# SPATIAL VARIABILITY AND LAND USE CHANGE: EFFECTS ON TOTAL SOIL CARBON CONTENTS IN THE COASTAL PLAIN OF GEORGIA

By

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(Under the Direction of Daniel Markewitz and Lindsay Boring)

## ABSTRACT

The spatial dependencies of soil carbon in relation to land use and soil type under longleaf pine (*Pinus palustris*) ecosystems in the Coastal Plain of Georgia were compared and soil carbon contents were predicted across the landscape. The effects of varying land use and soil types on carbon concentration and contents were investigated. Land use was found to be a more adequate predictor of soil C than soil type. Comparisons were made between land cover and soil type versus ordinary kriging from field samples to estimate soil C concentrations and contents. Samples were stratified according to land cover or soil great groups and mean values assigned to polygons. For comparison, point C estimates were used to predict C concentrations across the landscape. Black carbon (BC) contents were determined and compared across fire suppressed and regularly burned longleaf pine-wiregrass stands. BC contents were greatest in areas that have regular burn prescriptions.

INDEX WORDS: Geostatistics, Forest, Longleaf Pine, Krige, Land Use Change, Black Carbon Ordinary Kriging, Soot, Prescribed Fire, Georgia

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B.S., Georgia College & State University, 2008

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2010

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December 2010

# ACKNOWLEDGEMENTS

I would like to extend many thanks to my major advisors, Daniel Markewitz and Lindsay Boring, for their constant encouragement and guidance throughout my time at UGA; without their help this thesis would not have been possible.  I would also like to thank both Jeff Hepinstall-Cymerman and Larry West on my advisory committee for their help and input throughout the thesis process.

I would also like to thank the Joseph W. Jones Ecological Research Center and The Robert W. Woodruff Foundation for their financial support with this project.  I appreciate the assistance of the staff at the Jones Center as well; many thanks to Scott Taylor, Mary Cobb, Roger Winans, Jean Brock and Liz Cox for lending me their help and their time.  The efforts of John Holeman and the extensive field sampling he did of the soils for the long-term monitoring plots at the Jones Center are also greatly appreciated.  In addition, I would like to acknowledge Luke Worsham for giving me his knowledge and suggestions throughout my research.  I also appreciate the laboratory assistance of Patrick Bussell.  Special thanks to my fellow lab mates Raina Sheridan and Aaron Joslin; even though they were not around in the beginning, their assistance and input is greatly appreciated.  To Tiffany Williams, my roommate for the past two years, thank you for listening even when you had no idea what scientific jargon I was talking about.  And last but not least, thanks to my family and friends for all of their support throughout this process.

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# CHAPTER 1

# INTRODUCTION

Land use plays a critical role in shaping the biological and chemical processes within terrestrial environments. Land use and technological changes since the industrial revolution have contributed to massive alterations of terrestrial environments including a release of carbon from fossil fuels, and from forest soils and vegetation; this release has led to a 36% increase in concentrations of atmospheric $CO_2$ (Malhi et al. 2002; Buttler 2006). Given this large C release and atmospheric $CO_2$ increase as well as growing concerns about global climate change, there is increasing interest in sequestering C back into forest soils and vegetation during forest re-growth and management, which provides a biological sink for atmospheric $CO_2$ (Brown et al. 1996). Therefore, forming a better understanding between forest management and land use practices with carbon sequestration is required.

Within the global carbon budget soil organic carbon (SOC) plays a critical role as it contains more C than the atmosphere and aboveground terrestrial biosphere combined (Batjes 1996). Estimating the soil stocks of carbon across the landscape or changes in the stock with changing land use or land cover, however, has been difficult (Mishra et al. 2009). Some of the difficulties in quantifying soil C stem from inadequate classification of soil properties most often due to observations made at inadequate spatial scales. In the USA, regional soil data usually exist and the accuracy to the soil series level at 1:24000 is adequate at this scale to estimate soil C (Drohan et al. 2003). At finer scales, collecting soil samples at locations of interest can lead to more precise estimates of soil characteristics, but this approach is costly. Alternatively, geostatistical approaches such as kriging, a geostatistical process used to create continuous surfaces based on the statistical properties of collected point data, can be used to predict data at unknown locations (ESRI White paper 2001, Isaaks and Srivastava 1989, and ESRI 2001). Kriging will produce a prediction map from the interpolated values of measured data to estimate values for the variable at locations where data were not collected. These maps are useful in demonstrating the variability of SOC across the landscapes as well as showing the potential capacity for various parts of the landscape to store additional carbon.

Effects of changing land use and land cover on C storage in different soil types has also been difficult to quantify. Agricultural history, reforestation, prescribed fire, fire suppression and forest removal can all have great influence on soil C concentration (Richter and Markewitz 2001). The southeastern USA provides an interesting study of the effects of land use and land cover change on soil. Even prior to European settlement, Native Americans managed the land in the southeastern USA with fire impacting forest composition and soil. After European settlement vast tracts of southeastern USA forests, particularly longleaf pine ecosystems, were cut and converted to agriculture. Of the 45 million hectares of longleaf pine originally present in the southeast, approximately 1.5 million hectares remain today. However, many of these remaining longleaf pine areas are being managed to restore fire regimes and forest composition (Ware et al. 1993).

Prescribed fire is an integral process in the maintenance of a healthy longleaf pine forest. Fire regulates nutrient controls on productivity, forest floor and groundcover nutrient pools, as well as nutrient availability (Boring et al. 2004, Hendricks et al. 2002 and Wilson et al. 2002). Longleaf pine seeds also require bare mineral soil to germinate, thus low intensity fires every 2-5 years are required to maintain regeneration of the forest. These systems evolved with frequent fires due to natural ignition by lightning and prescribed fire by native Americans (Engstrom et al. 2001) Today fires are largely anthropogenic due to the highly fragmented state of the landscape caused by changes in land use (Goolsby, 2005). Fire, in pine grasslands, also aids in the control of hardwood species, reduces accumulated fuels, increases productivity of native plants and animals, and helps to maintain the longleaf pine overstory (Varner, III et al. 2005). During burning, there is also the possibility for an input of black carbon, or charcoal remains to the soil. Total C content beneath longleaf pine-wiregrass stands are greater than total soil C content beneath old agricultural fields and planted pine stands on old fields (Markewitz et al. 2002). In this system, black carbon (BC) may play a novel role in increasing soil C and potentially ecosystem C contents despite the short-term losses of aboveground biomass C during burning (Schmidt et al.2001).

This thesis focuses on soil carbon in the Coastal Plain landscape of the Southeast US with a particular interest in how fire management in longleaf pine ecosystems influences black carbon in soil. The specific area of study is the 12,000 hectare Joseph W. Jones Ecological Research Center in Baker County, GA. Chapter II of this thesis reviews existing literature and concentrates on land use legacies and how they affect soil C contents. In Chapter III of this thesis, the effects of land use and land cover on soil C is discussed. Kriging, a geostatistical method for mapping, is used to predict soil C contents across the landscape. In addition, land use/land cover and soil type will be discussed as meaningful attributes for predicting soil C concentration and contents. In Chapter IV I determined the effects of prescribed fire on total and black carbon contents within the fire maintained longleaf pine ecosystem. Quantifying black carbon content in soils is of particular interest as prescribed fire is an integral part of the longleaf pine ecosystem. In Chapter V, I briefly discuss the overall importance of this thesis relative to our understanding of soil C, particularly in lowlands of the southeast USA, as well as in regards to the management of longleaf pine ecosystems in this region.

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# CHAPTER II

# LITERATURE REVIEW

## Land Use Legacies

The longleaf pine (*Pinus palustrus*) ecosystem covered as much as 45 million hectares of the Southeast USA prior to European settlement. After settlement, however, much of this region was cleared for farming and was utilized heavily by the turpentine industry until the late 1940s; trees continue to be harvested for timber and removed for economic purposes today. Also, much of the forest conversion was via hardwood succession that resulted from fire suppression. Most longleaf pine remaining on private lands is the result of forest conservation management practices aimed at preserving bobwhite quail (*Colinus virginianus*) habitat (Landers et al. 1995). Longleaf regeneration is of interest, not only because it provides valuable habitat for both game and endangered species, but also has the capacity to store C. In particular, carbon stored in plant biomass and soils of forested ecosystems can provide a long-term sink for atmospheric $CO_2$ (Schlesinger 1997). Reforestation with longleaf pine may increase terrestrial C accumulation both above and belowground. Five aspects of land use and forest management within longleaf ecosystems are of particular interest: 1) agricultural history, 2) reforestation, 3) hardwood removal for restoration, 4) fire suppression and 5) prescribed fire. Below I briefly highlight important aspects of each component.

### *Agricultural History*

Humans have been cultivating the land for food crops for more than 10,000 years. In the coastal plains of the southeast USA, including Georgia, soils were depleted of their carbon rich A horizons during the late 1800s due to extensive and repeated cotton cropping. With the advent of center pivot irrigation systems in the 1960s and increasing soil disturbing activities (i.e. agriculture and tillage) came another contributor to depletion of soil organic matter.

Technological advancements in agriculture have made it increasingly economical to cultivate large tracts of formerly marginal land. This agricultural industrialization has depleted the global terrestrial soil carbon pool by 55 Pg over the last 200 years (Amundson 2001). On average, surface soil C contents tend to decrease by 50% with forest conversion to agriculture (Davidson and Ackerman 1993). The loss of C from soils to the atmosphere is a reversible process, however, but requires the replacement of tilled agricultural fields with no-till agricultural practices or with revegetation using grasses and/or woody plant species which aid in the accumulation of soil organic matter (SOM) (McLauchlan et al. 2006, Post and Kwon 2000).

In the specific case of conversion of the longleaf pine ecosystems in the southeast, the agricultural and forest history are two contributing influences upon the C content of soils with much of the landscape presently under planted longleaf pine stands, old field longleaf pine stands and agricultural fields. It has been estimated that as much as 15.5 Mg ha$^{-1}$ of soil C may have been lost from native longleaf pine ecosystems upon conversion to cultivation (Markewitz et al. 2002). On the other hand, it has been shown that SOM does accumulate over time in the absence of cultivation, however, the rate of this process is highly variable (Post and Kwon 2000). In fact, Markewitz et al. (2002) found there to be no significant accumulation of soil C during the first 14 years of longleaf pine growth within planted pine stands (n=3) located on previous agricultural fields; this is not to suggest that this ecosystem does not have the potential to sequester large amounts of soil C, but only that soil C accumulation processes operate on a multi-decadal time-scale and may be highly influenced by the establishment of groundcover grasses and legumes (Conant et al. 2001; Richter and Markewitz, 2001; Markewitz et al 2002). There is little question that one legacy of agricultural development throughout the world and the southeast US has been a decline in stocks of surface soil carbon.

### *Reforestation and Restoration*

Along with the massive decline of longleaf pine-wiregrass systems and the landowner demand for quality wildlife habitat, there has come a need for reforestation and restoration efforts. Reforestation and restoration either through natural succession or the replanting of agricultural lands can lead to accumulation of soil organic C (Kwon and Post 2000). The process of C accumulation and sequestration during reforestation, however, occurs on decadal time-scales (Richter et al., 1994, Post and Kwon, 2000, Markewitz et al. 2002). Secondary forest development increases not only soil C contents but also the C contents in aboveground stores. Mean rates of accumulation in aboveground biomass range from 9.6 Mg $ha^{-1}yr^{-1}$ in recently abandoned sites to 5.7 Mg $ha^{-1}yr^{-1}$ in 50 year old secondary growth forests with accumulation rates greatest in warmer latitudes (Hughes et al. 1999).

The rates of SOC accumulation under reforestation have also varied broadly and in some cases declines have been observed. For example, in a temperate forest converted to a red pine (*Pinus resinosa ait*) plantation, SOC was actually lost at the rate of -4.44 g $m^{-2}$ $y^{-1}$ in the first 42-88 years (Post and Kwon 2000).

In southeastern USA, planted pine ecosystems rates have typically been positive but small. For example, under a loblolly pine ecosystem on an old field, soil organic carbon (SOC) in 0 to 7.5 cm increased by 1.458 Mg ha$^{-1}$ over the first 35 yrs of forest growth (Richter et al. 1994). Working specifically in longleaf pine ecosystems planted on old agricultural fields no change was observed in the upper 0-10 cm over the first 14 years in the SOC, although changes in other soil attributes such as extractable $NO_3$ or bulk density had occurred (Markewitz et al. 2002). Observed land use transitions including pine plantings, forest succession and agricultural abandonment all have distinctive impacts on the pools of C across the landscape. The maintenance and restoration of fire as well as the open stand structure of pine ecosystems will also uniquely influence C pools and C quality. This study will explore the impact of longleaf pine reforestation and restoration on the sequestration of C as SOM.

### *Hardwood Removal*

Removal of successional hardwood trees and shrubs that colonize with fire exclusion is an important process in the restoration of longleaf pine ecosystems. In a fire managed system, hardwood species would be diminished in their dominance because of the frequent burning associated with the ecosystem. In longleaf pine ecosystems that have had limited fire management, encroaching hardwood basal area can be removed to reduce their negative influence upon wildlife habitat and to restore dominance of open structure pine-wiregrass savannas. Knowledge of the effects of hardwood removal on soil C is currently limited but is vital to understanding the net balance of this treatment on net carbon sequestration. Although the hardwood boles will be cut, piled and burned, accumulated leaf litter, humus, coarse woody fuels and fine woody fuels are left aboveground and large root systems are left belowground.

Belowground, the massive root systems associated with hardwoods remain available for decomposition beneath the soil. In the upper 10 cm of soil, Mou et al. (1995) found 4.4 ± 3.1 Mg $ha^{-1}$ of coarse root biomass with a loblolly pine stand that could decompose. It is unclear, however, if increased breakdown of taproots or large lateral roots (10-100 mm diameter) will contribute to the long-term soil C pool (Fahey et al. 1988). In contrast, it is clear that turnover of root litter is important to soil C (Norby and Jackson 2000). Within the longleaf-wiregrass system, mass loss of roots due to decomposition for both fine (< 2mm) and coarse roots was relatively similar, with approximately 27% lost within one year (Jansen 2007). In the case of forest harvest, (which may be an analog for hardwood removal) impacts on soil carbon have been idiosyncratic. Covington (1981) suggested that forest floor organic matter (soil organic carbon) declines by 50% within 20 years post harvest with decreases in forest floor matter being attributed to increases in decomposition rates and decreases in litter inputs as the forest re-established itself. Others suggest that increases in decomposition following harvest may be a function of harvesting practices(e.g., whole tree harvesting versus top tree harvest) and initial site conditions (e.g., harvest of second growth forests start with less forest floor mass than harvest of old growth forests due to previous forest floor removal or disturbance during past harvest) (Yanai et al. 2003).

