

SOIL CARBON SEQUESTRATION AND STABILIZATION IN TREE-BASED PASTURE
SYSTEMS IN FLORIDA

By

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To my beloved wife Helen G. Weldelibanos, my cherished children Delina, Nathan and Joshua,
my adored mother Medhin T. Haile, and to the memory of my father, Ghebremussie Haile

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Silvopasture that integrates deep-rooted trees in pasture production systems is likely to enhance soil carbon (C) sequestration in deeper soil profiles, compared to tree-less pasture systems. The total soil C content at six depths (0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75, and 75 – 125 cm) were determined in silvopastures of slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*), and adjacent open pastures at two sites, representing Spodosols and Ultisols, in Florida. The C contents within three fraction-size classes (250 – 2000, 53 – 250 and <53 µm) of each soil profile were determined, and using stable C isotope signatures, the plant sources (C3 vs. C4 plant) of C fractions were traced. Total soil organic carbon (SOC) in whole soil was higher under silvopasture by an average of 33% near trees (SP-T) and 28% in the alleys (SP-A) as compared to adjacent open pastures. Moreover, new SOC in macroaggregate fraction increased by 39% in SP-A and 20% in SP-T. The SOC protected in microaggregates were 12.3% and 18.8% more in SP-A and SP-T respectively than in open pastures. Isotopic-ratio analysis suggested that the SOC increase in silvopasture could largely be due to accumulation of new C3-derived SOC in macroaggregates fractions, retention of older C3-derived SOC in microaggregates, and retention of C in silt + clay fraction of soil (<53 µm). C3 plants (slash pine

trees) seemed to have contributed more C in the silt + clay fraction than C4 plants (bahiagrass), particularly in lower soil depths, in all sites, and the Spodosol contained more C in the $<53\mu\text{m}$ fraction at and below the spodic horizon (on average 50 cm deep) in silvopasture compared to open pasture. In both soil orders, the C3 plant contributed more C in the smallest soil fraction ($<53\mu\text{m}$) than the C4 plant, particularly at the lowest zone studied (75 – 125 cm). The results support the hypothesis that compared to open pastures, silvopasture contains more stable C in deeper soil profiles under similar ecological settings.

CHAPTER 1

INTRODUCTION

Increasing concentrations of the so-called greenhouse gases (GHGs) in the atmosphere and associated global warming are issues of serious environmental concern today. The most abundant among the GHGs are oxides of carbon, particularly carbon dioxide (CO_2). It is generally agreed that, if the world emission of GHGs continues unabated, atmospheric CO_2 concentration may double by the end of the 21st century. This doubling of CO_2 concentration is predicted to increase the world average surface air temperature by between 1.5 and 4.5°C (Kattenberg et al., 1996). Responding to this concern, the Kyoto protocol (UNFCCC, 1997) was embraced to stabilize the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate. The Kyoto protocol legally binds the developed nations (annex-1 countries) to reduce emission of GHGs by 5 % below the 1990 levels (Baker and Barrett, 1999; Faeth and Greenhalgh, 2000). Besides reduction in industrial emissions, the Kyoto Protocol also proposes sequestering carbon (C) in terrestrial sinks. Nevertheless, the effects of anthropogenic activities on C stocks of the world are still inadequately understood.

The idea of using soils to sequester C and mitigate risk of accelerated greenhouse effect is rather novel. Soil organic carbon (SOC) is a major pool in the terrestrial C cycle and it is linked to atmospheric CO_2 through inputs from plants and losses via decomposition. With approximately 1500 Pg C stored to one meter depth of the world's soil (Batjes, 1996; Bruce et al., 1999), shifts in land cover and/or land-use practices that affect pools and fluxes of SOC have large implications for the C cycle fluxes on a wide-reaching scale. Different models have been developed to calculate the C source vs. sink relationship between soil and atmosphere. However, disparity exists between model predictions and measurements of annual fluxes of C among the

various C pools even with the latest improved model accuracy, resulting in ambiguities in global C budget. Lal et al. (1995) suggested that the disparity is ascribed to terrestrial ecosystems, of which soils are a major component.

Estimating the global C budget has been difficult and remains controversial due to uncertainties in the quantitative aspects of C storage and dynamics in terrestrial ecosystems. Changes in soil C stocks that occur following a shift from one vegetation type to another is one of the great concerns in this context: land-use change may lead to a depletion of soil organic carbon and consequent increase in atmospheric CO₂. However, no clear conclusion has been reached whether terrestrial ecosystems are net C sources or sinks (Detwiler and Hall, 1988). Although some evidence points to a large terrestrial C pool as sink (Houghton et al., 1999; Pacala et al., 2001), the geographic location as well as C accumulation rates and mechanisms controlling this terrestrial sink are still largely non-quantified (Houghton et al., 1999). However, it is widely believed that the amount of C accumulated following tree integration in to non-forested ecosystems is a potentially large, yet uncertain sink for atmospheric CO₂ (Houghton et al., 1999; Pacala et al., 2001).

Silvopasture agroforestry systems that integrate trees into pastures have been studied as an alternative land-use approach to intensive open-pasture grass system for beef cattle production in the southeastern USA, mainly to diversify the enterprise and improve environmental quality of land (Garrett et al., 2000; Nair et al., 2007; Michel et al., in press). Such tree-based land-use systems may potentially store C in the soil beneath them. Information on soil C storage and dynamics of silvopasture is, however, inadequate. Furthermore, studies on soil C storage potential of silvopastoral and such other systems that integrate trees into pastoral and agricultural landscapes have the potential to substantiate and get better output from model of SOC by

allowing extrapolation of results from the ecosystem-level to the broader scales needed to predict terrestrial ecosystems' role in the global C cycle including potential of terrestrial ecosystems for long-term soil C sequestration.

Predicting the effects of land-cover changes induced by human activities on C dynamics and assessing future land-use options associated with integration of trees in pasture or other tree-based land-use systems in the region requires detailed information on SOC dynamics. Information on the mechanisms of organic C storage in the different soil C pools, especially those with longer residence time, is essential in understanding whether terrestrial ecosystem C sinks will continue to sequester C in the future. A major problem is that SOC is very heterogeneous and it comprises various fractions that differ in rate and extent of decomposition. Different constituents of SOC have relative stability ranging from labile to stable forms (Carter 1996). The different compartments cannot be determined directly by chemical or physical fractionation procedures (Paustian et al. 1992). Tiessen and Stewart (1983) and Feller et al. (1991) observed that sand-size organic matter (macroorganic matter, > 250 µm) is often more labile than the organic C in the clay and silt size fractions. Christensen (1992) also found that by physically fractionating soils, specific particle sizes can be linked to specific organic matter fractions and to soil structure and aggregation. These findings formed the fundamental basis for the widely used size- and density- fractionation of soil.

Tree-based pasture systems present a unique opportunity for using stable isotope methodology to study SOC dynamics following the shift in vegetation structure due to the integration of trees to open pasture. The differences in isotope ratio of the plant community associated with the C₃ vs. C₄ plants in silvopasture system can be used to quantify the contribution of plants of each photosynthetic pathway to soil organic matter (Balesdent et al.,

1988). No study has employed the natural abundance of $\delta^{13}\text{C}$ to study SOC in pine-based silvopatalor system where C₃ and C₄ plants are grown simultaneously. The analysis of $\delta^{13}\text{C}$ combined with soil physical fractionation could be used to quantify and serve as an indication of plant sources of each C quality. Specifically, it will show whether SOC accumulation is the result of increases in the most recent organic matter inputs derived from trees or organic C derived from the grasses or previous pasture land, or from a mixture of both sources (assuming that there is little contribution from herbaceous C3 plants in the system).

Objectives of the Study

The general objective of this study is to evaluate the consequences of integration of trees in pastures of cattle-beef production systems on the soil C cycles in Florida. The specific objectives are:

- Quantify some of the physical and chemical characteristics of SOC and evaluate how these characteristics change following pasture-to-silvopasture alteration;
- Estimate total SOC accumulation and sequestration in whole soil and fractionated soil particle size classes following tree integration into pasture or pasture-to-silvopasture conversion;
- Determine the relative importance of C derived from slash-pine trees (C₃) vs. behaigrass vegetation (C₄) in the silvopasture using the natural isotopic difference between C₄ grasses and C₃ woody plants; and
- Elucidate specific physical protection mechanisms of soil C sequestration in this system by combining the plant sources and determining where C is stored relative to soil aggregate sizes.

Organization of the Dissertation

The dissertation is presented in systematic progression with the above-stated individual objectives as chapter topics. It begins by explaining the rationale of the study and concepts used to address the study objectives. Thus, this chapter (Chapter 1) presents the general introduction, objectives and the over all organization of the dissertation. Chapter 2 is devoted to describing the

state and role silvopastural agroforestry and synthesizing current literatures on effects of tree integration into pasture on dynamics and storage of SOC. The results of investigations on soil characteristics in silvopasture and open pasture land-use systems are presented in Chapter 3; these soil characteristics are set out as basic background information for the study objectives presented in the subsequent chapters. The assessment of potential of silvopasture as opposed to open pasture in soil C storage and stabilization begins in Chapter 4 by presenting the results of carbon storage in whole and fractionated soil-size classes. Chapter 5 presents the results of analysis of stable carbon isotope ratio to identify the plant sources for SOC stored in each land-use system. Finally the summary and conclusions of the study are presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

Southeastern USA: State of Agriculture, Forestry, and Agroforestry

Small farms and non-industrial timber operations are significant drivers of the economy in Florida and other parts of the southeastern USA. Small farms, defined as having annual sales less than \$250,000 (USDA, 2002), accounted for 88% of Florida farms, but they constitute 56% of total agricultural income in the state. About 84% of small farms are individual- or family-owned (USDA, 2002). Similarly, out of the 6.6 million hectares (16.3 million acres) of forestland in Florida, 52% is non-industrial private land. Evidently, small-scale agricultural and timber operations constitute a major sector of the rural economy. The situation is similar in other states of the southeastern region too.

As in many parts of the USA, farm families in the Southeast are facing several new challenges. These are partly the result of changes related to urbanization of rural lands, agricultural land-use, agricultural and forestry intensification, availability and quality of water, climate change, and competition from foreign markets (Workman and Allen, 2004). The small-scale operations in particular are increasingly vulnerable because of capital constraints in facing many environmental problems – if not threats. The increasing impact of a rapidly urbanizing landscape, for example, creates significant changes in ecosystem characteristics such as increased fire danger, changes in water drainage patterns leading to soil erosion and flooding, and fragmentation of wildlife habitat that could affect the small-scale farms due to their vulnerability. The Environmental Protection Agency (EPA) has shown that agricultural non-point source pollution is a significant cause of stream and lake contamination and prevents attainment of water quality goals specified in the Clean Water Act (USEPA, 1996). The problem of phosphorus (P) loss from soils is a major concern in fertilized agricultural and forestry

enterprises, particularly in coarse-textured and poorly drained soils where drainage water ultimately mixes with a body of surface water (Nair and Graetz, 2004). Soils with these characteristics are prevalent in the southeastern states. Intensive high-input agriculture in a humid climate with frequent, heavy rainfall and wide use of irrigation and drainage would cause and/or accelerate P leaching in deep sandy soils (Sims et al., 1998).

Ranching is a significant land-use activity in Florida, with about 3.07 million ha (7.6 million acres) of rangeland. In the northern half of the state, where forests products are the primary source of income from the range, the land remains forested. However, millions of acres were “improved” with the fertilization and establishment of introduced grasses, mainly bahiagrass (*Paspalum notatum*). Florida has approximately 1 million ha (2.5 million acres) of bahiagrass pastures (USDA/ERS, 2006b). Traditionally, pasture (as opposed to range) was fertilized. The potential for P loss from fertilized pastures resulting in water quality degradation is a serious issue (Nair and Graetz, 2004).

Approximately 8 million ha (20 million acres) of land under row crop production in the Southern USA were reported as marginal lands (Dangerfield and Harwell, 1990) with low profit potential and high erosion risk when cropped in rows. Although conversion to pasture or forests may protect these lands (Dangerfield and Harwell, 1990), the combination of trees and pasture is reported to be the most efficient and economical production schemes on marginal land in the southern USA (Zinkhan and Mercer, 1997).

Under all these scenarios, there is mounting pressure on land owners of small-scale farms to adopt land management practices that are economically and ecologically sustainable. Integrated systems such as agroforestry – the integration of trees into the farm or/and pasture lands – that provide diversified economic advantages as well as improved land environmental

quality can be utilized as an appropriate strategy under these circumstances (Workman et al., 2003).

Today there is an increasing body of knowledge on agroforestry as well as increasing awareness about its potential as a land-management approach. Agroforests are planned and managed agroecosystems (Sharrow, 1997). Increasing the overall productivity and efficiency of the land-use system and its sustainability are major goals of agroforestry (Schroth, 1995). When trees and/or shrubs are deliberately combined with crops and/or livestock, due to the biophysical interactions of those components, the physical, biological, ecological, economic, and social benefits are optimized (MacDicken and Vergara, 1990; Garrett et al., 1991; Nair, 1993; Leakey, 1996). A distinction has to be drawn here between optimization and maximization: it is well known that in most agroforestry situations, the production of a specific component of the system may not be maximum compared to the production from the sole-stand system of that component (as reported in the case of beef-cattle production under silvopasture in this study site: Kalmbacher and Ezenwa, 2005), however, considering the productivity and other benefits derived from all components and the system as a whole over a longer period of time than the production cycle of crops, the overall benefits from the combined system could be more on a unit-area basis than the combined production from sole stands of the components in over the same period of time (Nair 1993; Alavalapati et al., 2004). Agroforestry uses specific structural and functional characteristics of natural ecosystems to create a sustainable agroecosystem (Winterbottom and Hazlewood, 1987; Vandermeer, 1995), and mimics the large patch scale dynamics and succession of natural ecosystems (Ong and Leakey, 1999). Thus, agroforestry has received considerable attention and importance as an alternative land-use practice to managing and protecting the land resources in a sustainable way.

As a land-use practice, agroforestry is not completely new to the Southeast. With introduction of cattle to the coastal area of Florida, grazing within pine forests was practiced as early as 1520 (Lewis, 1983). During the 1950s, tree-based pasture used to be practiced as "tree-pasture" or "pine-pasture" in which pine trees were planted in improved pasture as Conservation Reserve Soil Bank Program (Nowak and Long, 2003). Silvopasture that provides an opportunity for managing trees for high-value sawlogs and at the same time generates an annual income from livestock grazing is considered attractive to nonindustrial private forest landowners and livestock operators in southeastern USA who want to diversify their enterprise (Nair et al. 2005).

In the southeastern USA, five major agroforestry practices are identified: alley cropping, forest farming, riparian forest buffers, windbreaks and silvopasture (Table 2-1) (Garrett et al., 2000; Nair 2001). Silvopasture – the integration of trees into forage or/and livestock – is the most prevalent form of these agroforestry practices in North America (Garrett et al., 2000; Nair et al., 2005). Silvopasture is usually established by planting trees in well established and managed bahiagrass (*Paspalum notatum*), bermudagrass, (*Cynodon dactylon*) or other similar open pastures. This eliminates costs of forage establishment, shrub and brush control, or removal of timber harvest residues (Nowak et al., 2003; Nair et al. 2005).

Available information suggests that silvopasture can improve land environmental quality, especially as an approach to mitigating the problem of nutrient pollution resulting from beef-cattle pastures (Michel et al., in press; Nair et al., 2007). The technology is applicable on a wide range of geographic scale and is adaptable for small land holdings as well as operations with small numbers of animals. Silvopasture practices are known to have economic benefits and are good option for existing pastures in the southeast (Clason and Sharow, 2000). Studies on silvopasture in southeastern USA have found the practice to be an economical viable enterprise

(Lundgren et al., 1983; Clason, 1995; Grado et al., 2001, Stainback and Alavalapati, 2004). Stainback et al. (2004), however, found that combining slash pine with cattle production in Florida was not competitive with conventional ranching when the environmental costs and benefits were not considered in the analysis. Production of widely spaced rows of trees for timber, especially of pines, e.g., longleaf pine (*Pinus palustris*), in combination with the benefits of shade for animals offsets loss of pasture area and is attractive to a growing number of producers (Workman et al., 2003). As landowners are challenged to manage the natural resource in integrated approach, the conversion of pasture-to-silvopasture is expected to increase in the region.

Silvopasture has multiple plant species and is applicable in both livestock production and reforestation. Due to its multiple species nature, thus a more efficient production than monoculture, silvopasture could store substantial carbon (C) in its plant-soil system. This potential of silvopastoral systems has, however, not been even adequately studied, let alone exploited (Montagnini and Nair, 2004). It is believed that the potential to increase above- and below-ground productivity in tree-based system may lead to greater C sequestration in the system, particularly in soils, and therefore proper design and management of silvopasture practices can make them effective C sinks. Evidently, the effects of tree integration into pasture system or pasture-to-silvopasture conversion on soil C, though seemingly substantial, has not been quantified. Detailed studies on storage and dynamics of soil organic carbon (SOC) in silvopasture ecosystem as opposed to open pasture are therefore warranted.

Soil C Sequestration in Tree-based Pasture Systems

Soil C Sequestration: Process and Significance

Carbon sequestration has attained considerable prominence as a term and concept in the context of heightened interest in GHG mitigation and climate change, and it refers to the net

removal of CO₂ from the atmosphere into long-lived pools of C in terrestrial ecosystems. The pools can be living, aboveground biomass (e.g., trees), products with a long and useful life created from biomass (e.g., lumber), living biomass in soils (e.g., roots and microorganisms), or recalcitrant organic and inorganic carbon in soils and deeper subsurface environments. Although the soil C pool constitutes a major global C reserve, the concept of soil C sequestration has not been widely appreciated because of the lack of understanding of the role soil processes play in the global C cycle (Lal, 2002). Further, agriculture has been generally considered as a source of GHGs and other environmental pollutants.

Carbon is sequestered in soils in two ways: direct and indirect (SSSA, 2001). Direct soil C sequestration occurs by inorganic chemical reactions that convert CO₂ into soil inorganic carbon compounds such as calcium and magnesium carbonates. Indirect plant C sequestration occurs as plants photosynthesize atmospheric CO₂ into plant biomass. Some of this plant biomass is indirectly sequestered as SOC during decomposition processes. The amount of C sequestered at a site reflects the long-term balance between C uptake and release mechanisms. Because those flux rates are large, changes such as shifts in land cover and/or land-use practices that affect pools and fluxes of SOC have large implications for the C cycle and the earth's climate system.

Globally, soils play a vital role in the C cycle. The soil C pool comprises SOC estimated at 1550 Pg (1 petagram = 10¹⁵ g = 1 billion ton [metric]) and soil inorganic carbon (SIC) about 750 Pg both to 1-m depth (Batjes, 1996). The total soil C pool of 2300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg (Lal, 2001). About 5% of the global SOC pool, which is estimated to be 75 – 80 Pg C, is in soils of the USA (Waltman and Bliss, 1997, Bellamy et al. 2005). A reduction in soil C pool by 1 Pg is equivalent to an

atmospheric enrichment of CO₂ by 0.47 ppmv (Lal, 2001). Thus, any change in soil C pool would have a significant effect on the global C budget.

Uncertainties in the quantitative aspects of C storage and dynamics in terrestrial ecosystems, however, have created a controversy and delay in the global C budget assessments. Whether terrestrial ecosystems are net sources of C emission or sinks has been the center of the controversy (Detwiler and Hall, 1988). Several studies largely point to terrestrial ecosystems as a C sink (Houghton et al., 1999; Pacala et al., 2001). The C storage rates and mechanisms controlling this terrestrial sink and its geographic location are still largely unknown (Houghton et al., 1999).

Land-use and Soil C Storage

Tree-based land-use systems are expected to have better carbon sequestration potential than most agricultural systems. It has been suggested that the amount of C accumulated following tree integration into non-forested ecosystems is a substantial, yet uncertain sink for atmospheric CO₂ (Houghton et al., 1999; Pacala et al., 2001). It has been shown that land-use conversion from native prairies or forest vegetation to row crop production agriculture leads to a decrease in the SOC pool (Brown and Lugo, 1990; Burke et al., 1989). Although the C amount in native ecosystem may not necessarily represent the upper soil C limit (Six et al., 2002), notable SOC loss, due to inappropriate land-use and soil mismanagement practices, has caused a decline in soil quality and greater emission of C into the atmosphere. The SOC loss from croplands in the USA is estimated in the range of 30 to 50 Mg C/ha, or about 50% of the antecedent level (Lal, 2002).

Sharow and Ismail, (2004) reported that silvopasture system accumulated approximately 740 kg ha⁻¹ year⁻¹ more C than forests and 520 kg ha⁻¹ year⁻¹ more C than pastures. They concluded that the agroforest (silvopasture) had the advantage in terms of higher total annual

biomass production and had active nutrient cycling patterns of both forest stands and grasslands, compared to those of pasture or timber stands alone. More recently, in a plantation with native tree species established in a degraded pasture of the Caribbean lowlands of Costa Rica, the highest SOC pool was measured under trees species *Hieronyma alchorneoides* and *Vochysia guatemalensis* [132 and 119 Mg C ha⁻¹, respectively], whereas in treeless pasture it was 116 Mg C ha⁻¹ (Jimenez et al., 2007). These studies support the proposition that agroforestry practices, such as silvopasture, may be more efficient at accumulating C than tree plantations or pasture monocultures.

When trees are allowed to grow in grass-dominated land such as an open pasture, some functional consequences are inevitable, most notably alterations in above- and below-ground total productivity, modifications to rooting depth and distribution, and changes in the quantity and quality of litter inputs (Scholes and Hall, 1996; Connin et al., 1997; Gill and Burke, 1999; Jackson et al., 2000; Jobbágy and Jackson, 2002). These changes in vegetation component, litter, and soil characteristics modify the C dynamics and storage in the ecosystem and may lead to alterations of local and regional climate systems through feedback interactions (Schlesinger et al., 1990; Ojima et al., 1999). But not many studies are available on the mechanisms and processes associated with C dynamics and storage in tree-based grassland/pasture systems such as silvopasture, despite their local, if not regional, significance (Jackson et al., 2000, 2002; Archer et al.. 2001, 2004; Hudak et al., 2003).

Humification (conversion of biomass into humus), aggregation (formation of organomineral complexes as secondary particles), translocation of biomass into subsoil by deep roots and bioturbation, and leaching of soil inorganic carbon into groundwater as bicarbonates are processes that lead to SOC sequestration (Lal, 2001). All these processes are operational in

tree-based and-use systems. The impact of silvopastoral systems on soil C sequestration depends largely on the amount and quality of input provided by tree and grass components of the system, and on properties of the soils themselves, such as soil structure and their aggregations.

Below-ground Inputs and C Sequestration

Roots are an important part of the C balance, because they transfer large amounts of C into the soil. More than half of the C assimilated by the plant is eventually transported below ground via root growth and turnover, root exudates (of organic substances), and litter deposition. Therefore, soils contain the major stock of C in the ecosystem (Albrecht et al., 2004; Montagnini and Nair, 2004). Depending on rooting depth, a considerable amount of C is stored below the plow layer and is, therefore, better protected from disturbance, which leads to longer residence times in the soil. With some trees having rooting depths of more than 60 m, root C inputs can be substantial, although the amount declines sharply with soil depth (Akinnifesi et al., 2004). Most of the biomass of the roots of annual crops/ grasses consists of fine roots (< 2 mm in diameter) whereas biomass of tree roots, which is a large proportion of the below-ground productivity, consists of coarse roots (> 2 mm diameter) (Albrecht et al., 2004, Akinnifesi et al., 2004). Fine roots of both trees and crops have a relatively fast turnover (days to weeks) (van Noordwijk et al., 1998), but the lignified coarse roots decompose much more slowly and may thus contribute substantially to below-ground C stocks (Vanlauwe et al., 1996).

Soil Structure and C Stabilization

Soil structure can be described in terms of form and stability. Structural form refers to the arrangement of solid particles and void space between them whereas stability of the soil structure refers to the ability of the soil fabric to withstand the disrupting action of external forces, particularly drying and rewetting, and this ability is directly related to aggregation of soil particles. The most accepted model of aggregation involves two physical units, microaggregate

<250 µm diameter and macroaggregate >250 µm dia (Edward and Bremener, 1967; Tisdall and Oades, 1982). Microaggregates are the building blocks of soil structure but both macroaggregates and microaggregates depend on organic carbon for their integrity and stability. Humic molecules become associated with clay minerals and amorphous aluminum (Al) and iron (Fe) oxides with the formation of microaggregates (Brady and Weil, 2002). Through the cementing action of polysaccharides and humic substances, they can become united with one another and with other components such as fragments of decomposing organic material and sand particles to form macroaggregates. Macroaggregate may breakdown when exposed to disrupting actions of external forces such as slaking or rewetting of soils. This is caused primarily by pressure exerted by the entrapped air inside the aggregates and rapid swelling of clays (Kemper and Rosenau, 1986).

SOC contains a variety of fractions that differ in decomposability and are very heterogeneous in structure. The turnover of SOC is intimately linked with organic matter quality (Agren et al., 1996; Martens, 2000). Distinctive components of SOC have different residence times, ranging from labile to stable forms (Carter, 1996). The amount of carbon sequestered in a soil pool compartment reflects the long-term balance between inputs from plants and release mechanisms via decomposition. This concept has led to the suggestion that SOC can be viewed as having an active, labile pool (mean residence times [MRT's] ≈ 1 – 2 yr) a slow pool (MRT's ≈ 25 yr), and a passive, recalcitrant pool (MRT's ≈ 100 – 1000 yr) (Parton et al., 1987; Jenkinson, 1990; Schimel et al., 1994). Further, protection of SOC by silt and clay particles is well established (Sorensen, 1972; Ladd et al., 1985; Feller and Beare 1997; Hassink, 1997). It is also known that aggregation increases in less disturbed systems and that organic material within the

soil aggregates, especially the microaggregates, have lower decomposition rate than those located outside the aggregates (Oades, 1984; Elliott and Coleman, 1988; Six et al., 2000).

Soil aggregation is the main process whereby SOC is retained in soil. Such retention can be characterized by both short-term storage in macroaggregates or long-term sequestration in microaggregates. Size and density fractionation has shown promise for physically dividing SOC into pools. It is widely believed that soil size fractionation is linked to specific SOC fractions, soil structure and aggregation characteristics (Christensen, 1992). The fundamental basis for soil size fractionation is the observation that SOC associated with sand-size aggregates (or macroorganic matter > 250 µm) is often more labile than SOC in the clay and silt fractions (Tiessen and Stewart, 1983; Feller et al., 1991). In fact, soil aggregation and SOC accumulation are interrelated: SOC or fractions thereof are basic to the aggregation process, while SOC sequestered within aggregates is protected against decomposition. Both the degree of the soil aggregation and extent of SOC storage are influenced by land-use, and soil and crop management practices (Carter, 1996). The sundry compartments in non-living SOC cannot, however, be determined directly with chemical or physical fractionation procedures, which has been a major problem in predicting the dynamics of the SOC (Paustian et al., 1992).

Analyzing soil C fractions provides very useful information, particularly with respect to monitoring changes in land-use management. In a review, van Noordwijk et al. (1997) showed that in land-use change where deforestation was followed by long-term sugarcane (*Saccharum* sp.) cultivation the decline in forest-derived SOC continued during the 50 years of the study and that the apparent equilibrium value of the total SOC content of the soil was based on the balance between gradual build-up of sugarcane SOC and decay of forest-derived SOC. By comparison, when forest was converted to pasture, the decline of labile forest-derived SOC was much faster;

however, the accumulation of labile pasture-derived C returned the total SOC content to its original level 7 years after conversion.

Generally, soil organic matter (SOM) becomes stable through three mechanisms: chemical recalcitrance of the SOM, physical protection, and chemical and biochemical stabilization (Christensen, 1996; Stevenson, 1994). Under the current pressures on land owners to improve the environmental quality of farm lands, silvopasture agroforestry on a wide range of scales could be adaptable for small land holdings or small numbers of animals. As a strategy to mitigate accumulation of CO₂ in the atmosphere, soil under silvopasture could potentially sequester C mainly because of the potential increase in above- and below- ground productivity. Many biogeochemical consequence in general and the storage and dynamics of SOC in particular are not well understood when trees are integrated into pasture system or pasture-to-silvopasture conversions are undertaken.

Using Stable C Isotopes as an Indicator of Change: Background and Methodology

Carbon occurs in two stable isotopes, ¹³C and ¹²C with natural abundance about 98.89% of ¹²C and 1.11% of ¹³C in atom % (Barrie and Prosser, 1996). However, due to isotopic fractionation during physical, chemical, and biological processes, the ratio of these two stable isotopes (¹³C/¹²C) in natural materials fluctuates slightly around these proportions. Differences in C isotopes are relatively small in vegetation and SOC, with the most enriched (those highest in ¹³C) differing from the least enriched (those with lowest ¹³C) by only about 2%. Therefore, ¹³C/¹²C of the SOM must be measured with high precision if these small differences are to be utilized.

A gas isotopic ratio mass spectrometer equipped with three ion beam collectors is commonly used for this purpose. Briefly, SOM is quantitatively converted into CO₂ by combustion at about 900°C in an O₂ atmosphere, the CO₂ is isolated and purified by cryogenic

distillation or gas chromatography, and the isotopic compositions of CO₂ determined by simultaneous collection of masses 44 (¹²C¹⁶O¹⁶O), 45 (¹³C¹⁶O¹⁶O) and 46 (¹²C¹⁸O¹⁶O) in mass spectrometer. The isotopic composition of CO₂ from the sample is compared to that derived from a standard with known ¹³C/¹²C ratio.

Plants discriminate against ¹³CO₂ during photosynthesis due to the biochemical properties of the primary C-fixing enzymes and limitations to CO₂ diffusion into the leaf (Vogel, 1980; Leary, 1988; Farquhar, 1989). Plants with the C₃ photosynthetic pathway reduce CO₂ to phosphoglycerates, a 3-carbon compound via enzyme ribulose bisphosphate carboxylase/oxygenase (RuBisCO). About 85 % of all plant species possess the C₃ pathway of photosynthesis (Ehleringer et al., 1991), and C₃ species dominate in most ecosystems from the boreal region to the tropics. Terrestrial C₃ plants grown under natural conditions have a $\delta^{13}\text{C}_{\text{PDB}}$ value ranging between -22 ‰ and -34 ‰, with a mean of -28 ‰ (Boutton, 1991; Vogel, 1993). C₄ plants on the other hand reduce CO₂ to aspartic or malic acid, both 4-carbon compounds, via the enzyme phosphoenolpyruvate (PEP) carboxylase. The C₄ plant species comprises only 5 % of all plant species (Ehleringer et al., 1991) but they cover approximately 17 % of the terrestrial surfaces (Smith, 1979). Plants with the C₄ photosynthesis pathway discriminate less against ¹³CO₂ during photosynthesis and, therefore, have larger values $\delta^{13}\text{C}_{\text{PDB}}$ than C₃ plants, ranging from approximately -17‰ to -9‰, with mean -13‰. (Boutton, 1991; Vogel, 1993). Thus the ranges of $\delta^{13}\text{C}_{\text{PDB}}$ values for C₃ and C₄ plants do not overlap with an average difference of 15‰.

