in the spring; however, the poor soil structure resulting from peanut harvest may have allowed for increased compaction by cattle. Increased compaction would create an anaerobic environment, thus decreasing the amount of CO_2 produced. Because this effect was not seen in the subsequent Cotton-SBR crop, it is not likely that peanut harvest had a long-term effect on soil structure. In the summer at NFREC-LP, both Bahia1-SBR and Bahia2-SBR emitted more CO_2 than Cotton-SBR and Peanut-SBR, most likely due to the increased biomass that bahiagrass produces compared to summer peanut and cotton crops. Similarly, Tracy and Zhang (2008) observed higher CO_2 flux in perennial pasture compared to continuous corn or corn-oat-pasture cropping systems in Illinois. Increasing biomass may have increased the soil biological activity, thus increasing respiration rates.

Results for CO_2 flux indicate that grazing may decrease the amount of CO_2 emissions in an integrated crop-livestock system when a moderate stocking rate of 2.5 cattle ha^{-1} is used. The decreases observed for CO_2 flux may be negated by decreases in SOC storage that appeared in grazed treatments. Grazing of winter cover after the Peanut-SBR crop appeared to increase soil compaction, thus decreasing CO_2 production in grazing treatments. Differences in CO_2 flux for crops were typically between cool-season and warm-season crops at WREC-LP, CO_2 flux being higher when actively growing or when more root biomass was being produced.

Methane Flux

Methane emissions ranged from −6.46 to 3.28 g CH_4–C ha^{-1} d^{-1} at the WREC-LP (Table 3-4), and treatments did not differ with respect to CH_4 flux. At NFREC-LP, a season × grazing × crop interaction was observed for CH_4 flux (Table 3-3). In Bahia1-SBR during the fall, CH_4 emission was higher for ungrazed (0.140 g CH_4–C ha^{-1} d^{-1}) than for grazed treatments (−4.19 g CH_4–C ha^{-1} d^{-1}). In grazed plots, CH_4 was taken up by the soil. The same was true for ungrazed plots (2.93 g CH_4–C ha^{-1} d^{-1}) compared to grazed plots (−2.02 g CH_4–C ha^{-1} d^{-1}) under Bahia2-SBR in the winter. Higher stocking rates likely contributed to more urine patches in grazed areas that may have increased CH_4 uptake. Flessa et al. (1996) reported that soils with urine patches (−17.8 to −2.64 g CH_4–C ha^{-1} d^{-1}) took up more CH_4 than soils unaffected by urine patches (−6.48 to −0.72 g CH_4–C ha^{-1} d^{-1}) in grazed pastures. In the winter, Peanut-SBR grazed treatments had higher CH_4 emissions under grazing. Poor soil structure after peanut harvest may have allowed for increased compaction under grazing. This correlates with results from CO_2 flux for Peanut-SBR that indicated increased compaction from digging and subsequent grazing results in decreased pore space and aeration, thus creating a negative environment for CO_2 production, but instead a favorable environment for CH_4 production. No differences for CH_4 flux were observed during the summer or spring seasons, indicating that CH_4 is more affected by active grazing than by temperature.

Few differences were observed in CH_4 flux; however, soils often acted as a sink for CH_4. This is consistent with other studies that have observed grazed pastureland (Flessa et al., 1996; Liebig et al., 2010; Schönbach et al., 2012) and conservation-tilled cropland (Ussiri et al., 2009) to act as a sink for CH_4. Following the release of manure from livestock, Flessa et al. (1996) observed that soils became a net sink for CH_4 after 20 days had passed. Liebig et al. (2010) found that approximately 1.9 kg CH_4-C ha^{-1} yr^{-1} was taken up by the soil in pastures moderately or heavily grazed by cattle.