Roots play an important role in soil C dynamics. What is unknown is how removal of the aboveground components of hardwood trees during longleaf pine ecosystem restoration and the subsequent input of dead taproots, large lateral roots and all other smaller roots will affect soil C. This study will compare the content of soil C in areas containing successional hardwoods with areas where hardwoods have been removed.

### *Prescribed Fire and Fire Suppression*

Prescribed fire is an integral management tool for the maintenance of a healthy longleaf pine forest. Fire regulates nutrient controls on productivity, forest floor and groundcover nutrient pools, as well as nutrient availability (Boring et al. 2004, Hendricks et al 2002, Wilson et al, 2002). Longleaf pine seeds require bare mineral soil to germinate, thus low intensity fires every 2-5 years are required to maintain the health of the system; today these fires are largely anthropogenic due to the highly fragmented state of the landscape (Goolsby, 2005) and fire suppression. Fire also aids in the control of hardwood species, reduces accumulated fuels, increases productivity of native plants and animals, and helps to maintain the longleaf pine overstory (Varner, III et al. 2005).

The longleaf pine ecosystem is known to have decreased dramatically in extent with the absence of fire. Fire suppression allows for the invasion of hardwood species, thus the succession of longleaf pine woodlands to mixed hardwood forests (Monk, 1968). With fire exclusion, the overstory pine savanna rapidly converts to a closed canopy forest and the understory quickly decreases in cover and richness; leaf litter decomposition is reduced, light penetration is scant, and grasses, forbs and seedlings are scarce (Varner, III et al. 2005). Forest floor litter and duff accumulation lead to an increased risk of hazardous, high intensity wildfires; these fires will often be accompanied by increased smoldering, smoke and overstory mortality (Wade and Lunsford 1988, Varner, III et al. 2005).

Fire exclusion can increase the amount of C storage in forests by eliminating the C lost during combustion of aboveground biomass (Houghton et al. 2000). In addition, in the absence of fire, C will accumulate in forest litter; a number of studies have demonstrated a loss of forest floor carbon with fire in longleaf pine ecosystems (Binkley et al., 1992; Boring et al., 2004). The effect of fire on soil carbon has been more variable with both increases and decreases being reported across a range of systems (Johnson 1992; Boerner et al 2009). A meta-analysis of 48 observations found a mean of zero change in surface soil carbon with both prescribed and wild fire (Johnson and Curtis, 2001).

In longleaf pine forests, although, studies have shown that prescribed fire removes a substantial amount of aboveground biomass (90%), generally from pine litter, shrubs and grasses, these fine fuel components can then re-grow rapidly with accumulations of biomass ranging from 300-1200 g $m^{-2}$ within 1 to 3 years after burning (Boring et al. 2004). These aboveground pools of fine fuels also are not typical long lived carbon fractions but will decompose over time even without fire. Only a small fraction of these will be incorporated into soil organic matter as recalcitrant material. For example, after only three years of litter bag collections, slash pine and longleaf pine needles had 2.51 and 27.2% of biomass remaining while blackberry had just 3.9% litter biomass remaining (Hendricks et al. 2002).

Under conditions of a relatively short-term carbon equilibrium between fine fuel loses during fire and re-growth shortly after, it is actually possible that during burning there is an input of black carbon or charcoal that can accumulate in the soil (see below). Black carbon may play a novel role in increasing soil C and potentially ecosystem C contents despite the short-term losses of aboveground biomass C during burning. Black carbon remaining after a burn will be only a small portion of the combustion loss of litter and ground cover but could prove significant over multiple burns (Boring et al. 2004). DeLuca and colleagues (2008) estimate that black carbon or charcoal may account for 15-20% of the total C in temperate, coniferous forests soils. Black carbon may also play a role in nutrient cycling by leading to increased microbial nitrification by inhibiting those factors combating microbial activity (DeLuca et al 2006).

## Black Carbon

Black carbon (BC) is defined as the material produced by the incomplete combustion of fossil fuels and vegetation (Schmidt and Noack 2000). This material is also referred to as soot, charcoal or graphite and is often classified based on particle size. BC can be associated with vegetative wild fires, controlled burns, increased industrialization, motor vehicle emissions and is transported to marine sediments through fluvial avenues. Given the ubiquitous nature of BC and its potential role in the global C budget, research on the subject is becoming more prevalent. It is even thought that BC could account for a portion of the “missing sink” in the global carbon cycle (Forbes et al. 2006, Schmidt and Noack 2000). BC is highly recalcitrant and cannot easily combine with oxygen to form $CO_2$; Forbes et al. (2006) hypothesize that this recalcitrant characteristic leads to the strong potential for the formation of BC to remove C from the atmospheric cycle to the geological C cycle.

BC can be formed in one of two ways; soot BC forms when small molecules are released during combustion and then come back together to form soot particulates (Schmidt and Noack 2000). Char BC forms in high heat conditions during the flaming and smoldering phase of combustion; at this stage, “oxygen combines with carbon that builds up on solid surfaces” (Schmidt and Noack 2000). Fuel loading has a large impact on the amount of BC produced during a fire. With increased deforestation, increased agriculture intensity and coal combustion within the last 100 years, the amount of BC produced annually has increased. Globally, it is estimated that 50-270 Tg year$^{-1}$ of BC is being produced; of this total 80-90% is estimated to remain locked in terrestrial systems (Simpson and Hatcher 2004).

Black carbon is often found in soils as microscopic or macroscopic charcoal particles (Schmidt and Noack 2000). As BC is a remnant of previous fire events, it is common to find charred fragments at depths greater than 1 meter due to belowground root and stump burning. Rain events also act to both wash BC from the air and the soil surface. These BC particles eventually make their way into large rivers, such as the Mississippi where they are transported to ocean sediments. Mitra et al. (2002) suggested that the BC transported by the Mississippi River accounts for 5% of all the BC that is buried annually in the ocean.

It has been reported that BC may represent as much as 30-45% of the total soil organic C pool; however, a standard BC quantification method does not exist therefore quantification is quite variable (Simpson and Hatcher 2004, Schmidt and Noack 2000). Forbes (2006) published a Global Carbon Cycling schematic where he estimates that 40-241 Tg.yr$^{-1}$ or ~30% of the BC is retained in terrestrial soils. There have been some findings suggesting that BC may be mineralized by “severe oxidative” mechanisms; studies of wildfire in the boreal region suggest that charcoal particles can act as “foci for microbial activity” (Schmidt and Noack 2000). Most views are in agreement, however, that BC is accumulating in soils and terrestrial sediments as it is not being mobilized to other pools at high rates (Schmidt and Noack 2000).

Black carbon (BC) in soils is important to the global carbon cycle as it is highly recalcitrant and will remain in the soils for long periods of time. BC is often in higher quantities in areas associated with regular agricultural burning. Today some of the soils with increased BC quantities can be found in Australian grasslands and forests, areas of tropical deforestation in the Amazon, Boreal forests, Savanna and subtropical grasslands in Africa and Mediterranean forests in Spain (Forbes et al. 2006). All these areas contain BC in the forms of char and soot and are mostly associated with forest and pasture/grassland burning or forest clearing. BC does decay in our natural environment, however, at substantially lower rates than organic materials. There is a strong need for a standard method for quantifying BC and continued assessment of the BC pools and fluxes. Further exploration of the behavior of BC in soils is needed in order to more adequately predict BC patterns, characteristics and behaviors in terrestrial soils, particularly in fire dominated ecosystems like longleaf pines.

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# CHAPTER III

# SPATIAL APPROACHES TO ESTIMATE SOIL CARBON WITHIN A LONGLEAF PINE DOMINATED LANDSCAPE

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[1] J. Claire Ike, Lindsay Boring, and Daniel Markewitz. To be submitted to the *Soil Science Society of America Journal*.

## Abstract

Increasing atmospheric concentrations of $CO_2$ and recent global interest in C cap-and-trade systems have led to increasing interest in sequestering C in forest soils. Affects of land use and land cover on soil C, however, remain poorly quantified as do means for estimating soil C across landscapes. This work compares variation in soil carbon with land cover or soil great group. In addition, the use of land cover or soil great group delineations versus kriging to estimate soil C concentrations and contents is compared across 12,000 hectares of a highly variable landscape that is actively managed for longleaf pine (*Pinus palustrus*). Soil samples were collected from 731 permanent plots from depths of 0-5, 5-20, and 20-50 cm. Samples were stratified according to land cover or soil great groups and mean values were assigned to polygons. For comparison, point C estimates were used to predict C concentrations across the landscape for all three depths. Soil C concentrations were lowest in land covers previously cleared for agriculture and highest in land covers that are perennially wet. Wet soil great groups (i.e., Paleaqults) also had higher soil C concentrations. Soil carbon contents followed similar trends although they were affected by low bulk densities under wet land covers. Kriged C concentrations and contents also reflected land cover and soil variance, and demonstrated greater spatial structure in soil C at depth than at the surface. Although the land cover, soil, and kriged maps share similarities the approaches differ in representing variance across the landscape. Estimates of total C contents were 580 Gt for the paint-by-numbers approach to mapping and 680 Gt for the kriged surface.

## Introduction

Land use plays a critical role in shaping the biological and chemical processes within terrestrial environments. Land use and technological changes since the industrial revolution have contributed to massive alterations of terrestrial environments including a release of carbon from fossil fuels, and from forest soils and vegetation. This release has led to a 36% increase in concentrations of atmospheric $CO_2$ (Malhi et al. 2002; Buttler, 2006). Given atmospheric $CO_2$ increase as well as growing concerns about global climate change, there is increasing interest in sequestering C back into forest soils and vegetation during forest re-growth and management (Brown et al. 1996). Therefore, there is a need for better understanding of how forest management and land use types influence carbon sequestration in forest soils.

The southeastern USA provides an interesting study of the effects of land use and land cover change on soil. Even prior to European settlement, Native Americans managed the land in the southeastern USA with fire impacting forest composition and soil. After European settlement vast tracts of southeastern USA coastal plain forests, particularly longleaf pine ecosystems, were cut and converted to agriculture. Of the 45 million hectares of longleaf pine originally present in the coastal plain region, approximately 1.5 million hectares remain today. Many of these acres are being managed to restore fire regimes and forest composition (Ware et al. 1993).

Presently, the southern Coastal Plain is a mosaic of agriculture lands, wetlands, longleaf pine (*Pinus palustris*) stands actively managed with prescribed fire, reforested agricultural lands (typically with *Pinus taeda* or *Pinus elliotti* but some longleaf), and mixed hardwood-pine forests that have experienced fire suppression. Some of these woodlands are being restored to longleaf ecosystems through hardwood removal and reintroduction of fire, especially on lands being managed for wildlife. Differences in C content between differing land use/land cover (LULC) types and practices have been investigated generally (Post and Kwon, 2000; Guo and Gifford, 2002) and in longleaf ecosystems (Markewitz et al 2002). In both cases, surface soils in agricultural fields tend to have less carbon than reforesting or forested landscapes (up to 50% less).

In addition to LULC, soil attributes such as clay content (Hassink, 1994) or moisture content (Craft and Chaing, 2002) can affect soil C contents. This is particularly relevant in the Coastal Plain of the southeast were marine parent materials might be derived from almost pure sand and where low lying areas might be regularly inundated. Kandiudult (2839 ha) and Paleudult (2828 ha) soil types dominate the landscape at Ichauway, while Quartzipsamment (518 ha) soils are found along river corridors and alluvial sand hills. In addition to soil type, LULC and land cover can have great effects on soil C storage. Longleaf pine (5470 ha) is the dominant land cover at Ichauway, with agricultural areas, wetlands, and mixed-pine hardwood stands also being scattered throughout the property.

Previous mapping and quantification of C across landscapes at multiple scales has made use of the relationships between soil C concentration (% C) and contents (kg-C $ha^{-1}$) with LULC and soil type (Rodriguez-Murillo, 2001). In some cases this approach has simply multiplied hectares of a particular LULC or soil type by its average soil C content and summed over the landscape; an approach referred to as "paint-by-numbers" (Schimel, 1995). Many other geostatistical interpolation techniques have also developed that are based on spatial autocorrelation such as kriging (Webster and Oliver, 2001). In a geostatistical analysis of soil carbon in a low lying area of north Florida both LULC and soil type were shown to vary with soil C content (Vasques et al., 2010). Vasques' study also indicated that these coastal landscapes can store large quantities of soil carbon with a mean concentration of 62 Mg ha$^{-1}$ in the upper 0-30 cm. Similar estimates of soil carbon content in these landscape remain relatively limited.

## Objectives

As natural longleaf pine (*Pinus palustris*) was once a significant land cover in the southern coastal plain region and requires prescribed fire to maintain health and regenerate, understanding net carbon content and the influence of management practices is important to provide a context for potential soil carbon changes with changing LULC. The main objective of this study is to quantify and map total soil carbon contents in a landscape dominated by longleaf pine. It is assumed that LULC and land cover heavily influence soil carbon and can therefore be used as predictors of soil carbon contents. It is hypothesized that total soil C content beneath long leaf pine – wiregrass stands will be greater than C content beneath old field, planted pine stands due to previous loss of C during clearing and agricultural practices. Similarly soil C contents in mixed oak – pine or hardwood dominant sites that lack regular fire will have greater soil C contents than sites that have been exposed to recent anthropogenic disturbance. Finally, as agricultural disturbance leads to a decrease in soil C, sites located within agricultural areas will have minimal C content as compared with sites devoid of an organic rich Ap horizon. In addition to LULC, soil type will also be a meaningful predictor of soil C content. Stands present on soils with moderately well-drained to extremely well-drained classifications will have the lowest soil C contents. In contrast, oak depressions and depressional wetlands will sequester the most C as they will retain more water and receive much of the char and ash runoff from the surrounding upland forests during prescribed fires.

Another objective of this project is to compare the “paint-by-numbers” approach for landscape soil carbon content estimation to ordinary kriging soil C contents for soils in this area.

## Materials and Methods

### *Study Location*

The Jones Ecological Research Center (JERC) at Ichauway in Baker County, Georgia covers 12,000 hectares consisting of mature longleaf pine/wiregrass woodlands, undisturbed riparian zones and wetlands, young pine plantations, old abandoned agricultural fields and active agricultural fields (Figure 3.2 A). The climate is characterized by long, hot summers and short, cool winters (Lynch et al. 1986). Mean annual temperature is 20°C and mean annual precipitation averages 131 cm (Goebel et al. 2001). The promotion of game bird habitat has defined the land management regime at Ichauway since 1929 with prescribed fire being frequently used to maintain longleaf pine–wiregrass woodlands and to prevent hardwood encroachment (Boring et al. 2001). Intense hardwood removal has also taken place throughout the majority of the property as it is currently practiced as a longleaf restoration approach.