Alteration of pasture-to-silvopasture, as the case in point, presents a unique opportunity to use stable isotope methodology to study SOC dynamics following a shift in vegetation structure due to the integration of trees onto open pasture. In Florida, the plant community of the silvopasture system comprises of C₃ plants slash pine (*Pinus elliottii*) trees ($\delta^{13}\text{C} \approx -29.5\text{ ‰}$;

Parasolova et al., 2003) and C4 grass species as in open pasture bahiagrass (*Paspalum notatum*) (Roots and shoots $\delta^{13}\text{C} \approx -13.3\text{ ‰}$, Nakano et al 2001). The $\delta^{13}\text{C}$ value ranges of C3 and C4 plants do not overlap; differences in isotope ratio, therefore, can be used to quantify the contribution of each photosynthetic pathway to SOM (Balesdent et al., 1988). The isotopic difference between the plant community types allows determining the contribution of each plant type to the SOC accumulation following pasture-to-silvopasture conversion, and for identifying the plant source for specific SOC fraction by which SOM is sequestered in silvopasture system. Few studies have employed the natural abundance of $\delta^{13}\text{C}$ to study SOC in mixed plant communities where C3 and C4 are grown simultaneously. Specifically, it will indicate whether SOC accumulations are the result of increases or decreases in the most recent organic matter inputs derived from trees or from organic C derived from the grasses or previous pasture land, or from a mixture of both sources.

Summary

Land owners in southeastern USA are currently under pressure for change in land management to improve the environmental quality of the farm lands. Tree-integration practices on agricultural/pasture landscape such as silvopasture, intercropping, and riparian buffers are some of the available alternate land-use options and approaches. Silvopastoral practices that are known to have diversified economic and ecological benefits are marked as a good option for existing open pastures in the Southeast. In fact, silvopastoral technologies are applicable on a wide range of scale, and could be adaptable particularly for small land holdings or operations with small numbers of animals. Silvopasture has the potential to increase the total biomass productivity of the pasture system both above and below ground compared to open pastures, and consequently sequester more carbon, particularly in the soil in the long term. The functional

consequences of tree integration into a pasture system or conversion of pasture-to-silvopasture on many biogeochemical characteristics of this agroecosystems in general and the storage and dynamics of SOC in particular are, however, poorly understood.

The impact of silvopastoral systems as functioning agroecosystems on C sequestration depends largely on the amount and quality of input provided by trees and grass components of the system, and on properties of the soils themselves, such as soil structure and its aggregation characteristics. The literature suggests that below-ground inputs in tree-based systems can be substantial. Soil C sequestration in soils is strongly related to their clay + silt content. Water-stable aggregates provide physical protection for C and reduce soil erodibility. Because soil size fractionation is found to be linked to specific SOC fractions, soil structure, and aggregation characteristics, soil size fractionation has shown promise for physically dividing SOC into pools. Furthermore, soil aggregation and SOC accumulation are interrelated: SOC or fractions thereof are basic to the aggregation process, while SOC sequestered within aggregates is protected against decomposition. Both the degree of soil aggregation and extent of SOC storage are influenced by land-use, and the nature of soil and crop. Furthermore, integration of trees into open pasture (C4 grass) systems presents a unique opportunity for using stable isotope methodology to study SOC dynamics in the mixed system.

Table 2-1 Agroforestry practices in the Southeastern U.S.A.

Agroforestry practice	Description
Silvopasture	Silvopasture is the intentional combination of trees, forage plants and livestock together as an integrated, intensively-managed system. Bermuda (<i>Cynodon dactylon</i>) L. (Pers.) and bahia (<i>Paspalum notatum</i> Flüggé) mix with pines; winter grazing under pecans; poultry litter and manure application on trees/pasture; forage crops for cow/calf or fodder for confined operation; pastured poultry and free range with tree shade; fruit trees with animal pasture/hay; livestock-and - fruit for biogas on family farm, plant browse species along fence lines; cattle or goats with scattered trees managed for shade;
Alley cropping	Alley cropping is the cultivation of food, forage or specialty crops between rows of trees. Pecans (<i>Carya illinoiensis</i>) Wangenh. (K.Koch) with hay and/or clover; pecans with peaches (<i>Prunus persica</i> (L.) Batsch) for first 10-12 years; Vegetables in alleys during pecan or citrus establishment; ornamentals with blueberries (<i>Vaccinium corymbosum</i> L.); fruit or nut (e.g., persimmon, <i>Diospyros virginiana</i> L., or chestnut, <i>Castanea dentata</i>) Marshall(Borkh.) with intercrop (e.g., vegetables or cut flowers)
Riparian Forest Buffers	Riparian forest buffers are strips of trees, shrubs and grass planted between cropland or pasture and surface water courses. Including shrubs and trees for wildlife use and bee forage, managed timber or short rotation woody crops, managed along stream sides and in farm drainage ravines, shrubs and trees with deeper roots to aid nutrient absorption, artificial wetlands/add woody buffer for animal waste lagoons (including fish ponds)
Forest Farming	Forest farming is the intentional cultivation of edible, medicinal or decorative specialty crops beneath native or planted woodlands that are managed for both wood and understory crop production. Pine straw; N & P fertilization increase straw; farmer to chef – herbs, mushrooms, specialty vegetables; growing edible and medicinal mushrooms (e.g., on melaleuca); ferns under natural woodland (e.g., oak, <i>Quercus laurifolia</i> Michx.) shade; saw palmetto (<i>Serona repens</i> (W. Bartram Small management on native woodland range; ornamentals under shade trees; honey bees-(apiculture) and wildflowers grown for seed; and native medicinals/botanicals grown under forest shade: mosses, Queen's delight, mints, mushrooms
Windbreaks	Windbreaks are linear plantings of trees and shrubs designed to enhance crop production, protect people and livestock, and benefit soil and water conservation. Border plantings for vineyards, around citrus or other orchards, for protecting from frost, avocado, <i>Persea americana</i> Mill., for carambola, <i>Averrhoa carambola</i> L. (needs wind protection), palms on bunds in flooded rice (field rotation with vegetables), along lot lines increase assessed land value at sale, as barriers against pesticide drift, odor, noise, dust, or roadsides, and protection of animals from ocean winds and excess salt

Source: modified from Workman et al. (2003).

CHAPTER 3

SOIL CHARACTERISTICS OF TREE-BASED AND OPEN PASTURE SYSTEMS

Introduction

Pastureland is an important land resource in the southeastern USA. This sector supports 6.5 million beef cattle and more than 990,000 dairy cows and covers more than 12.6 Million ha (12%) of the total land area the southeastern region (AL, FL, GA, KY, MS, NC, SC, TN, and VA) (USDA, 1992). Managing these agroecosystems and the natural resources in them in an economically and ecologically sustainable manner has become very challenging. This is partly due to problems caused by intensified chemical agriculture leading to land-quality deterioration and ecosystem degradation, and social changes resulting from commercialization leading to disappearance of family farms (Workman and Allen, 2004). Tree integration into pasture land is increasingly becoming one of the prime candidate land management options in addressing these challenges in the rapidly changing social and economic conditions of the Southeast.

Integration of trees into forage and pasture systems changes above- and belowground productivity, modifies the rooting depth and distribution, and may result in a shift in the quantity and quality of litter inputs (Scholes and Hall, 1996; Connin et al., 1997; Gill and Burke, 1999; Jackson et al., 2000; Jobbágy and Jackson, 2000). These changes in vegetation, litter, and soil characteristics are widely believed to alter some of the physical and chemical characteristics and dynamics of soil ecosystem. The need for a thorough understanding of these dynamics of the soil ecosystem and developing effective land management strategies warrants a systematic study of the important soil characteristics such as soil pH and bulk density in different soil layers in pasture systems. The objective of this study was, therefore, to determine these characteristics and assess how these characteristics change following tree integration into pasture systems.

Materials and Methods

Study Area

The study was conducted in four sites, located in Alachua ($29^{\circ}45' N$, $82^{\circ}33' W$), Osceola ($28^{\circ}9' N$, $81^{\circ}10' W$), Hardee ($27^{\circ}13' N$, $82^{\circ}8' W$), and Suwannee ($30^{\circ}24' N$, $83^{\circ}0' W$) counties (Figure 3.1) in Florida. Two sites represented privately owned farms of Mr. Fred Clark in Alachua and Mr. Harris Hill in Osceola counties; the other two were at the Florida Sheriff Boys ranch in Live Oak and the IFAS Range Cattle Research and Education Center, Ona, Florida. For the sake of convenience, the sites are designated by county names where the farms are located. Detailed climatic and edaphic characteristics of the sites are given in Table 3-1. At each site, a silvopasture and an adjacent open pasture plot were selected from which soil samples were drawn. Slope, aspect, and soil series were uniform across plots in a site, ensuring that land-use system (pasture vs. silvopasture) was the primary factor influencing the soil C content in plots.

Soils of Study Area

The sites selected for this study represented two out of the seven soil orders found in Florida. The soils in Alachua and Suwannee sites are Ultisols whereas Hardee and Osceola are Spodosols. Spodosols and Ultisols are the most prevalent soil orders in the southeastern USA. Spodosols have a sandy A horizon, followed by an eluted E horizon underlying which is the Bh or spodic horizon, followed by the Bw horizon (Soil Survey Staff, 1999). The Ap horizon of the Ultisols is about 15 cm thick and is followed by Bt horizons with sand grains coated and bridged with clay (Soil Survey Staff, 1999).

The soil at the Alachua site is Kendrick in the series and consists of well drained, slowly to moderately slowly permeable soils formed as thick beds of loamy marine sediments on nearly level sloping areas in the coastal plain. It has a taxonomic class of loamy, siliceous, semiactive and hyperthermic Arenic paleudults. The Blanton series soils of Suwannee site consists of very

deep, somewhat excessively drained to moderately well drained, moderately to slowly permeable soils on uplands and stream terraces in the Coastal Plain. Such soils are formed in sandy and loamy marine or eolian deposits (NRCS, 2006).

Soils in Hardee site were of the Ona series characterized as poorly drained and moderately permeable, formed in thick sandy marine sediments with a sandy, siliceous, hyperthermic Typic Alaquods taxonomic class. Similar soils are found in the flatwood areas of central and southern Florida. Slopes range from 0 to 2 percent. The Osceola site consists of deep and very deep, poorly drained and very poorly drained soils that are formed in sandy marine sediments. This soil type occurs on flatwoods and in depressions of Peninsular Florida. Slopes are dominantly 0 to 2 percent but range to 5 percent (NRCS, 2006).

Descriptions of Pasture Systems

The term silvopasture can be defined as intentional combination of trees, forage plants and livestock in an integrated and intensively managed system (Nair et al., 2005). In three of the sites (Suwannee, Hardee and Osceola), the silvopasture was established by planting slash pine trees in existing pastures of bahiagrass where as the silvopasture in Alachua site was under a pine forest and was grazed naturally.

The silvopasture in Hardee site was established in December 1991 by planting south Florida Slash pine at $1120 \text{ tree ha}^{-1}$ in $1.2 \times 2.4 \times 12.2 \text{ m}$, double row configuration (Kalmbacher and Ezenwa, 2005). In Osceola slash pine was planted in $3.1 \times 1.2 \times 12.2 \text{ m}$ spacing in double row configuration. In the Alachua and Suwannee sites, trees were planted in a single row configuration with spacings of $1.5 \times 3.0 \text{ m}$ and $1.5 \times 7.2 \text{ m}$ respectively.

No fertilizers were applied to the silvopasture and the open pastures in both Osceola and Alachua sites. The pasture at Suwannee site had been fertilized twice with 19-5-19 NPK

fertilizer at 336 kg ha^{-1} in 2003, and 224 kg ha^{-1} in 2004. Since 1978, dolomite had been applied to the open pasture at the rate of 4.5 Mg ha^{-1} once every 4 years. The pasture in Hardee was fertilized with N, P, and K at 55, 6, and 45 kg ha^{-1} .

Plant Components

In all the study sites, the silvopastoral system consisted of a combination of slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) and an adjacent open pasture system of exclusively bahiagrass (Figure 3.1). Slash pine and bahiagrass are important species in the southeastern USA for timber and forage respectively. Coniferous and broadleaved tree species are also considered for establishment of silvopasture. However, due to its light crowns and good self-pruning abilities, slash pine is the most suitable tree species among the southern slash pines. The species grows best on moderate to poorly drained sandy soils. Slash pine is one of the most commercially important pine species in the southern USA (Walker and Oswald, 2000). The species grows naturally from southern South Carolina to central Florida and west to eastern Louisiana, but has also been planted and direct-seeded in Louisiana and eastern Texas where it now reproduces naturally (Lohrey and Kossuth, 1990).

Bahiagrass is a sod-forming, deep-rooted, warm-season perennial grass (Watson & Burton, 1985). It was introduced to the USA from Brazil in 1913 by the Bureau of Plant Industry at the Florida Agricultural Experiment Station, Gainesville (Scott, 1920). Several cultivars of *P. notatum*, such as the hardy ‘Pensacola’ or ‘Paraguay’ strains, were introduced into North America for forage and erosion control. ‘Pensacola’ is the most common cultivar in Florida (Werner & Burton, 1991). Bahiagrass has been extensively planted for forage and soil stabilization in the southern USA, especially in Florida, where a 1 million hectares have been

planted (Ipiales, 2003). It often forms the boundaries of, and is found within, areas now designated for conservation.

Soil Sampling

Soil samples were collected in August 2005 from three different sample sets: two locations in a silvopasture that includes locations between trees in a row (SP-T) and at the center of an alley (SP-A); and another set on an open pasture (OP). Each of these sample sets had stratified grid sampling points made by three rows with four sampling points in a row. At each sampling point, soils were collected from six soil depths 0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75, and 75 – 125 cm. While in the field, a composite for each depth interval was prepared by mixing soils of four sampling points in a row, resulting in composite samples of three per set (treatment); the total number of samples was 216 (6 depths× 3 replication× 3 location × 4 sites).

Bulk Density and pH Determination

Soil bulk density (ρ_d) for each layer was measured by the core method (Blake and Hartge, 1986). Using a tube of stainless steel (5 cm in diameter and 75 cm deep) cores samples were collected from all depth intervals. Initial weight of soil core from each layer was measured in the lab immediately after collection. Simultaneously, soil moisture content was determined gravimetrically by oven-drying a sub-sample at 105.8 C° for 48 h to calculate the dry bulk density. The pH (H_2O) was determined in 1:2 soils: water (w/v) suspension using a pH-meter.

Statistical Analysis

Planned-comparison analysis of variance with Tukey's studentized range test (HSD) means comparison test was used to test for land-use treatments effect on soil pH, bulk density, SOC in whole, macroaggregates, microaggregates and silt + clay associated fractions at all four sites. Statistical analyses were carried on depth-wise data. All statistical tests were performed with

SAS (1985) and differences were considered significant when $P < 0.05$. The composite sample in a row (grid line in open pasture) within each soil depth constituted the experimental unit of the analysis and each unit had three replications (rows).

Results

Soil pH

The results showed that OP lands in Suwannee site had higher soil pH value than SP-A or SP-T across all soil profiles. In the upper 5 cm of Osceola soil, however, pH increased in the order of SP-A < OP < SP-T ($p < 0.05$) with corresponding mean values 5.3, 5.8 and 6.4. At all soil depth intervals of Hardee site as well as other depths of Alachua and Osceola, soil pH showed no change with alteration of the pasture to silvopasture (Table 3-2).

Bulk Density

At the upper 5 cm depth and at lower than 75 cm depths of the soil profile, OP had a soil bulk density of 0.9 g/cm³ and 1.8 g/cm³ and was different than the silvopasture (1.7 g/cm³ and 2.0 g/cm³) in Osceola. At the subsurface (5-15cm) depth and at depth lower than 50 cm, soil bulk density of OP, with values of 1.8 g/cm³ and 2.6 g/cm³, was higher than silvopasture values (1.6 g/cm³ and 2.0 g/cm³) in Suwannee site. At all depths in Alachua, and the rest of depth intervals of the other three sites, the bulk density values of silvopasture and open pasture lands were not different.

Discussion

The higher soil pH values observed under silvopasture compared with open-pasture old-growth silvopastoral stands (Suwannee, 40 yr) can be attributed to the regular dolomite application to pasture since 1978. Changes in species composition as a result of tree integration into pasture systems could be expected to influence soil pH through soil-plant feedbacks resulting from changes in litter quality. Plant roots alter the pH in the rhizosphere soil by

production or consumption of H⁺ or by exudation of organic acids, and thereby induce changes in pH compared to the bulk soil. Whether H⁺ exudation or consumption dominates depends on the plant species, the nutritional status of the plants and the form of nitrogen supply (Marschner et al., 1986). The mechanisms by which tree species influence soil acidity are and include interspecific differences in the uptake of exchangeable cations and anions (Alban, 1982). Biogeochemical processes that cause plant-induced changes in soil pH included nitrogen fixation and ensuing nitrification (van Miegroet and Cole, 1984), production and soil deposition of litter high in organic acid concentration (Ovington, 1953), and stimulation of mineral weathering (Tice et al., 1996). Furthermore, changes in above- and belowground productivity, modification of rooting depth and distribution, and a likely shift in the quantity and quality of litter inputs in silvopasture could have result in a shift in soil reaction.

The bulk density did not show significant difference between silvopasture and open pasture in most of the sites except in Suwannee sites at the lower depth profile and the upper 5 cm of the Osceola site. Generally, soil bulk density increases with decrease in organic matter content and is higher in soils of sandy texture. Differences in soil texture between the silvopasture and the open pasture within a site are small, as expected. However, the SOC content in Suwannee was higher in the silvopasture than in the open pasture, particularly at the lower depth of the profile (Chapter 4). Thus, the lower bulk density of soils in silvopasture could be related to their higher SOC content.

Conclusion

Soil pH was lower in silvopasture compared to open pastures on the old-growth of silvopastoral stands (Suwannee, 40 yr), which is a reflection of the regular application of dolomite to pasture. Although minimum, pH change could also be caused due changes in species composition as a result of tree integration into pasture systems and consequent changes in litter

quality. Furthermore, this could be a reflection of the possible influence of previous land-use on subsequent biogeochemical processes in the soil. The long-term consequences of land conversion from open pasture or natural stands to silvopasture in terms of soil reaction and soil quality need further investigation.

Table 3-1 Climatic and edaphic characteristics of silvopasture (SP) and open pasture (OP) in four study sites Florida, USA

Site	Land-use	Size (ha)	MAT(°C)		MAP (mm)	Soil series	Prior land-use	Age (years)
			Maximum	Minimum				
Alachua	SP	28.3	25.7	-3.0	1332.3	Kendrick	Grazed naturally	8
	OP	16.2	25.7	-3.0	1332.3	Kendrick	Agriculture (Corn field)	55
Osceola	SP	8.5	28.1	3.3	1232.5	Immokalee	Pasture (15 years)	12
	OP	6.1	28.1	3.3	1232.5	Immokalee	Florida Flatwoods	45-50
Hardee	SP	17.2	35.9	-0.2	1346.7	Ona	Bahiagrass pasture	14
	OP	8.6	35.9	-0.2	1346.7	Ona	Grazed naturally	22
Suwannee	SP	16.2	25.8	-3.2	1365.7	Blanton	Agriculture, pasture	40
	OP	16.2	25.8	-3.2	1365.7	Blanton	Agriculture	40

MAT = mean air annual temperature, MAP = mean annual precipitation

Table 3-2 Soil pH (H₂O) values of sampling locations across soil depth in the four study sites.

Soil depth, (cm)	Sites											
	Alachua			Suwannee			Hardee			Osceola		
	OP	SP-A	SP-T	OP	SP-A	SP-T	OP	SP-A	SP-T	OP	SP-A	SP-T
0–5	5.6	5.6	5.8	6.9 ^a	5.6 ^b	5.3 ^b	4.9	5.0	4.9	5.8 ^b	5.3 ^c	6.4 ^a
5–15	5.7	5.8	5.8	6.6 ^a	5.6 ^b	5.3 ^b	5.2	5.2	5.2	5.6	5.1	5.3
15–30	6.0	6.0	6.1	6.6 ^a	5.7 ^b	5.5 ^b	5.7	5.2	5.3	5.5	5.7	5.5
30–50	6.2	6.0	6.1	6.6 ^a	5.8 ^b	5.7 ^b	5.7	5.2	5.2	5.6	5.9	5.6
50–75	5.9	5.9	5.8	6.7 ^a	5.6 ^b	5.6 ^b	5.7	5.0	5.0	5.7	5.8	5.7
75–125	5.6	5.6	5.7	6.6 ^a	5.7 ^b	5.5 ^b	5.3	5.0	4.9	5.8	5.5	5.4

Note: Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth

Table 3-3 Soil bulk density for two land-use treatment locations across soil depth in the four study sites.

Soil depth,(cm)	Bulk density (g/cm ³)							
	Alachua		Suwannee		Hardee		Osceola	
	OP	SP	OP	SP	OP	SP	OP	SP
0–5	1.9	2.1	1.4	1.6	1.2	1.3	0.9 ^b	1.7 ^a
5–15	1.1	1.4	1.8	1.5	1.2	1.5	1.5	1.3
15–30	1.5	1.4	1.4 ^b	1.7 ^a	1.6	1.4	1.6	1.9
30–50	1.2	1.2	1.7 ^a	1.4 ^b	1.4	1.2	1.4	1.3
50–75	2.1	2.0	2.6 ^a	2.2 ^b	1.3	1.7	1.5	1.5
75–125	1.4	1.6	2.6 ^a	1.8 ^b	1.4	1.4	1.8 ^b	2.0 ^a

Note: Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth

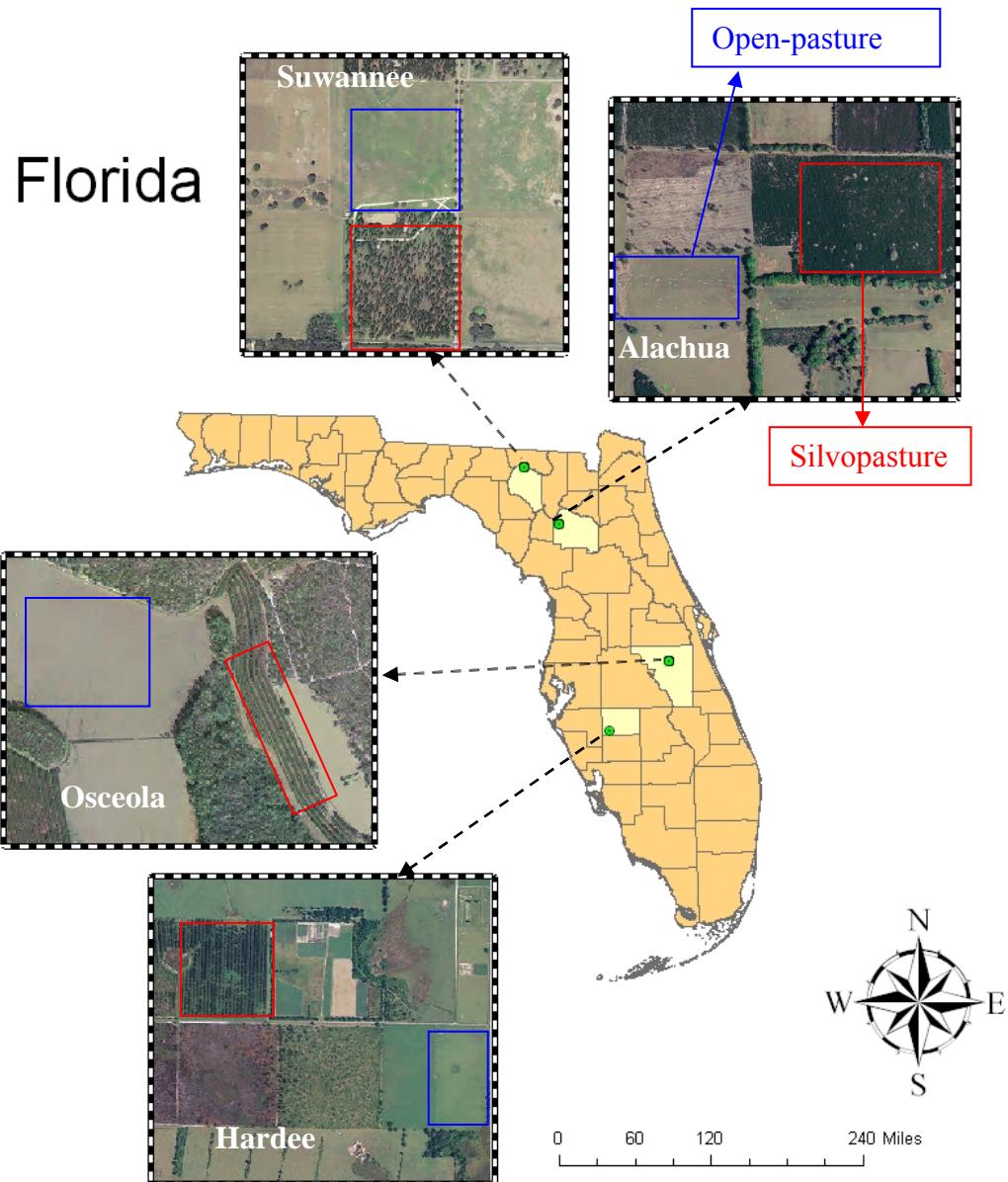


Figure 3-1 Location of soil sampling sites

CHAPTER 4

CARBON STORAGE IN DIFFERENT SIZE FRACTIONS OF SOILS IN SIVOPASTORAL SYSTEMS OF FLORIDA

Introduction

Pastureland is an important land resource in the southeastern United States. It covers more than 12.6 million ha (12% of the total land area) and supports 6.5 million beef cattle and more than 990,000 dairy cows, (USDA, 1992). These agroecosystems and the people inhabiting them are challenged with natural resource management problems due to farm intensification and rapid changes in land-use in of the region. As a result the small-scale farm communities are at a crossroads in search of land management practices that are economically and ecologically sustainable to cope with the problems. Agroforestry land-use practices are among the prime candidates of alternate land management choices (Nair, 1993; Garrett et al., 2000).

Silvopasture – integrating trees into pasture and forage plant production – is the most widespread form of agroforestry in North America (Garrett et al., 2000; Nair et al., 2005). Available information suggests that silvopataloral system is an ecologically sustainable and environmentally desirable approach to mitigate the problem of nutrient pollution resulting from open pastures (Nair et al., 2007) and other avenues of non-point sources of pollution. In areas where nutrient pollution is a very serious environmental problem, e.g., in the coarse-textured soils of the southeastern USA, silvopasture could be an alternative land-use option particularly for non-industrial private forest land owners and livestock operators.

When silvopasture is established by integrating trees into grass vegetation of pasture systems, above- and belowground productivity, the rooting depth and distribution, and the quantity and quality of litter inputs to soil will change (Scholes and Hall, 1996; Connin et al., 1997; Gill and Burke, 1999; Jackson et al., 2000; Jobbágy and Jackson, 2000). However, the soil C dynamics and storage in a continuum of tree-grass systems in general and silvopastoral system

in particular are poorly understood (Jackson et al., 2000, 2002; Archer et al., 2001, 2004; Hudak et al., 2003). The fore mentioned changes in tree-grass systems are believed to impact the soil C dynamics and storage. Through feedback interactions, it may lead to alterations of local and regional climate systems (Schlesinger et al., 1990; Ojima et al., 1999). Presence of large land area of pasture lands and a tree-based non-forest land use practice warrants a detailed study of the soil C dynamics and storage of these ecosystem and implications of their importance in the global C cycle.

Tree-based land-use systems are expected to have better soil C sequestration potential than most row crop agricultural systems (Montagnini and Nair, 2004). Conversion of agricultural crop land to forest usually results in substantial increases in soil C (Johnson, 1992); a recent estimate assumed that 50 Mg C/ha would be sequestered in afforested soils in 30 yr (Bouwman and Leemans 1995). On the other hand, land-use conversion from native prairies or forest vegetation into cultivated agriculture leads to a decline in the SOC pools (Brown and Lugo, 1990; Burke et al., 1989). Native C, however, may not necessarily represent the upper soil C limit (Six et al., 2002). Sharroo and Ismail (2004) reported from their studies in Oregon that silvopasture system accumulated approximately $740 \text{ kg ha}^{-1} \text{ year}^{-1}$ more C than forests and $520 \text{ kg ha}^{-1} \text{ year}^{-1}$ more C than pastures. They concluded that agroforestry may produce more total annual biomass and have synchronized mixed nutrient cycling patterns of both forest and grassland. Claims on C sequestration potential of agroforestry systems are based on the premise that the tree components in agroforestry systems can be significant sinks of atmospheric C due to their fast growth, high and long-term biomass stock, and extensive root systems (Montagnini and Nair, 2004)

The purpose of the research reported here was to quantify C storage in the whole soil and size-fractionated soil pools in a slash pine-based silvopasture (SP) and an adjacent open pasture

(OP) system across six soil depths, at four sites representing Spodosols and Ultisols of Florida.

The specific objectives were: (1) quantify total SOC accumulation and sequestration of open and tree-based pasture systems; (2) quantify SOC stored in the different fractionated particle size classes; and (3) Elucidate specific physical protection mechanisms of soil C sequestration in open and tree-based pasture systems.

Materials and Methods

Study Area

Soil samples were collected in August 2005 from four sites, located in Alachua ($29^{\circ}45' N$ and $82^{\circ}33' W$), Osceola ($28^{\circ}9' N$, $81^{\circ}10' W$), Hardee ($27^{\circ}13' N$, $82^{\circ}8' W$), and Suwannee ($30^{\circ}24' N$, $83^{\circ}0' W$) counties (Figure 3-1) in Florida. Two sites represented privately owned farms of Mr. Fred Clark in Alachua and Mr. Harris Hill in Osceola counties; the other two were at the Florida Sheriff Boys Ranch in Live Oak and the IFAS Range Cattle Research and Education Center, Ona, Florida. For the sake of convenience, the sites are designated by county names where the farms are located. Detailed climatic and edaphic characteristics of the sites are given in chapter 3 (Table 3-1). At each site, a silvopasture and an adjacent open pasture plot were selected from which soil samples were drawn. Slope, aspect, and soil series were uniform across plots in a site, ensuring that land use system (pasture vs. silvopasture) was the primary factor influencing the soil C content in plots.

Soil Sampling

Soil samples were collected from three different sample sets: two locations in a silvopasture that includes locations between trees in a row (SP-T) and at the center of an alley (SP-A); and another set on an open pasture (OP). Each of these sample sets had stratified grid sampling points made by three rows with four sampling points in a row. At each sampling point, soils were collected from six soil depths $0 - 5$, $5 - 15$, $15 - 30$, $30 - 50$, $50 - 75$, and $75 - 125$

cm. While in the field, a composite for each depth interval was prepared by mixing soils of four sampling points in a row, resulting in composite samples of three per set (treatment); the total number of samples was 216 (6 depths \times 3 replications \times 3 locations \times 4 sites).

Physical Fractionation

All field moist composite samples were air dried and passed through a 2 mm sieve. Soils were physically fractionated by wet-sieving following a procedure modified from Elliott (1986) and Six et al. (1998). The procedure involved using disruptive forces of slaking and wet-sieving through a series of two sieve sizes (250 and 53 μm) to obtain three aggregate size classes.