Nitrous Oxide Flux

Nitrous oxide flux ranged from 2.29 to 12.8 g N_2O–N ha^{-1} d^{-1} in the fall, 1.74 to 11.6 g N_2O–N ha^{-1} d^{-1} in the winter, 3.62 to 26.4 g N_2O–N ha^{-1} d^{-1} in the spring, and 4.51 to 26.7 g N_2O–N ha^{-1} d^{-1} in the summer at WREC-LP (Table 3-5). Based on ranges, N_2O flux was often greater during the warmer spring and summer seasons at WREC-LP. An overall effect of season was observed for N_2O emissions at NFREC-LP ($P < 0.001$). Emission of N_2O at NFREC-LP was higher in the spring than for all other seasons. Higher emissions during the spring could be a combined effect of high temperature in June at NFREC-LP and recent fertilizer application on the winter cover crop that occurred before the spring sampling dates. Nitrous oxide ranged from 0.466 to 4.18 g N_2O-N ha^{-1} d^{-1} in the fall, 0.331 to 4.75 g N_2O-N ha^{-1} d^{-1} in the winter, 3.81 to 49.5 g N_2O-N ha^{-1} d^{-1} in the spring, and 0.879 to 5.19 g N_2O-N ha^{-1} d^{-1} in the summer at NFREC-LP. Increases in N_2O flux during summer and spring seasons are commonly observed (Ussir et al., 2009).

A season × grazing × crop interaction was observed for N_2O flux ($P = 0.025$) at WREC-LP. During the spring, Cotton-SBR, Peanut-TR, and Cotton-TR had approximately 290, 70, and 280% higher N_2O flux, respectively, in ungrazed compared to grazed treatments (Table 3-5). In the summer, Peanut-SBR and Cotton-SBR were also higher when ungrazed. No differences were observed between treatments during the fall or winter months. All differences at WREC-LP displayed an increase in N_2O flux when ungrazed. Other analyses have reported decreases (Schönbach et al., 2012) or no differences (Liebig et al., 2010) for N_2O flux in grazed compared to ungrazed treatments. Flessa et al. (1996) observed N_2O-N flux from cattle manure hotspots at 3.84 to 15.6 g ha^{-1} d^{-1}. However, they reported that out of the total N_2O produced in a grazed pasture, 63% of N_2O emissions were from urine hotspots and only 1.7% was from manure hotspots. They reported that maximum N_2O production occurred 10 d after the release of urine. Other studies have also reported increased N_2O flux under grazing management (Oenema et al., 1997). Although gas samples were not collected on fresh manure spots, increases in N_2O flux would be expected in grazed treatments based on these results. However, increases in N_2O flux were observed in ungrazed treatments. In particular, this effect was seen at the end of winter grazing treatment. Like CO_2 flux observations, this might be due to increased soil microbial activity attributable to the larger amount of residue that remains in ungrazed treatments. No differences were observed between treatments during the fall or winter months. Differences in N_2O flux due to grazing were observed only at the WREC-LP location, and often resulted in higher N_2O flux when ungrazed. Production of N_2O at NFREC-LP did not differ according to grazing treatment. Differences between WREC-LP and NFREC-LP are likely caused by changes in cattle stocking rate, although other management practices (e.g., timing of fertilizer application, cotton stalk removal practices) varied between locations as well. Increasing cattle stocking rate can provide more easily decomposable substrates that are available for respiration. All differences between grazed and ungrazed treatments at WREC-LP occurred in the spring or summer seasons. Grazing did not appear to have a negative effect on N_2O emissions and decreased N_2O production in most instances.

When examining differences between crops in the fall at WREC-LP, Cotton-SBR had consistently lower N_2O flux than all other crops in ungrazed treatments (Figure 3-4b), although only Peanut-SBR was statistically higher. Low N_2O flux for ungrazed Cotton-SBR may have been caused by differences in fertilizer application timing at planting of winter cover crops. At WREC-LP, N fertilizer had been applied to all plots with the exception of Cotton-SBR and Cotton-TR for the 2012 sampling time. It is unclear why this effect was only seen in Cotton-SBR, and not Cotton-TR. It is also unclear why differences were only seen in ungrazed treatments. In the winter, Bahia1-SBR was consistently lower in N_2O flux than all other crops, whether grazed or ungrazed (Figure 3-4). Grazed Peanut-SBR and Cotton-SBR had statistically higher N_2O flux than grazed Bahia1-SBR; ungrazed Cotton-SBR was higher than ungrazed