The site has a diversity of soils (Figure 3.2 B) including Ultisols (Kandiudults, Paleudults, Paleaquults), Inceptisols (Dystrudepts), and Entisols (Psamments) (Goebel et al. 200). Ultisols are the dominant soil order present in the southeastern United States; they are highly leached forest soils with increased presence of Fe oxides (McDaniel P, 2010). Inceptisols and Entisols are lacking increased Fe Oxides. Their color is grayer and they are both found in steep topographical regions (NRCS, 2010). Initial classifications of soils within the study area were based on NRCS data. Following an internal soil survey, soils of Ichauway were reclassified. A great deal of ecological information including geology, soil type, stand type, and land use history is also available for Ichauway as geospatial data layers. The existing data layers are available for Ichauway use only and are used for the LULC analysis along with a recently completed soil survey (Goebel et al. unpublished 1998 and Holeman unpublished 2008).

### *Plot Selection and Collection*

A soil classification survey of Ichauway was completed in the summer of 2008 in which 894 long-term monitoring (LTM) plots were established using a systematically, random, tessellated design within the property boundary (Stephens and Olsen 2004); 731 of these plots contain data and are used for this study. Soil profiles were described morphologically in the field but no chemical analyses were completed. At each plot location, sub-samples were collected at 0º, 135º, and 225º azimuths, radiating approximately 9 meters from the plot center. Distances were adjusted to avoid excessive disturbances such as roads, fire breaks, stump holes, or trees. In some cases, a sub-sample leg was omitted, and two or more sub-samples were collected along one of the remaining azimuth rays. Known C contents collected from 731 permanent plots across the landscape were used to predict soil C contents at unmeasured locations. All land cover and land use types present within the study area are represented by the permanent plots (Table 3.1).

Samples were collected using a JMS Back saver handle probe, with a 38 cm high and 1.9 cm diameter core. At each of the three sample locations, sub-samples were collected for 0-5, 5-20, and 20-50 cm, soil depth classes. Each depth sample was a composite of three sampling locations within each LTM plot. The samples were then bagged and labeled using Nasco Whirl-pak sterile sample bags. Non-decomposed litter, suspended above or on the mineral soil surface at the point of sample collection, was removed prior to mineral soil sample collection. In rare cases, the probe would not penetrate dry, heavier, or compacted soil profiles. At these locations, sub-samples were acquired utilizing a 8.9 cm soil auger.

Bulk density samples were taken as part of a secondary study at Ichauway for Kandiudult, Paleudult and Quartzipsamment soils in LULC of the following categories: agriculture, longleaf pine- wiregrass stands, fire suppressed (upland pine hardwood stands) and hardwood removal plots (upland pine hardwood stands) (Ike, unpublished 2010). Bulk density measurements by other authors for LULC and soil type at Ichauway were also utilized. Markewitz et al. 2002, Craft et al. 1999, and Craft and Chaing 2002 published bulk density data from Ichauway. Additional bulk density numbers were also taken from the 1986 NRCS Web Soil Survey for Baker and Mitchell Counties; as C concentrations and contents only correspond to depths up to 50 cm, bulk density values associated with increased depths (e.g., 0-100 cm) were weighted based on depth of sampling.

### *Plot Classification*

Plots were classified based on 14 different LULC categories and three different soil types. The three soil great groups (Kandiudult, Quartzipsamment and Paleudult) comprise the dominant soil types at Ichauway. The 14 LULC categories were modified from the Ichauway Ecological Classification System Land Cover (ECS) and were field validated in 2010. The LULC types were chosen based on their dominance in the landscape and interest regarding their potential management effects on soil carbon sequestration.

### *Soil Analysis*

Each composite soil sample was oven-dried at 60°C and flattened using a wooden rolling pin to break up aggregates, separated from rocks and roots and then sieved using a 2mm mesh. Approximately 2 g of each composite sample was pulverized for three minutes using a SPEX 8000 ball mill grinder. A portion of each soil sample (~ 0.1 g) was weighed and combusted in a Flash EA 1112 Series CN soil analyzer to yield a soil C concentration value.

### *Data Analysis*

Means and variances of soil C concentration, bulk density, and soil carbon contents by LULC, soil type, and LULC x soil type were analyzed after log transformation to adjust for non-normality. Mean separation tests were analyzed as a two-way ANOVA using Duncan's multiple range tests for significant difference at $p<0.05$. Soil data was also georeferenced through a geospatial dataset marking soil sample centers. Soil samples collected at areas classified as urban, shrub/scrub, open water, road or hedgerow/edge were removed from analysis as soils were not collected at these points. This resulted in no soil data for approximately 200 points. Plots that were inundated at the time of sampling were also omitted as soil samples were not collected as standing water makes uniform sampling impractical. Ordinary Kriging was used and the Spherical, Gaussian and Exponential models were compared for a semi-variogram analysis. The best model was selected based on the root mean square error (RMSE), the overall mean standard error (MSE), and the root mean square standard error (RMSE SE). For all models the lag size varied between 95 and 150m and the total number of lags for all models was 10. For the "paint-by-numbers" approach the area of each LULC or soil great group was estimated based on the summation of the polygons in that LULC and soil type category. The average soil C contents by LCLU and soil type were then multiplied by the total area ($m^2$) of each class to yield C content (tons) for each category of interest (Campbell et al. 2006).

## Results

### *Carbon concentrations and contents*

Soil C concentration varied by land cover and soil great group with differences depending on soil depth (Table 3.2). In the 0-5 cm depth, soil carbon concentration for great groups varied from 1.0 to 2.5% and were significantly greater in Paleaqults and Hapludepts. For land cover, the Cypress/Tupelo land cover had the highest surface soil carbon (3.15%) while current agricultural fields had the lowest (1.3%). C concentrations in soil surface horizons within areas dominated by longleaf pine were not significantly different from those dominated by floodplain pine and hardwood species or upland pine and hardwood species. There were also no significant differences in surface soil C accumulation among forested wetlands and sites characterized by Cypress/Tupelo characteristics. Young longleaf pine plantations had similar soil C concentration values as fallow agricultural fields at this depth and there was no significant difference between the two.

In the 5-20 cm depth there was still substantial variation in soil C with land cover but soil great groups were relatively homogeneous. Soils at the wet end of the hydrologic gradient (i.e. Forested Wetland and Cypress/Tupelo) retained the most carbon at this depth but % C in other land cover classes only differed significantly for fallow agriculture, pine plantation, and upland hardwoods (Table 3.2).

In the 20-50 cm layer soil carbon varied from 0.25 to 0.90 % C but most samples were between 0.3 to 0.4 %. The forested wetland and cypress/tupelo land covers again had the highest concentration. There was no variation in soil C concentration by soil type at this depth with no significant differences among categories; Hapludepts (0.9%) and Paleaquults (1%) maintained the highest C concentrations while differences in % C of other soil types were minimal (Table 3.2).

Bulk density differed slightly among LULC and soil types for all depths. Bulk densities ranged from 0.46-1.50, 0.47-1.60, and 0.48-1.71 for depths 1, 2, and 3 respectively. Paleaquults were significantly different from other great groups at all depths. Hapludepts and Quartzipsamments remained statistically similar, however, proved to be different from all categories other than Paleaquults, which were statistically different from all soil types. Bulk density values for land cover types did vary considerably with many more statistical differences among LULC categories. For LULC Forested Wetland, Cypress/Tupelo and Pine Depression had the lowest bulk densities while Agriculture, Longleaf Pine, and Pine Plantations has the highest.

Soil carbon content varied by depth with the thickest 20 – 50 cm depth layer having the greatest C contents. The C contents in the 0-5 cm surface depth, however, were greater than soil C contents at 5 – 20 cm depth for both land cover and soil type. Differences among LULC and soil great groups were also apparent for soil C content. Mean C content for the pine depression land cover type was significantly lower than all other land cover types at all depths while mean C content for the Hapludept soil type was greater than all other soil types overall (Table 3.2).

### *Paint-by-Numbers Carbon Contents*

The "paint-by-numbers" approach to estimating soil carbon was used to estimate C content across the Ichauway landscape. Longleaf pine is the predominant land cover (5470 ha) and Kandiudults (3830 ha) the predominant great group. These classes also contain the majority of the soil C content for each category 322,775 or 303,971 tons-C for longleaf or Kandiudults, respectively. Over the entire study area, this approach returned a total of 580±2 Gt C by LULC and 570±0.09 Gt C by soil type for the entire study area (Table 3.4).

### *Semi-variogram Analysis*

Prior to prediction mapping, three variogram models were compared to determine the most adequate model for these data. The Spherical, Gaussian and Exponential models were compared. Results based on MSE and RMSE indicated that the Spherical model provided the best data fit as the overall RMSE was the smallest, the overall MSE was closest to zero, and the RMSE SE was closest to one (Table 3.3). For all models the lag size varied between 95 and 150m and the total number of lags for all models was 10. Lags sizes up to 8000m were possible but these added no additional information. The models were tested for anisotropy and drift but these were not found to improve the models.

As evident by the high nugget:sill ratio, the spatial structure proved to be weak for C concentration at depth one (0.85) , this is perhaps due to the high landscape and soil variance at the surface. A moderate amount of spatial dependence is present at the 5 – 20 (0.55) and 20 – 50 (0.44) cm depths for C concentration. C contents follows a similar pattern as C concentration, however, spatial structure increases two fold at each progressive depth. The major range for both C concentration and C contents is largest at the 5 – 20 cm depth; here, sample locations up to ~ 600 m are autocorrelated. For C concentration the major range is ~ 250 m for the surface depth as well as the 20 – 50 cm depth. Autocorrelation among soil C concentrations is greater overall than autocorrelation among soil C contents. C contents at the surface and the 5 – 20 cm depth are not highly autocorrelated, while the subsoil depth autocorrelation is more prevalent.

### *Kriged Prediction Mapping*

Ordinary kriging predicted surface soil C concentration to vary between 1.07 and 3.07%. The majority of the landscape was predicted to have between 2.16 and 3.06% carbon while values at the low and high end of the spectrum are more scant (Figure 3.3 A). At depth 5 – 20 cm, C ranged from nearly zero to 3.90 %. Variation across the landscape was much greater at this depth than at the 0 – 5 cm surface; a gradient of C from greater to smaller amounts was much more evident (Figure 3.3 B). C concentrations are greatest in lands with a wet moisture regime or along river corridors. C concentration variability is much less at depth 20 – 50 cm. Here, C is expected to range from 0.2 to 0.7% with the bulk of the landscape being dominated by C in the 0.4 – 0.5 % range (Figure 3.3 C).

Carbon content varied from ~6000 kg C/ha to ~20000 kg C/ha at the 0 – 5 cm depth with the majority of the landscape ranging between ~16000 – 20000 kg C/ha (Figure 3.4 A). Again, C is much more variable at depth 5 – 20 cm; here C ranges between 280 kg C/ha to 220000 kg C/ha. There does not seem to be any landscape variables influencing C at this depth (Figure 3.4 B). C content at depth 20 – 50 cm is significantly less than that of the previous depth. C contents here range from ~8600 kg C/ha to ~30000 kg C/ha with the majority of the landscape falling in the ~18000 kg C/ha to ~22000 kg C/ha range (Figure 3.4 C).

## Discussion

Results demonstrate significant differences for carbon concentrations and contents among land cover but only at the 0-5 cm layer for soil type. Conversion of forest land to agriculture use can deplete soil C stocks by up to 50% (Davidson and Ackerman, 1993; Lal, 2005). In contrast, conversion from agricultural use to forested land is known to increase soil C (Dixon et al. 1994, Lal 2005, Markewitz et al. 2002 and Schelsinger 2000). Our results are consistent with these preceptions as pine plantations, fallow agricultural lands, current agricultural lands and old field agricultural lands contain soil C stocks significantly lower than other LULC types (Table 3.2). The greater variation among land cover types compared to soil types, suggests that land cover maps may allow for better prediction of landscape soil C variance.

The lack of significant difference among soil types below the surface may be partly attributed to the depth of soil sampling. As soil classification is often based on subsoil features, differences in soil types within the first 50 cm may be a poor predictor of C contents. For example, the Kandiudult and Paleudult great groups are distinguished by charge characteristics in the argillic horizon (Soil Survey Staff, 1997). Although the upper portion of the argillic horizon was likely sampled in the 20-50 cm layer soil attributes in these layers could be very similar for these two soil great groups. Physical characters such as drainage class or surface soil textural class may be more appropriate predictors of soil C (Hassink, 1994 and Thompson and Kolka, 2005).

In general, soil C concentrations appear to increase based on the moisture gradient in soils. Soils following the Flint River and Ichawaynotchaway Creek, for example, are predicted to have greater C contents than those in sandier upland soils. The forested wetlands and Cypress/Tupelo swamps also have increased C concentrations and contents relative to other LULC categories while moisture rich soils such as Paleaquults and Hapludepts contain increased C stock (Table 3.2). Decreased root respiration and microbial decomposition due to frequent inundation has been previously demonstrated (Davidson and Janssens 2006). The opposite can be said for upland sites dominated by sandy soils; here soil C concentration and content remains low (Table 3.2).

The use of land cover or soil type to estimate landscape soil C contents using the paint-by-numbers approach resulted in relatively similar contents of ~575 Gt-C (Table 3.4). In both cases estimates were dominated by the areal coverage of the predominant category. In other words, despite high soil carbon contents in Cypress/Tupelo, for example, this land cover was a small portion of the Ichauway landscape. This differs from nearby results in the Santa Fe watershed of north Florida where wetlands and inundated portions of the landscape contributed significantly to landscape carbon contents (Vasques et al. 2010).

Estimates of C contents from kriged prediction (680 Gt) exceed that from paint-by-numbers (580 Gt). Kriged carbon content estimates also differed somewhat from the mean C contents based on the long-term monitoring (LTM) data, which decrease from depth 0 – 5 cm to depth 5 – 20 cm but then increase again at depth 20 – 50 cm; the opposite is true for the kriged predicted C contents. C contents at 5 – 20 cm depth are much more variable than C content at the other depths (Figures 3.3 A, B, C and 3.4 A, B, C), however, C concentration generally decreases with increased depth. The increase in C content at the 5 – 20 cm depth is a function of increased bulk density and total thickness (i.e.15 cm at depth 2 and 30 cm at depth 3). Sampling across generic horizons (0-5, 5-20 and 20-50 cm) may have contributed to the large variance at depth 5-20 cm; increased variance could be a result of proportions of the A horizon being sampled in the second depth. If this is the case, sampling by genetic horizons (A, E, B, C) may help reduce variance when estimating landscape C contents.