Briefly, a sub-sample of 100 g of the composite soil sample was submerged in deionized water as disruptive forces of slaking for about 5 min prior to placing it on top of 250 μm sieve. The sieving was done manually by moving the sieve up and down approximately 50 times in 2 minutes. The fraction remaining on the top of a 250 μm sieve was collected in a hard plastic pan and allowed to dry in oven at 65°C and weighed. Water plus soil $< 250 \mu\text{m}$ was poured through a 53 μm sieve and the same sieving procedure was repeated. The overall wet sieving procedure yielded a water-stable fraction sizes of a macroaggregate-sized fraction 250 – 2000 μm ; a microaggregate-sized fraction 53 – 250 μm , and silt +clay fraction size $< 53 \mu\text{m}$. The recovery of mass soil fractions after overall wet sieving procedure ranged from 96 to 99% of the initial soil mass.

Chemical Analysis

For chemical analysis, whole and fractionated soil were oven-dried at 60°C for 72 h, and ground to fine powder using a ball mill (Cianflone Scientific Instruments, Pittsburgh, Pa.). Total soil organic C concentration was determined for whole and fractionated soil samples by dry

combustion on an automated FLASH EA 1112 N C elemental analyzer (LECO Corporation, St. Joseph, Mich.).

Statistical Analysis

Planned-comparison analysis of variance with Tukey's studentized range test (HSD) means comparison test was used to test for land-use treatments' effect on SOC in whole, macroaggregates, microaggregates and silt + clay associated fractions at all four sites. Statistical analyses were carried out separately for all depth-classes. All statistical tests were performed with SAS (1985) and differences were considered significant when $P<0.05$. The composite sample in a row (grid line in open pasture) within each soil depth constituted the experimental unit of the analysis and each unit had three replications (rows).

Results

SOC Storage in Whole Soil

In all four sites, SOC storage declined with increase in soil depth on both silvopasture and open pastures systems. At the Alachua site, at soil depth interval 5 – 15 cm and at the lowest depth (75 – 125 cm), the SOC in the whole soil was significantly different ($p<0.05$) across sampling locations with highest values in the SP-A, 22.6 and 2.2 kg/m², respectively. In all other depths of Alachua site, SOC in whole soil was not different among the sampling locations (Figure 4-1).

At the upper 5 cm of soil in Suwannee site, the whole soil SOC was significantly higher in both SP-T (47.7 kg/ m²) and SP-A (41.8 kg/ m²) of the silvopasture than in the open pasture (28.5 kg/ m²). Similarly, at soil depths below 15 cm and above 75 cm, this value was higher in SP-T (range: 8 – 17 kg/ m²) than in the two other land-use elements (Figure 4-2). At the lowest

soil profile (75 – 125 cm), however, the total SOC in the whole soil increased in order of SP-A < OP < SP-T with corresponding values of 1.4, 4.4, and 14.8 kg/ m², respectively.

In soil profile below 5 cm in Hardee site, the silvopasture, both SP-T and SP-A, stored greater SOC in whole soil compared with the open pasture (Figure 4-3). At the upper 5 cm of the soil profile, however, SOC values in whole soil for SP-A were slightly lower than the SP-T or OP. In the Osceola site, highest SOC accumulations were observed in whole soil of SP-T at the lowest soil profiles (50 – 75 cm and 75 – 125 cm) but for the upper 50 cm soil depth no differences in SOC storage was shown among the sampling locations (Figure 4-4)

SOC in Macroaggregates (250 μm –2000 μm)

At both the surface (0 – 5 cm) and subsurface (5 – 15 cm) soil layers of Alachua site, SP-A had the highest (42.7 and 23.2 kg m⁻², respectively) value of C associated with the largest aggregate size. At a soil depth below 15 cm, however, carbon associated with this fraction size was not different between any two sampling locations (Figure 4-5). No differences in macroaggregate C were observed among the sampling locations at the Suwannee site (Figure 4-6).

In Hardee site, the SP-A (47.8 kg m⁻²) stored C about three times that of OP and 17 times that of SP-T in the macroaggregate fraction size at the 75 – 125 cm depth. At subsurface (5 – 15 cm) and middle depths (30 – 50 cm), SP-A and OP were consistently higher than SP-T but no differences among sampling locations were observed in the remaining soil profiles (Figure 4-7).

At the lowest two depths of the soil profiles, the SP-T of Osceola site had higher SOC than the SP-A and OP in macroaggregate size (Figure 4-8). At the soil surface, however, SP-A had significantly lower C storage in this fraction size than both SP-T and OP with no difference between the latter two sampling locations.

SOC in Microaggregates (53 µm – 250 µm)

The C accumulated in the microaggregate fraction did not show differences among the sampling locations in Alachua for all the depths although it consistently decreased with the increase in soil depth (Figure 4-9). Similarly, in Suwannee site (Figure 4-10) both silvopasture and open pasture did not differ at any depth except for the lowest (75 – 125 cm) depth where SP-T (4.35 kg m^{-2}) had stored significantly more than SP-A and OP.

SOC in Silt and Clay (<53 µm)

The C content in silt + clay did not show difference between land-use locations in all profiles of Alachua site, Hardee sites, and most sections of the Suwannee site (Figures 4-13, 4-14, and 4-15). At the lowest depth of the soil profile in Suwannee site, the open pasture retained slightly more C than at both locations of silvopasture. In Osceola site, the C associated with silt + clay fraction of OP field was significantly higher than that of the SP-T at both surface (0 – 5 cm) and subsurface (5 – 15 cm) profile depth (Figure 4-16). On the contrary, at the lowest depth (75 – 125 cm), SP-T was significantly higher in C content for the same fraction size. Generally, with an increase in soil depth, the C content of silt + clay fraction consistently decreased in all locations of Ultisol sites. At the Spodosol sites, C content in the silt + clay C fraction followed a sporadic pattern with no trend across soil depth; however, C content was higher in and around the spodic horizon than other horizons of the soil profile (40 – 55 cm).

The SOC across the Spodosol and Ultisol locations for the whole and fractionated soils are shown in Figures 4-17 and 4-18. In both the Spodosol and Ultisol locations, higher SOC in whole soils was observed at the lower depth (below 15 cm) in silvopasture (SP-T and SP-A) as compared to the open pasture. Similar patterns were also observed in the fraction sizes of macroaggregates (250 – 2000 µm) (Figures 4-17B and 4-18bB) and the microaggregates (53 –

250 μm) (Figures 4-17C and 4-18C). However, at both soil orders no difference in SOC was observed between silvopasture (SP-T and SP-A) and the open pasture in the silt + clay fraction ($<53 \mu\text{m}$) (Figures 4-17D and 4-18D).

The over all mean storage of the SOC in whole soils (Figure 4-19A), macroaggregates (250 – 2000 μm) (Figures 4-19B) and microaggregates (53 – 250 μm) (Figures 4-19C) showed higher values for the silvopasture at all depths but the surface (0 – 5 cm) as compared to the open pasture.

Discussion

The main objective of this section of the study was to assess the potential of tree-based pasture system to retain C in the soil. In order to accomplish this objective, it is important to understand the specific physical SOC protection mechanisms in open and tree-based pasture systems. Comparison of total SOC accumulation at any given soil depth, particularly at the deeper soil depths, for open and tree-based pasture systems showed an increase in total C storage in whole soils of the silvopasture in most of the sites (Figure 4-2, 4-3, and 4-4) except at the Alachua site, (Figure 4-1). The absolute quantities of such increases, however, varied at the three sites. The silvopasture plot in Alachua that was established only 8 years ago is the youngest of the sites.

Evidence from physical soil fractionation showed that the SOC in macroaggregates was higher for silvopasture (SP-A or SP-T) than open pasture, particularly at lower soil profile at all but Suwannee site (Figure 4-5, 4-6, 4-7, and 4-8). Similarly, the SOC in microaggregates was higher under silvopasture than open pasture in both sites of Spodosol. Except for Osceola site, where higher SOC storage in silt + clay fraction was found, SOC in silt+clay fraction did not differ significantly among the three pasture locations across soil depth. The results demonstrate

the potential of silvopasture to enhance total soil C storage. The amount of C accumulation varied in the different soil aggregate size classes. More C was accumulated in the largest aggregates. SOC in silvopasture increased by an overall average of 33 % in SP-T and 28 % in SP-A as compared to the adjacent open pasture (Figure 4-19). This indicates that the tree-based pasture system resulted in significant increase in C sequestration since its establishment.

Integrating trees into open pasture increases temporal and spatial species diversity. Thus the system, compared with open pasture system, could be closer to natural ecosystems in terms of better soil quality and increased C storage. Information on specific impact of integration of pine trees into pasture on the biogeochemistry of the ecosystem is limited. Some information that is available on C-storage of land-use systems where trees had encroached into a natural grassland ecosystem is relevant to this discussion.

Most studies on this subject in a variety of ecosystems have shown greater concentrations of SOC in soils on sites where trees encroached a grass-dominated ecosystems compared with an adjacent grassland without any trees (Tiedemann and Klemmedson, 1973; Virginia and Jarrell et al., 1983; Mordelet et al., 1993; Stock et al., 1995; San Jose et al., 1998; Geesing et al., 2000; Burrows et al., 2002; Reyes-Reyes et al., 2002; Yelenik et al., 2004). Results of the current study are consistent with those trends of increase in SOC. Some results from assessments of this nature, however, dispute whether such a phenomenon, trees encroachment into grassland ecosystem, would lead to a net C sink. Jackson et al. (2002) studied the direct effect of native woody vegetation on SOC at six sites in plots of grassland invaded by common native woody species such as *Prosopis* (mesquite), *Larrea* (creosote), and *Juniperus* (juniper) spp. and an adjacent plot of grassland without trees in the southwestern USA. They predicted a decline in SOC in grassland invaded by woody vegetation for areas that received > 600 mm mean annual

precipitation: The authors attributed this to higher rate of decomposition. In contrast, some studies show no changes in SOC following woody plant invasion of grasslands (McCarron et al., 2003; Smith and Johnson, 2003).

Furthermore, it is not yet clear why responses to tree incorporation can range from net losses to net gains in soil C. Increase in SOC under silvopasture in the current study could be a direct manifestation of the higher rates of net primary productivity (NPP) in tree-based land-use relative to open grass pasture as reported by Belsky et al. (1993), Mordelet et al. (1993), Boutton et al. (1998), Archer et al. (2001), and Hibbard et al. (2001). Sharroo et al. (1996), for instance, reported that 10-year-old Douglas-fir (*Pseudotsuga menziesii*)/grass/ clover pasture/sheep agroforests produced 1.6 times as much phytomass as did pastures or forests of the same age, on the same site. Typical rates of aboveground NPP in grass-dominated vegetation in the Rio Grande Plains of southern Texas, USA, were found to be $1.9 - 3.4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$; in contrast, the rates of aboveground NPP in areas adjacent grassland encroached by woody vegetation were $5.1 - 6.0 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ (Archer et al., 2001; Hibbard et al., 2001). Other studies also suggested that belowground productivity was accelerated following tree establishment in grassland vegetation although rates of belowground NPP were not quantified. Coarse and fine root biomass were found to be two-to-five times greater and showed significantly larger seasonal fluctuations in areas with trees than in grasslands (Boutton et al., 1998, 1999; Hibbard et al., 2001). Thus, increases in above- and belowground primary production are potentially able to account for observed increases in SOC in this study in silvopastures relative to open pasture. However, a direct determination of NPP in both silvopasture and open pasture – which was not undertaken in this study – may help to confirm this.

Quantification of SOC stored in the different particle size classes (fractions) showed that in both land-use systems highest SOC was stored in the largest size fraction (macroaggregates) followed by microaggregates and then in the smallest size fraction (Figure 4-17, 4-18 and 4-19). This suggests a hierarchical aggregation process as reported by Oades and Waters (1991). In this process of aggregation, the silt + clay build up to form the microaggregates and further building up of the microaggregates forms the macroaggregates. Much of the C associated with larger size aggregates is of recent C deposition into the soil system. The macroaggregate is considered to be an important pool of bioavailable C. But, the amount of C in macroaggregates is sensitive to fluctuation in plant litter input and may show significant seasonal and spatial variability in land-use systems (Karlen and Cambardella, 1996). Results from the fractionation in this study clearly showed increases in total SOC pools in silvopasture compared to adjacent open pasture (Figure 4-19). Further examination of the results show that this increase in SOC pools could be due to a number of factors:

- 1 Accumulation of new SOC in macroaggregates fraction: compared to open pasture, there was an overall mean increase of 39 % in the alleys of silvopasture (SP-A) and 20 % in silvopasture near the trees (SP-T) (Figure 4-19). This increase was as high as 114% in the alleys of silvopasture (SP-A) and 78 % in silvopasture near the trees (SP-T) for the Hardee site (Figure 4-7). In the Ultisol site, however, this increase was observed only in the alleys of silvopasture (SP-A), an increase by 46 % in Alachua (Figure 4-9).
- 2 Retention of older SOC by protection in microaggregates: compared to open pasture, there was an overall mean increase of 12.3% in the alleys of silvopasture (SP-A) and 18.8 % in silvopasture near the trees (SP-T) (Figure 4-19). This increase was as high as 108% in the alleys of silvopasture (SP-A) and 111 % in silvopasture near the trees (SP-T) for the Hardee site (Figure 4-11); whereas in the Ultisol site, this increase was observed only in SP-A, an increase by 46 % in Alachua (Figure 4-9)
- 3 Association of SOC with silt + clay: compared to open pasture, there was an increase of 72% in the alleys of silvopasture (SP-A) and 60% in silvopasture near the trees (SP-T) at Hardee site (Figure 4-15). Although relatively small, there was an increase of 35% in the alleys of silvopasture (SP-A) at Suwannee site.

In most of the study sites, the amount of mineral-associated C at a given depth did not differ significantly between land-use systems across almost all the soil profiles. Although stabilization of soil organic C by association with mineral soil – silt and clay – particles is directly related to the silt plus clay content of the soil in a variety of ecosystems (Hassink 1997; Six et al. 2002), the soils at all sites of this study are characterized by high content of sand, more than 95% (Nair et al., 2007; Michel et al., in press). The C in this fraction size is older and more stabilized in nature. Hence it is less likely that the effects of changes in land use due to integration of tree in the current land use will be indicated. In contrast, the Spodosol sites differed significantly from the Ultisols site on average by nearly 1.2 kg C m^{-2} (54%) (Figures 4-17 and 4-18) in silt + clay associated C. These soils may have some potential to stabilize more soil C in organo-mineral complexes due to the spodic horizon which differs from the other soil materials due to the prevalence of organically-associated Al that has very high surface area for retention (Eswaran et al., 2003).

At least part of the C in largest fraction size is involved in the formation and stabilization of the macroaggregates in the form of C within macroaggregate and C associated with clay. The bulk of available information is in agreement with current results in that the macroaggregate soil C presents a factor of potential use in assessing shorter-term changes in soil C storage induced by changes in soil management-, land-use-, and vegetation regimes. Thus, macroaggregation and physical protection of SOC are more closely linked to the abundance and turnover of larger-sized fraction of C than to the whole soil C level. Clearly, in this case larger-sized fraction C must be considered to encompass an active SOC pool. Furthermore, other studies indicated that the larger-sized class fraction C is quantitatively more important in sandy than clayey soils (Greenland and Ford, 1964; Leuschner et al., 1981)

Generally, water-stable aggregates provide physical protection for C and reduce soil erodibility. The formation of these aggregates is enhanced by root and faunal activity. Most of the increased differences in total SOC in silvopasture relative to an open pasture were in the lower depth of the soil profile suggesting that inputs from the deep root systems of trees in silvopasture could be significant. The deep rooting nature is, however, a conjecture; robust data are not available to support this. Available data from root development studies suggest that for plantations, maximum observed rooting depth for fast growing loblolly pine (*Pinus taeda*) in Spodosols of the Georgia lower Coastal Plain was 85, 85, 85, and 95+ cm at ages 1, 2, 3, and 4 yr, respectively (Adegbidi et al., 2004). Further investigations are needed on this aspect.

Conclusions

Although silvopasture is practiced in the Southeast and elsewhere in the USA, the biogeochemical consequences of tree integration into pasture system in general and the soil carbon storage and dynamics in particular are little known. This study indicates that tree integration into open pasture systems increased SOC in whole-soil, particularly at lower depths. Increases in above- and belowground primary production may account for observed increases in SOC in silvopasture portions of the landscape relative to an open pasture land. Furthermore, results from the soil fractionation revealed that the increase in C in the silvopasture could be due to retention of more SOC of older C (by protection in microaggregates), and association of C with silt + clay and accumulation of more new SOC in macroaggregates fraction in silvopasture. The potential of silvopasture as a strategy for C sequestration thus seems clear. However, critical information on several key issues that is needed for making valid conclusions is still missing. These include determination of NPP in both silvopasture and open pasture, further isolation of microaggregates and silt + clay fractions from the macroaggregates and microaggregates respectively, and determination of microbial activity and biomass in the different fractions.

Research on these areas needs to be intensified in order to better understand and exploit this seemingly important environmental benefit of silvopasture.

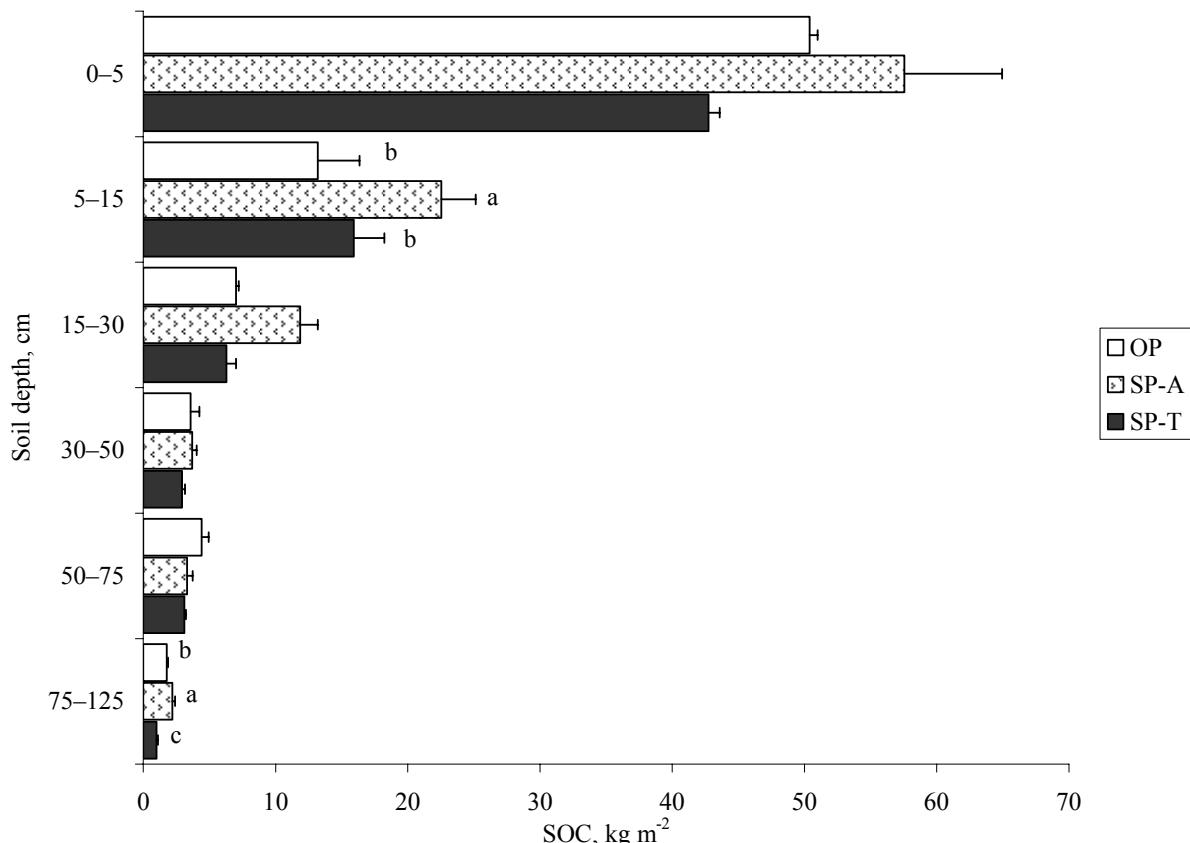


Figure 4-1 Changes in SOC with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for whole-soil of Alachua site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

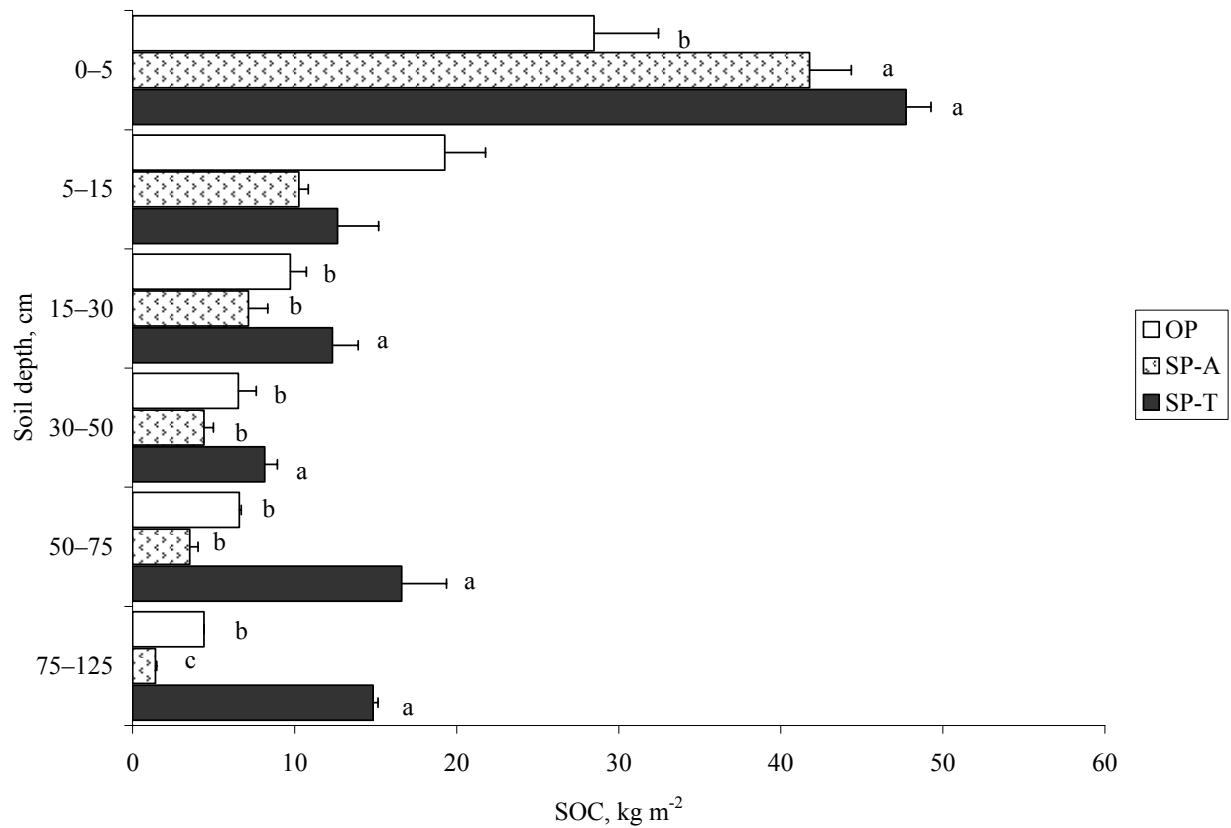


Figure 4-2 Changes in SOC with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for whole-soil of Suwannee site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

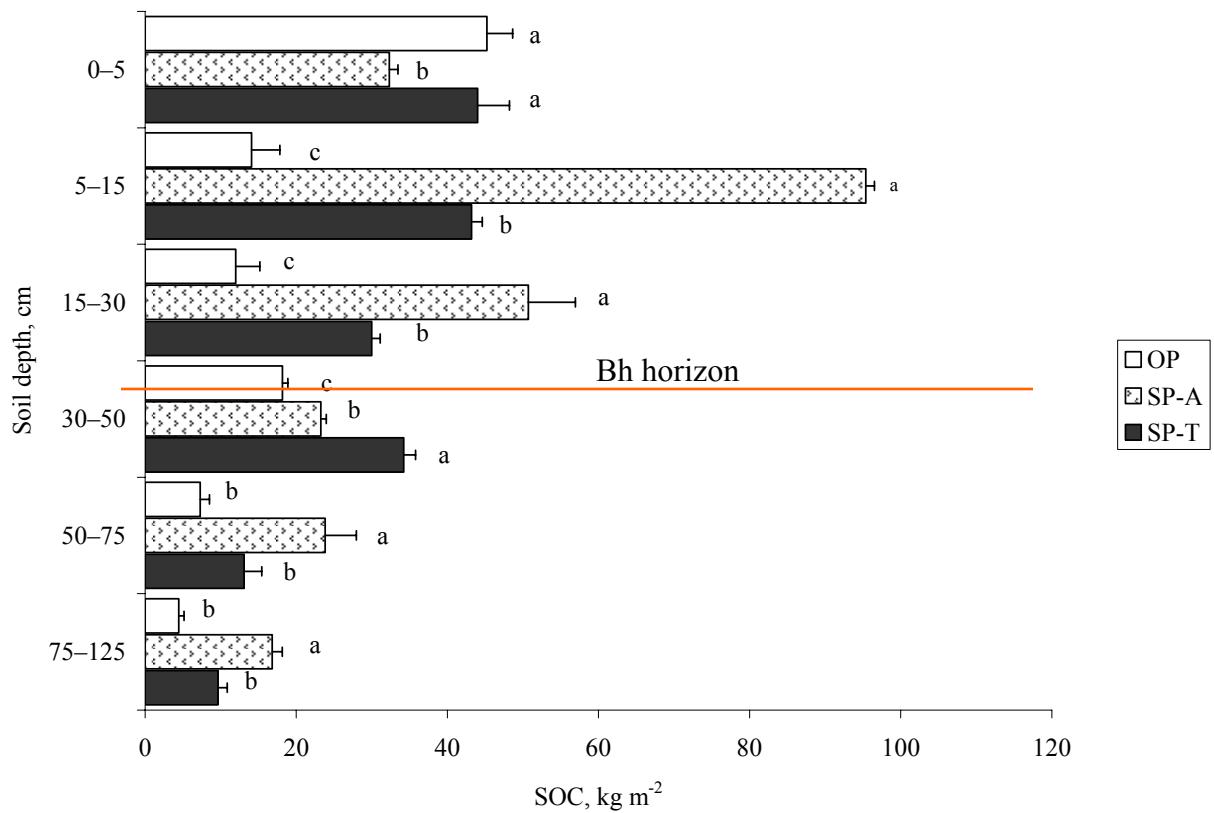


Figure 4-3 Changes in SOC in whole-soil with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for whole-soil of Hardee site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

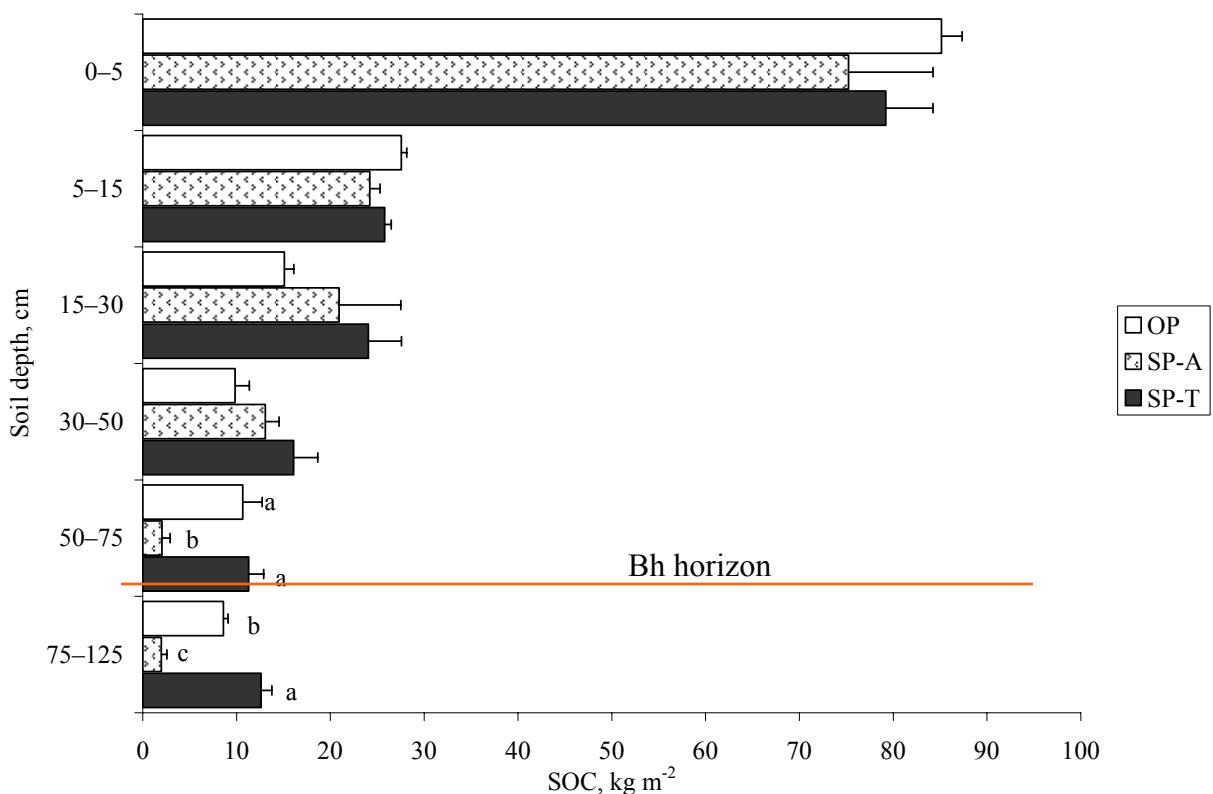


Figure 4-4 Changes in SOC in whole-soil with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T)]; and open pasture (OP) for whole-soil of Osceola site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