Bahia1-SBR. Similar to results for CO_2 flux, this could be caused by lower soil biological activity when bahiagrass is dormant. In the spring, Bahia2-SBR had higher N_2O flux than all other crops for grazed treatments (Figure 3-4a). Because the increase in N_2O flux was only observed in grazed treatments, it can be assumed that this resulted from labile forms of N to be respired by denitrifying microorganisms. At the spring sampling, cattle were actively grazing only in Bahia2-SBR at WREC-LP. For ungrazed treatments in spring, Cotton-SBR was higher than Peanut-SBR; all crops with the exception of Peanut-SBR were higher than Bahia1-SBR (Figure 3-4b). In summer, no differences occurred for grazed treatments. However, in ungrazed treatments, Peanut-SBR and Cotton-TR were higher than Bahia2-SBR, Cotton-SBR, and Peanut-TR. Differences for N_2O production between summer crops were difficult to explain, and were most likely caused by timing of fertilizer application. Studies that examine N_2O flux from soil have been highly variable when comparing grazing systems (Chroňáková et al., 2009; Liebig et al., 2010; Oenema et al., 1997; Schönbach et al., 2012).

CONCLUSION

The SBR appeared to increase SOC compared to the TR in the top 5 cm at WREC-LP. There were indications that SOC storage may be reduced under grazing of bahiagrass, despite previous studies in the SBR showing no difference in grazed and ungrazed treatments in the top 15 cm of soil (George et al., 2013). Grazing did not appear to have a long-term effect on SOC pools. Production of CO_2 and N_2O tended to increase in warmer seasons. When using a stocking rate of approximately 2.5 cattle ha^{-1}, increases in CO_2 and N_2O production were occasionally observed for ungrazed treatments, dependent upon season and crop. Using a higher stocking rate of 3.4 cattle ha^{-1}, no differences between grazing treatments occurred for CO_2 or N_2O flux. However, increased CH_4 uptake by the soil was observed in some instances for the 3.4

cattle ha^{-1} stocking rate. In most cases, flux of CH_4 could be considered negligible. Grazing of the winter cover crop following peanut appeared to increase soil compaction due to poor soil structure after the peanut harvest. Emissions of GHG did differ between SBR and TR for a given crop (i.e., peanut, cotton), indicating that the SBR neither increased nor decreased GHG emissions in this study compared to a TR. For moderate cattle stocking rates used in this study, grazing did not appear to have a negative effect on GHG emissions in integrated crop-livestock systems, whether in a SBR or TR. Further research of GHG emissions in the SBR may be useful to quantify the effect of grazing in the Southeast.

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Table 3-1. Soil organic carbon (SOC) for all crop phases of the sod-based rotation and traditional rotation at the Wiregrass Research and Extension Center large plots (WREC-LP), Wiregrass Research and Extension Center large plots (WREC-LP) and North Florida Research and Education Center large plots (NFREC-LP) at 0-5, 5-10, 10-15, 15-30, and 30-60 cm depths for grazed and non-grazed treatments.

Location	**Crop**	**Soil Organic Carbon**					
		0-5 cm		**5-10 cm**		**10-15 cm**	
		Grazed	Ungrazed	Grazed	Ungrazed	Grazed	Ungrazed
		Mg ha^{-1}					
WREC-LP	Bahia1-SBR	12.62	12.55	7.43	9.95**	7.52	7.25
	Bahia2-SBR	11.70	11.26	6.79	11.06**	6.01	5.64
	Peanut-SBR	12.31	11.50	7.01	6.25	5.01	5.98
	Cotton-SBR	13.76	10.83	8.42	6.51	5.98	5.56
	Peanut-TR	5.25	6.76	6.48	8.07	6.35	6.00
	Cotton-TR	7.68	7.85	8.35	7.67	6.15	5.55
NFREC-LP	Bahia1-SBR	5.63	8.90	5.73	7.11	4.49	6.83
	Bahia2-SBR	7.56	11.32	7.48	10.43	6.15	8.86
	Peanut-SBR	4.64	3.76	4.58	3.78	3.97	3.50
	Cotton-SBR	5.07	4.51	5.56	4.45	4.85	4.22
	Peanut-TR	–	–	–	–	–	–
	Cotton-TR	–	–	–	–	–	–

* Difference between grazed and ungrazed treatments is significant at P ≤ 0.1.

** Difference between grazed and ungrazed treatments is significant at P ≤ 0.05.

Table 3-2. Effects of grazing on carbon dioxide flux according to season and crop sequence in the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center large plots (WREC-LP) and the North Florida Research and Education Center large plots (NFREC-LP).