The variogram analysis indicated the major range for this landscape was high compared to some other published results with ranges <200 m (Worsham et al. 2010 and Kravchenko et al.

2006). Relative to these studies the greater range could be attributed to the increased size (i.e., scale) of the study area. Both Worsham (2010) and Kravchenko (2006) were dealing with 1 ha grid based study designs compared to Ichauway, which is comprised of 12,000 ha. Relative to studies at a larger scale the range was smaller. For example, working in a ~3500 km$^2$ watershed in north Florida Vasquez et al. (2010) found a major range of 5,000 – 11,000 m and Mishra et al., (2009) mapping the entire state of Indiana found a major range of 27 km. In the current study, the major range also varied with depth. At the 5 – 20 cm depth the major range for C concentration was nearly three-fold greater (~600 m) and that for C content was also greater although the reasons for this elevation are unknown.

Spatial dependence is not only a function of the range but also relies heavily on the spatial structure in the data as defined by the nugget:sill ratio. A nugget:sill ratio of one indicates no structure with values closer to zero being better. Regardless of the major range, spatial structure increased with depth for both C concentration and C content. These variogram models for soil C content with depth are novel and suggest that prediction at depth might be better than for that at the surface, at least within this coastal plain landscape.

## Conclusion

Different land use types and prior land use has a tremendous influece on soil C stocks; as data indicate, soil C in LULC types absent of agricultural legacies is nearly double that of lands that have been cleared previously. These relationships have been demonstrated previously and are well supported by this study. Furthermore, the role of soil inundation in increasing soil carbon contents was similarly supported by these data. In contrast, use of soil great group to estimate soil C concentrations or content in 50 cm of soil was not a strong predictor.

Characteristics such as moisture or clay content are known to effect soil C stocks and might be better used as variables for predicting soil C.

The use of ordinary kriging for predicting soil carbon concentrations and contents on the landscape level does yield useful information regarding soil C stocks. Patterns of soil C can be recognized, and in this case attributed back to LULC effects at the surface. The accuracy of this approach, however, remains ambiguous; even though kriged results yielded C contents 17% greater than the paint-by-numbers approach used, claiming that one approach is superior to the other is not presently possible.

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Table 3.1: Land use/land cover type and descriptions for the Jones Ecological Research Center at Ichauway in Baker Co. GA.

| Land Cover Type | Land Cover Description |
|---|---|
| Longleaf Pine | Longleaf Pine Wiregrass savanna |
| Pine Plantation | Planted Slash and Longleaf Pine, no Wiregrass |
| Agriculture | Current Agriculture |
| Fallow Agriculture | Agriculture that has been fallow < 3 years |
| Old Field Agriculture | Agriculture that has been fallow > 3 years |
| Forested Wetland | Depressions prone to inundation, dominated by Oaks and other Riparian Hardwoods |
| Nonforested Wetland | Wetland depressions dominated by grasses and shrubs |
| Pine Depression | Low-lying depressions associated mostly with Slash Pines |
| Cypress/Tupelo | Depression and sloughs dominated by Cypress and Tupelo |
| Upland Pine/Hardwood | Mixed Pine and Hardwood stands located in upland soils |
| Upland Hardwood | Successional Hardwood stands located in upland soils |
| Other Upland Pine | Loblolly, Slash and shortleaf Pine located on dry upland soils |
| Mesic and Floodplain Pine/HW | Moderately moist Hardwood and mixed Pine stands located on alluvial sandy soils |
| Mesic and Floodplain HW | Moderately moist Hardwood stands located on alluvial sandy soils |

Table: 3.2: Mean carbon concentration and mean carbon content for land cover and soil type. Samples were collected at the Jones Ecological Research Center at Ichauway in Baker Co. GA in 2007 and 2009.

| | Category | N | Mean C Concentration (%) | | | | | | Mean C Content (kg/ha) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Depth 1 | [1]IQR | Depth 2 | IQR | Depth 3 | IQR | Depth 1 | Depth 2 | Depth 3 |
| Land Cover | Longleaf Pine | 267 | 2.19 BC | 1.460 | 0.887 BC | 0.451 | 0.382 B | 0.174 | 15132 AB | 5071 AB | 17684 AB |
| | Pine Plantation | 51 | 1.51 CDE | 1.210 | 0.799 C | 0.470 | 0.385 B | 0.211 | 11346 BC | 4612 AB | 18003 A |
| | Agriculture | 24 | 1.29 E | 1.110 | 0.872 BC | 0.674 | 0.378B | 0.213 | 8898 CD | 4956 AB | 19395 A |
| | Fallow Agriculture | 24 | 1.38 DE | 1.560 | 0.741C | 0.436 | 0.386 B | 0.175 | 9479 CD | 4297 AB | 19779 AB |
| | Old Field Agriculture | 19 | 1.33E | 0.904 | 0.844 BC | 0.684 | 0.397 B | 0.228 | 9157 CD | 5019 AB | 20296 A |
| | Forested Wetland | 12 | 2.66 A | 6.070 | 1.311 A | 3.195 | 0.606 A | 1.114 | 6122 CD | 11907 B | 8721 BCD |
| | Nonforested Wetland | 41 | 2.03 BC | 1.740 | 0.891 AB | 0.764 | 0.357 B | 0.184 | 9241 CD | 4774 AB | 17788 AB |
| | Pine Depression | 11 | 2.41 B | 3.350 | 1.301 ABC | 1.089 | 0.462 B | 0.371 | 5552 D | 9011 B | 6648 D |
| | Cypress/Tupelo | 13 | 3.15 A | 3.204 | 1.367 ABC | 1.180 | 0.685 A | 0.202 | 7243 CD | 14054 B | 9871 CD |
| | Upland Pine/Hardwood | 39 | 2.10 BCDE | 1.230 | 0.895 BC | 0.275 | 0.374 B | 0.132 | 12270 A | 5016 AB | 16244 ABC |
| | Upland Hardwood | 46 | 2.05 BCDE | 1.120 | 0.697 C | 0.529 | 0.329 B | 0.163 | 11964 A | 3439 AB | 14292ABC |
| | Other Upland Pine | 46 | 2.11 BCD | 1.360 | 0.801 BC | 0.659 | 0.380 B | 0.298 | 11527 BC | 4571 AB | 19170 A |
| | Mesic and Floodplain Pine/HW | 41 | 2.20 BC | 1.220 | 0.885 BC | 0.391 | 0.354 B | 0.253 | 15428 AB | 4698 AB | 13803 ABC |
| | Mesic and Floodplain HW | 87 | 2.51 B | 1.490 | 0.767 BC | 0.701 | 0.365 B | 0.328 | 17579 A | 4198 AB | 14225 AB |
| Soil Type | Hapludepts | 60 | 2.46 AB | 1.579 | 0.915 A | 0.443 | 0.908 AB | 0.306 | 16480 A | 12456 A | 37040A |
| | Hapludults | 29 | 2.28 BC | 1.520 | 0.839 A | 0.418 | 0.396 B | 0.207 | 15628 AB | 4978A | 18164A |
| | Kandiudults | 242 | 1.97 CD | 1.378 | 0.839 A | 0.430 | 0.371 B | 0.139 | 14074 BC | 4677 A | 17161 A |
| | Kanhapludults | 35 | 1.10 CD | 1.162 | 0.884 A | 0.476 | 0.379 B | 0.172 | 13396 BC | 5028 A | 17285 A |
| | Paleaquults | 102 | 2.60 A | 2.470 | 1.097 A | 0.891 | 0.450 A | 0.376 | 12941 BC | 7398 A | 16593 A |
| | Paleudults | 204 | 1.98 CD | 1.290 | 0.845 A | 0.466 | 0.390 B | 0.179 | 13570 BC | 4940 A | 17773 A |
| | Quartzipsamments | 48 | 1.54 D | 1.580 | 0.541 A | 0.302 | 0.259 C | 0.199 | 10928 C | 2099 A | 11101 B |

[1] IQR = Interquartile range

*Letters indicate significant differences among categories based on Duncan’s Multiple Range test at P<0.0

Table 3.3: Paint-by-numbers estimation of soil C content (tons/ha) for both land cover type and soil great group type.

| Category | N | Area (ha) | C Content (tons/ha) | | | Total |
|---|---|---|---|---|---|---|
| | | | Depth 1 | Depth 2 | Depth 3 | |
| Longleaf Pine | 266 | 5470 | 96969 ±32 | 119410 ±39 | 106397 ±35 | 322775 ±106 |
| Pine Plantation | 51 | 634 | 8378 ±36 | 14007 ±67 | 12700 ±57 | 35084 ±160 |
| Agriculture | 24 | 69 | 678 ±7 | 1600 ±17 | 1530 ±16 | 3807 ±40 |
| Fallow Agriculture | 24 | 206 | 2672 ±77 | 3913 ±106 | 3773 ±97 | 10358 ±280 |
| Old Field Agriculture | 19 | 91 | 939 ±16 | 2069 ±37 | 2159 ±36 | 5166 ±89 |
| Forested Wetland | 12 | 50 | 516 ±11 | 788 ±16 | 697 ±14 | 2001 ±41 |
| Nonforested Wetland | 41 | 621 | 6296 ±30 | 19836 ±202 | 11435 ±51 | 37567 ±283 |
| Pine Depression | 11 | 82 | 508 ±11 | 826 ±19 | 609 ±14 | 1943 ±44 |
| Cypress/Tupelo | 13 | 62 | 547 ±8 | 743 ±11 | 726 ±10 | 2017 ±29 |
| Upland Pine/Hardwood | 39 | 277 | 5483 ±32 | 5622 ±29 | 4846 ±24 | 15951 ±85 |
| Upland Hardwood | 45 | 313 | 6326 ±32 | 5688 ±32 | 4993 ±28 | 17007 ±92 |
| Other Upland Pine | 46 | 553 | 7182 ±46 | 11053 ±73 | 12882 ±83 | 31117 ±202 |
| Mesic and Floodplain Pine/HW | 41 | 500 | 9361 ±95 | 12748 ±140 | 8829 ±82 | 30938 ±317 |
| Mesic and Floodplain HW | 87 | 1076 | 17784 ±60 | 25965 ±77 | 19216 ±50 | 62964 ±187 |
| **Total** | | | **163640 ±493** | **224266 ±865** | **190791 ±597** | **578696 ±1955** |
| Hapludepts | 60 | 953 | 9743 ±3 | 12320 ±7 | 9544 ±9 | 31607 ±19 |
| Hapludults | 29 | 454 | 11663 ±5 | 14176 ±7 | 12539 ±6 | 38379 ±18 |
| Kandiudults | 242 | 3830 | 92263 ±2 | 113524 ±3 | 98183 ±3 | 303971 ±8 |
| Kanhapludults | 35 | 599 | 5448 ±2 | 6272 ±5 | 5565 ±5 | 17285 ±12 |
| Paleaquults | 100 | 385 | 6884 ±6 | 9540 ±8 | 8700 ±7 | 25123 ±21 |
| Paleudults | 203 | 2828 | 28637 ±0.4 | 52662 ±0.6 | 56461 ±0.5 | 137761 ±3 |
| Quartzipsamments | 48 | 518 | 6374 ±3 | 6293 ±4.3 | 5553 ±4 | 18221 ±11 |
| **Total** | | | **161012 ±22** | **214789 ±35** | **196546 ±35** | **572346 ±92** |

Table 3.4: Input parameters and output statistics for kriged prediction maps. Ordinary kriging was applied and the spherical model was used to predict C concentrations and contents across the landscape.

| | Depth (cm) | Lag Size | Number of Lags | Neighbors | Neighbors to Include | Sector Type | Major Range | Nugget | RMSE | MSE | RMSE SE | Sill | Nugget:Sill Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carbon Concentration % | 0 - 5 | 95 | 10 | 15 | 10 | 4 with a 45° offset | 255 | 2.07 | 1.5000 | -0.0001 | 0.9477 | 2.445 | 0.85 |
| | 5 - 20 | 150 | 10 | 15 | 10 | 5 with a 45° offset | 620 | 1.47 | 1.5800 | 0.0019 | 0.9707 | 2.915 | 0.50 |
| | 20 - 50 | 100 | 10 | 15 | 10 | 4 with a 45° offset | 259 | 0.037 | 0.3080 | -0.0005 | 1.0530 | 0.084 | 0.44 |
| Carbon Concentration Kg/ha | 0 - 5 | 100 | 10 | 10 | 5 | 4 with a 45° offset | 501 | 7.48E+07 | 9163 | -0.0006 | 0.9477 | 86832665 | 0.86 |
| | 5 - 20 | 150 | 10 | 5 | 5 | 4 with a 45° offset | 609 | 5.37E+08 | 30800 | -0.0021 | 0.9707 | 1037096884 | 0.52 |
| | 20 - 50 | 100 | 10 | 15 | 5 | 4 with a 45° offset | 262 | 2.32E+07 | 12140 | 0.0148 | 1.0530 | 126694653 | 0.18 |