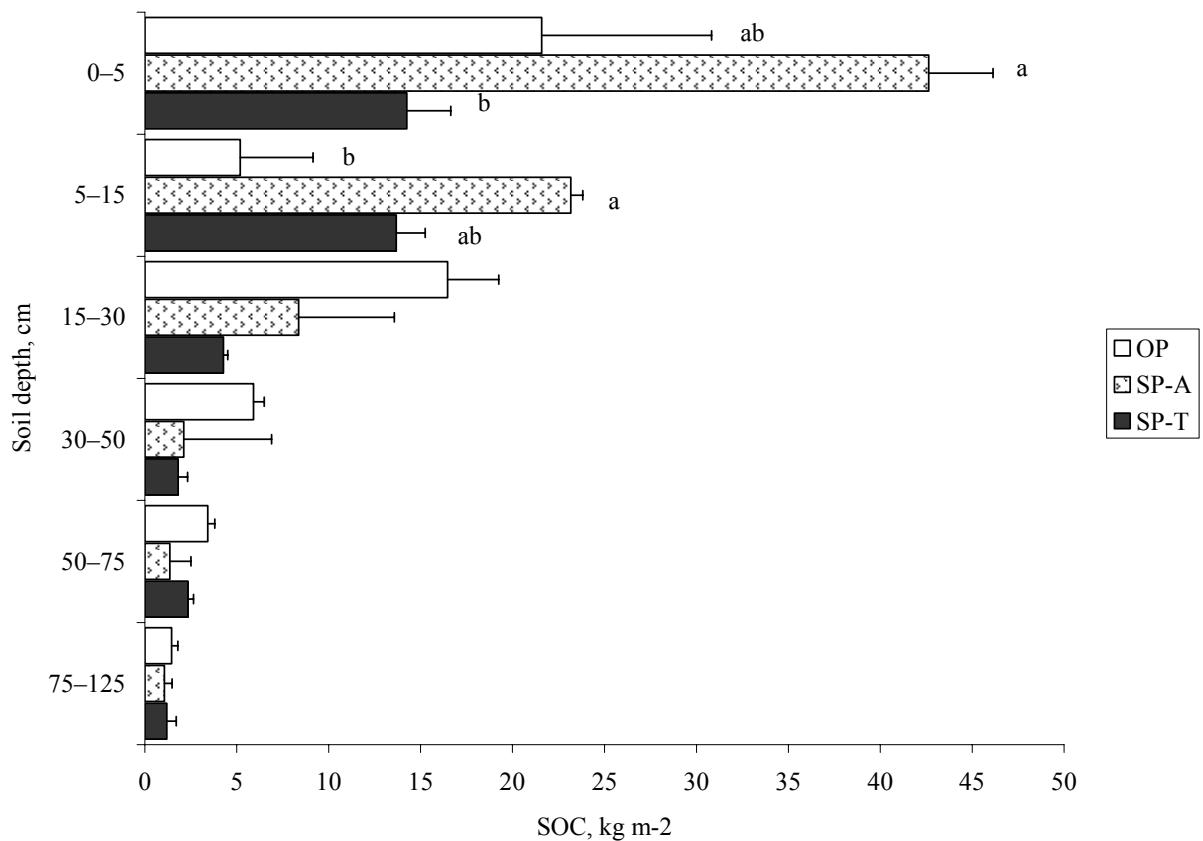


Figure 4-5 Changes in SOC in macroaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Alachua site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

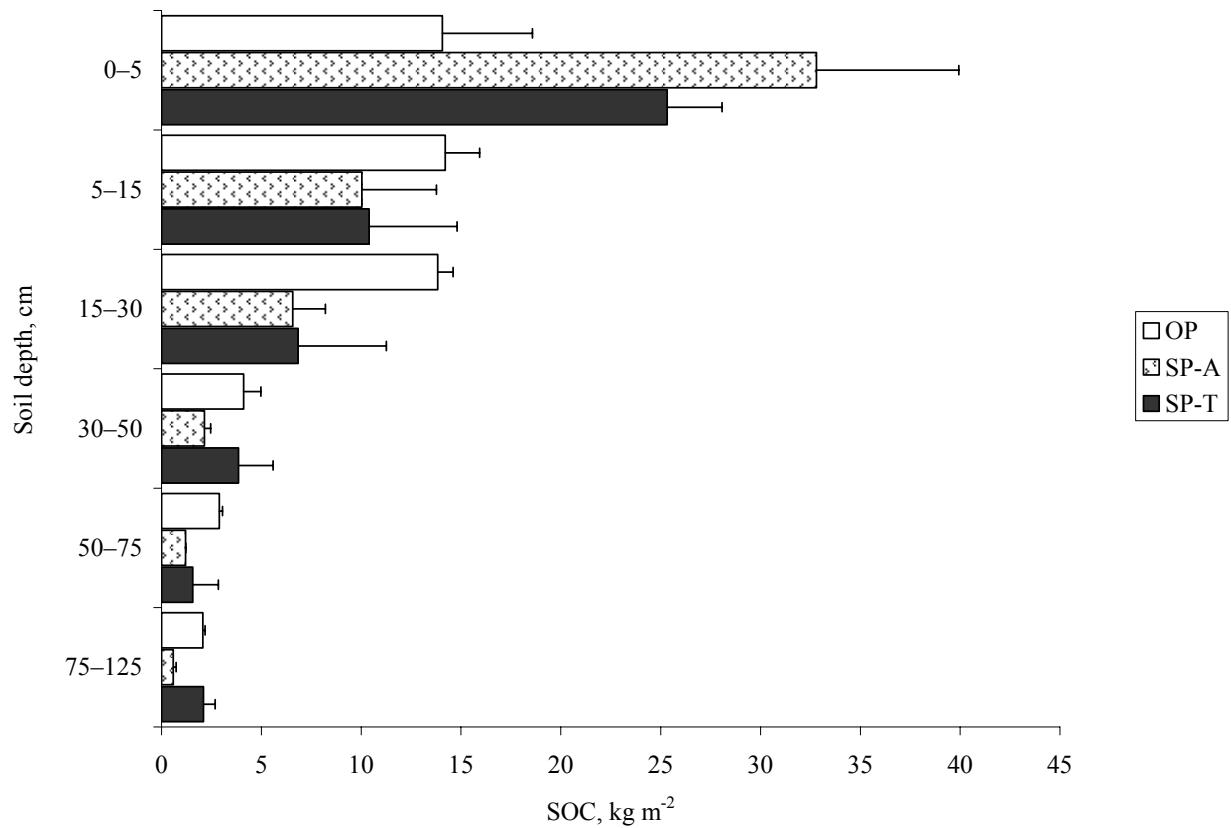


Figure 4-6 Changes in SOC in macroaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Suwannee site.

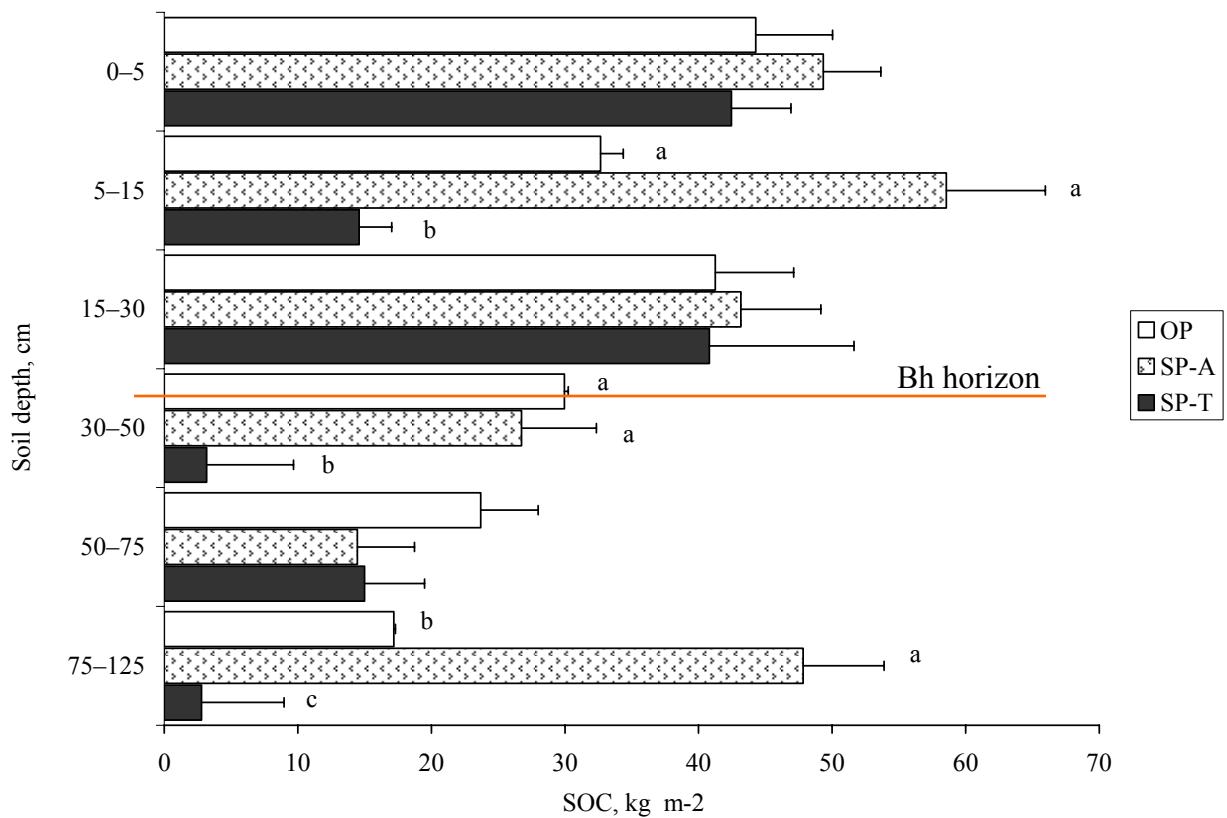


Figure 4-7 Changes in SOC in macroaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Hardee site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth

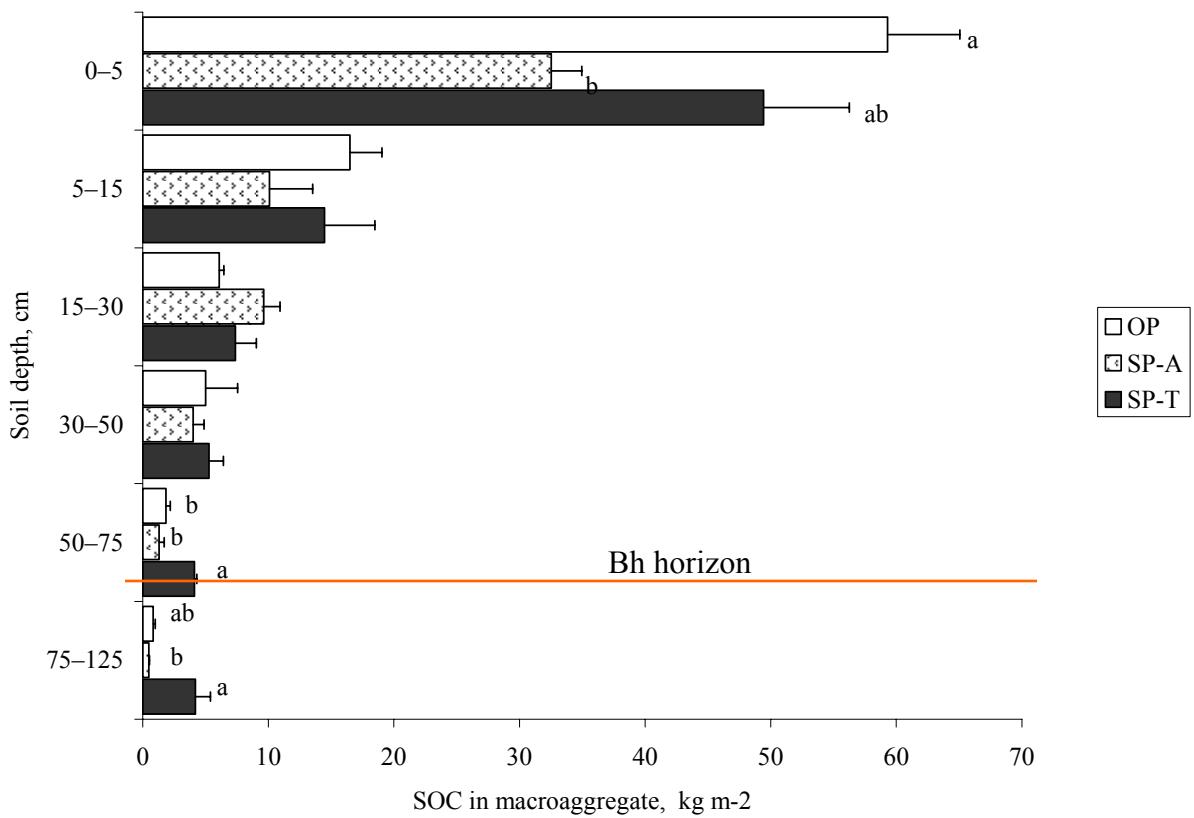


Figure 4-8 Changes in SOC in macroaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Osceola site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

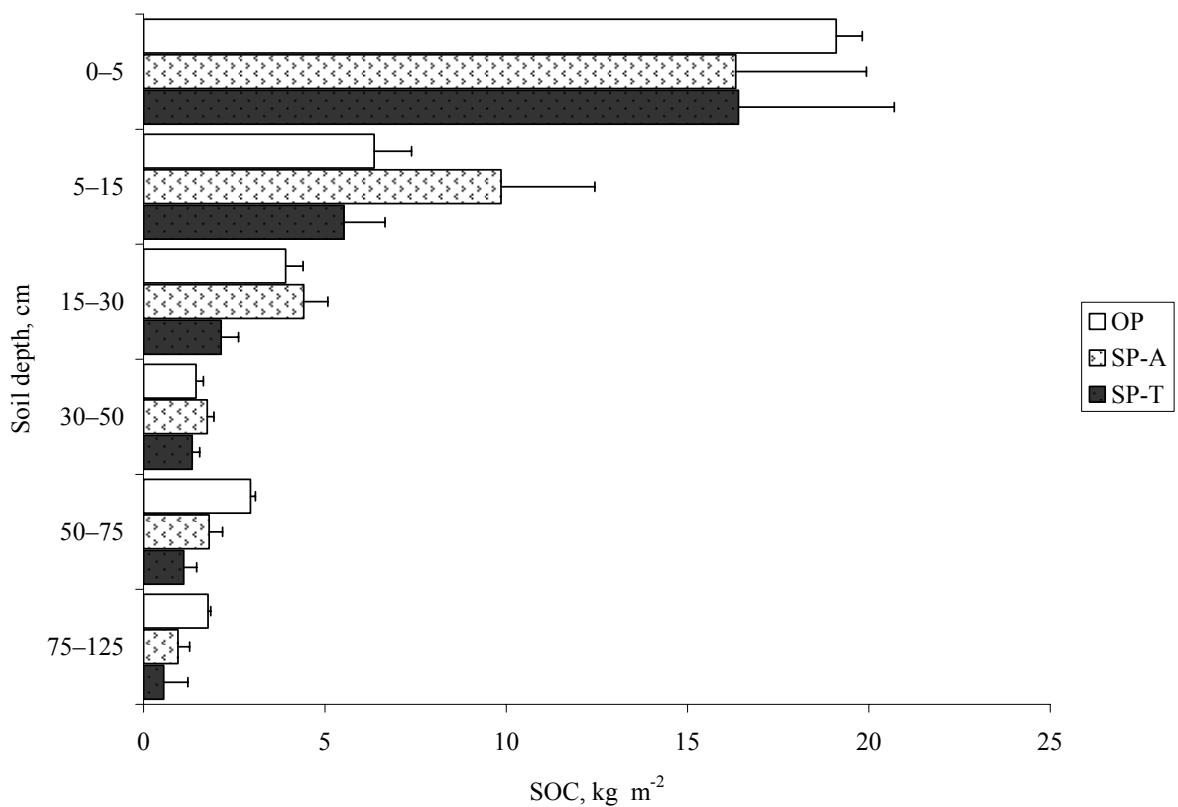


Figure 4-9 Changes in SOC in microaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Alachua site.

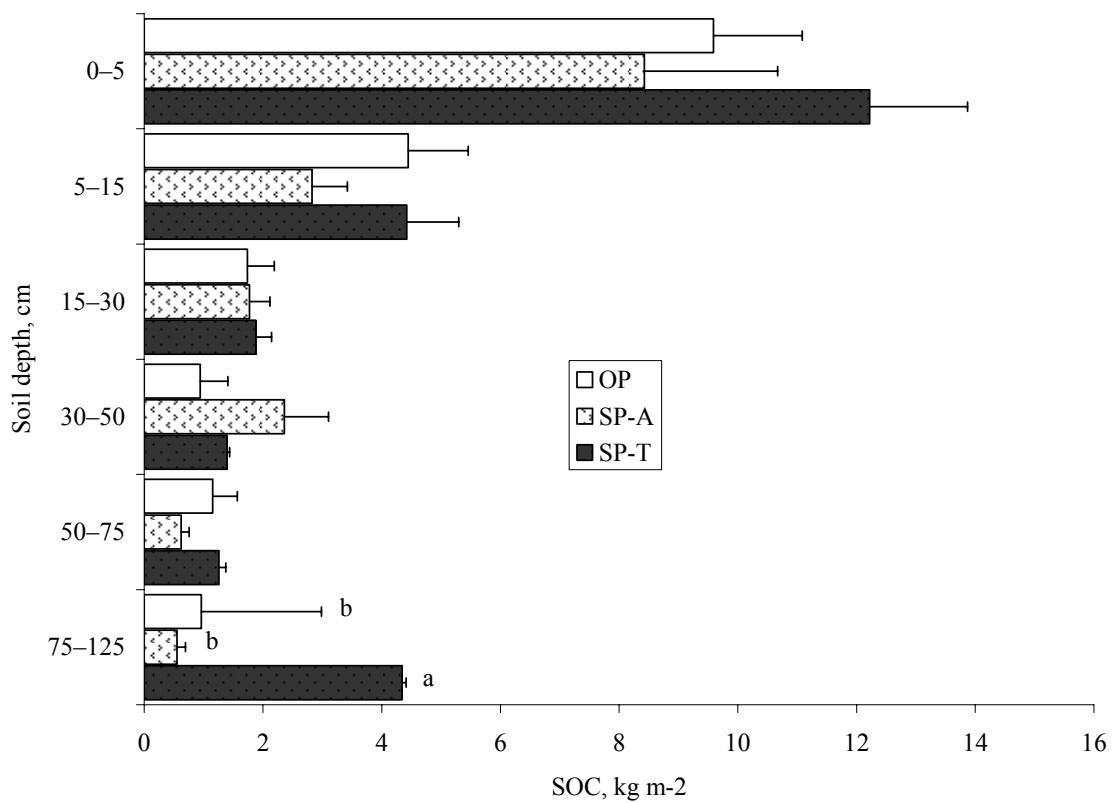


Figure 4-10 Changes in SOC in microaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Suwannee site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

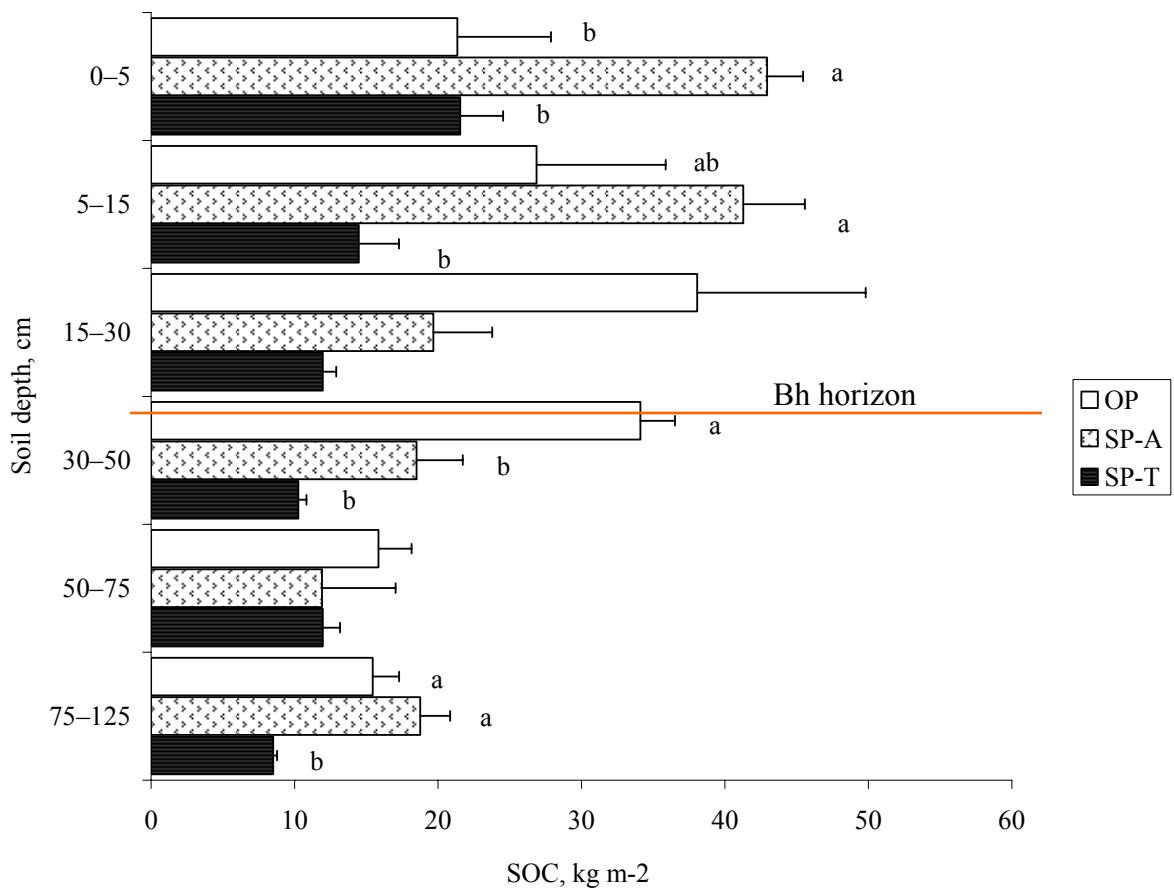


Figure 4-11 Changes in SOC in microaggregates with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Hardee site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

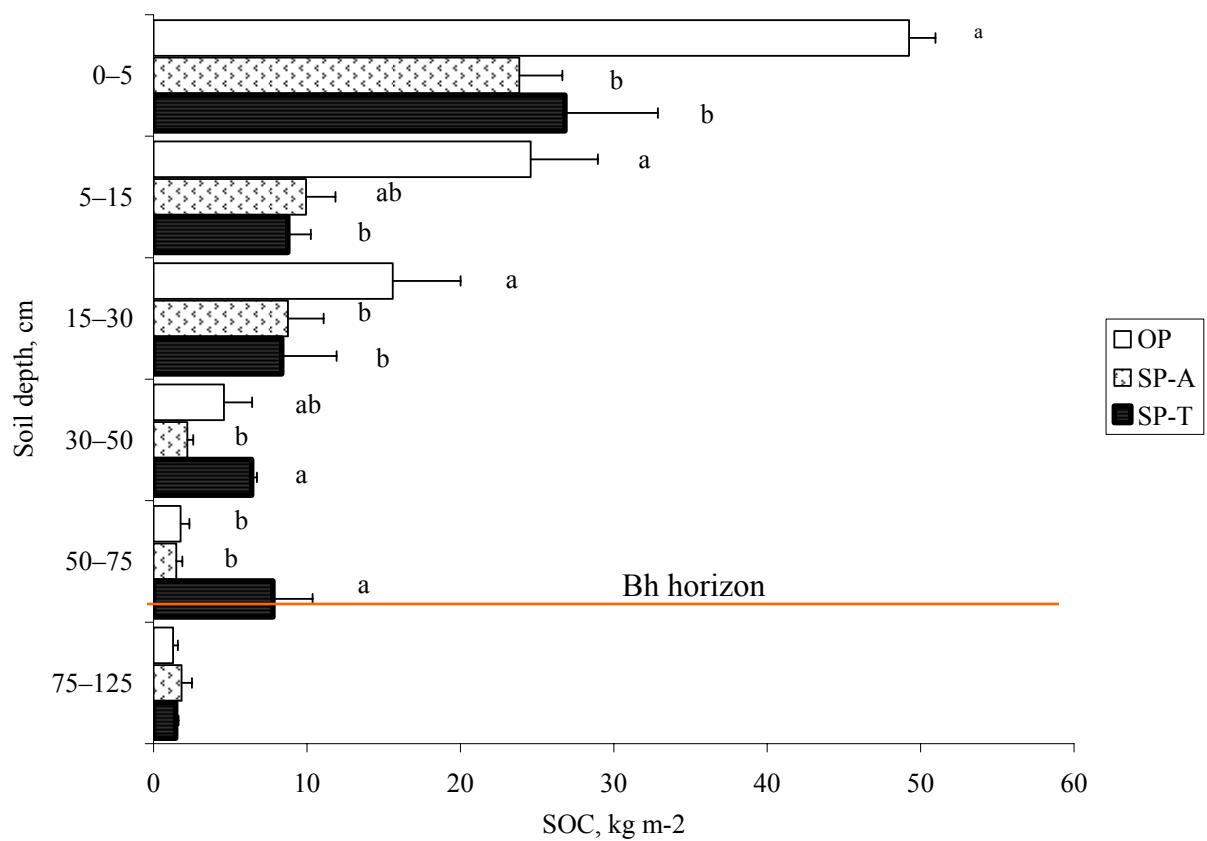


Figure 4- 12 Changes in SOC in microaggregates with depth at three pasture locations [(SP-A, SP-T and OP)] for Osceola site. Lower case letters next to the error bars indicate significant differences in SOC among pasture locations at a given depth.

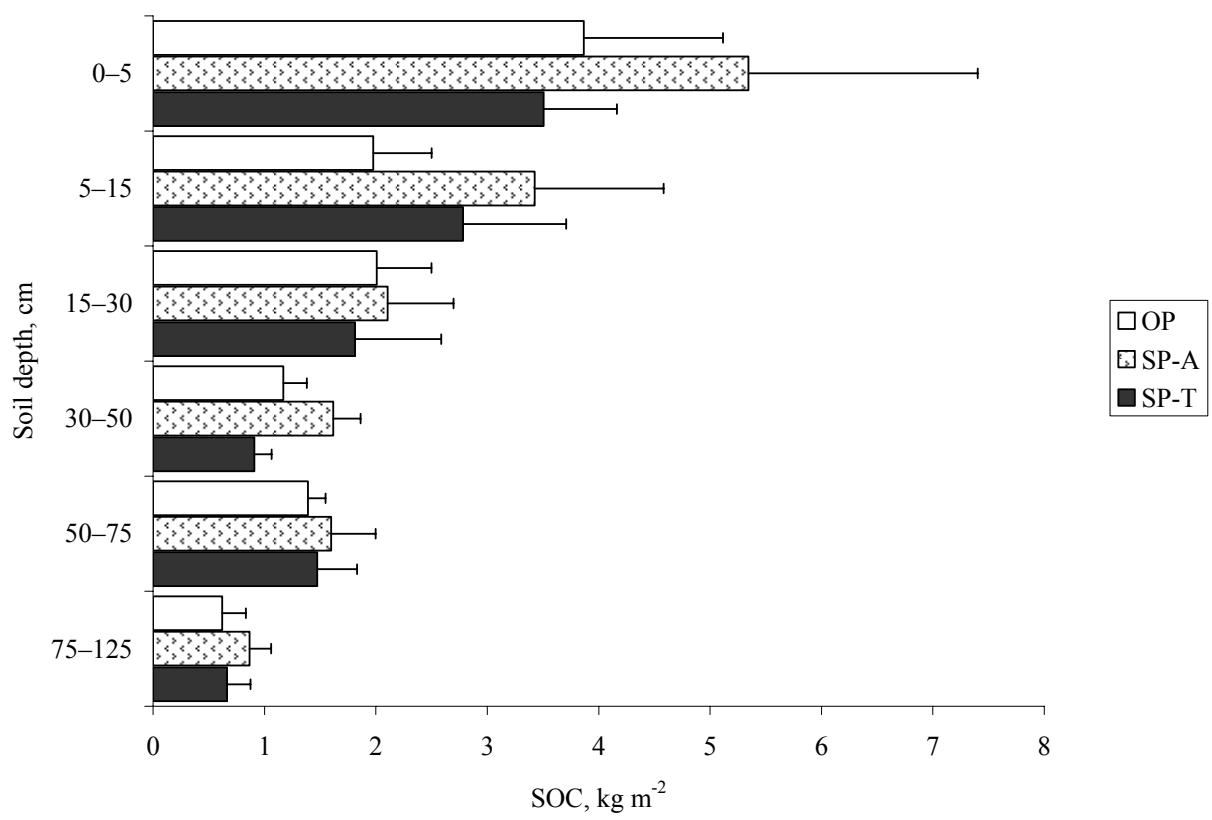


Figure 4-13 Changes in SOC in silt+clay fraction with depth at three pasture locations at Alachua site.

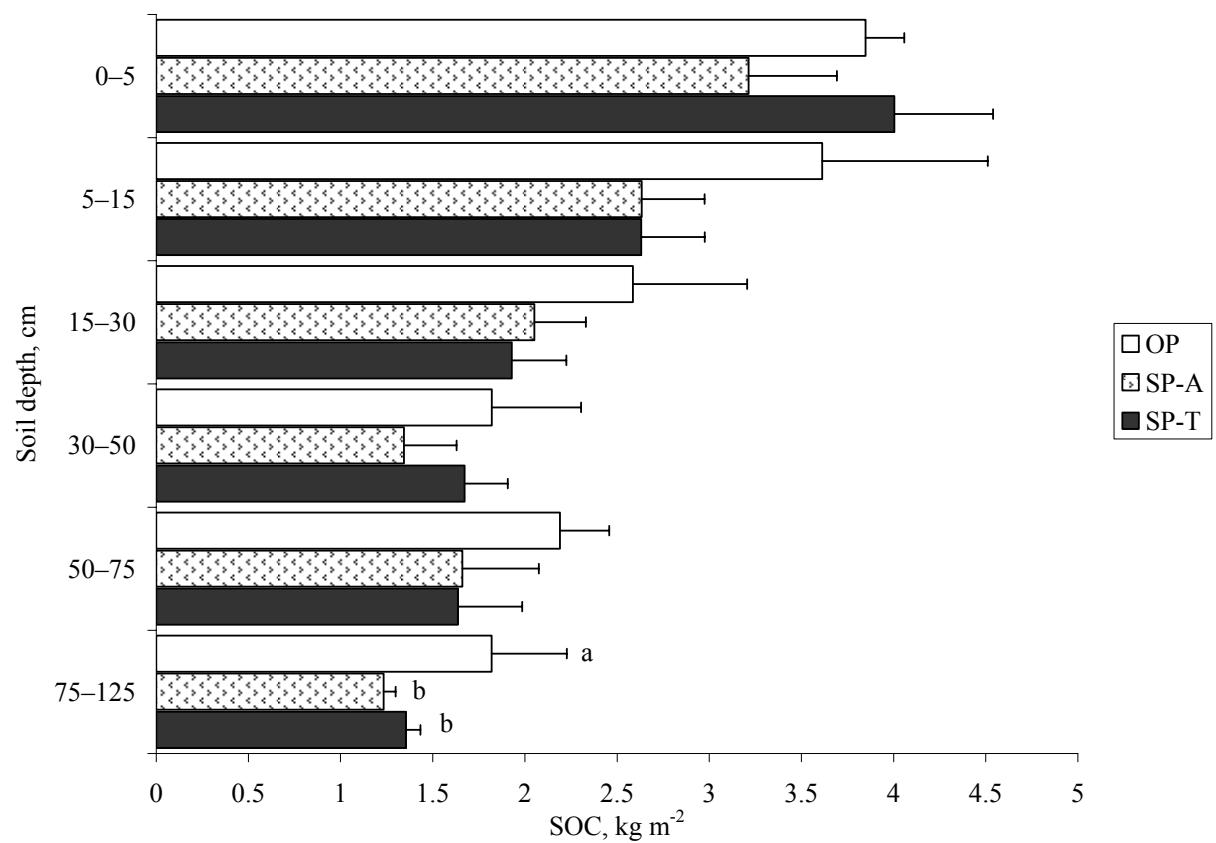


Figure 4-14 Changes in SOC in silt + clay fraction with depth at three pasture locations for Suwannee site.