		CO_2-C flux											
		Bahia1-SBR†		**Bahia2-SBR**		**Peanut-SBR**		**Cotton-SBR**		**Peanut-TR**		**Cotton-TR**	
Location	**Season**	**G**	**UG**	**G**	**UG**	**G**	**UG**	**G**	**UG**	**G**	**UG**	**G**	**UG**
		kg ha^{-1} d^{-1}											
WREC-LP	Fall	10.7	13.6	8.2	10.7	14.3	9.9	12.5	9.9	12.3	9.5	11.0	15.0
	Winter	8.8	14.3*	17.4	29.8**	28.1	24.7	23.9	28.1	22.4	23.5	27.6	30.5
	Spring	48.4	38.4	20.0	27.1	24.7	23.9	22.1	26.0	19.5	25.8	17.6	32.8**
	Summer	49.6	38.9	49.3	39.6	37.4	53.1**	48.4*	30.3	26.7	34.7	37.9	35.0
NFREC-LP	Fall	10.8	11.7	18.0	16.3	20.7	18.4	27.9	17.3	–	–	–	–
	Winter	16.2	16.2	19.6	25.0	16.8	20.6	23.5	28.8	–	–	–	–
	Spring	58.7	42.8	36.2	32.8	26.8	24.9	52.6	44.1	–	–	–	–
	Summer	59.0	58.3	52.3	67.8	34.6	24.4	26.9	25.3	–	–	–	–

† Crop labels are listed according to rotation sequence for the SBR: 1st year bahiagrass (Bahia1-SBR), 2nd year bahiagrass (Bahia2-SBR), peanut (Peanut-SBR), and cotton (Cotton-SBR) and for the TR: peanut (Peanut-TR) and cotton (Cotton-TR). In winter and spring seasons, all crops were planted in winter cover crop with the exception of Bahia1-SBR.

* Difference between grazed (G) and ungrazed (UG) treatments is significant at $P \leq 0.1$.

** Difference between grazed (G) and ungrazed (UG) treatments is significant at $P \leq 0.05$.

Table 3-3. Degrees of freedom (df) and P-values for differences in carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) based on grazing, season, and crop variables and their interactions.

Source of Variation	WREC-LP				NFREC-LP			
		CO_2	CH_4	N_2O		CO_2	CH_4	N_2O
	df		*P*-value		df		*P*-value	
Grazing	1	0.135	0.457	0.008	1	0.316	0.786	0.096
Season	3	<0.001	0.734	0.001	3	<0.001	0.702	<0.001
Crop	5	0.699	0.224	0.044	3	0.066	0.767	0.172
Grazing x season	3	0.098	0.767	0.003	3	0.116	0.815	0.994
Grazing x crop	5	0.236	0.097	0.293	3	0.453	0.329	0.456
Season x crop	15	0.002	0.144	0.010	9	<0.001	0.457	0.045
Grazing x season x crop	15	0.009	0.989	0.025	9	0.547	0.060	0.421

Table 3-4. Effects of grazing on methane flux according to season and crop sequence in the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center large plots (WREC-LP) and the North Florida Research and Education Center large plots (NFREC-LP).

		CH_4-C Flux											
		Bahia1-SBR		**Bahia2-SBR**		**Peanut-SBR**		**Cotton-SBR**		**Peanut-TR**		**Cotton-TR**	
Location	**Season**	**G**	**UG**	**G**	**UG**	**G**	**UG**	**G**	**UG**	**G**	**UG**	**G**	**UG**
		g ha^{-1} d^{-1}											
WREC-LP	Fall	0.99	−0.13	0.05	−3.77	−2.13	0.20	−1.82	−0.73	1.09	0.31	0.61	−1.19
	Winter	−1.44	1.56	0.68	−0.77	−0.79	−0.93	−1.49	−0.45	−1.07	0.61	1.96	1.14
	Spring	0.34	−0.44	1.61	0.72	−0.02	0.76	−1.27	−0.31	−0.28	−0.32	−2.70	−6.47
	Summer	1.73	3.28	0.53	−2.63	−2.00	−1.33	−0.31	0.09	0.42	0.91	−0.43	−2.79
NFREC-LP	Fall	−4.19	0.14**	2.92	−0.30	1.81	−1.31	−1.05	1.56	–	–	–	–
	Winter	−0.69	−2.11	−2.02	2.93**	5.31**	−1.09	1.03	0.53	–	–	–	–
	Spring	0.83	−0.33	−1.46	−1.37	−0.03	−0.92	−0.31	−1.26	–	–	–	–
	Summer	−0.49	1.32	0.89	−0.27	−1.29	0.18	0.30	−0.21	–	–	–	–

* Difference between grazed (G) and ungrazed (UG) treatments is significant at $P \leq 0.1$.