[1] RMSE=root mean square error

[2] MSE=mean square error

[3] RMSE SE=root mean square error standard error

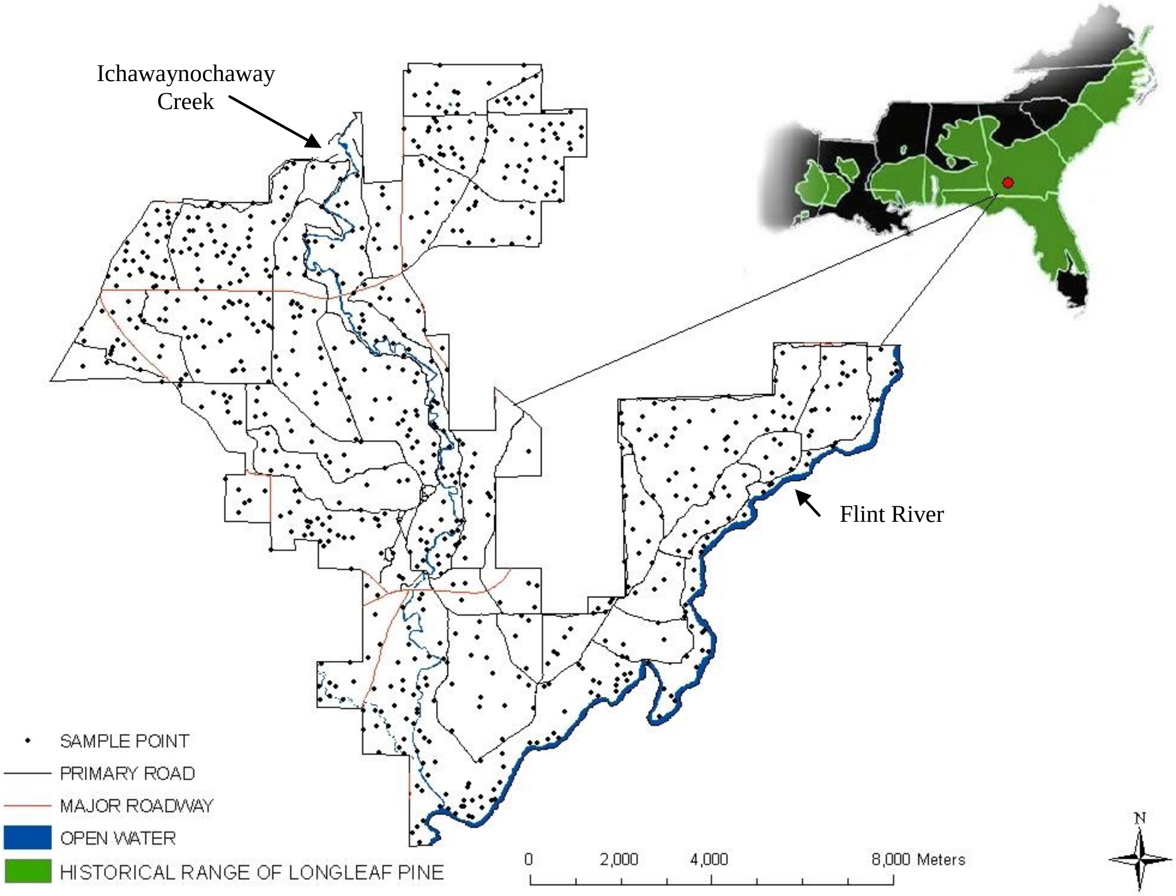

Figure 3.1: Study area and sample point location map. The study area is comprised of the Jones Ecological Research Center at Ichauway located in Baker Co. GA.

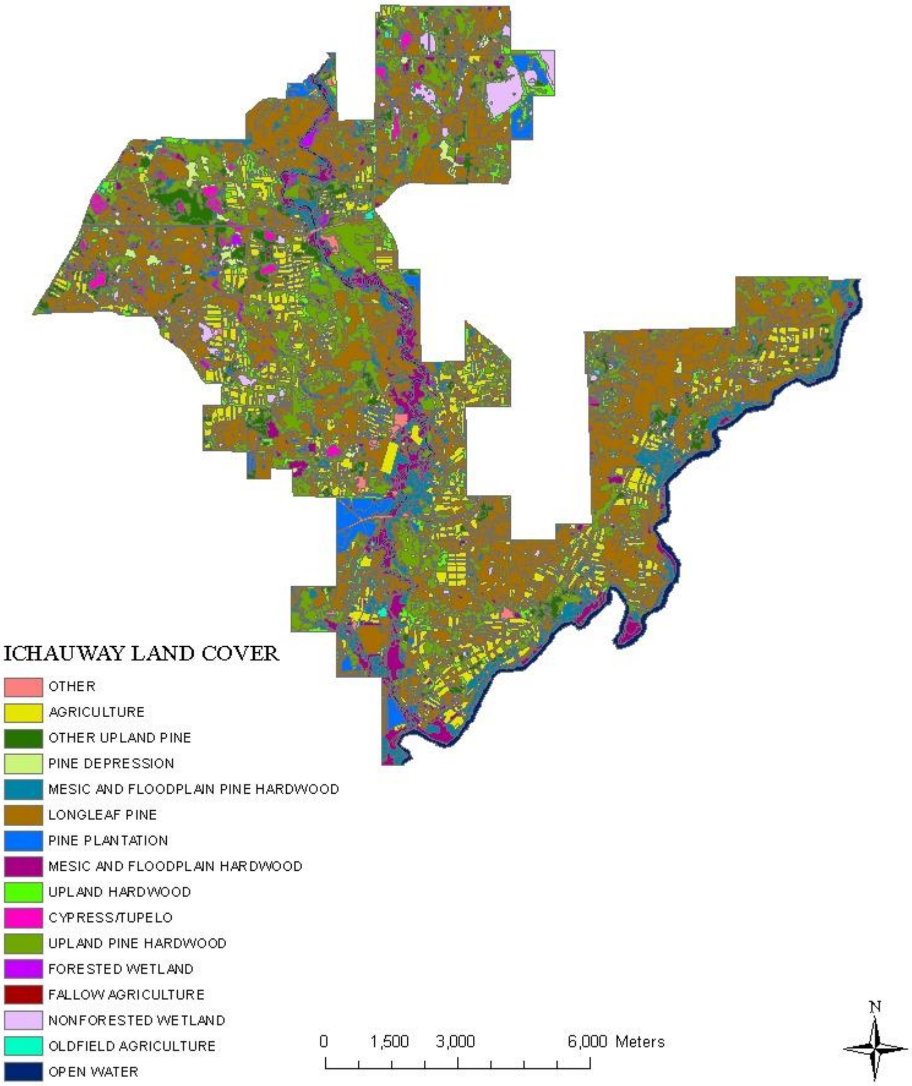

Figure 3.2 A: Land Cover map of The Jones Ecological Research Center. Data based on the 2010 land cover classification developed by The Jones Ecological Research Center.

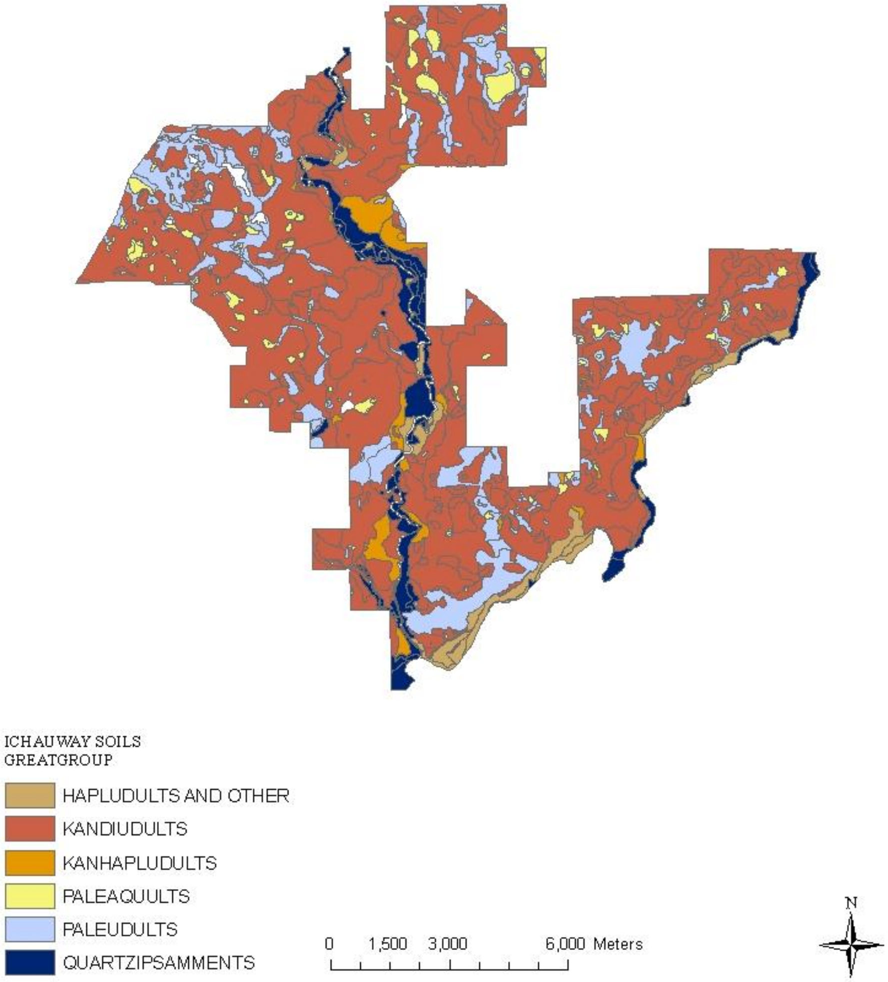

Figure 3.2 B: Soils map of the dominant soil types used; soil types based on great group soil classification. The study area is the Jones Ecological Research Center at Ichauway located in Baker Co. GA

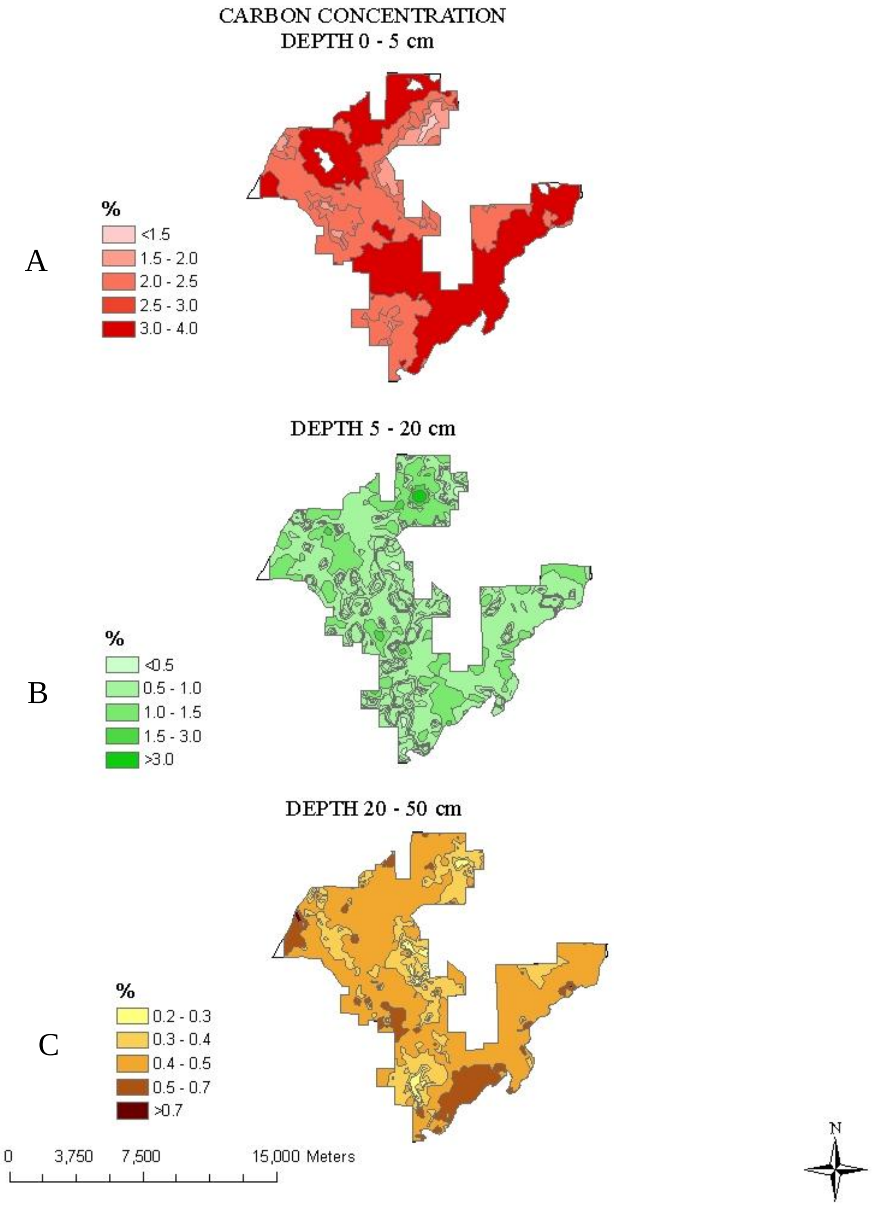

Figure 3.3: (A) Predicted soil carbon concentration % at depth 0 – 5 cm. (B) Predicted soil carbon concentration % at depth 5 – 20 cm. (C) Predicted soil carbon concentration % at depth 20 – 50 cm. Predicted values based on soil samples collected from long-term monitoring plots at The Jones Ecological Research Center at Ichauway in Baker Co. GA.

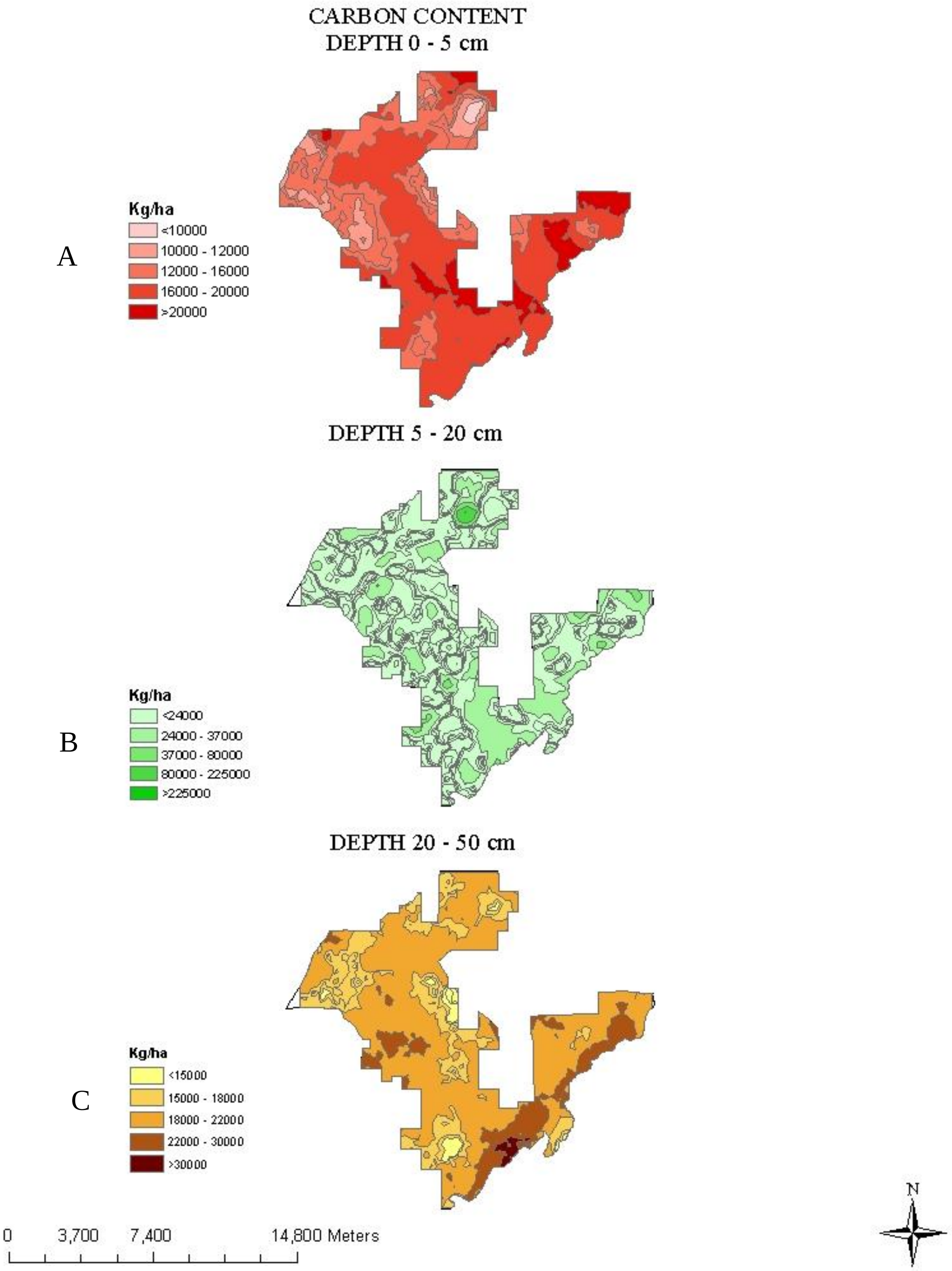

Figure 3.4: (A) Predicted soil carbon content in kg/ha at depth 0 – 5 cm. (B) Predicted soil carbon content in kg/ha at depth 5 – 20 cm. (C) Predicted soil carbon content in kg/ha at depth 20 – 50 cm. Predicted values based on soil samples collected from long-term monitoring plots at The Jones Ecological Research Center at Ichauway in Baker Co. GA.