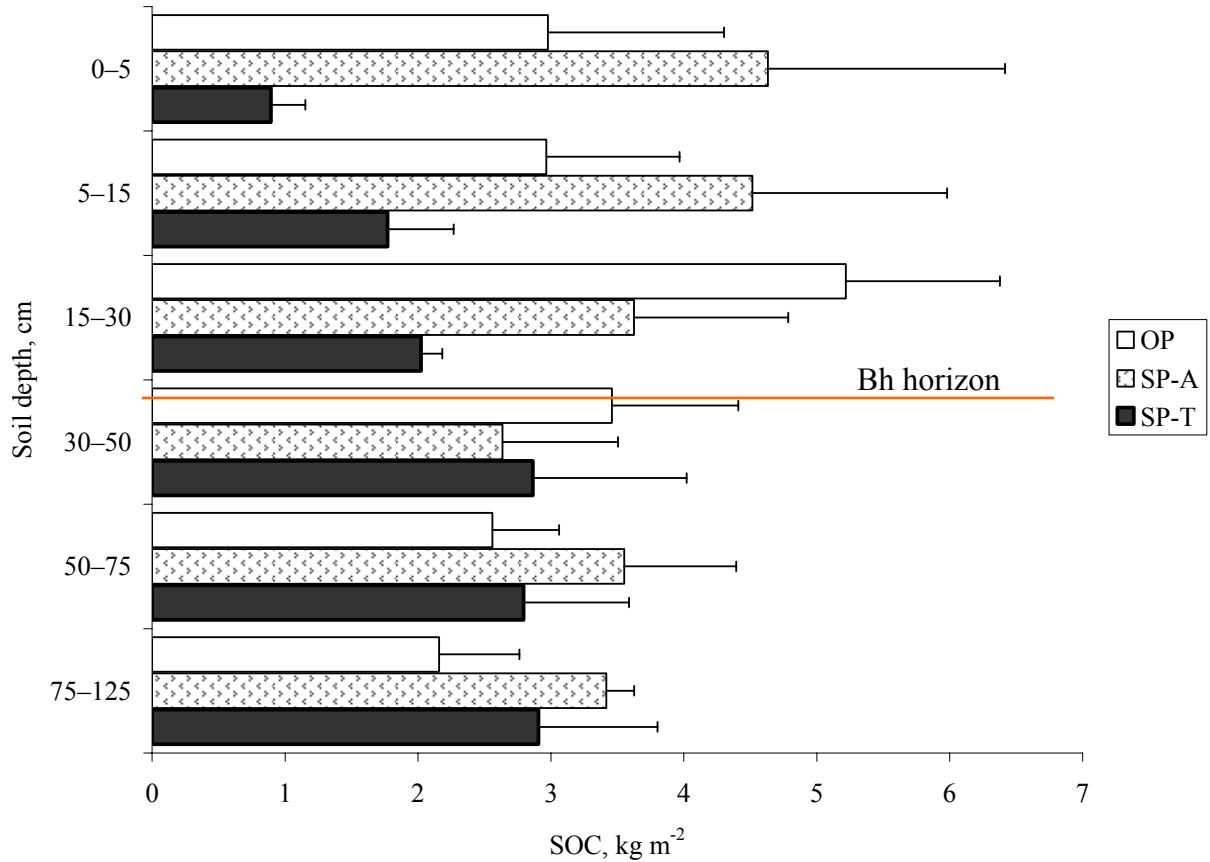


Figure 4-15. Changes in SOC in silt+clay fraction with depth at three pasture locations for Hardee site.

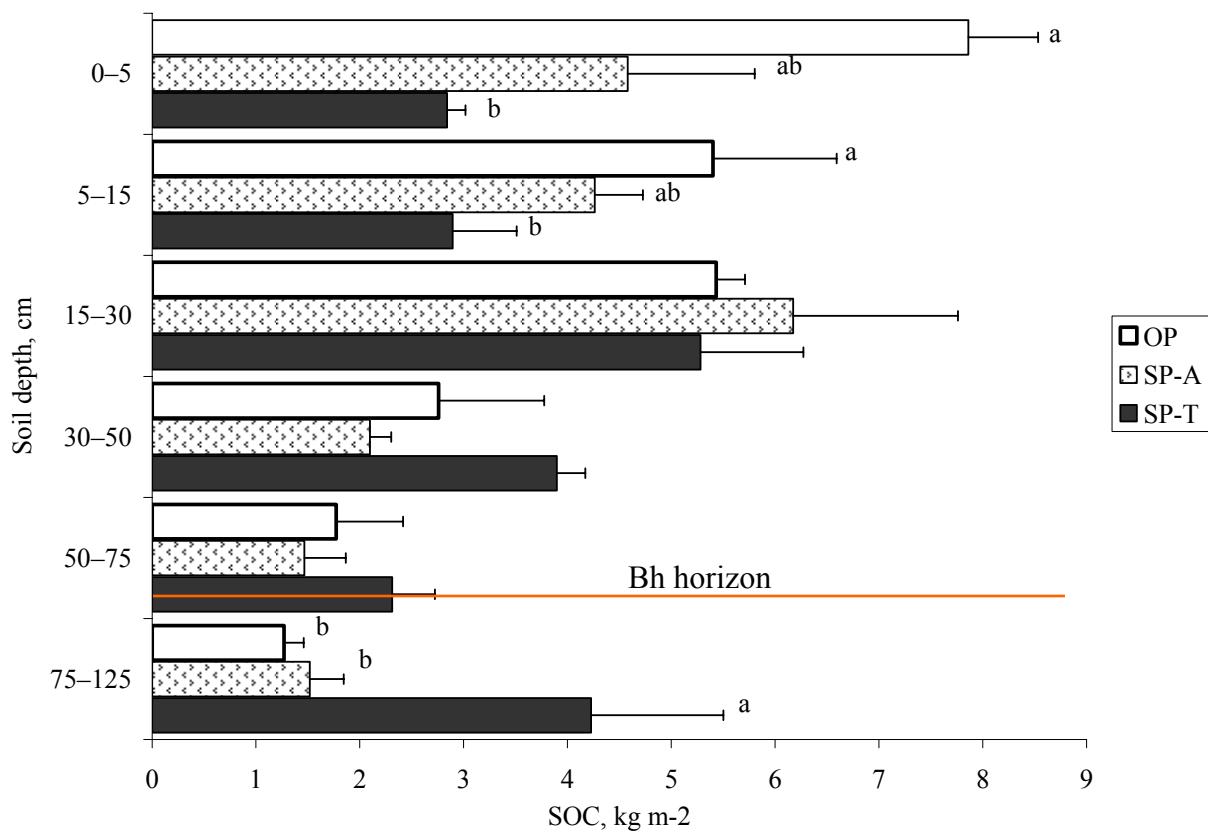


Figure 4-16 Changes in SOC in silt+clay fraction with depth at three pasture locations [(silvopasture: the center of the alley (SP-A) and in-between tree rows (SP-T); and open pasture (OP)] for Osceola site.

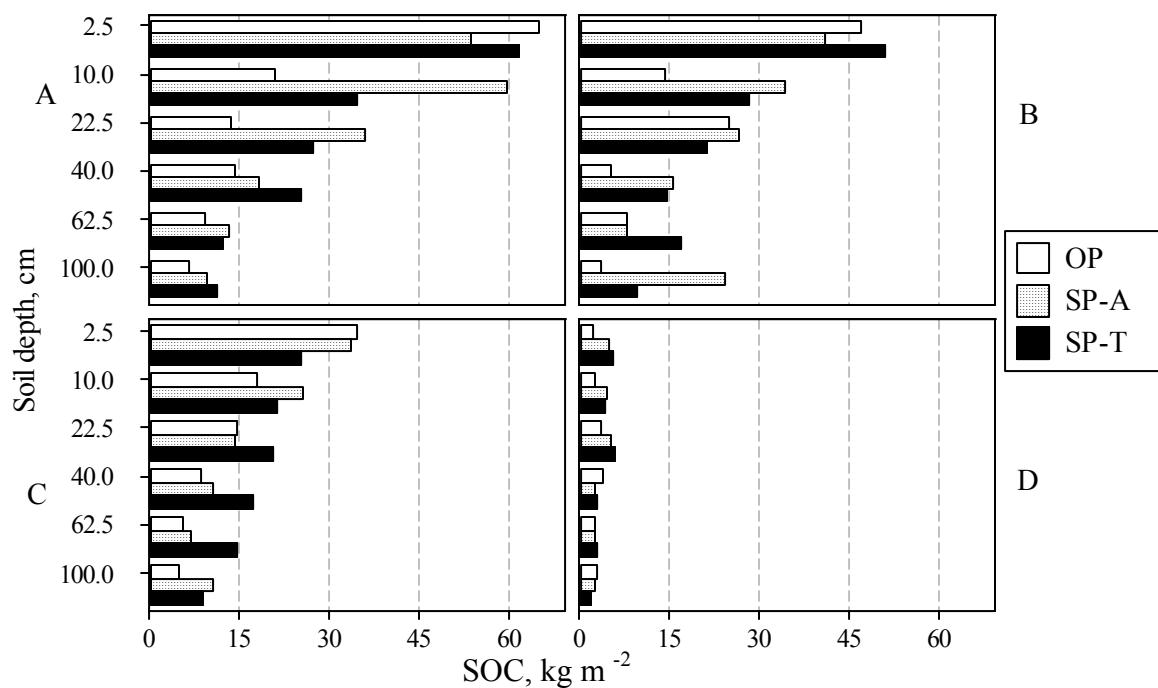


Figure 4-17 Changes in mean SOC across the Spodosol locations (Hardee and Osceola) in A) whole soil, B) macroaggregates C) microaggregates, and D) silt + clay fraction down the soil profile depths at three pasture locations (SP-A, SP-T; and OP).

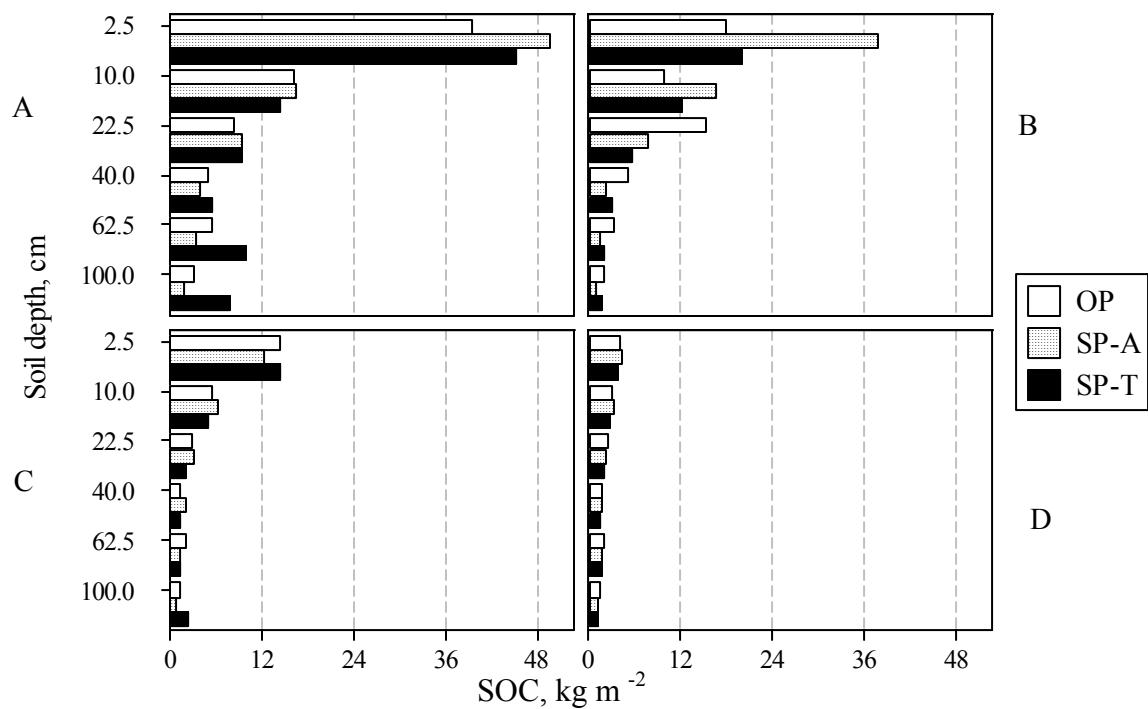


Figure 4-18 Changes in mean SOC across the Ultisol locations (Alachua and Suwannee) in A) whole soil, B) macroaggregate C) microaggregate, and D) silt + clay fraction down the soil profile depths at three pasture locations (SP-A, SP-T; and OP).

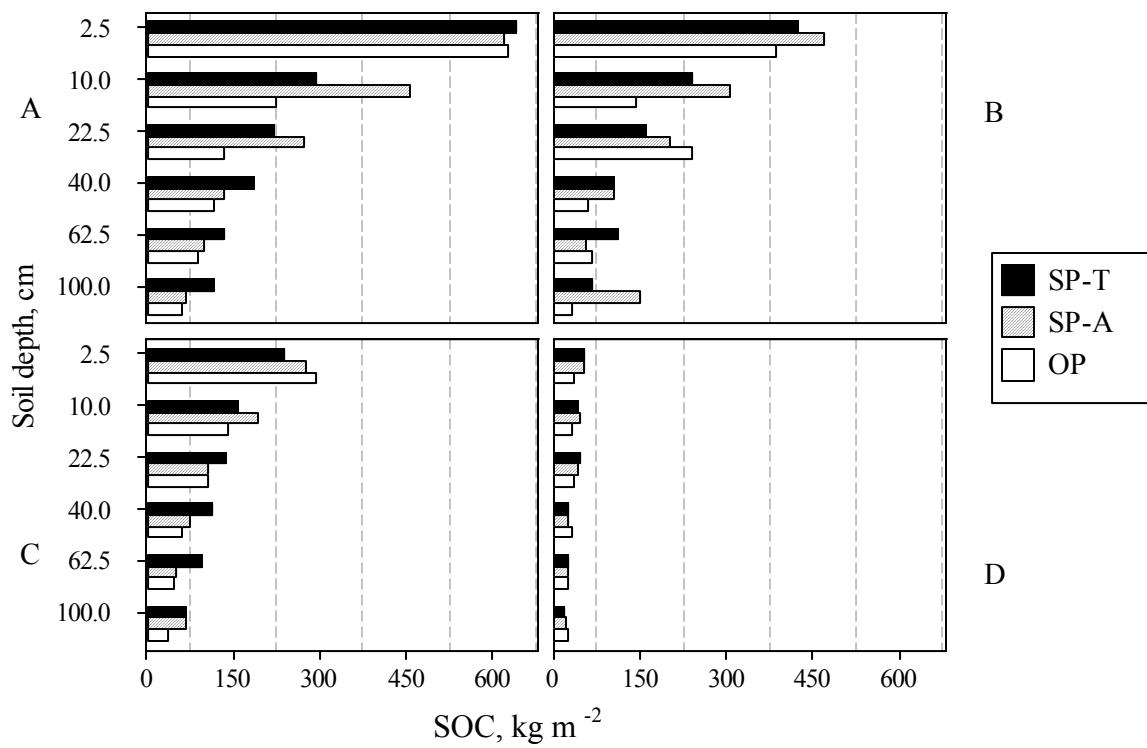


Figure 4-19 Changes in overall mean SOC across all locations in A) whole soil, B) macroaggregate C) microaggregates, and D) silt + clay fraction down the soil profile depths at three pasture locations (SP-A, SP-T; and OP).

CHAPTER 5

SOIL CARBON SEQUESTRATION BY TREES AND GRASS IN SILVOPASTORAL SYSTEMS: EVIDENCE FROM STABLE ISOTOPE ANALYSIS

Introduction

Soils in agroecosystems can function as both source and a sink for atmospheric C. The direction of this dynamic equilibrium is generally determined by the way in which these agroecosystems are managed. Agroforests are planned and managed agroecosystems (Garrett et al., 2000). Increasing the overall productivity and efficiency of the land-use system and its sustainability are major goals of agroforestry (Nair, 2005).

The overall goal of combining trees and/or shrubs with crops and/or livestock production is to optimize the physical, biological, ecological, economical, and social benefits resulting from the interactions between or among the components (MacDicken and Vergara, 1990; Garrett et al., 1991; Nair, 1993; Leakey, 1996). Agroforestry and other tree-based systems are believed to enhance C sequestration in soil compared with treeless (agricultural) systems (Montagnini and Nair, 2004). Such claims on C sequestration potential are based on the premise that the tree components in agroforestry systems can be significant sinks of atmospheric C due to their fast growth, long-term storage of high amounts of C in biomass, and extensive root systems.

Silvopasture – the integration of trees into forage or/and livestock – has been practiced in the southeastern USA as "tree-pasture" or "pine-pasture" since the early 1950s (Nowak and Long, 2003). Indeed, silvopasture is the most common form of agroforestry in North America (Garrett et al., 2000; Nair et al., 2005). These agroecosystems are usually established by incorporating trees in existing, managed pastures of bahiagrass, bermudagrass, or other similar grasses (Nowak and Long, 2003). Silvopastoral agroforestry systems currently are of great interest due to their potential to improve the environmental quality of land in the southeast as alternative land-use systems to treeless pastures and tree plantations. Recent information

suggests that silvopasture is an ecologically sustainable and environmentally desirable approach to mitigating the problem of nutrient pollution resulting from beef-cattle pastures (Nair et al., 2007; Michel et al., in press). Information on the importance of plant components in general and the biogeochemical consequence of tree integration into pasture monoculture systems or conversion of pasture-to-silvopasture on the SOC storages and dynamics in particular, however, are still not quantified.

Available information indicates that functional consequences of integration of trees into grass-dominated vegetation include changes of above- and belowground productivity, modifications to rooting depth and distribution, and changes in the quantity and quality of litter inputs (Scholes and Hall, 1996; Connin et al., 1997; Gill and Burke, 1999; Jackson et al., 2000; Jobbágy and Jackson, 2002). These changes in vegetation, litter, and soil characteristics following tree integration into pasture systems modify ecosystem C dynamics and storage and may lead to alterations of local and regional climate systems through feedback interactions (Schlesinger et al., 1990; Ojima et al., 1999). The mechanisms and processes associated with C dynamics and storage in natural tree-based grassland or pasture systems such as silvopasture systems are still poorly understood (Jackson et al., 2000, 2002; Archer et al., 2001, 2004; Hudak et al., 2003). Given their great significance, therefore, thorough and detailed studies on soil C dynamics and storage in silvopastoral agroforestry systems are crucial.

The stable C isotope ratio analysis in SOC studies emerged as a tool to describe the dynamics of C₃ and C₄ components in vegetation (Stout et al., 1981). The relative isotope (¹²C and ¹³C isotopes) composition expressed as $\delta^{13}\text{C}$ in plant biomass is related to the photosynthetic pathway (C₃, plants average -27 ‰ and C₄ plants average -12 ‰; Boutton 1991), and the $\delta^{13}\text{C}$ value of SOC is approximately equal to the plant C deposited in the upper soil layers

(Nadelhoffer and Fry, 1988; Melillo et al., 1989; Boutton, 1991). Typically, the C3 component is either woody shrubs or trees and the C4 component is grass. The application of stable C isotopic analysis to SOC studies has therefore focused largely on descriptions of grass-woody plant dynamics and particularly the dynamics at the savanna-grassland ecotone where the principal question has been the stability of the grassland-savanna boundary (Schwartz et al., 1986; Volkoff and Cerri, 1987; Tieszen and Archer, 1990; Ambrose and Sikes, 1991). This author has not come across any previous research using the natural abundance of $\delta^{13}\text{C}$ to study carbon dynamics in pine-based silvopastoral system where C3 and C4 plants are grown simultaneously.

The technique requires comparison between a site where the photosynthetic pathway type of dominant vegetation has been changed and reference site where photosynthetic pathway type of vegetation remains unchanged. The plant community in the common silvopasture systems in southeastern USA comprises slash pine (*Pinus elliottii*) (C3 plants; $\delta^{13}\text{C} \approx -29.5\text{\textperthousand}$) and C4 plants dominated by bahiagrass (*Paspalum notatum*) ($\delta^{13}\text{C} \approx -13.3\text{\textperthousand}$). The $\delta^{13}\text{C}$ value ranges of C3 and C4 plants do not overlap; differences in isotope ratio, therefore, can be used to quantify the contribution of plants of each photosynthetic pathway to soil organic matter (Balesdent et al., 1988). A shift from open pasture to silvopasture presents a unique opportunity to use stable C isotope methodology to study soil organic matter dynamics following the alteration in vegetation structure due to the integration of trees to open pasture by comparing with adjacent open pasture. The isotopic difference between the plant community types allows for identifying the contribution of trees in specific fraction size in which SOC is sequestered in silvopasture system. Therefore, the objective of the present study was to determine the relative importance of C derived from woody vegetation (C3) vs. grass vegetation (C4) in silvopasture systems where

trees were integrated into open pasture using the natural C isotopic difference between bahiagrass C4 and slash pine C3 plants.

Materials and Methods

Study Area

Soil samples were collected in August 2005 from four sites, located in Alachua ($29^{\circ}45' N$, $82^{\circ}33' W$), Osceola ($28^{\circ}9' N$, $81^{\circ}10' W$), Hardee ($27^{\circ}13' N$, $82^{\circ}8' W$), and Suwannee ($30^{\circ}24' N$, $83^{\circ}0' W$) counties (Figure 3-1) in Florida. Two sites represented privately owned farms of Mr. Fred Clark in Alachua and Mr. Harris Hill in Osceola counties; the other two were at the Florida Sheriff Boys Ranch in Live Oak and the IFAS Range Cattle Research and Education Center, Ona, Florida. For convenience, the sites are designated by county names where the farms are located. Detailed climatic and edaphic characteristics of the sites are given in chapter 3 Table 3.1. At each site, a silvopasture and an adjacent open pasture plot were selected from which soil samples were drawn. Slope, aspect, and soil series were uniform across plots in a site, ensuring that land-use systems (pasture vs. silvopasture) was the primary factor influencing the soil C content in plots.

Soil Sampling

Soil samples were collected from three different sample sets: two locations in a silvopasture that includes locations between trees in a row (SP-T) and at the center of an alley (SP-A); and another set on an open pasture (OP). Each of these sample sets had stratified grid sampling points made by three rows with four sampling points in a row. At each sampling point, soils were collected from six soil depths $0 - 5$, $5 - 15$, $15 - 30$, $30 - 50$, $50 - 75$, and $75 - 125$ cm. While in the field, a composite for each depth interval was prepared by mixing soils of four sampling points in a row, resulting in composite samples of three per set (treatment); the total number of samples was 216 (6 depths \times 3 replication \times 3 location \times 4 sites).

Size Fractionation

All field-moist composite samples were air dried and passed through a 2 mm sieve. Soils were physically fractionated by wet-sieving following a procedure modified from Elliott (1986) and Six et al. (1998). The procedure involved using disruptive forces of slaking and wet-sieving through a series of two sieve sizes (250 and 53 μm) to obtain three aggregate size classes.

Briefly, a sub-sample of 100 g of the composite soil sample was submerged in deionized water as disruptive forces of slaking for about 5 min prior to placing it on top of 250 μm sieve. The sieving was done manually by moving the sieve up and down approximately 50 times in 2 minutes. The fraction remaining on the top of a 250 μm sieve was collected in a hard plastic pan and allowed to dry in oven at 65°C and weighed. Water plus soil < 250 μm was poured through a 53 μm sieve and the same sieving procedure was repeated. The overall wet sieving procedure yielded a water-stable fraction sizes of a macroaggregate-sized fraction 250 – 2000 μm ; a microaggregate-sized fraction 53 – 250 μm , and silt +clay fraction size <53 μm . The recovery of mass soil fractions after overall wet sieving procedure ranged from 96% to 99% of the initial soil mass.

Chemical Analysis

For chemical analysis, whole and fractionated soils were oven-dried at 60°C for 72 hr, and ground to fine powder using a ball mill (Cianflone Scientific Instruments, Pittsburgh, Pa.). Total soil organic C and N concentration was determined for whole and fractionated soil samples by dry combustion on an automated FLASH EA 1112 N C elemental analyzer (LECO Corporation)

Stable C Isotope Analysis

Soil samples were analyzed for C concentrations and for $\delta^{13}\text{C}$ values using a Carlo Erba EA-1108 (CE Elantech, Lakewood, NJ) interfaced with a Delta Plus (ThermoFinnigan, San Jose,

CA) isotope ratio mass spectrometer operating in continuous flow mode at the Department of Soil and Water Sciences, University of Florida. Carbon isotope ratios are presented in δ -notation:

$$\delta^{13}\text{C} = [(R_{\text{SAMPLE}} - R_{\text{STD}})/R_{\text{STD}}] \times 10^3 \quad (5-1)$$

Where R_{SAMPLE} is the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample, and R_{STD} is the $^{13}\text{C}/^{12}\text{C}$ ratio of the VPDB standard (Coplen, 1996). Precision of duplicate measurements was 0.1‰. None of the samples contained CaCO_3 or other forms of inorganic C. Relative proportions of SOC derived from the bahiagrass, a C₄ plant, vs. the slash pine, a C₃ plant, was estimated

$$\% \text{ C}_4\text{-derived SOC} = (\delta - \delta_T) / (\delta_G - \delta_T) \times 100 \quad (5-2)$$

$$\% \text{ C}_3\text{-derived SOC} = 100 - \% \text{ C}_4\text{-derived SOC} \quad (5-3)$$

Where δ is the $\delta^{13}\text{C}$ of a given sample, δ_T a composite sample of the C₃ plant and δ_G is a composite sample of pasture grass tissues (C₄)

Results

Changes in the Natural Abundance of ^{13}C SOC

Whole Soil Sample

The average $\delta^{13}\text{C}$ value of whole soil in open pasture was $-19.8\text{\textperthousand}$. The value was significantly higher ($p < 0.001$, not shown) than in SP-A and in SP-T of silvopasture with average $\delta^{13}\text{C}$ value of $-22.6\text{\textperthousand}$ and $-22.9\text{\textperthousand}$, respectively, but there was no difference between SP-A and SP-T locations. In general, whole soil $\delta^{13}\text{C}$ values in silvopasture had strongly C₃-dominated signatures ranging $-24\text{\textperthousand}$ to $-23\text{\textperthousand}$ in Alachua, $-24\text{\textperthousand}$ to $-23\text{\textperthousand}$ in Suwannee, $-24\text{\textperthousand}$ to $-23\text{\textperthousand}$ in Hardee and $-24\text{\textperthousand}$ to $-23\text{\textperthousand}$ in Osceola (Table 5-1). At the surface (0–5 cm), the $\delta^{13}\text{C}$ values of whole soil in open pasture with values $-15.9\text{\textperthousand}$ in Alachua, $-16.9\text{\textperthousand}$ in Suwannee, $-15.2\text{\textperthousand}$ in Hardee and $-16.0\text{\textperthousand}$ in Osceola were the highest top in its respective site.

Fractionated Samples

The $\delta^{13}\text{C}$ values of the macroaggregate fraction (250 – 2000 μm , Figure 5-1) showed a similar trend as the whole soil sample with highest values at the surface of the open pasture in all four sites. At the upper 5 cm, the values in the open pasture were higher by 38 % in Alachua (Figure 5-1C, $p<0.001$) 33% in Suwannee (Figure 5-1D, $p<0.001$) 27% in Hardee (Figure 5-1C, $p<0.001$) 25% in Osceola sites (Figure 5-1C, $p<0.01$) than the average value of SP-A and SP-T in silvopasture. Except for Hardee site (Figure 5-1A), the open pasture $\delta^{13}\text{C}$ values in macroaggregate fraction were significantly higher than values on an adjacent silvopasture across all but one depth interval (Figure 5-1B, C, &D).

The results on $\delta^{13}\text{C}$ values in microaggregate size fraction (53 – 250 μm) are shown in Figure 5-2. At any given soil depth interval in the Ultisol sites (Figure 5-2 C & D), the $\delta^{13}\text{C}$ values in open pasture system (average value –21 ‰ in Alachua and – 25.5 ‰ in Suwannee) were consistently higher than the two sampling location in silvopasture, with average values of –24.6 for SP-A and –24.7 for SP-T in Alachua and –25.5 for Sp-A and –25.6 for SP-T in Suwannee. In silt +clay size fraction (<53 μm) a clear difference between $\delta^{13}\text{C}$ values on open pasture and silvopasture was observed in Ultisol sites as opposed to Spodosol sites that showed no difference across depths (Figure 5-3C and D). In the upper 5 cm, for Alachua the values were –17.45 on OP as opposed to –23.8 and –23.5 on SP-A and SP-T respectively.

Plant Sources of SOC in Whole Soil Sample

In all the sites, the values of SOC percent derived from the C3 in the whole soil sample were consistently higher at the two silvopasture sampling locations than in the open pasture systems. Generally the amount of SOC derived from C3 plants showed an increasing trend with

soil depth. On average, these values range from 16.5% in OP, 55% in SP-A and 65% in SP-T at the surface soil profile to 71% in SP-T, 69% in SP-A and 56% on OP at the deepest soil profile.

Plant Sources of SOC in 250 to 2000 μm Fraction

The C3-derived SOC in large (macro) aggregate size fraction at both SP-A and SP-T of silvopasture accounted for significantly higher percentage at any given soil depth interval for all the sites except in Hardee site where no difference between land-uses was observed at depth 15 cm and below (Figures 5-8, 5-9, 5-10 and 5-11). The percent C3-derived SOC consistently increased with an increase in soil depth on both land-use systems for all the sites. For Alachua site the values were 11%, 68% and 75% of SOC in OP, SP-A and SP-T respectively on surface soil (0–5 cm). The corresponding values were 63%, 93% and 82 % in the lowest profile (75 –125 cm) in the same site.

Plant Sources of SOC in 53 to 250 μm Fraction

The C3 (slash pine) contributed relatively insignificantly to SOC in surface soils of the open pasture in the microaggregate size (53 – 250 μm) fraction. The trend was similar to that of the larger fraction in that there were significant difference between open pasture and the silvopasture locations. The highest difference in percent contribution was in the surface in all four sites, ranging from 13 – 19% in open pasture and 30 – 76% in the silvopasture in the top 5 cm soil (Figure 5-12, 5-13, 5-14, and 5-15).

Plant sources of SOC in <53 μm Fraction

The C3-derived SOC percent in the silt + clay fractions showed no differences among sampling locations on the Spodosol sites except in the upper 15 cm where tree (C3) contribution was higher in the silvopasture. In the Spodosol sites at and below spodic horizon (40 – 50 cm), C3-derived C in the <53 μm fraction was relatively high.