** Difference between grazed (G) and ungrazed (UG) treatments is significant at $P \leq 0.05$.

Table 3-5. Effects of grazing on nitrous oxide flux according to season and crop sequence in the sod-based rotation (SBR) and traditional rotation (TR) at the Wiregrass Research and Extension Center large plots (WREC-LP) and the North Florida Research and Education Center large plots (NFREC-LP).

		N_2O-N flux											
		Bahia1-SBR		Bahia2-SBR		Peanut-SBR		Cotton-SBR		Peanut-TR		Cotton-TR	
Location	Season	G	UG	G	UG	G	UG	G	UG	G	UG	G	UG
		g ha^{-1} d^{-1}											
WREC-LP	Fall	5.95	3.85	12.83	9.31	7.74	11.41	5.08	2.29	4.80	9.85	5.27	8.06
	Winter	1.74	2.12	6.22	3.04	12.21	6.36	10.78	11.58	2.92	4.09	7.76	2.57
	Spring	3.62	4.75	26.37	23.12	4.69	11.09	7.54	29.25**	8.21	21.15**	4.37	16.55**
	Summer	7.92	12.98	6.48	10.27	6.66	23.41**	11.67	6.71	8.36	4.51	8.53	26.68**
NFREC-LP	Fall	1.67	0.56	1.81	0.47	1.38	1.15	4.18	1.37	–	–	–	–
	Winter	0.88	1.21	1.85	0.33	4.46	1.95	4.72	4.75	–	–	–	–
	Spring	32.40	31.55	12.97	3.81	8.09	5.40	32.84	49.47	–	–	–	–
	Summer	4.76	1.17	5.19	4.48	3.92	3.10	1.31	0.88	–	–	–	–

* Difference between grazed (G) and ungrazed (UG) treatments is significant at $P \leq 0.1$.

** Difference between grazed (G) and ungrazed (UG) treatments is significant at $P \leq 0.05$.

Figure 3-1. The 20.2 ha large plot experiment at the Wiregrass Research and Extension Center (WREC-LP) was divided into six blocks. Blocks A, B, C, and D rotate crop phases of the sod-based rotation (SBR). Blocks F and G rotate phases of the traditional rotation (TR).