# CHAPTER IV

# LAND USE AND PRESCRIBED FIRE EFFECTS ON BLACK CARBON CONTENTS IN A LONGLEAF PINE MANAGED ECOSYSTEM

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[1] J. Claire Ike, Lindsay Boring, and Daniel Markewitz. To be submitted to the *Soil Science Society of America Journal*.

## Abstract

The health and growth of the longleaf pine (*Pinus palustris*) ecosystem relies heavily upon the use of fire. Within this ecosystem fire derived black carbon (BC) may constitute a significant proportion (15-20%) of the soil organic carbon pool. BC is the charcoal, char, or soot residues from fire and is operationally defined in the laboratory by resistance to chemical or thermal digestion. BC is a sink for carbon dioxide and has the potential to sequester large amounts of $CO_2$ for thousands of years given its recalcitrant nature. Restoration of longleaf pine ecosystems includes not only the re-introduction of fire but also the removal of hardwood tree competition that may also contribute to the soil organic carbon (SOC) pool via the decay of coarse and fine roots. Here, we demonstrate the effects of longleaf pine management and restoration practices on total soil carbon contents relative to fire suppressed pine-hardwood stands and agricultural fields. Soil samples at three depths were stratified based on land management regime (reference longleaf pine-wiregrass, hardwood removal for restoration, fire suppression, and agriculture) and soil type (Kandiudult, Paleudult and Quartzipsamment). Total soil C contents were greatest in fire suppressed areas, mineral soil C contents were greatest in agricultural areas, and BC and soot C amounts were greatest in regularly burned longleaf pine-wiregrass stands.

## Introduction

The health and growth of the longleaf pine (*Pinus palustris*) ecosystem relies heavily upon the use of fire. As the longleaf pine forest is one of the most fire dependent ecosystems in North America, the use of prescribed burning as a management tool is crucial (Stober 2010). The use of fire reduces fuel loads, exposes the bare mineral soil necessary for longleaf pine regeneration, prevents hardwood encroachment and promotes diversity of wildlife and understory species (Gagnon and Jack 2004). Longleaf pine seeds require bare mineral soil to germinate, thus low intensity fires every 2-5 years are required to maintain regeneration of the forest. Historically, natural fire was able to move extensively across the landscape, but with increased landscape fragmentation and long periods of fire suppression, hardwood species were able to advance into the ecosystem. Restoration of longleaf pine that has had fire exclusion relies not only on the use of fire but also aggressive and repeated hardwood removal.

Removal of successional hardwood trees and shrubs that colonize with fire exclusion is an important process in the restoration of longleaf pine ecosystems. Hardwood removal by whole tree harvest (aboveground only) has been shown to decrease soil C in the A horizon by up to 6% (Johnson and Curtis 2000). Belowground processes associated with selective hardwood removal in pine forests are less evident; it is unclear if increased breakdown of taproots or large lateral roots (10-100 mm diameter) will contribute to the long-term C pool (Fahey et al. 1988). In contrast, it is apparent that turnover of root litter is important to soil C (Norby and Jackson 2000). Within the longleaf-wiregrass system, mass loss of roots due to decomposition for both fine (< 2mm) and coarse roots was relatively similar, with approximately 27% lost within one year's time (Jansen 2007). Prescott (1997) found rapid litter decomposition of lodgepole pine (*Pinus contorta loudon*) after clearcutting in comparison to old-growth hardwoods; however, effects on root decay were less clear. Nevertheless, organic C from dead, decaying tree root systems may contribute to the overall soil C pool as fine root decomposition is as much as 35% mass loss within the first 6 months after clearcut (Lytle and Cronan 1997).

As prescribed fire is used as a tool for longleaf pine management, its effects upon organic carbon in soils are of interest. In addition to the direct benefits of burning to longleaf pine, the use of prescribed fire also aids in the cycling of cations and phosphorus as well as the deposition of charcoal and/or soot particles into the soil (Christensen 1977; Forbes et al. 2006). Fire regulates nutrient controls on productivity, forest floor and groundcover nutrient pools, as well as nutrient availability (Boring et al. 2004, Hendricks et al 2002 and Wilson et al, 2002). In actively fire maintained grassland ecosystems, charcoal may account for 15-20% of the total C in the mineral soil (DeLuca and Aplet 2008). This is important as charcoal in soils may lead to increased microbial nitrification by inhibiting those factors combating microbial activity (DeLuca et al 2006). Increases in microbial activity may lead to decreases in soil organic matter especially in sandy soils. Also, prescribed fire and natural forest burning can add 1 – 4 Mg charcoal as C to soils; with repeated fire, this input could account for a substantial proportion of the total soil C pool in fire maintained ecosystems (DeLuca and Aplet 2008).

In the absence of fire and hardwood removal, the overstory pine savanna rapidly reverts to a closed canopy forest and the understory quickly decreases in cover and richness; leaf litter decomposition is reduced, light penetration is scant, and grasses, forbs and seedlings are scarce (Varner, III et al. 2005). Forest floor litter and duff accumulation lead to an increased risk of hazardous, high intensity wildfires; these fires will often be accompanied by amplified smoldering, smoke and overstory mortality (Wade and Lunsford 1988, Varner, III et al. 2005).

A more developed forest floor may lead to increases in mineral soil organic carbon, but this may only be demonstrated in the surface horizon.

The conversion of forested systems to agriculture also affects the soil C pool. On average, surface soil C contents tend to decrease by 50% with forest conversion to agriculture (Davidson and Ackerman 1993). In the specific case of conversion of the longleaf pine ecosystems in the southeast, the agricultural and forest history are two contributing influences upon the C content of soils with much of the landscape presently under planted longleaf pine stands, old field longleaf pine stands and agricultural field sites. It has been estimated that as much as 15.5 kg $ha^{-1}$ of soil C may have been lost from native longleaf pine ecosystem upon cultivation (Markewitz et al. 2002).

A clearer understanding of soil impacts in relation to longleaf pine management regimes, specifically hardwood removal and prescribed fire, will lead to a greater understanding of land use and forest management effects on soil organic carbon, black carbon and belowground processes associated with harvesting. The quantification and variance among soil charcoal and soot C among varying forest management regimes and soil types will lead to a better understanding of soil C sequestration in fire maintained ecosystems.

## Objectives

The main objective of this study is to determine the effects of varying land use and land management regimes, more specifically prescribed fire and hardwood removal, on total soil C contents across a longleaf pine dominated landscape. Soil organic carbon (SOC) contents from samples collected under reference longleaf pine stands that are prescribe burned every two to three years are compared to longleaf pine stands recently restored with hardwood removal and fire, hardwood stands that have not been burned for >10 years, and actively tilled and cropped agricultural fields. It is presumed that prescribed fire effects soil C contents through the removal of organic C from the surface but also by the incorporation of black carbon in the soil profile. As such it is hypothesized that total soil C contents will be greatest in areas that have been fire suppressed while total BC and soot C contents will be greatest in reference longleaf pine-wiregrass stands. Furthermore, agriculturally dominated sites will contain the least amount of soil C, BC and soot C. In stands with hardwood removal it is also hypothesized that fine root decay will not contribute to soil carbon contents within the first year as most of this C will be lost via $CO_2$ efflux. The decay of coarse roots, however, especially below the surface horizon, will decay at slow rates such that in stands that have been devoid of hardwood species upwards of 5 years, it is expected C content will increase.

## Materials and Methods

### *Study Location and Sampling*

Samples for this study were collected during the fall of 2009 from the Jones Ecological Research Center at Ichauway in Baker County, Georgia. The 12,000 ha property is dominated by managed longleaf pine (4760 ha) with a smaller proportion of unmanaged mixed pine-hardwood stands (2878 ha). There are also some agricultural fields on the property (1370 ha) with a range of other minor land cover/land uses. Soils at the Jones Center have formed in marine sediments and are largely comprised of Ultisols (9963 ha), Entisols (730 ha) and Inceptisols (304 ha). The sample space spans the entire area of the property, and plots were selected from areas with four management legacies: 1) mixed pine-hardwood stands under fire suppression; 2) longleaf pine reference sites with prescribed fire on a two year burn interval; 3) restored mixed pine-hardwood stands treated with hardwood removal followed by burning and; 4) crop fields following grain harvest (Table 4.1 and Figure 4.2). Sites were also chosen based on soil great group and consist of Kandiudult, Quartzipsamment or Paleudult soil types.

Fire suppressed plots used in this study have been under fire suppression for at least 10 years and are dominated by overstory longleaf pine (*Pinus palustrus*) and successional hardwood species in both the understory and overstory. These sites are often on bluffs adjacent to riparian zones, roads and firebreaks, or property boundaries (Figure 1). Grouped with suppressed sites are reference plots characterized by frequently burned longleaf pine and also formerly suppressed sites where hardwood removal and restoration operations were conducted. Most often these plots were located adjacent to the fire suppressed sites, but avoiding locations where large slash piles were burned. Plots were grouped based primarily on soil type. Soils were identified by great group for all plots and grouped accordingly.

Approximately 141 potential sample plots were identified and a subset of 90 plots was randomly selected for sampling. Each sample plot consists of a 10 m radial plot with a 3 m radial plot nested within the larger plot. Overstory vegetation was recorded using a prism at BAF level 10 while ground cover, understory, coarse woody debris, seedlings, liter and a soil composite were recorded within the nested 3 m radial plot. Within each 3 m plot composite soil samples were collected at depths of 0 - 5, 5 – 20 and 20 – 50 cm using a slide hammer soil probe at plot center, and 1.5 and 3 m from center. A subset of 40 of the 90 sample plots distributed by land use and soil type was selected for bulk density sampling; samples were collected with a 7.5 cm deep by 7.5 cm diameter corer at 0 -7.5, 10 – 17.5 and 30 – 37.5 cm depths. Two bulk density samples were collected at the surface and composited while one sample was collected at the other depths; sampled were collected using a bulk density corer.

### *Analytical Procedures*

Each composite soil sample was air-dried and lightly crushed using a wooden rolling pin to break up aggregates, separated from rocks and roots and then sieved using a 2mm mesh. Approximately 2 g of each composite sample was pulverized for 3 minutes using a SPEX 8000 ball mill grinder. A portion of each soil sample (~0.1 g) was weighed and combusted in a CE Elantech EA 1110 CNS analyzer. All bulk density samples were oven dried at 105°C to a constant weight before using dry weights to calculate bulk density. There are few rocks in the landscape but if present weight and volume of rocks was removed prior to estimate of bulk density (Blake 1965)

As there is no existing standard reference material for black carbon, we used an internal standard for quality control purposes. Pine chip char (0.25 g) made at the University of Georgia Bioconversion facility at 500°C in the absence of oxygen was mixed with sterilized sand (24.75 g) and pulverized using a SPEX 8000 ball mill grinder. This standard was then used for quality control purposes for black carbon and soot analysis. Environmental Resource Associates (ERA, Arvada, CO) soil nutrients were also ground and used as a quality control standard for total soil organic matter.

Presently there is no standard method for quantification of black carbon. There are a number of methods in the literature; Kurth et al. (2006), from which our method is adopted, specifically estimated charcoal in forest soils. Samples were analyzed for black carbon using a low temperature peroxide-nitric acid digest. All surface samples were analyzed as was a subset of 40 samples distributed by land use and soil type at 5 – 20 and 20 – 50 cm depths. In the method 1.0 g sample of dry soil was weighed into a digestion tube and 20 ml of 30% $H_2O_2$ and 10 ml of 1 M $HNO_3$ were added. The tubes were swirled using an oscillating shaker and placed into a digestion block. Samples were slowly heated to 50 ºC where the temperature remained constant for 8 hours. The temperature was then slowly ramped up to 100º C for 16 hours. Samples were filtered through Whatman #2 filter paper and then dried overnight in a 70º drying oven. Dry samples were removed from the filter paper and homogenized using a mortar and pestle then weighed and analyzed for total carbon by dry combustion. The total C remaining after digestion and combustion is considered black carbon.

Soil samples were also analyzed for soot by chemo-thermal-analysis at 375º C (i.e., CTO-375) following the methods of Nguyen et al. (2003). Though there is no standard method for soot quantification, CTO – 375 is well known and commonly used in soot quantification. All surface samples were analyzed along with the same subset of 40 samples at 5 – 20 and 20 – 50 cm. A 1.0 g sample of dry soil was weighed into Ag capsules for solid combustion (5 X 9 mm, Costech Analytical Technologies reference no. 041067). Sample capsules were left open and were placed into steel sample trays that had been fabricated to hold 20 capsules; sample trays were then placed into a pre-heated muffle furnace (Thermolyne Tabletop F30430CM) at 350ºC. The temperature was then ramped up to 375º C where it remained for 24 hours. Samples were removed from the furnace, allowed to cool and then subjected to 0.75 ml of 1 N HCl. Acid treatment is designed to remove carbonates. After acid addition and reaction, samples were dried in a 70ºC drying oven overnight and prepared for dry combustion analysis by simply folding Ag capsules. The total C remaining after CTO – 375 is considered soot carbon.