The overall mean amount of SOC contributed by C3 and C4 plants in whole and fractionated samples at a given soil depth for the Ultisol and Spodosol locations are shown on Figure 5-20 and 5-21. At the surface (0–5 cm), much of the SOC accumulated was C3-derived C in SP-T and SP-A in the whole and the entire fraction sizes in the Ultisol locations. For the Spodosol locations, however, the SOC accumulation at surface had comparable contributions from both C4 and C3 plants in the silvopasture locations. C4-derived SOC in OP remained to be substantially greater in the whole and all three fractionated sizes in both Ultisol and Spodosol. Although total SOC was found to decrease with increasing soil depth, the proportion of C3-derived as opposed to C4-derived SOC consistently increased in the whole soil and three fraction sizes in both soil orders. The overall means across all locations for C3 and C4-derived SOC at a given depth in the whole soil and three fractions are presented in Figure 5-22. It has similar change pattern to that of mean values of the separate soil orders.

Discussion

The main objective of the present study was to substantiate the relative importance of C derived from slash pine (C3) vs. bahiagrass (C4) in the silvopasture systems compared with an adjacent open pasture using difference in ratio of naturally abundant stable C isotopes ($\delta^{13}\text{C}$ values) between C4 grasses and C3 woody plants. From this study, it is apparent that the current land-use significantly affected the $\delta^{13}\text{C}$ values of total SOC in whole soil and soil fractions (Table 5-1, Figures 5-1, 5-2, & 5-3).

Generally, the $\delta^{13}\text{C}$ values of terrestrial C3 plants grown under natural conditions are between $-22\text{\textperthousand}$ and $-34\text{\textperthousand}$ (Vogel, 1993). The $\delta^{13}\text{C}$ value of composite sample of plant part or soil underneath for slash pine reported in literature are within the above expressed range of values. Parasolova et al. (2003) reported $\delta^{13}\text{C}$ range between $-25\text{\textperthousand}$ and $-29.5\text{\textperthousand}$ for slash pine x

Caribbean pine (*Pinus caribaea*) hybrids. Similarly, Mortazavi and Chanton (2002) found value between $-27.3\text{\textperthousand}$ to $-28.5\text{\textperthousand}$, and on average -27.9 for slash pine needles. Although the $\delta^{13}\text{C}$ values measured in the silvopasture soil in this study were (on average $\approx -24\text{\textperthousand}$) within the above expressed range of values for terrestrial C3 plants, they were somewhat high for a typical soil beneath a slash pine stand, suggesting that the bahiagrass (C₄) in silvopasture had augmented the SOC storage that caused an increase in the $\delta^{13}\text{C}$ values.

The most negative values (on average $-24\text{\textperthousand}$) in the silvopasture soils and the least negative values (on average $-15\text{\textperthousand}$) in the open-pasture soil were found on the surface soil profiles. Evidences from radiocarbon studies indicate that the average age of SOC increases with depth in the profile (Scharpenseel and Neue, 1984; Balesdent et al., 1990). Thus, the soil C at surface is believed to be composed of recent accumulation or young organic C as a case in point a reflection of the current difference in land-use. Given that the a value of $-13.3\text{\textperthousand}$ has been reported for shoots or roots of bahiagrass (Nakano et al., 2001), the current results where the least negative value of $\delta^{13}\text{C}$ was at the surface on the open pasture, confirm that bahiagrass was the main plant source of the SOC in the surface soil. By contrast, the more negative values in the surface silvopasture soils indicate that a significant proportion of the SOC beneath the silvopasture on the SP-T and SP-A locations was derived from slash pine litter and fine roots. The calculated means of C3- and C4- derived SOC at a given depth in the whole soil and three fractions presented in Figure 5-22 consistently substantiate this observation.

As a consequence of the variations in their C turnover, the $\delta^{13}\text{C}$ values of fraction size separates provide an enhanced view of plant community history. The $\delta^{13}\text{C}$ values of fraction size separates (Figure 5-8 – 5-16 B& C, Figure 5-20 B &C, Figure 5-21B&C, and Figure 5-22B & C) revealed that the larger (macro) aggregate size fraction and micro-size aggregate contributed

most of the C derived from the C3 woody plant in the silvopasture compared to open pasture across the soil depth, but particularly so in the lower profiles. The fact that the soil C in the larger fraction represents C that is largely newly incorporated into the soil suggests that most this SOC, including in the lower profile, is contributed by the current C3 plant component in the silvopasture, i.e. slash pine, that has deeper root systems than the grass component. When comparing $\delta^{13}\text{C}$ values of functionally distinct SOC fractions within the same soil type, the silt + clay fraction (<53 μm) always showed a significantly higher percentage of C3-derived SOC signatures, particularly at the lower soil profile as opposed to larger fraction sizes. However, in the silt + clay fraction no significant difference was observed between silvopasture and open pasture in the lower depths for most sites except the Alachua site where the prior land-use history for the current open pasture was agriculture (corn field). The silt + clay fraction was less enriched with ^{13}C than whole soil and appeared to contain SOC largely derived from C3. In fact, the C associated with the silt + clay fraction tends to be ‘older’ C, indicating that the prior land-use history of the site has substantial effect on the current status of C storage in soil. The study sites in the current study were previously under forest vegetation, popularly called Florida Flatwoods, and it is logical to surmise that the current C status of the site is a reflection of this.

At the Spodosol sites, at and below spodic horizon, older C3-derived C was relatively high (Figure 5-21). The spodic horizons differ from other soil materials due to the prevalence of organically-associated Al and have very high surface area for retention of older SOC. From an analysis of the depth distribution of $\delta^{13}\text{C}$ in podzols developed under C₄ savanna in the Congo, Schwatz and Mariott (1986) showed that the spodic Bh horizons exhibited typical C3 values because the podzolic morphology was inherited from past forest phases > 30,000 years old.

Change from a C₄- dominated herbaceous community (bahiagrass) to a mixed plant community (in the silvopasture) of C₃ woody slash pine and bahiagrass in the current study provides a good situation for the use of the natural ¹³C-leveling technique. The quantification of the progressive incorporation of new C into soil organic fractions provides a powerful means with which to elucidate the pathways of C transformations and stabilizations. However, the ¹³C method is unable to distinguish between residual “primary forest” C and new C derived from tree component in the silvopasture. In this regard, the use of ¹⁴C and bomb C models will be relevant to ‘date’ soil fractions and to distinguish newly incorporated C derived from tree component in the silvopasture from old residual C retained from “primary forest”. Such methods could also reduce uncertainties in turnover rates.

Conclusions

The results of this study showed an increase in total SOC pools following tree integration into pasture. This seems to be due to retention of older C₃-driven SOC by protection in microaggregates, retention of C associated with silt + clay, and largely due to accumulation of new C₃-derived SOC in macroaggregate fractions. C₃ plants seemed to have consistently contributed more C in the silt + clay fraction (<53 µm) than C₄ plants at all soil depths, particularly in the lower depths, in all sites. Sites where the silvopasture was older, the impacts of trees on SOC were greater. The results suggest that, in the long term, silvopasture may help sequester more SOC and stabilize C in the soil.

These results have promising implications in the context of the Kyoto protocol in view of the evidenced potential of silvopasture to sequester and stabilize C in the soil in the long term. The study also points out the need for intensifying research to address several issues before the suggested potential can be convincingly established. A line of research of considerable promise is the use of ¹⁴C and bomb C models to ‘date’ soil fractions and to distinguish newly

incorporated C derived from tree component in the silvopasture from old residual C retained from “primary forest.”

Table 5-1. $\delta^{13}\text{C}$ values of whole soil SOC in different land-use locations at four sites across soil depth.

Soil depth (cm)	$\delta^{13}\text{C}$ values of SOC (‰)											
	Ultisol sites						Spodosol sites					
	Alachua			Suwannee			Hardee			Osceola		
	OP	SP-A	SP-T	OP	SP-A	SP-T	OP	SP-A	SP-T	OP	SP-A	SP-T
0-5	-15.9 ^a (0.9)	-23.6 ^b (0.5)	-24.2 ^b (0.4)	-16.9 ^a (0.3)	-23.5 ^b (0.5)	-23.9 ^b (0.3)	-15.2 ^a (0.4)	-20.9 ^b (0.0)	-22.4 ^c (0.2)	-16.0 ^a (0.1)	-17.5 ^b (0.3)	-20.7 ^c (0.6)
5-15	-20.6 (1.0)	-23.0 (0.6)	-24.6 (1.1)	-19.2 ^a (0.4)	-23.6 ^b (0.1)	-24.2 ^b (0.3)	-19.1 ^a (0.1)	-20.3 ^{ab} (0.5)	-21.7 ^b (0.4)	-17.2 ^a (0.5)	-19.7 ^b (0.4)	-19.8 ^b (0.2)
15-30	-20.6 ^a (0.3)	-24.9 ^b (1.7)	-23.2 ^b (0.1)	-20.9 ^a (0.3)	-25.1 ^b ..(0.9)	-24.4 ^b (0.4)	-21.0 (0.2)	-21.7 (0.8)	-21.2 (0.1)	-19.5 (0.4)	-20.5 (0.3)	-20.0 (0.1)
30-50	-19.8 ^a (0.3)	-25.0 ^b (1.7)	-23.2 ^b (0.3)	-21.5 ^a (0.1)	-25.0 ^b (1.0)	-24.7 ^b (0.4)	-22.2 (0.7)	-21.0 (1.2)	-21.8 (0.4)	-20.8 (0.1)	-21.2 (0.2)	-21.5 (0.5)
50-75	-19.5 ^a (0.6)	-25.0 ^b (1.7)	-23.3 ^b (0.6)	-22.0 ^a (0.3)	-23.9 ^b (0.3)	-24.7 ^b (0.1)	-23.7 (0.1)	-23.6 (0.7)	-24.4 (0.3)	-20.9 (0.3)	-21.5 (0.5)	-21.6 (0.5)
75-125	-20.3 ^a (0.9)	-23.3 ^b (0.6)	-23.3 ^b (0.5)	-22.0 ^a (0.4)	-24.3 ^b (0.2)	-25.1 ^b (0.1)	-23.3 ^a (0.5)	-24.7 ^b (0.2)	-24.7 ^b (0.1)	-20.4 (0.7)	-21.4 (0.3)	-21.4 (0.8)

Note: Lower case letters next to the mean values indicate significant differences in SOC among pasture locations at a given depth (Tukey's studentized range test (HSD) performed following ANOVA); the values in parenthesis are standard deviations of means.

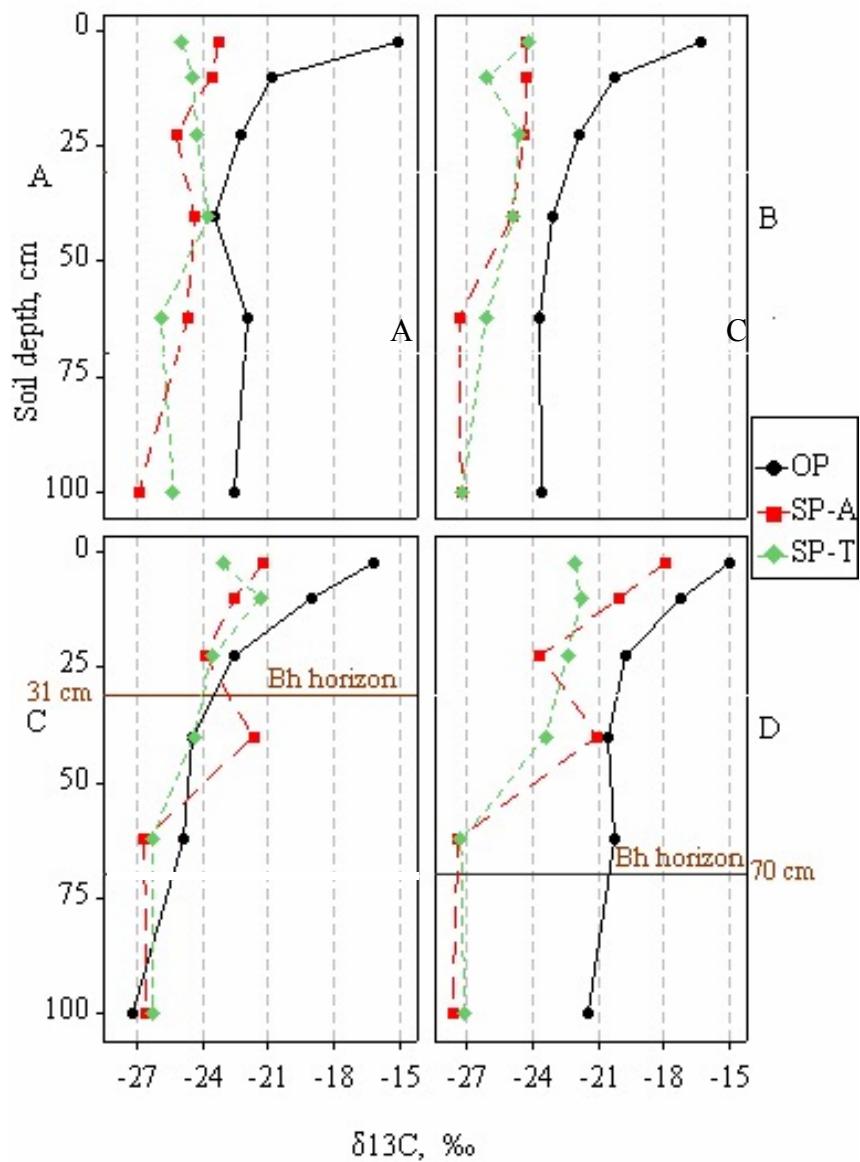


Figure 5-1. Changes in $\delta^{13}\text{C}$ values of SOC in macroaggregate fraction in different land-use locations at four sites across soil depth: A) Alachua, B) Suwannee C) Hardee and D) Osceola across soil depth.

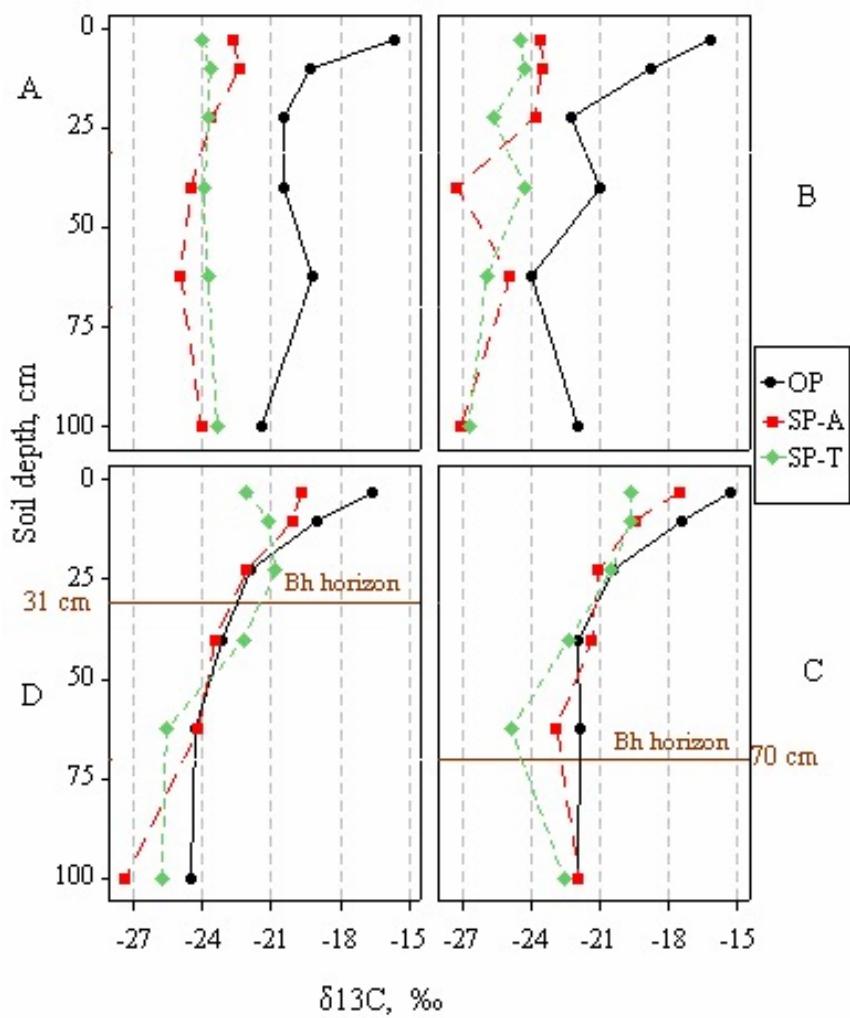


Figure 5-2. Changes in $\delta^{13}\text{C}$ values in microaggregates size in sites: A) Alachua, B) Suwannee
C) Hardee and D) Osceola across soil depth.

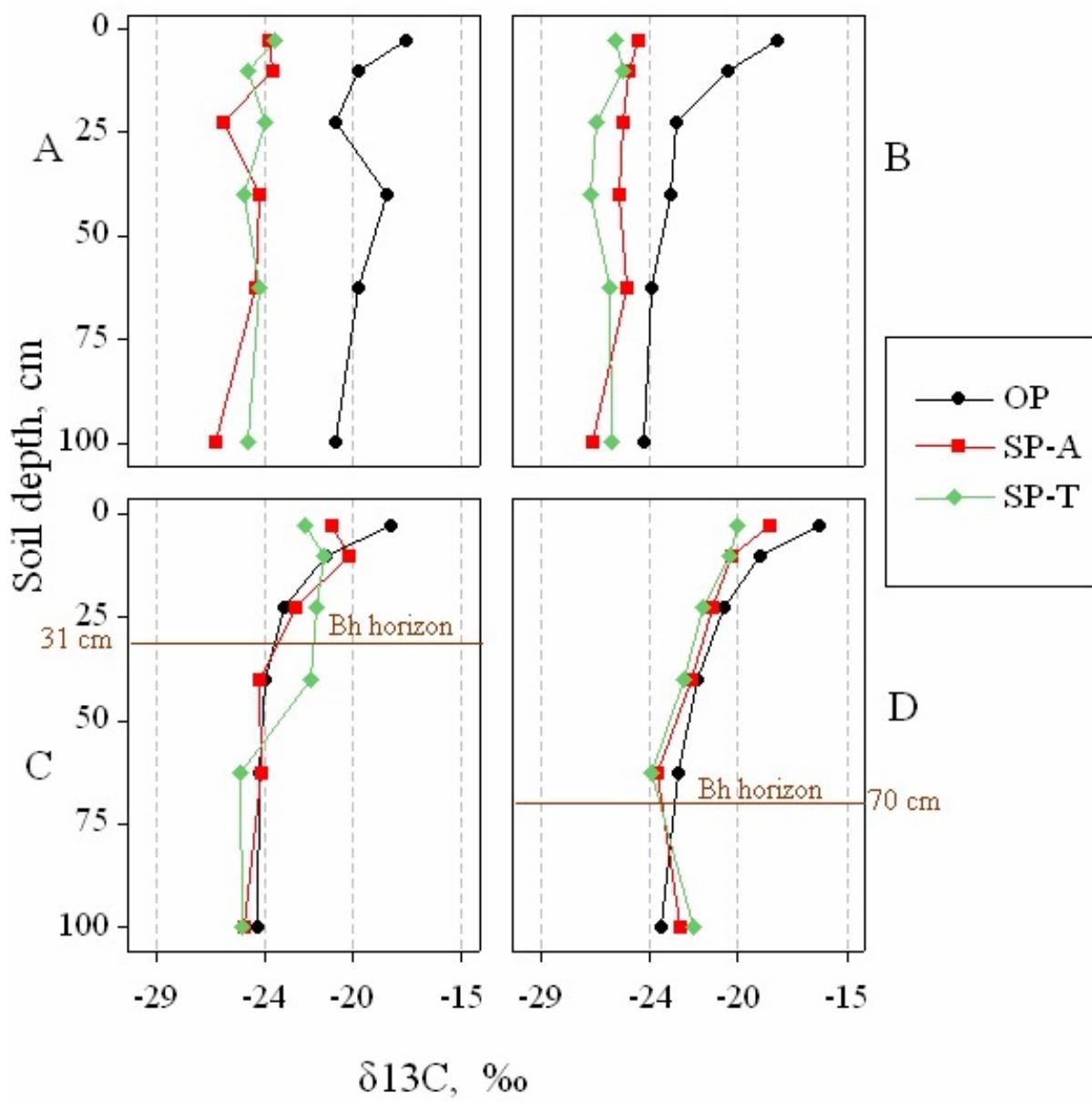


Figure 5-3. Changes in $\delta^{13}\text{C}$ values in silt + clay size fraction for sites: A) Alachua, B) Suwannee C) Hardee and D) Osceola across soil depth.

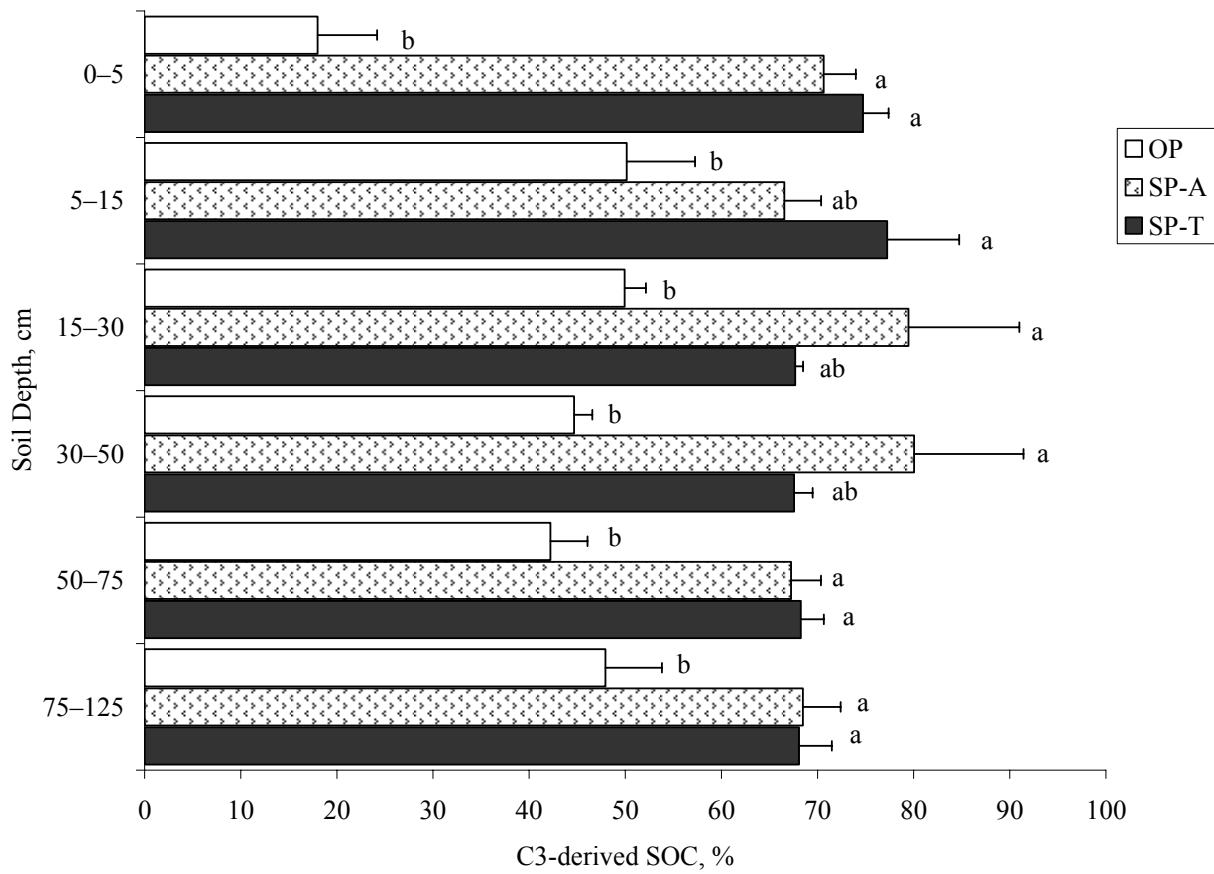


Figure 5-4. Changes in percent of C₃-derived C in whole-soil with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Alachua site

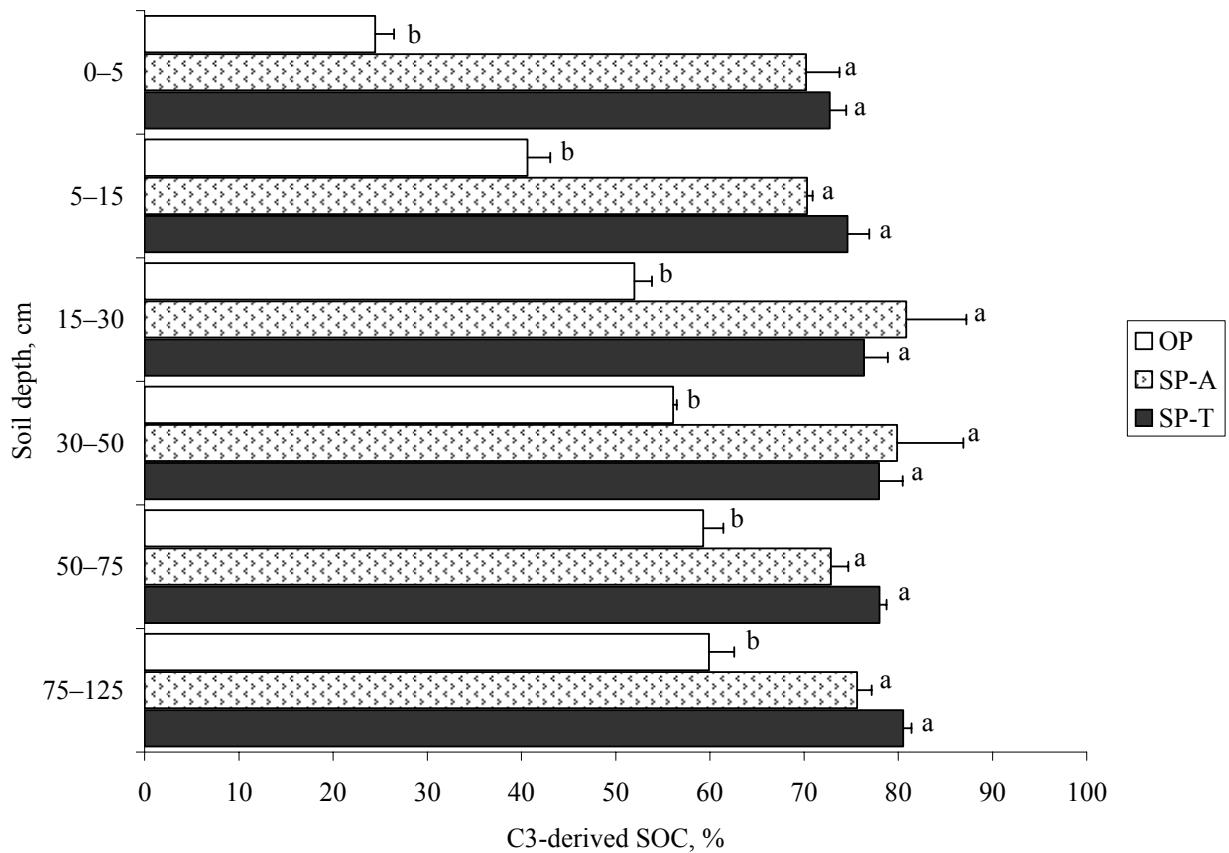


Figure 5-5. Changes in percent of C3-derived C in whole-soil with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Suwannee site.

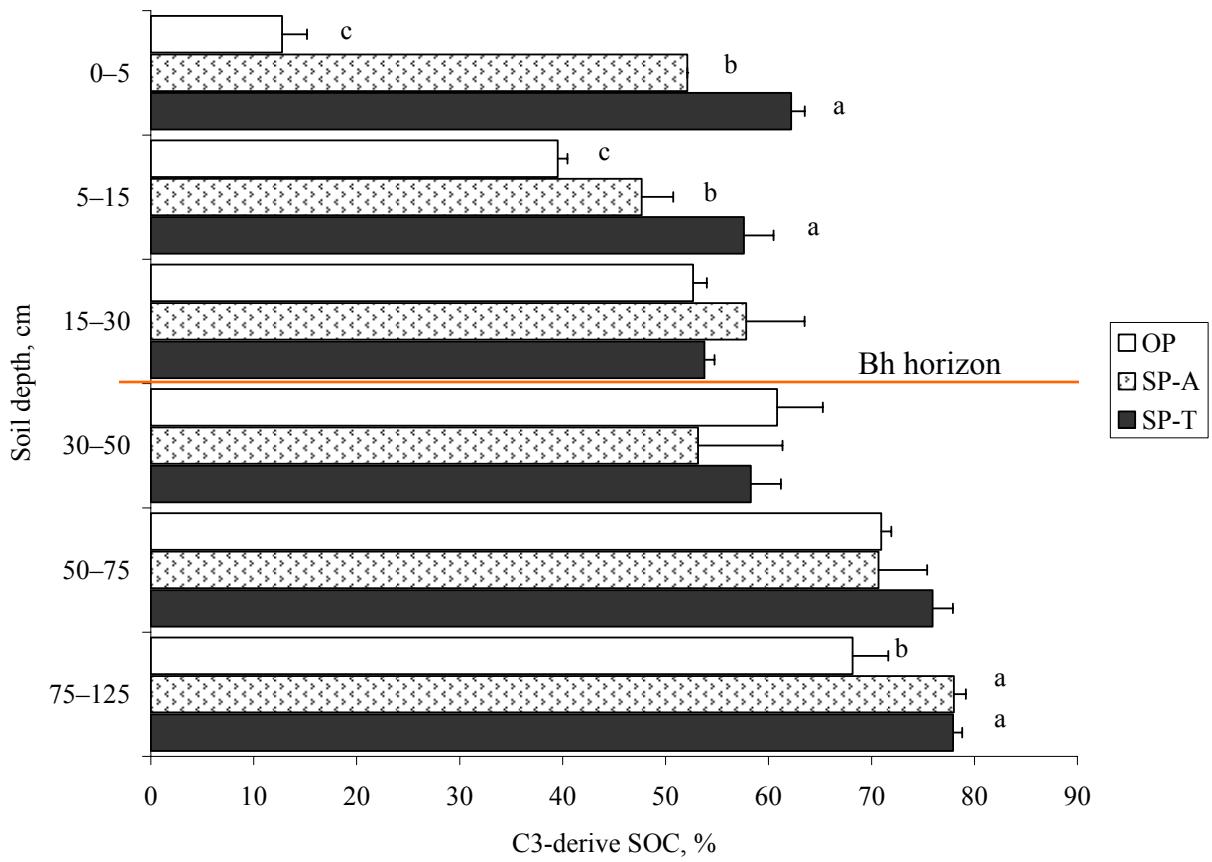


Figure 5-6. Changes in percent of C3-derived C in whole-soil with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Hardee site.