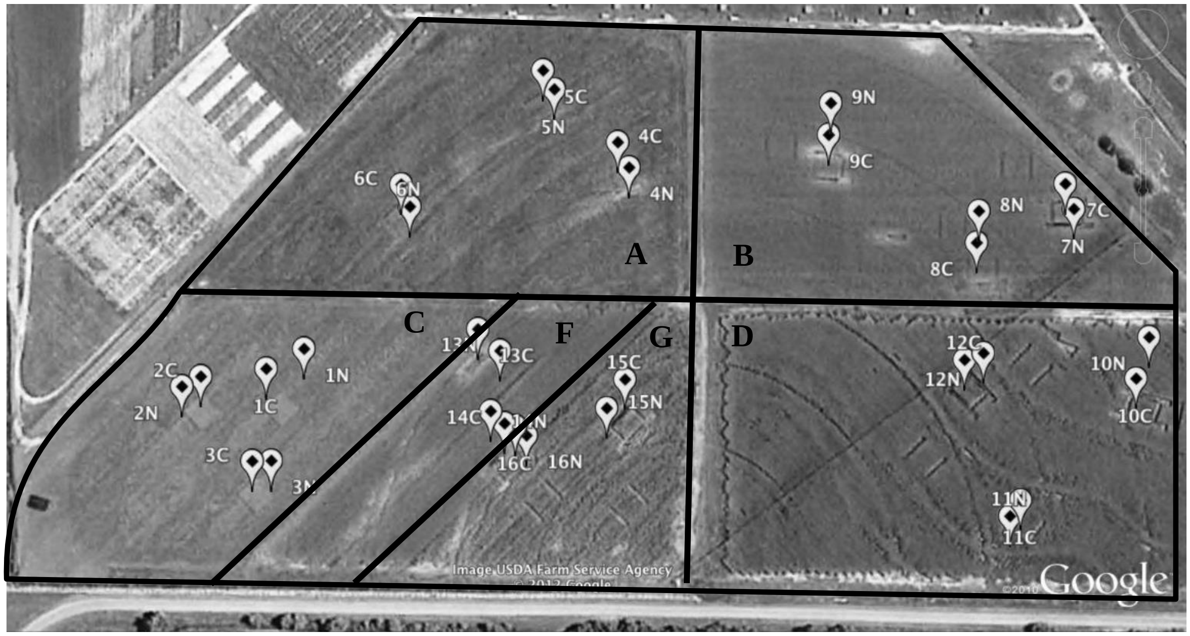


Figure 3-2. The 61 ha large plot experiment at the North Florida Research and Education Center in Marianna, FL was divided into four blocks. Blocks rotate crop phases of the sod-based rotation (SBR).

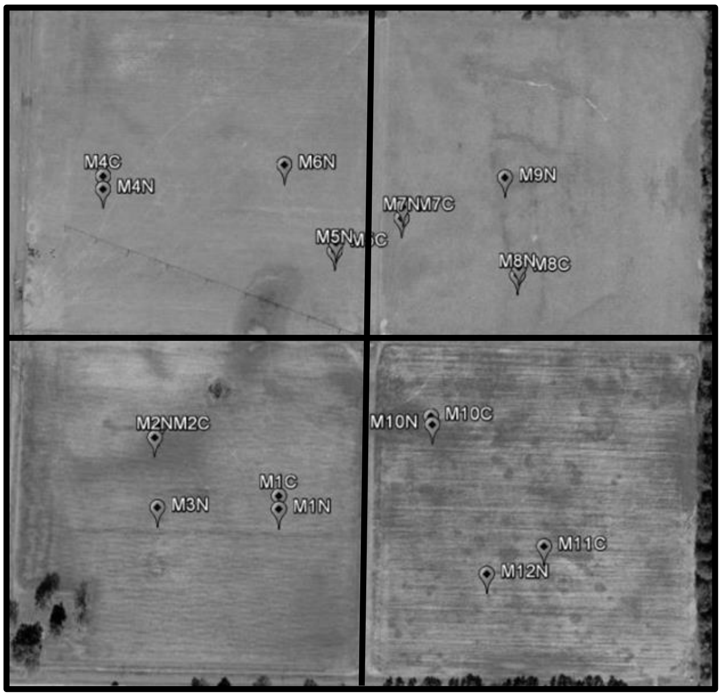


Figure 3-3. Carbon dioxide flux at Wiregrass Research and Extension Center for (A) grazed plots and (B) ungrazed plots. Crops follow the sequence for which they appear in the sod-based rotation (SBR): 1st year bahiagrass (Bahia1-SBR), 2nd year bahiagrass (Bahia2-SBR), peanut (Peanut-SBR), and cotton (Cotton-SBR) or the traditional rotation (TR): peanut (Peanut-TR) and cotton (Cotton-TR). Columns with the same letter do not differ within a season for grazed or ungrazed treatments ($\alpha = 0.05$).