### *Data Analysis*

A two-way ANOVA was performed on soil C concentration, soil C contents and soil bulk density for each depth separately. The ANOVA was conducted using land use, soil type and land use by soil type. Mean separation tests were analyzed as a two-way ANOVA using Duncan's multiple range tests for significant difference at $p < 0.05$.

## Results

### *Carbon Concentrations and Contents*

Bulk soil C, soot C and black carbon (BC) data for all soil samples were used, along with bulk density data, to calculate C content for the four land uses and three soil types of interest (Table 4.2 A). Significant differences were found among land management and soil great group when analyzed for bulk carbon concentration; however, data indicate no significant interaction for land management by soil type (Table 4.3). These results are the same for black carbon, soot and bulk density. Bulk C concentration at the 0 – 5 cm depth was greatest in areas that have been fire suppressed (2.6%); soil C based on soil type differed statistically at this depth with Quartzipsamment soils being significantly lower than the others. Bulk soil C contents were also greatest in fire suppressed areas (~15000 kg/ha) and contents in Paleudult soils tended to be higher than other soil types (~13000 kg/ha). At depth 5 – 20 cm bulk C concentration was greatest in agricultural areas (1.3%). Paleudult and Kandiudult soils contained the most C at this depth as well. Like % C, C contents at depth 5 – 20 cm was greatest at agricultural sites as well as on soils designated as Kandiudults. Results are similar at depth 20 – 50 cm; again, agricultural areas have the highest C concentration and C contents and Kandiudult soil C concentrations and C contents were greatest among soil types.

At depth 0 – 5 cm, soot C concentration and C content was most prevalent in areas of hardwood removal (0.009% and 56 kg/ha). Paleudult soils retained the most soot C at this depth (0.012%). Even though agricultural areas dominated the soot concentration and content at depth

5 – 20 cm (0.006% and 146 kg/ha), differences among land management types was not present; differences among soil types were also not detected. At depth 20 – 50 cm, reference longleaf pine-wiregrass sites contained the most soot C concentration and contents (0.008% and 351 kg/ha); Paleudult soils contained the most soot at this depth (0.007 % and 316 kg/ha).

At depth 0 - 5 cm, black carbon (BC) concentrations were greatest in fire suppressed areas (0.13%); BC contents however, are greatest in reference longleaf pine-wiregrass sites (850 kg/ha). For soils, Quartzipsamment soils had the most BC concentration and contents (0.12% and 758 kg/ha). Like soot, agricultural sites contained the most BC at depths of 5 -20 cm (0.12%). Kandiudult soils retained the most BC (0.083%) at this depth but statistically there was no significant difference in BC concentration or content by soil type. At depth 20 – 50 cm reference longleaf pine-wiregrass sites had the greatest BC concentration and content (0.11% and ~5200 kg/ha). Interestingly, the Paleudult soil category had the greatest BC concentration and content at the 20 – 50 cm depth (0.09% and ~4400 kg/ha).

### *Bulk Density*

At depth 0 – 5 cm, mean bulk density (BD) was greatest in reference longleaf pine-wiregrass stands (1.38 g/cm$^3$); BD contents at this depth, however, do not differ statistically from hardwood removal sites or fire suppressed plots (Table 4.2 A). BD based on soil type varies only among Quartzipsamment soils, as they are statistically greater than the Paleudult and Kandiudult types. Depth two (5 – 20 cm) is slightly less variable than at the surface. Again, mean BD at sites with agricultural history differ from fire suppressed and reference longleaf pine-wiregrass sites, but show no variation from hardwood removal sites. Soils at this depth show statistical difference among Kandiudults and Quartzipsamments only. At depth 20 – 50 cm, mean BD at fire suppressed and hardwood removal sites are similar with fire suppressed sites being statistically different from reference longleaf pine-wiregrass and agriculturally dominated sites. Soils at this depth are relatively homogenized and show no variation based on BD.

### *Surface litter and Coarse Woody Debris*

Surface litter contained substantial C and was greatest in the fire suppressed sites (27206 kg/ha) and lowest in the agricultural fields (1364 kg/ha) (Table 4.3). Longleaf reference and hardwood removal sites were intermediate to these sites but did not differ from each other. There were no differences in surface litter C content by soil type. CWD contained a relatively small amount (1-2 kg/ha) of C and did not differ by land use or soil type.

## Discussion

### *Mineral Soil Bulk C*

Increased levels of mineral soil organic carbon (bulk carbon) found in fire suppressed sites are likely a function of increased incorporation of surface organic matter (Tilman et al. 2000). Nutrient rich duff layers have been accumulating on these sites with some found to be ~10 cm thick (Ike, unpublished 2010). Opposed to this natural method of C incorporation, elevated levels of bulk C content in agricultural sites below the first 5 cm are likely due to mechanical incorporation. In agricultural sites, organic C deposition on the surface after recent harvest followed by mechanical incorporation by plowing of the three horizons enriched the two deeper depths (Angers and Eriksen-Hamel 2008). Of the nine agriculture plots sampled, seven of them showed signs of recent harvest; crop residues were indicative of brown-top millet and sunflower, while winter rye had just been planted. Bulk density also reflects the increased organic matter content in agricultural sites. Dao (1998) found a correlation between increased crop residue and decreases in bulk density in the 0 – 5 cm layer. Increased plant residue leads to greater organic C and therefore higher aggregation, porosity, sorptivity and lower bulk density (Shaver et al. 2002).

Although fire suppression did lead to increased C contents, this increase was only apparent within the first 5 cm where humified organic matter at the surface is incorporated by macro- and micro-invertebrates into the mineral soil. Working in grassland ecosystems Tilman et al. (2000) found the opposite to be true. Tilman et al, (2000) found belowground carbon (0-20 cm) to be lower in fire suppressed sites than in those with high fire frequency; although they did conclude that sites experiencing increased fire frequencies are sequestering less organic C overall than those that remain fire suppressed.

### *Soot and Black Carbon*

Black C quantification is difficult and highly variable among methodologies. One of the major problems in quantifying BC is that it is not a single substance; BC varies based on degree of char, size, material (grasses, wood fragments, pine needles, etc) and fire temperature (Hammes et al. 2007). Soot and char (BC) chemistry also differ. Sharma et al. (2004) found that char from woody biomass retains plant chemistry and morphology, while soot C reflects more of a combustion signature with no plant or fuel aspects. The differences in black carbon chemistry, paired with the lack of well developed standard reference material, make quantification methods for soils and sediments comparisons quite difficult.

Chemo-thermal oxidation with a pre or post treatment using HCl, $HNO_3$ or NaOH are the most common methods for determining BC in soils (Hammes et al. 2007, Nguyen et al. 2004).

Using this method, the charring of non-BC fractions is minimized, however, there is potential for oxidation of BC depending on kinetics and the possible creation of BC due to charring if oxygen transfer is not properly controlled (Nguyen et al. 2004). The peroxide-weak nitric acid digest approach to determining BC in soils is also widely used (Kurth et al. 2006). For low intensity burn charcoal fragments, this method is especially useful as it combines weak acid and peroxide and is therefore less likely to consume low temperature generated charcoal fragments (Kurth et al. 2006). Our internal pine chip char standard contained 0.84% char-C. Using the CTO-375 method with HCl treatment yielded 0.021 % soot for the sample or on average 2.5% of the biochar was recovered as soot. With the peroxide method, we measured 0.66 % BC or a recovery of 79% of our internal pine chip char standard reference material as BC.

Soot C (0.88%) and BC (13%) contributed approximately 14% to the total C stock in the study area. There was greater variation among land management regimes than among soil great groups, therefore suggesting that land management practices have significant and lasting effects on BC and soot storage in soils. Reference longleaf pine-wiregrass stands have been burned historically at Ichauway on two year burn intervals; a fraction of the charcoal that remains on the surface after burning is incorporated into the mineral soil where it remains indefinitely (Schmidt and Noack 2000, DeLuca and Aplet 2008). Our results are consistent with this model as BC contents were greatest for sites that are subjected to prescribed fire (reference longleaf-wiregrass stands) (Figure 4.1).

Not all charcoal produced ends up incorporated into the soil; erosion by wind or rain can result in charcoal removal from the original surface (Schmidt and Noack 2000). Once transported, charcoal and soot particles can make their way to low-lying depressions or be scattered over neighboring sites via atmospheric fallout and soil erosion (Accardi-dey and Gschwend 2002 and Mitra et al. 2002).

Increased soot C contents in agriculturally dominated sites may be attributed to wind transport. Agricultural fields are open areas with no canopy cover; soot particles being carried through the air could easily make their way to the soil surface and become incorporated via tillage. Others have also found BC to accumulate by as much as 30% (relative to total soil organic carbon) over time in cultivated soils (Czimczik and Masiello 2007). Particle size was not quantified in this study to confirm wind deposition, however, our results do indicate BC and soot accumulation in agriculturally dominated areas although total amounts are small compared to other land management practices (Table 4.2 C).

It is also possible that the elevated soot and BC accumulation in agricultural areas as well as fire suppressed sites is a function of the methods used in analysis. We assumed that all C remaining after BC and soot treatments was in fact BC and soot; however, this material might be recalcitrant or humified organic matter. Chemical methods for determining BC rely on removing labile organic matter components from the sample; Simpson and Hatcher (2004) suggest that not all organic matter is being removed and is therefore causing biased quantities of BC to be reported.

It is also possible that what we are referring to as BC and soot, could in fact be soot or BC that was formed during analysis. The pine chip char we used as a reference was burned at 500°C in anoxic conditions, while the BC and soot formed in the study area is the product of cool burning under aerobic conditions. The lower formation temperature of chars at Ichauway, may allow for more cellulose and lignin to be preserved in the material and therefore converted to BC or soot during chemical analysis (Hammes et al. 2007). Nuclear magnetic resonance

(NMR) spectroscopy is perhaps a more useful method in quantifying BC. NMR provides chemical structure information and can confirm the presence or absence of BC in a sample (Simpson and Hatcher 2004).

### *Total Carbon Contents*

The overall balance of carbon loss or accumulation from fire management is of interest relative to carbon sequestration. Although the above results indicate some accumulation of black carbon in fire managed longleaf pine ecosystems this seems to be out-weighed by a loss in surface organic matter (Figure 4.2). In fact, the fire suppressed sites that had the greatest surface organic matter accumulation also had the greatest total C contents. While fire suppression results in increased C accumulation, this approach to increase C stocks is not sustainable. Wildfires result from these conditions, with potential impacts decimating the forest and emitting increased amounts of C into the atmosphere (Hurteau et al. 2009). Weidinmyer and colleagues (2010) suggests that regular prescribed fire can lead to the reduction of $CO_2$ by 52-68%. Management of forest fuels with fire does decrease C stock associated with forest litter, however, over the long-term may be more appropriate for increasing C in soils.

One surprise was the relative large amounts of C in the agricultural soil systems. It is typically assumed that conversion of forest to agriculture reduces soil organic carbon (Davidson and Ackerman, 1993; Lal 2005). It is possible that our results were impacted by sampling soon after harvest. In contrast, it is possible that our deeper sampling captured a portion of soil carbon that is typically not measured in agricultural soil studies. A recent review of the literature on the impacts of no-till agriculture relative to conventional till agriculture argued that many studies on this topic have failed to adequately capture the dynamics of soil C change due to only sampling soils surficially (i.e., <30cm) (Baker, Ochsner et al. 2007). In fact, of 140 conventional till-no till studies identified by West and Post (2002) none sampled soil below 30 cm and in a second review by Franzluebbers (2005) of 96 such studies average sampling depth was only 19±5 cm. In either case, the current study reflects a potential for maintenance of soil C under agriculture. More importantly it suggests that fire management does reduce the stock of total soil C.

## Conclusion

Within this longleaf pine ecosystem, prescribed fire had important effects upon soil C stocks; as data indicate, BC and soot C are greatest in areas with regular burn prescriptions. In contrast, soil type, based on depths to 50 cm, has less of an effect on BC and soot C; although there is a clear trend in BC, Soot C and total C decreases with decreased soil moisture content as Quartzipsamment soils have less moisture content than Paleudult and Kandiudult soils. As expected, reference longleaf pine-wiregrass stands did house more BC than the other land management categories. Given the functional importance of prescribed fire for the health and maintenance of longleaf pine, as well as its chemical and thermal stability, BC inputs are significant for the system and should therefore be accounted for when estimating C stocks. These additions should remain in the system for long periods of time and should continue to build; however, more research is needed on this topic as BC storage based on a long timescale is not well studied.

The effect of hardwood removal on soil C contents was limited; total C for both reference longleaf pine-wiregrass stands and hardwood removal plots had no significant differences. The hypothesis that root decay in hardwood removal stands will lead to increased long-term carbon stocks is not supported. Sample depth may play a role, however, as decomposition in the upper 50 cm is much more rapid than at depth. Increased bulk carbon contents in the 5-20 and 20-50 cm depths of agricultural sites was a surprise and may be due to the recent incorporation of harvest residues from the surface via plowing.

Inputs of BC and soot to total soil carbon did comprise an important component of the bulk carbon found in the system. Offsetting the amount of C lost in the system through hardwood removal and prescribed fire, however, with BC and soot inputs is not realistic as bulk C is found to be six to eight times that of black carbon.