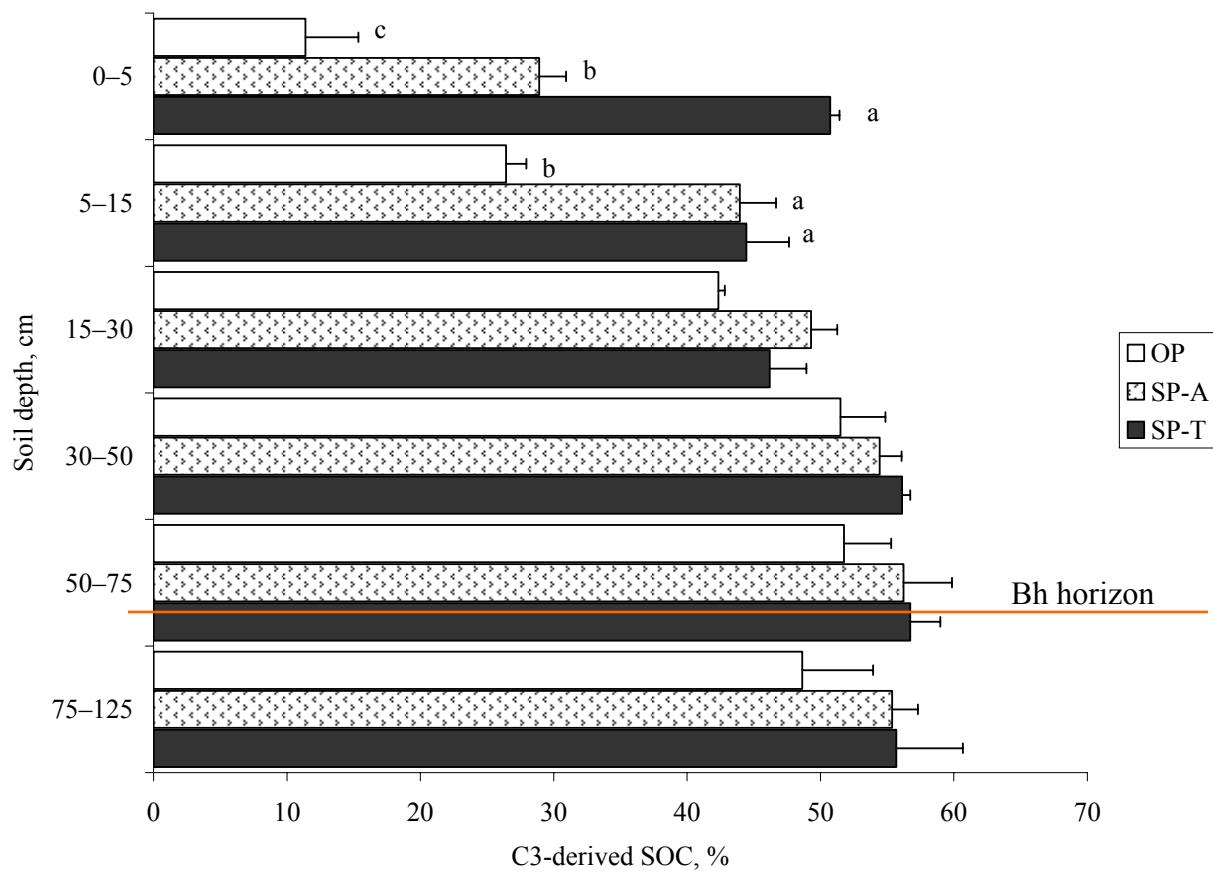


Figure 5-7. Changes in percent of C3-derived C in whole-soil with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Osceola site.

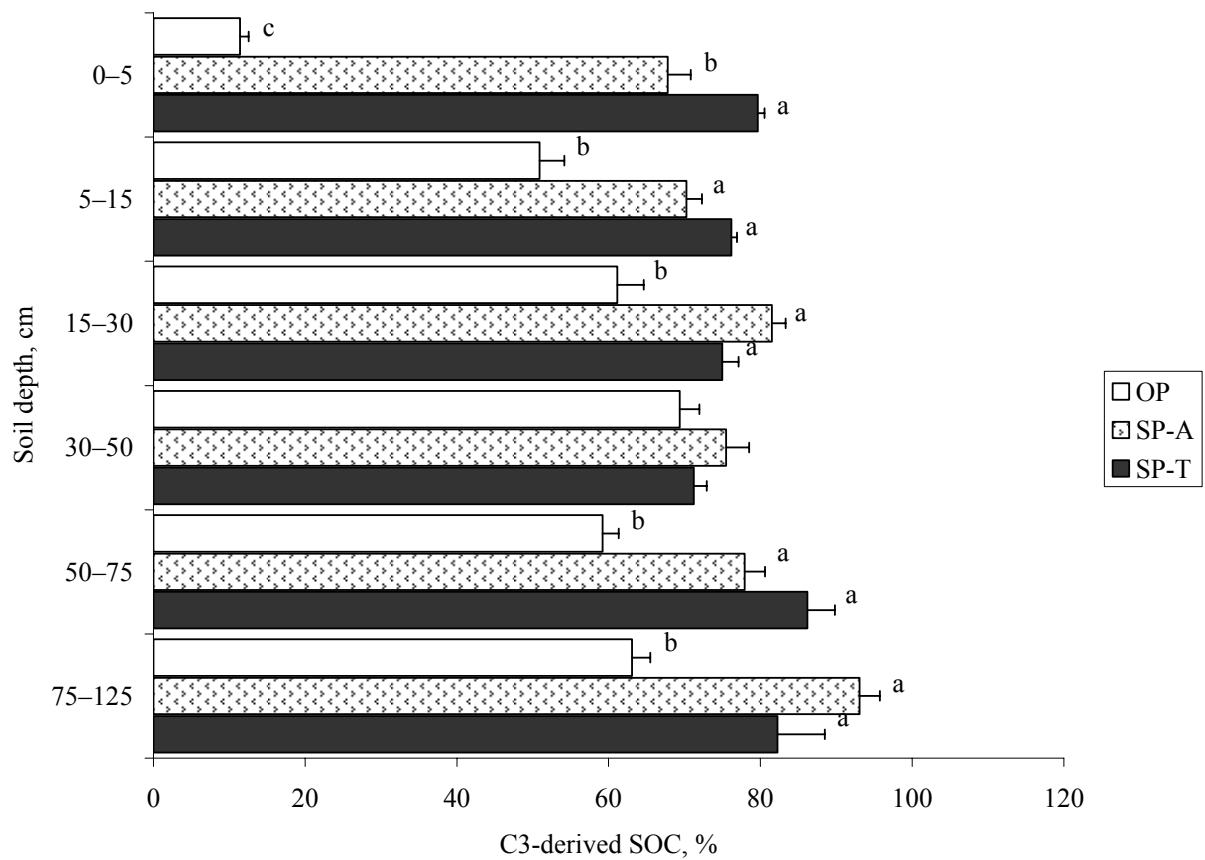


Figure 5-8. Changes in percent of C3-derived C in 250 – 2000 µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Alachua site.

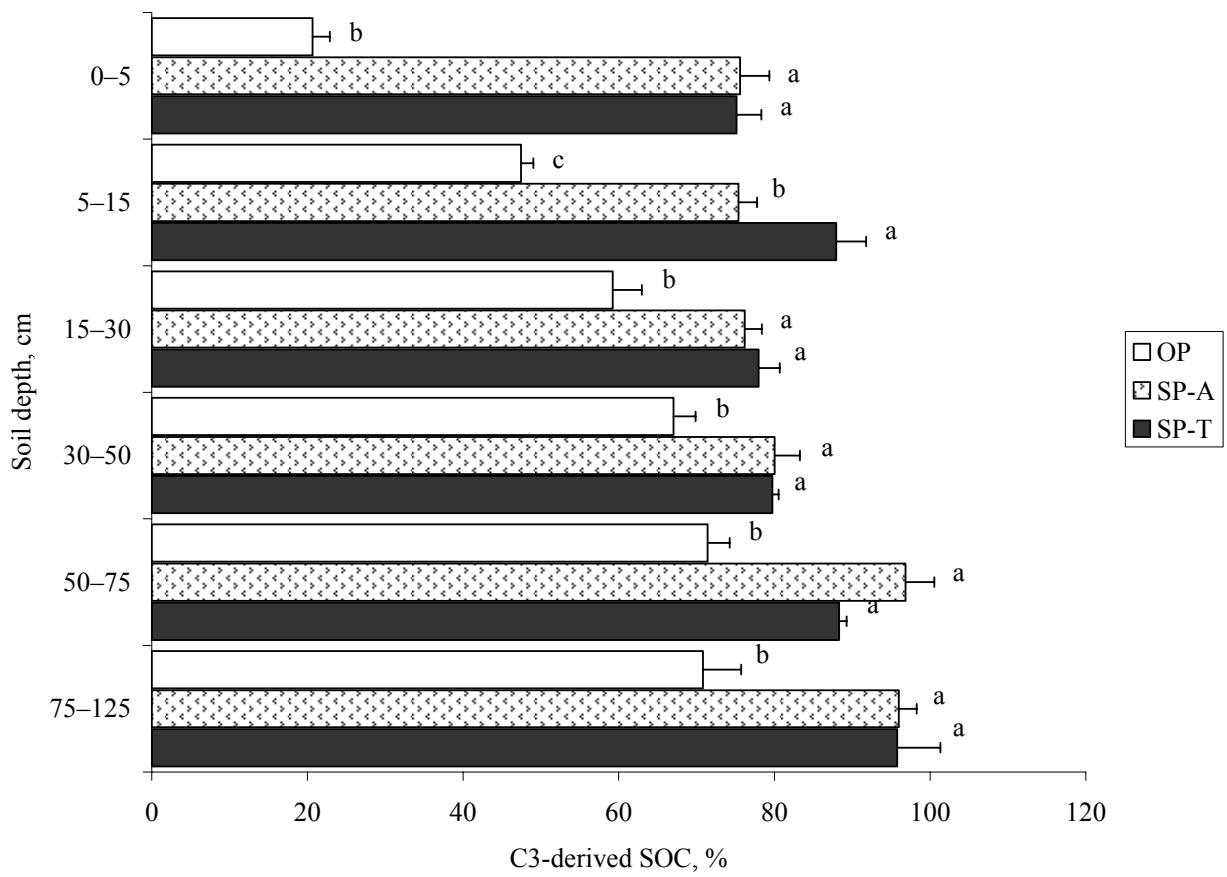


Figure 5-9. Changes in percent of C₃-derived C in 250 – 2000 µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Suwannee site.

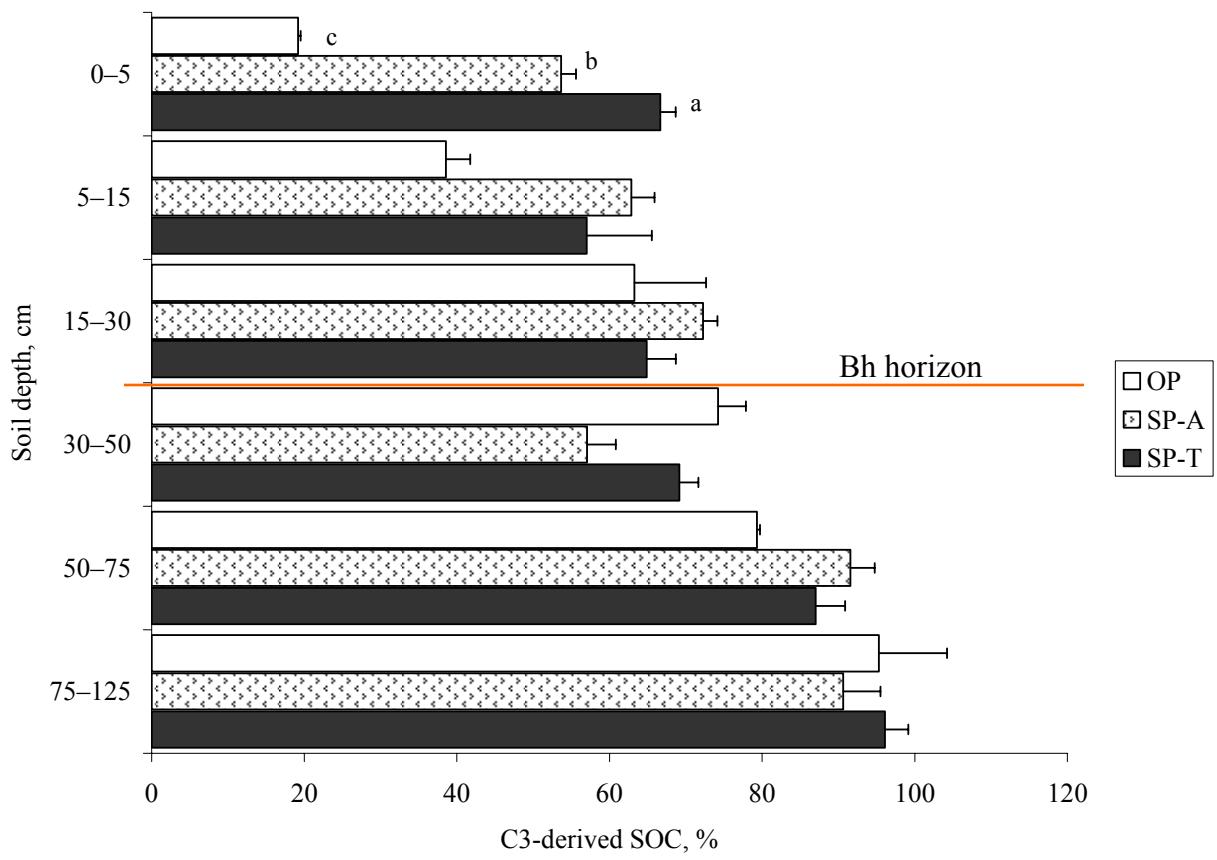


Figure 5-10. Changes in percent of C3-derived C in 250 – 2000 μ m with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Hardee site.

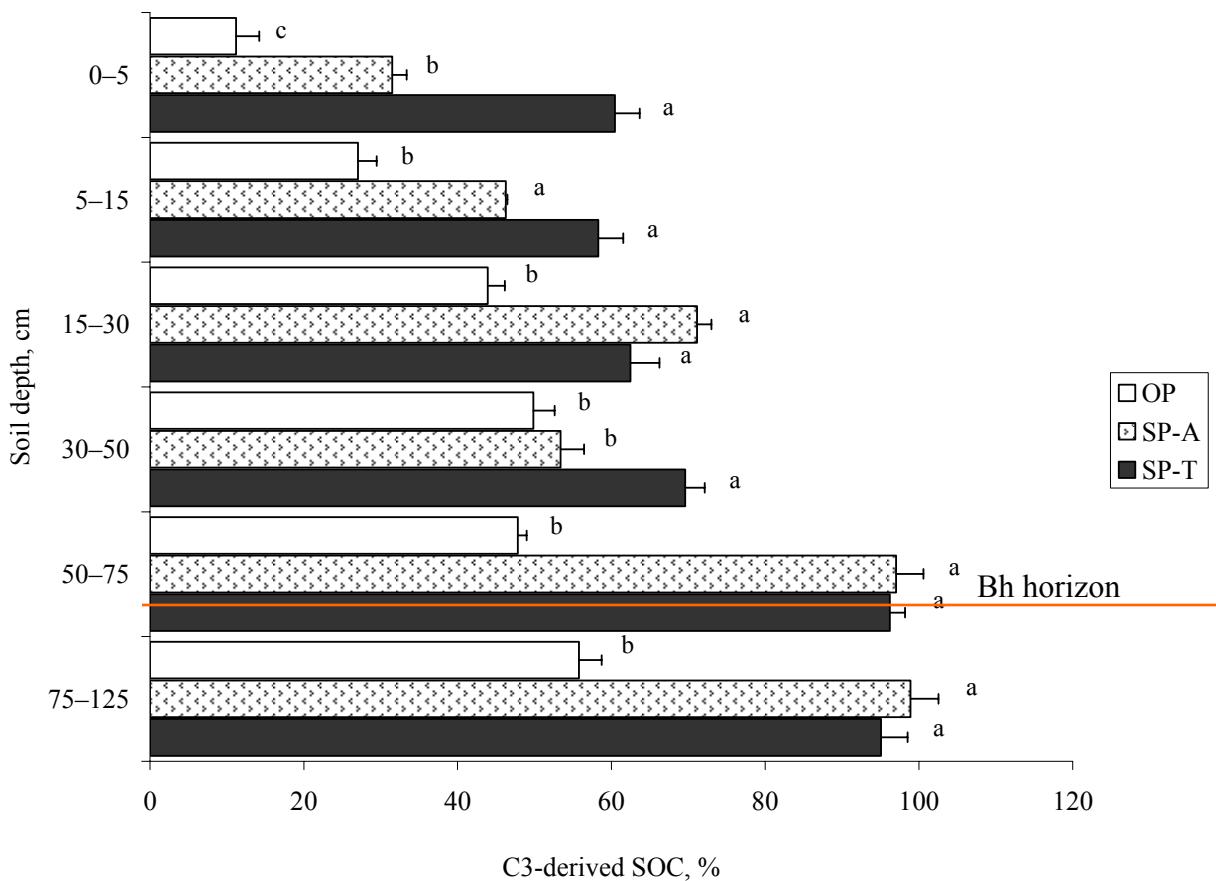


Figure 5-11. Changes in percent of C3-derived C in 250 – 2000µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Osceola site.

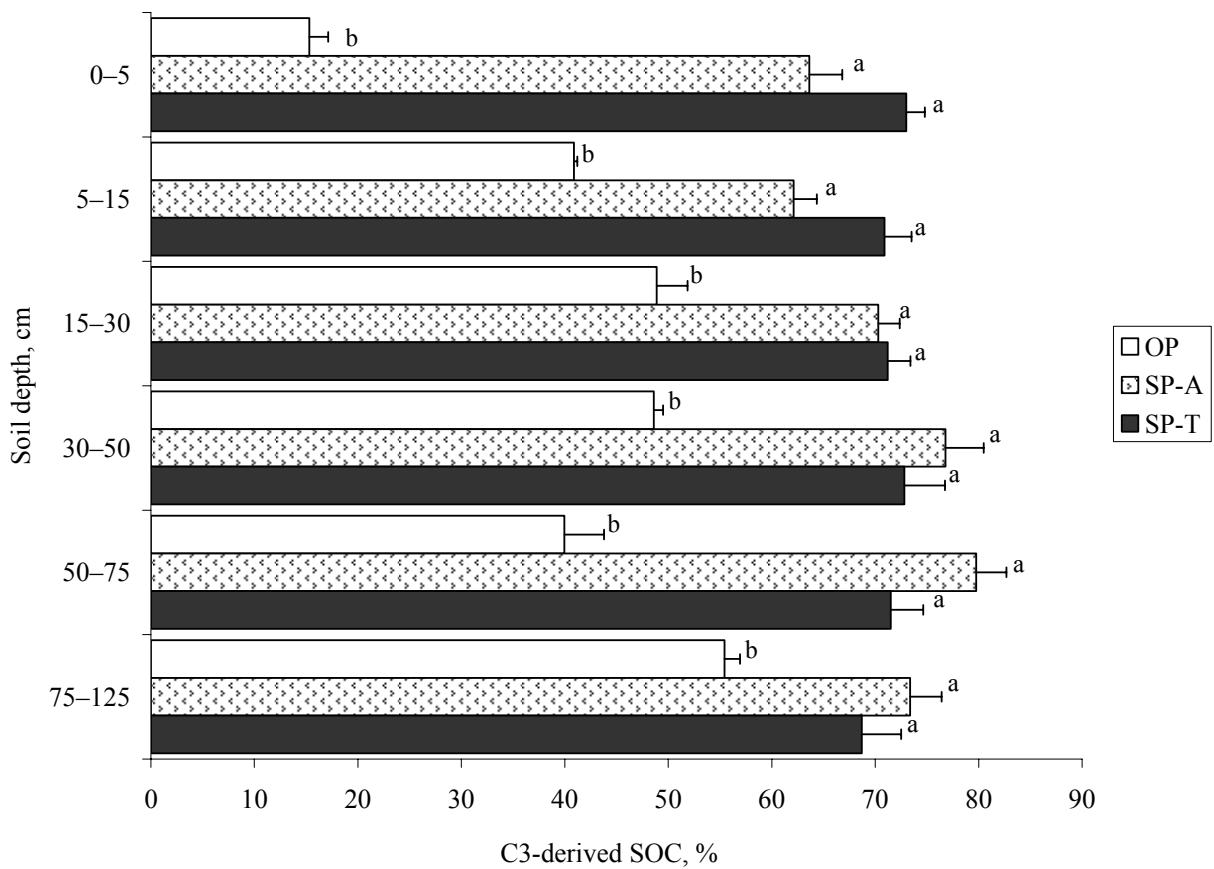


Figure 5-12. Changes in percent of C3-derived C in 53 – 250 μm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Alachua site.

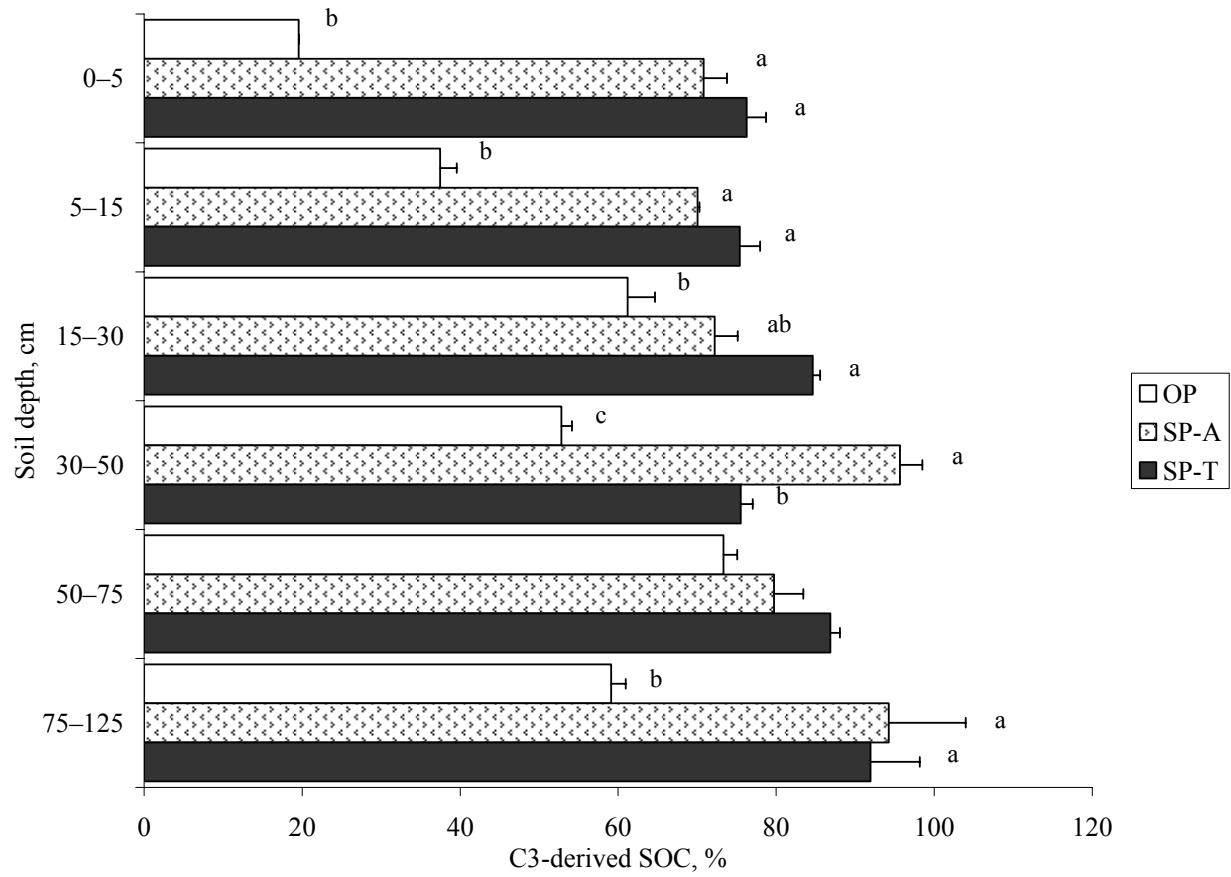


Figure 5-13. Changes in percent of C3-derived C in 53 – 250 µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Suwannee site.

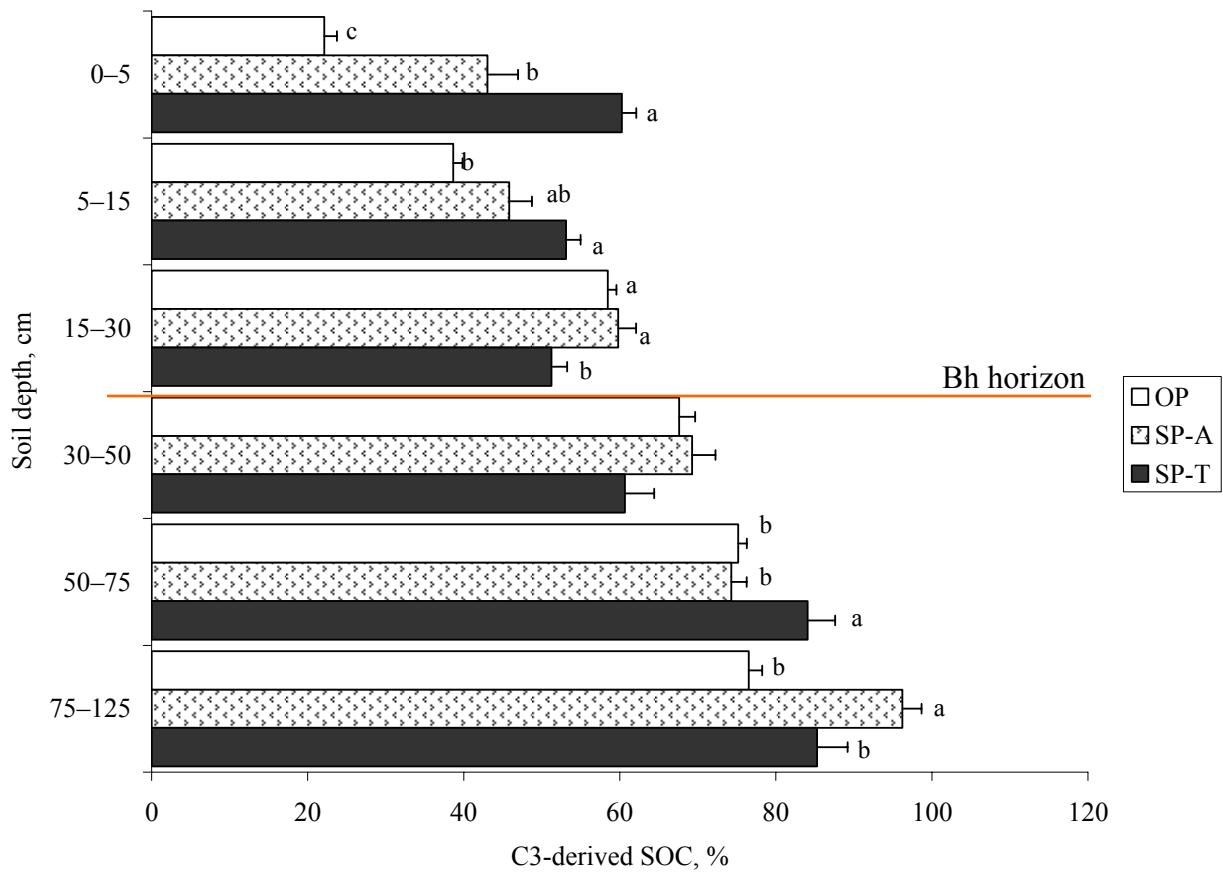


Figure 5-14. Changes in percent of C3-derived C in 53 – 250 μm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Hardee site.

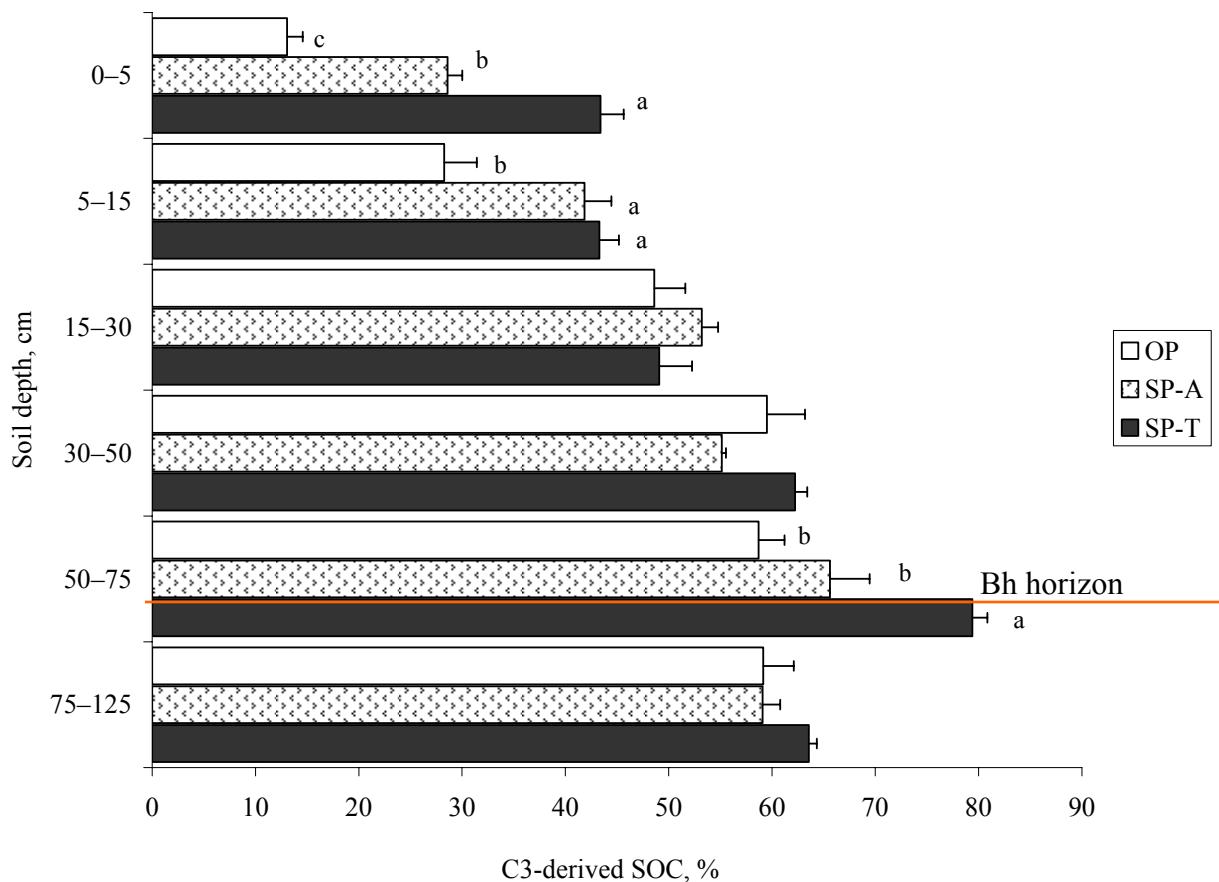


Figure 5-15. Changes in percent of C3-derived C in 53 – 250 μm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Osceola site.