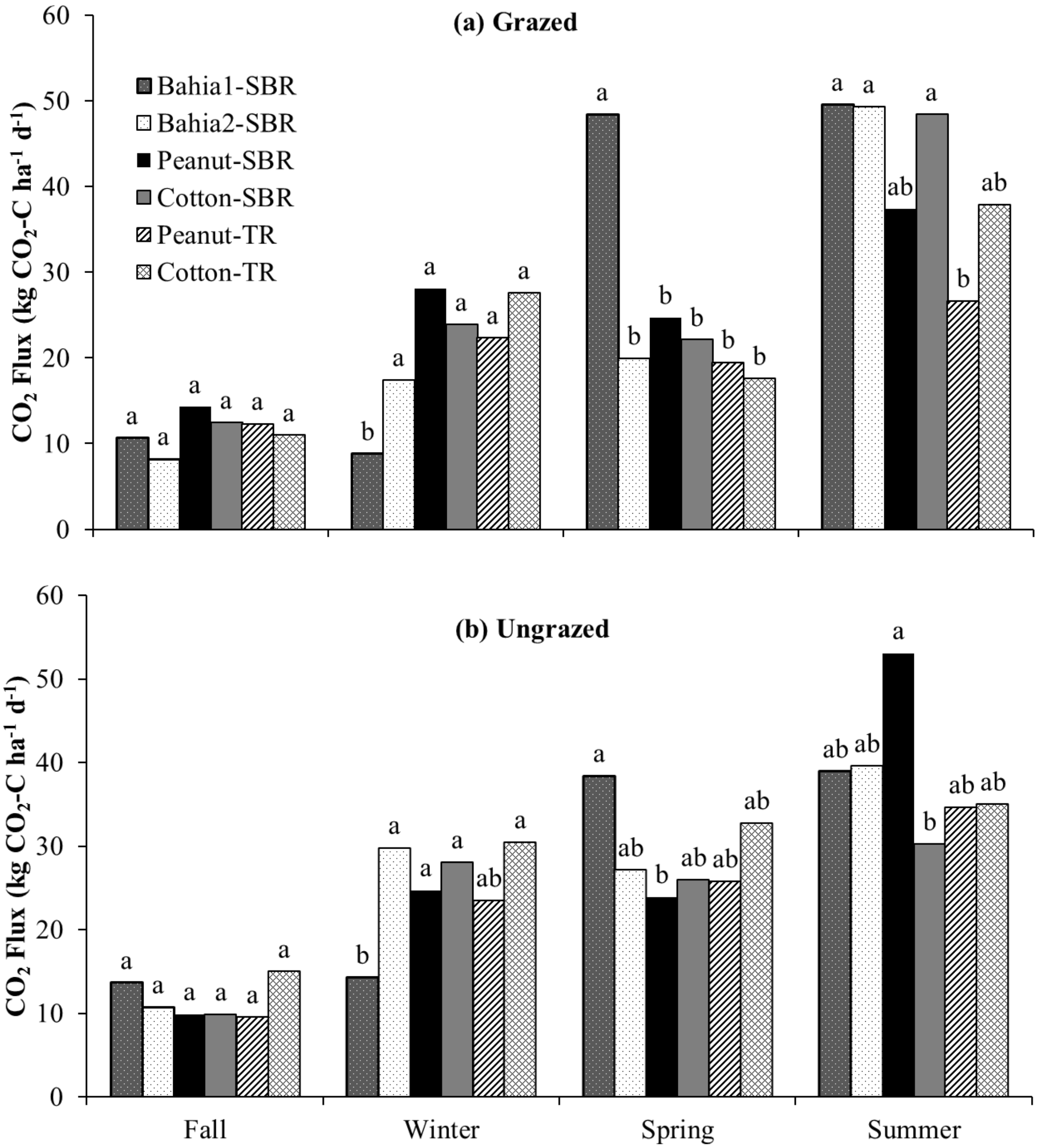
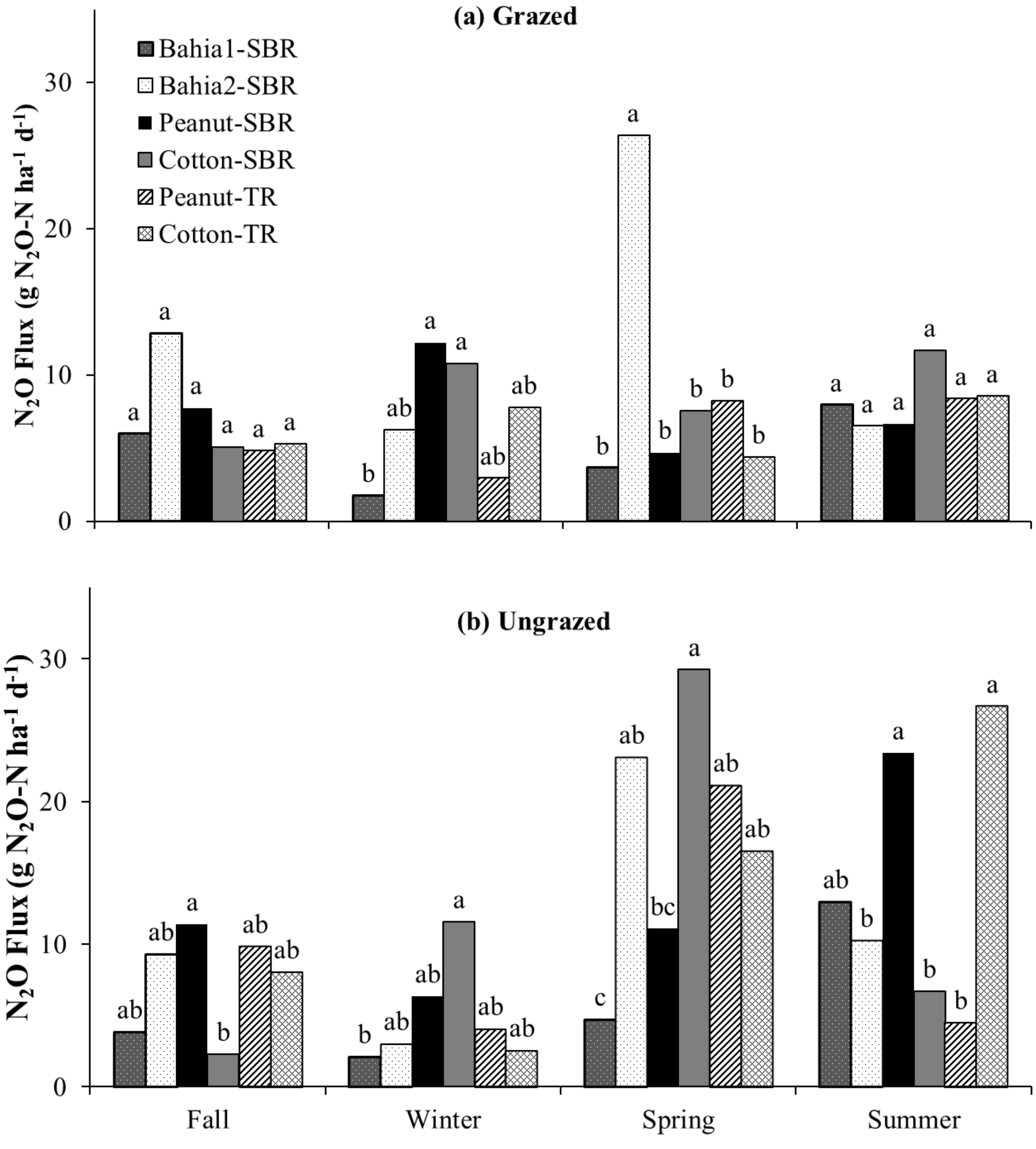


Figure 3-4. Nitrous oxide flux at Wiregrass Research and Extension Center for (A) grazed plots and (B) ungrazed plots. Crops follow the sequence for which they appear in the sod-based rotation (SBR): 1st year bahiagrass (Bahia1-SBR), 2nd year bahiagrass (Bahia2-SBR), peanut (Peanut-SBR), and cotton (Cotton-SBR) or the traditional rotation (TR): peanut (Peanut-TR) and cotton (Cotton-TR). Columns with the same letter do not differ within a season for grazed or ungrazed treatments ($\alpha = 0.05$).



APPENDIX

Two closed chamber measurements were compared for measuring soil CO_2 flux, one using a static closed chamber method according to Hutchinson and Mosier (1981) and the other using a LiCOR 8100 system. Using the static method, gas samples were taken from a closed chamber at 0, 30, and 60 min between 12:00 and 16:00. Concentration of CO_2 was determined for each time interval using a Shimadzu GC-2014 gas chromatograph (Shimadzu Scientific Instruments, Columbia, MD), which was equipped with a methanizer and flame ionization detector to measure CO_2. Flux of CO_2 was determined linearly by regressing time against change in mass per unit area. Using the LiCOR 8100 (LI-COR Co., Lincoln, NE) system, an Infra-Red Gas Analyzer (IRGA) determined CO_2 concentrations in the field. Measurements with the LiCOR were taken the day following the static closed chamber gas sampling between 12:00 and 16:00. The LiCOR system compares two calculations for determining flux (i.e., linear and exponential). The appropriate calculation method is determined by the LiCOR system.