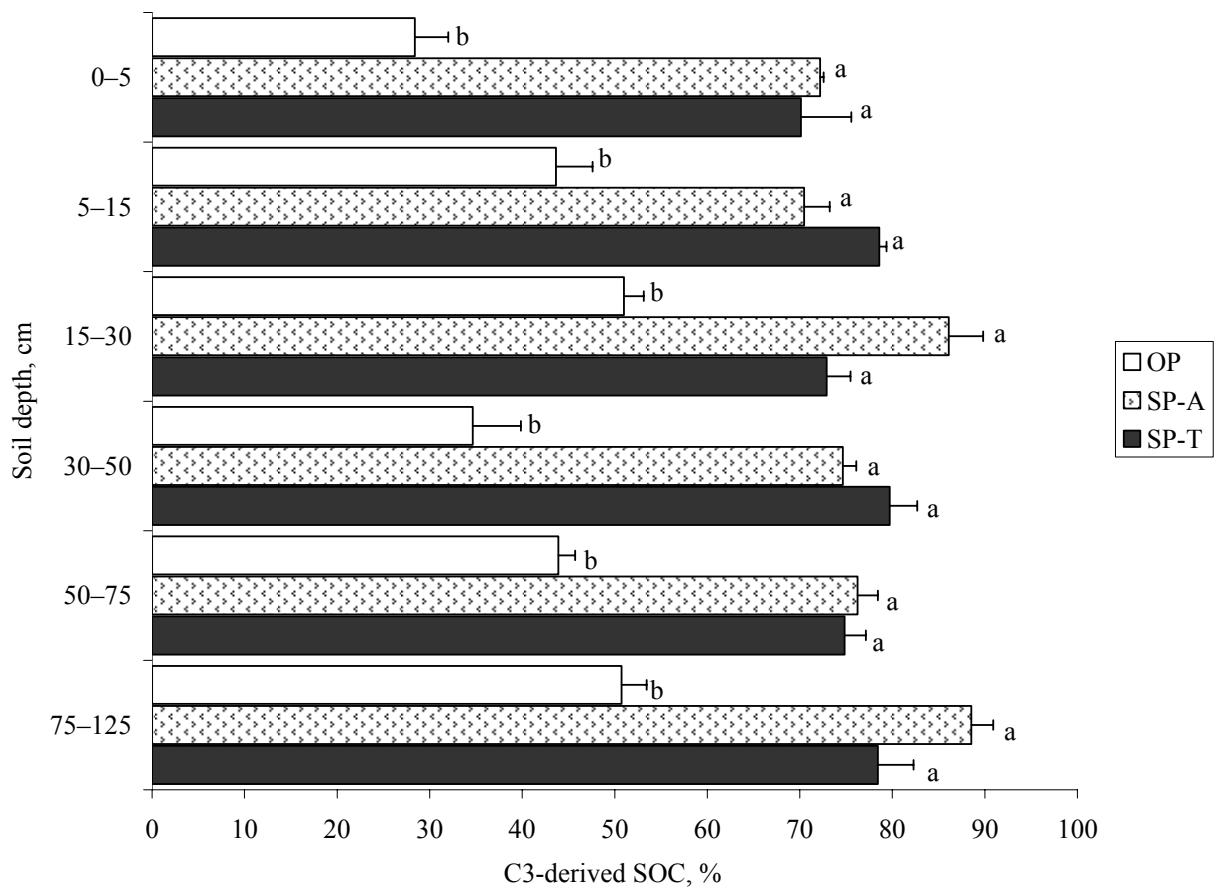


Figure 5-16. Changes in percent of C3-derived C in <53 µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Alachua site.

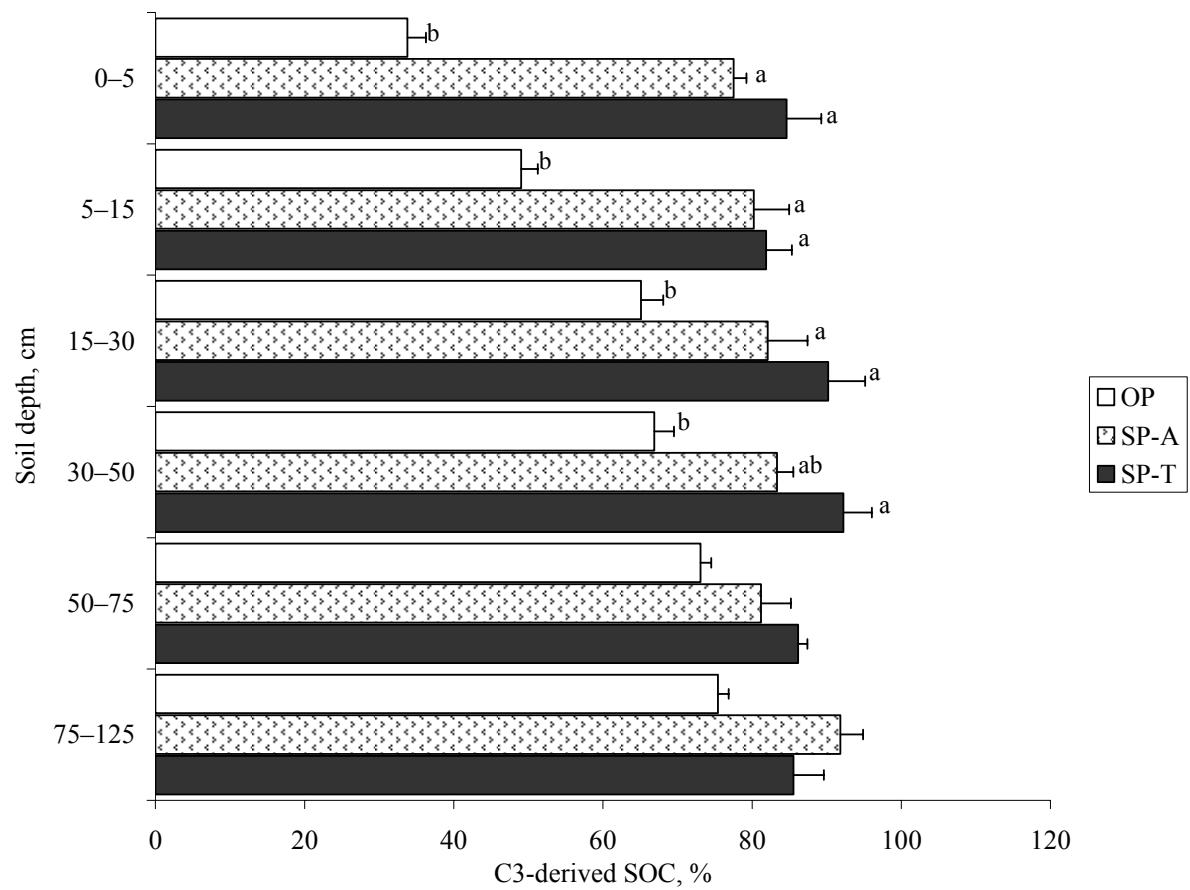


Figure 5-17. Changes in percent of C3-derived C in <53 µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Suwannee

site.

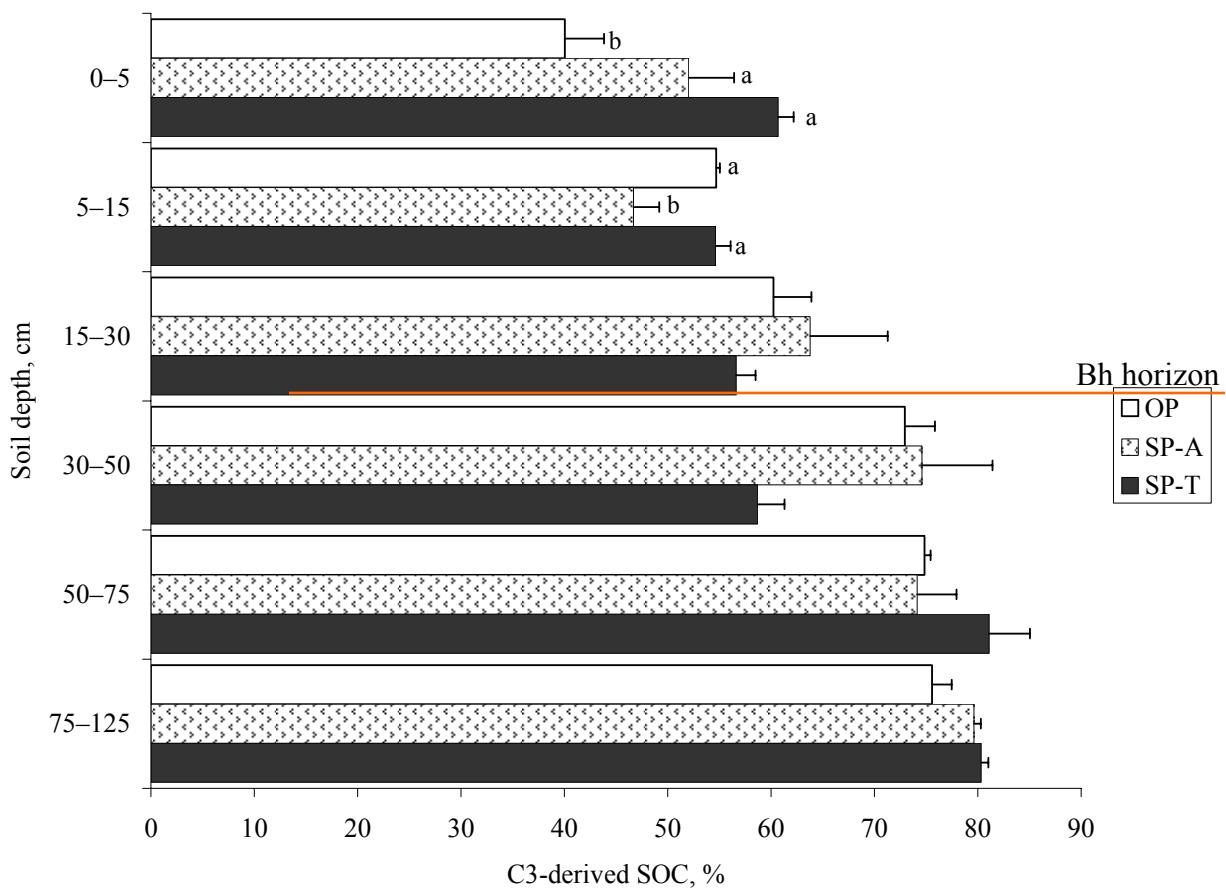


Figure 5-18. Changes in percentage of C3-derived C in the <53 µm fraction with soil depth on silvopasture (SP-T and SP-A) and on an adjacent open pasture (OP) in Hardee site.

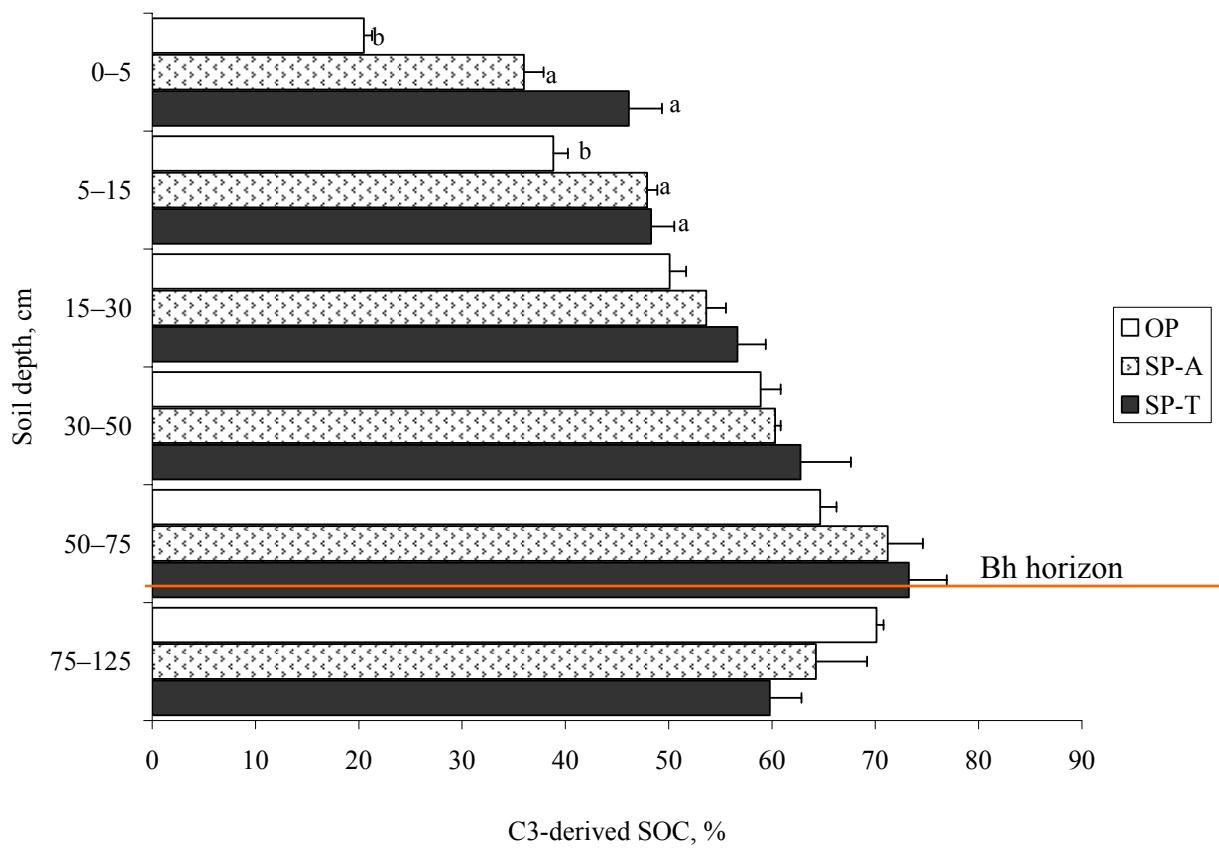


Figure 5-19. Changes in percent of C3-derived C in <53 µm with soil depth on silvopasture (SP-T and SP-A) and adjacent open pasture (OP) in Osceola site.

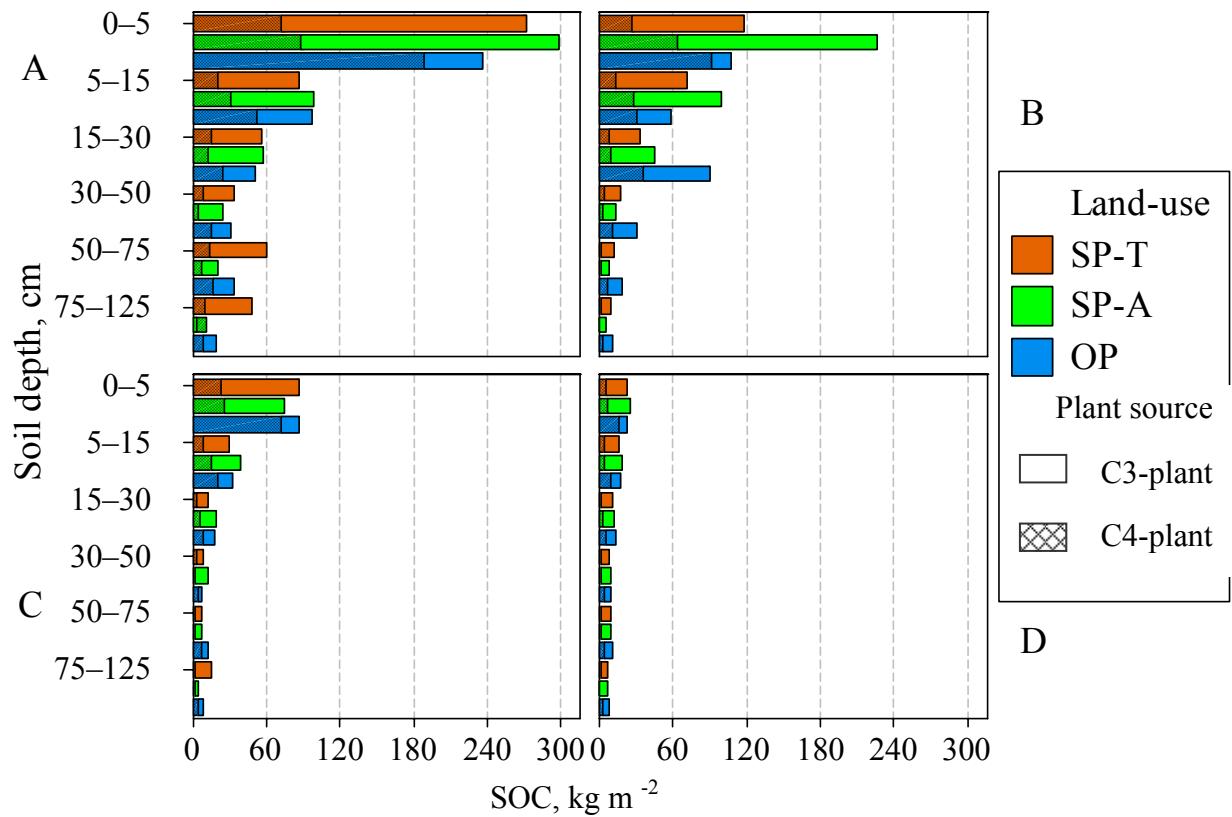


Figure 5-20. Changes in overall mean C3-derived and C4-derived SOC across all locations in A) whole soil B) macroaggregate C) microaggregate, and D) silt + clay fraction down the soil profile depths in Ultisols at three pasture locations (SP-A, SP-T; and OP).

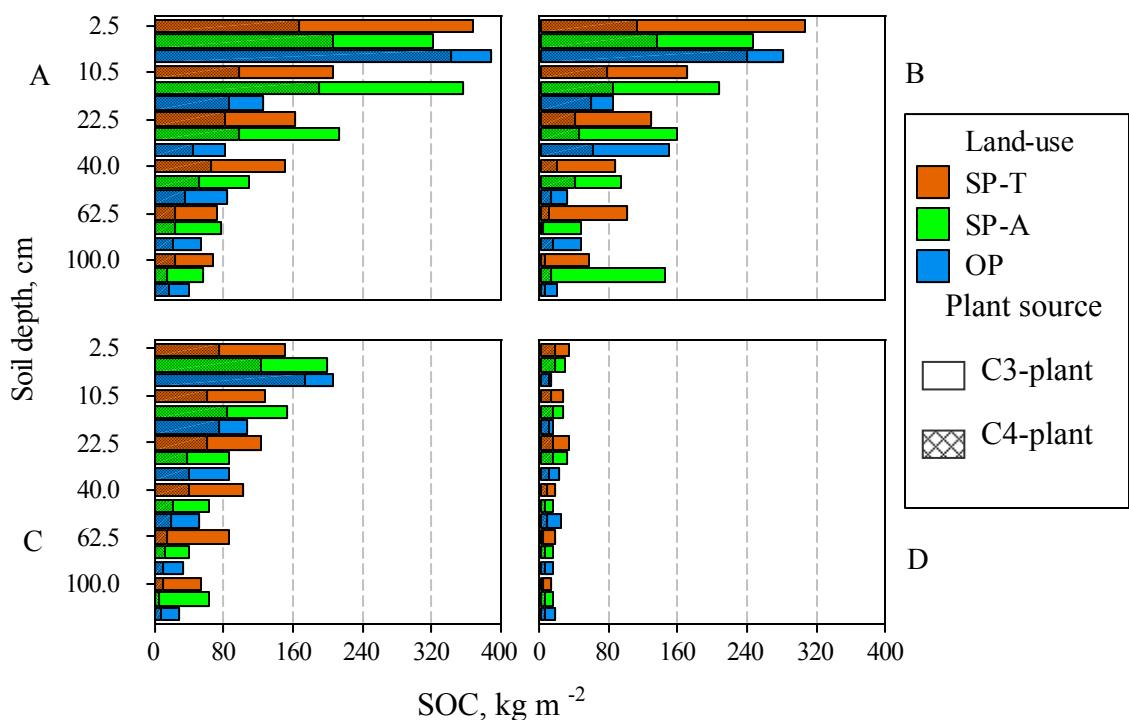


Figure 5-21. Changes in overall mean C3-derived and C4-derived SOC across all locations in A) whole soil B) macroaggregate C) microaggregate, and D) silt + clay fraction down the soil profile depths in Spodosols at three pasture locations (S-A, SP-T; and OP).

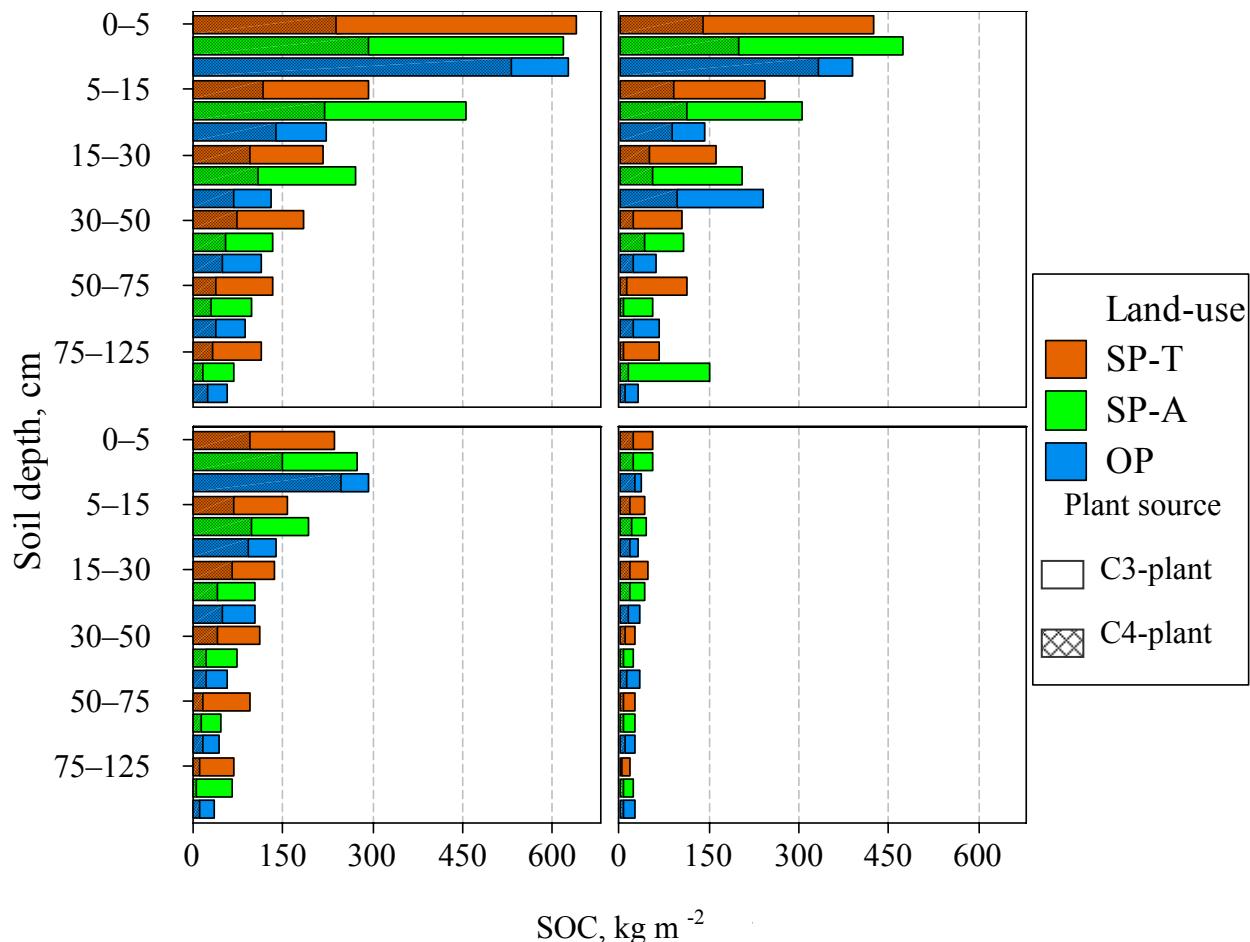


Figure 5-22. Changes in overall mean C3-derived and C4-derived SOC across all locations in A) whole soil B) macroaggregate C) microaggregates, and D) silt + clay fraction down the soil profile depths at three pasture locations (SP-A, SP-T; and OP).

CHAPTER 6

SUMMARY AND CONCLUSIONS

Although soil organic carbon (SOC) is a major pool in the terrestrial C cycle and is directly linked to atmospheric CO₂, the idea of using soils in agroecosystems to sequester C and mitigate the risk of accelerated greenhouse effect is a relatively new concept. At the same time, the role of silvopasture as an alternative to intensive open-grass pasture systems in the Southeastern USA for improving environmental quality has received some attention. An underexplored area of such tree-based systems is their potential for enhancing C storage and stabilization in the soils. Current knowledge on the dynamics of soil C storage following tree integration into pasture systems is scant and largely not quantified. This study was undertaken in this scenario, with the objectives of determining the amounts of C stored in the soil, quantifying the C fractions stored within soil profiles, tracing the plant sources of C fractions using stable isotope signatures, and elucidating the mechanisms of physical protection and stabilization of SOC. The study was undertaken in slash pine (*Pinus elliottii*) + bahiagrass (*Paspalum notatum*) silvopasture and adjacent open (treeless) pasture systems at four sites on Spodosols and Ultisols in Florida.

Soil samples were collected from Alachua (29°45' N, 82°33'W), Osceola (28° 9' N, 81° 10' W), Hardee (27°13' N, 82°8' W), and Suwannee (30°24' N, 83° 0' W) counties in Florida. Each site had a silvopasture system and an adjacent treeless pasture of bahiagrass. Soil samples were collected from three different sample sets: between trees in a row (SP-T) and at the center of an alley (SP-A); and another set on an open pasture (OP). Each of these sample sets had stratified grid sampling points representing three rows with four sampling points in a row. At each sampling point, soils were collected from six depths 0 – 5, 5 – 15, 15 – 30, 30 – 50, 50 – 75, and 75 – 125 cm. Soils were physically fractionated by wet-sieving through a series of two sieve sizes (250 and 53 µm).

In general, soils under silvopasture had lower pH and bulk density compared to those under open pasture, especially under the old-growth (40 years) of silvopastural stands at Suwannee. This could primarily be due to the regular application of dolomite in the open pasture during the past 40 years. Changes in above- and belowground productivity, modification of the rooting depth and distribution, and the input of substantial quantities of pine litter could also have resulted in lower soil pH under silvopasture. Total SOC in whole soil was higher under silvopasture, especially at deeper soil depths, by an overall average of 33% in SP-T and 28% in SP-A as compared with adjacent open pastures. Again, this could be a likely consequence of the increases in total biomass productivity above- and belowground in silvopasture relative to the open pasture land.

Soil fractionation studies revealed increased retention of older C in SOC in microaggregates (53 – 250 μm), enhanced association of C with silt + clay (<53 μm) fractions of soil, and greater accumulation of new SOC in macroaggregate (250 – 2000 μm) fraction under silvopasture compared to open pasture. These findings demonstrate the significant levels of C sequestration that occur in the tree-based pasture system.

Studies on stable C isotopic ratio showed that the increase in total SOC pools following tree integration into pasture was possibly due to retention of older C3-derived SOC by protection in microaggregates, retention of C associated with silt + clay, and largely accumulation of new C3-derived SOC in macroaggregate fractions. C3 plants seemed to have consistently contributed more C to the silt + clay fraction (<53 μm) than C4 plants at all soil depths, particularly in the lower depths, in all sites. Sites where the silvopasture was older, this impact of trees on SOC was greater. The results show that, in the long term, silvopasture may help sequester more SOC and stabilize C in the soil.

Collectively, the results suggest that increases in SOC have occurred primarily due to higher organic matter inputs and slower turnover of the organic matter, possibly due to the poorer quality of pine litter relative to herbaceous grassland litter. Protection of organic matter within microaggregates and by finer soil fractions also seems to be an important mechanism contributing to the significant increases in soil C in the silvopasture system as compared to the open pasture lands.

Critical information on several key issues, however, is needed to make valid conclusions. For example, the increase in total SOC pools following tree integration into pasture is attributed to possible retention of older C₃-derived SOC by protection in microaggregates, retention of C associated with silt + clay, and accumulation of new C₃-derived SOC in macroaggregate fractions. These hypotheses need to be investigated in detail. Further investigations are also needed on the nature of contribution from the deep rooting systems. Indeed, the rooting pattern of slash pine and development of its root system with age of trees have not been reported – which means that the rate at which slash pine trees of different age groups accumulate or help sequester soil C is also unknown. Rigorous data are also needed on the net primary productivity in both silvopasture and open pasture. Further, isolation of microaggregates from macroaggregates and silt+clay fractions from the microaggregates is required. Determination of microbial activity in the different fractions is important to understand and explain mechanisms SOC stabilization and dynamics in silvopasture systems. The use of ¹⁴C and bomb C models in future studies could be relevant to ‘date’ soil fractions and to distinguish newly incorporated C derived from the tree component in the silvopasture from old residual C retained from “primary forest,” and to reduce uncertainties in turnover rates.

It is recognized that, being a pioneering study of this nature on silvopastoral systems, the data presented here may not be of highest level of scientific rigor. For example, the dissimilar site history of the plots and uneven stand characteristics could have impacted the results. Nevertheless, as a first approximation and best possible effort under the given conditions, it represents an important contribution, and these results have promising implications in the context of Kyoto Protocol. The potential of silvopasture as a strategy for C sequestration is clear. Silvopasture systems can sequester rapidly and stabilize C in the soil systems in the long term. Besides, the techniques used in the study (SOC fractionation coupled with the use of stable C isotopes) provided a powerful means with which to elucidate the pathways of C transformations and stabilizations. Overall, this study enhances the understanding of the effects of tree integration into land uses (livestock production) and land cover changes (grassland-to-tree-based land conversion) on mechanisms of soil C sequestration in grasslands. Since agroforestry systems where trees are combined in non-forest land and land-use conversions are occurring rather extensively in many parts of the world, the processes and mechanisms of soil C storage and dynamics documented here could have significance in understanding the global C cycles and the earth's climate.

Expectations might be raised on how these results could be used and “extrapolated” to answer the larger question of the role of agroforestry systems in general, and silvopasture in particular, in global C sequestration and greenhouse gas mitigation. Given the preliminary and incomplete nature of the data, any such effort will be largely speculative. Furthermore, lack of authentic data on the extent of area under agroforestry systems – mainly because of the lack of approved methods to express the areas under such integrated systems – is a major problem in extrapolating agroforestry research results on a global or even regional scale. Although these

larger and global issues are beyond the scope of this dissertation study, the author hopes that this study will be useful to the research community who will take on the challenge of addressing these important issues.

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BIOGRAPHICAL SKETCH

Solomon Ghebremussie Haile was born in a small town called Adi-Quala located in Southern Eritrea, North-East Africa. Solomon received his B.Sc. in Forestry from the University of Alemaya, Alemaya, Ethiopia on August 28, 1993. He worked for a year as a research officer at Research Department of Ministry of Agriculture and another year as graduate assistant at University of Asmara in Eritrea. In August 1995, Solomon was awarded a scholarship at Wageningen University and Research Center, Wageningen, the Netherlands, where he received his M.Sc. in Tropical Forestry on January 30, 1997. Solomon was appointed as a lecturer at Department of Plant Sciences, University of Asmara, Eritrea. He taught forestry and agroforestry courses for five years. In spring 2002, Solomon joined the school of Forest Resource and Conservation at University of Florida for his PhD study in agroforestry program under Dr. P.K.R. Nair as his major advisor.