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Table 4.1: Land management descriptions for dominant land management types at the Jones Ecological Research Center in Baker Co., GA.

| Land Management Type | Land Cover Description |
|---|---|
| Hardwood removal | Sites that have had extensive hardwood removal (surface only) prior to 2004 and are dominated by longleaf pine ov |
| Fire Suppressed | Sites that have been under fire exclusion for a minimum of 10 years and are dominated by longleaf pine overstory |
| Reference longleaf pine-wiregrass | Frequently burned longleaf pine stands without history of soil disturbance |
| Agriculture | Sites under current agricultural management regimes( Winter Weat, Brown-top Millet, and Sunflower) with clear p |

Table 4.2 A: Mean total carbon concentration and contents for sample plots.  Samples were not subject to any black carbon or soot treatments prior to combustion.

| **Bulk C** | Category | N | Mean C Concentration (%) | | | | | | | | | Bulk Density ($g/cm^3$) | | | | | | Mean C Content (kg/ha) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Depth 1 | | IQR[1] | Depth 2 | | IQR | Depth 3 | | IQR | Depth 1 | | Depth 2 | | Depth 3 | | Depth 1 | Depth 2 | Depth 3 | ∑ |
| Land Management | Hardwood Removal | 27 | 1.220 | B | 0.639 | 0.731 | B | 0.285 | 0.349 | B | 0.133 | 1.27 | B | 1.45 | BA | 1.59 | BA | 9946 ± 1246 | 16493 ± 502 | 16550± 331 | 36389 |
| | Fire Suppression | 27 | 2.590 | A | 1.091 | 1.090 | B | 0.534 | 0.516 | AB | 0.458 | 1.17 | C | 1.45 | B | 1.45 | B | 15196 ± 1611 | 23937 ± 1150 | 22482 ± 624 | 61975 |
| | Reference Longleaf Pine-wiregrass | 27 | 1.700 | B | 0.750 | 0.887 | B | 0.446 | 0.508 | AB | 0.562 | 1.38 | CB | 1.44 | B | 1.54 | A | 11838 ± 1976 | 19231 ± 688 | 23682 ± 643 | 54751 |
| | Agriculture | 9 | 1.220 | C | 0.587 | 1.290 | A | 1.487 | 0.713 | A | 0.809 | 1.37 | A | 1.57 | A | 1.70 | A | 8282 ± 2970 | 31603 ± 4607 | 37044 ± 3070 | 76929 |
| Soil Type | Kandiudults | 36 | 1.983 | A | 1.597 | 1.138 | A | 0.613 | 0.588 | A | 0.427 | 1.31 | A | 1.51 | A | 1.63 | A | 12586 ± 1570 | 26277 ± 1318 | 28829 ± 832 | 67692 |
| | Paleudults | 27 | 1.982 | A | 0.672 | 0.918 | AB | 0.389 | 0.500 | AB | 0.517 | 1.31 | A | 1.49 | BA | 1.56 | A | 13294 ± 2204 | 20275 ± 423 | 22546 ± 542 | 56115 |
| | Quartzipsamments | 27 | 1.672 | B | 1.069 | 0.689 | B | 0.381 | 0.326 | B | 0.203 | 1.23 | B | 1.41 | B | 1.23 | A | 9961 ± 1143 | 1477 ± 589 | 13850 ± 428 | 25288 |

[1] IQR=Interquartile Range

*Letters indicate significant differences among categories based on Duncan’s Multiple Range test at P<0.05

Table 4.2 B: Mean soot carbon concentration and contents for sample plots. Samples were subjected to a CTO-375 treatment prior to combustion. Refer to Table 4.2 A for bulk density data used.

| **Soot C** | Category | | Mean Soot C Concentration (%) | | | | | | Mean Soot C Content (kg/ha) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Depth 1 | IQR[1] | Depth 2 | IQR | Depth 3 | IQR | Depth 1 | Depth 2 | Depth 3 |
| Land Management | Hardwood Removal | 27 | 0.009 AB | 0.003 | 0.004 A | 0.003 | 0.003 B | 0.003 | 56 ± 4 | 100 ± 3 | 134 ± 4 |
| | Fire Suppression | 27 | 0.007 B | 0.004 | 0.003 A | 0.002 | 0.004 B | 0.002 | 42 ± 4 | 63 ± 30 | 155 ± 4 |
| | Reference Longleaf Pine-wiregrass | 27 | 0.006 AB | 0.004 | 0.004 A | 0.001 | 0.008 B | 0.007 | 45 ± 9 | 86 ± 5 | 351 ± 3 |
| | Agriculture | 9 | 0.005 A | 0.000 | 0.006 A | 0.002 | 0.007 A | 0.002 | 35 ± 4 | 146 ± 12 | 175 ± 7 |
| Soil Type | Kandiudults | 36 | 0.007 A | 0.003 | 0.005 A | 0.003 | 0.004 A | 0.003 | 34 ± 6 | 108 ± 5 | 185 ± 5 |
| | Paleudults | 27 | 0.006 B | 0.002 | 0.004 A | 0.002 | 0.003 AB | 0.005 | 77 ± 5 | 79 ± 2 | 316 ± 4 |
| | Quartzipsamments | 27 | 0.006 B | 0.003 | 0.004 A | 0.003 | 0.002 B | 0.003 | 32 ± 3 | 76 ± 28 | 136 ± 3 |

[1] IQR=Interquartile Range

*Letters indicate significant differences among categories based on Duncan's Multiple Range test

Table 4.2 C: Mean black carbon concentration and contents for sample plots. Samples were subjected to a peroxide/weak nitric acid digest treatment prior to combustion. Refer to Table 4.2 A for bulk density data used.

| **Black C** | Category | | Mean Black C Concentration (%) | | | | | | | | | Mean Black C Content (kg/ha) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Depth 1 | | IQR1 | Depth 2 | | IQR | Depth 3 | | IQR | Depth 1 | Depth 2 | Depth 3 |
| Land Management | Hardwood Removal | 27 | 0.081 | B | 0.046 | 0.078 | A | 0.893 | 0.050 | B | 0.050 | 526 ± 148 | 1771 ± 43 | 2400 ± 26 |
| | Fire Suppression | 27 | 0.134 | A | 0.081 | 0.048 | A | 0.038 | 0.092 | AB | 0.115 | 772 ± 110 | 1043 ± 170 | 4154 ± 49 |
| | Reference Longleaf Pine-wiregrass | 27 | 0.125 | B | 0.135 | 0.015 | A | 0.041 | 0.113 | B | 0.109 | 850 ± 145 | 887 ± 113 | 5172 ± 65 |
| | Agriculture | 9 | 0.045 | B | 0.005 | 0.117 | A | 0.048 | 0.037 | A | 0.037 | 311 ± 336 | 2724 ± 296 | 1948 ± 220 |
| Soil Type | Kandiudults | 36 | 0.115 | A | 0.139 | 0.083 | A | 0.063 | 0.079 | A | 0.106 | 744 ± 110 | 1911 ± 124 | 3739 ± 64 |
| | Paleudults | 27 | 0.075 | A | 0.053 | 0.041 | A | 0.035 | 0.093 | AB | 0.079 | 490 ± 104 | 914 ± 98 | 4366 ± 21 |
| | Quartzipsamments | 27 | 0.121 | A | 0.109 | 0.055 | A | 0.029 | 0.071 | B | 0.117 | 758 ± 160 | 1137 ± 90 | 3080 ± 71 |

[1] IQR=Interquartile Range

*Letters indicate significant differences among categories based on Duncan's Multiple Range test

Table 4.3: ANOVA for C concentration values for bulk C, Black C and Soot C.

| Component | Depth | Landuse | Soil Great Group | Landuse x Soil |
|---|---|---|---|---|
| | cm | ------------------*p*-value------------------ | | |
| Bulk C | 0-5 | 0.003 | 0.192 | 0.385 |
| | 5-20 | 0.244 | 0.103 | 0.660 |
| | 20-50 | 0.412 | 0.225 | 0.736 |
| Black C | 0-5 | 0.028 | 0.067 | 0.975 |
| | 5-20 | 0.109 | 0.326 | 0.403 |
| | 20-50 | 0.069 | 0.556 | 0.374 |
| Soot C | 0-5 | 0.923 | 0.077 | 0.308 |
| | 5-20 | 0.054 | 0.510 | 0.709 |
| | 20-50 | 0.000 | 0.002 | 0.043 |

Table 4.4: C concentration and C contents for litter samples.

| **Litter** | Category | C Concentration (%)<br>Mean | C Content (kg-C ha-1)<br>Mean |
|---|---|---|---|
| Land Management Regime | Hardwood Removal | 29.25 | 6348 ± 890 |
| | Fire Suppression | 35.87 | 27206 ± 1270 |
| | Reference Longleaf Pine-wiregrass | 27.12 | 6417 ± 970 |
| | Agriculture | 18.89 | 1364 ± 700 |
| Soil Type | Kandiudults | 28.89 | 12503 ± 2250 |
| | Paleudults | 31.41 | 12042 ± 2000 |
| | Quartzipsamments | 29.78 | 13698 ± 2400 |

Table 4.5: C concentration and C contents for coarse woody debris (CWD) samples.

| **CWD** | Category | Mean C Concentration (%) | Mean C Content (kg/ha) |
|---|---|---|---|
| Land Management Regime | Hardwood Removal | 36.97 | 1.9 ± 0.18 |
| | Fire Suppression | 41.16 | 2.3 ± 0.10 |
| | Reference Longleaf Pine-wiregrass | 38.58 | 2.0 ± 0.22 |
| | Agriculture | NA | NA |
| Soil Type | Kandiudults | 41.78 | 2.2 ± 0.19 |
| | Paleudults | 45.09 | 2.2 ± 0.08 |
| | Quartzipsamments | 41.33 | 2.0 ± 0.16 |

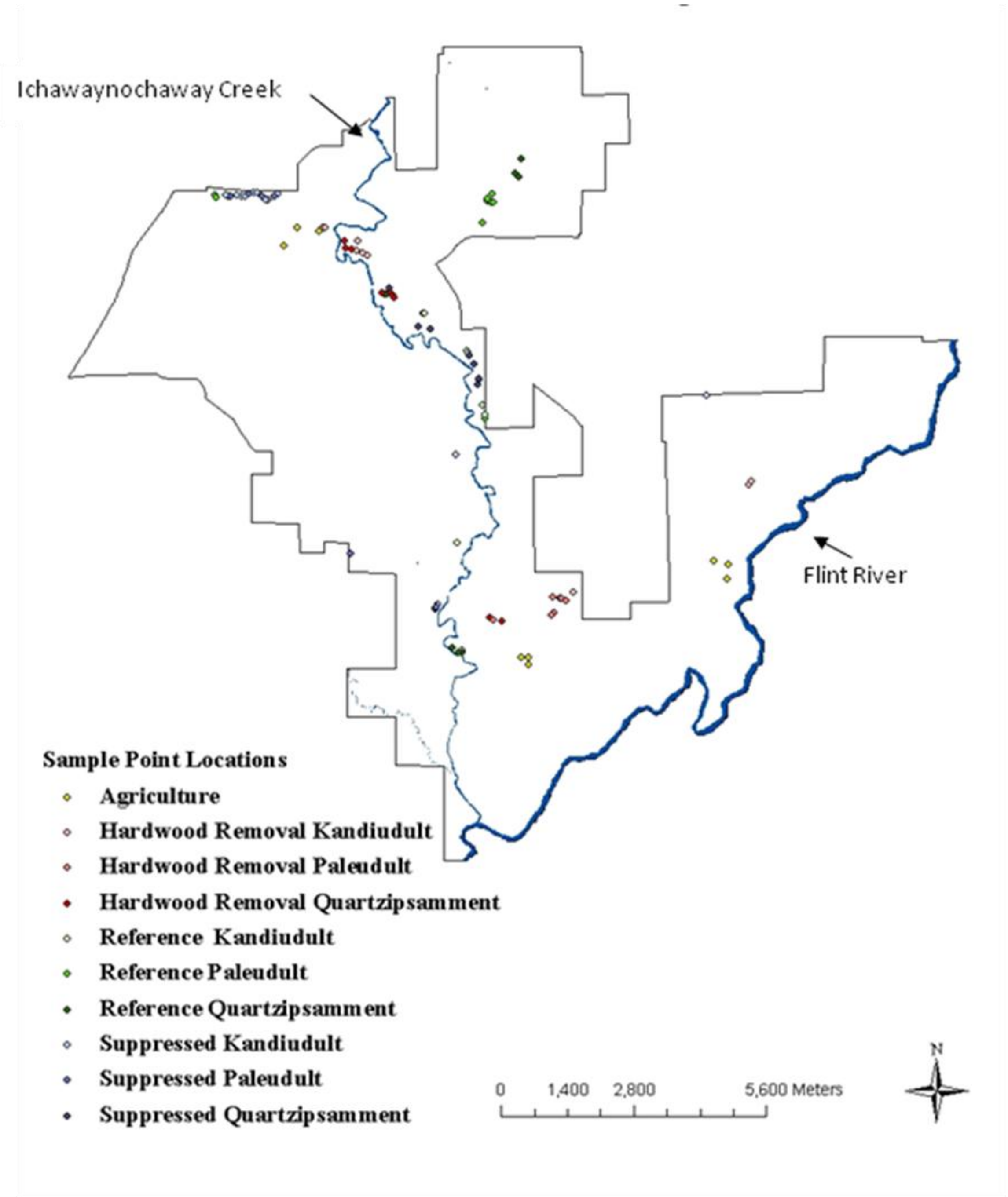

Figure 4.1 Carbon sample location map.

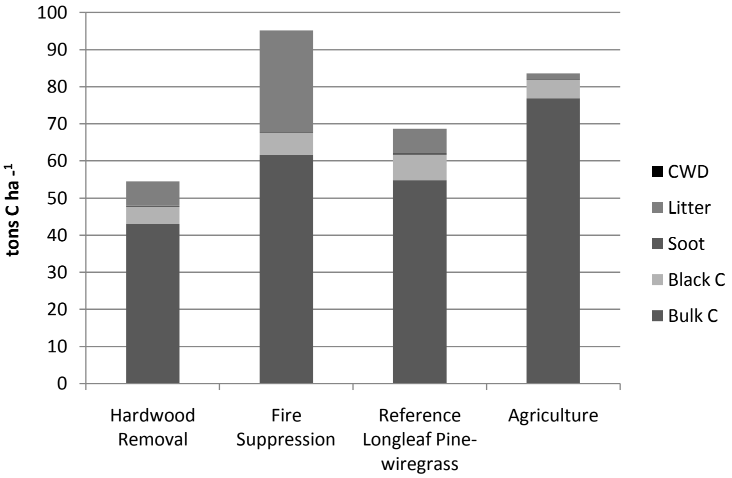

Figure 4.2: Bulk C, black C, soot C, litter and coarse woody debris (CWD) contents for soils up to 50 cm depth. Measured at 2009/2010 in the Jones Ecological Research Center within the Coastal Plain of Georgia.k/;’

# CHAPTER 5

# CONCLUSION

Sampling based on land cover rather than soil type will allow for better prediction of landscape soil C variance. Land use and land cover change can have great effects on soil C stocks either through aforestation gains or deforesatation losses. The data from the different land use types indicated varying spatial dependencies and spatial structure for soil C. Spatial structure of the data increased with depth indicating that predictions of soil C will be poorer at the surface than at depth. This is also consistent with spatial autocorrelation between data. The distance at which predictive values retain structure decreases with depth for C contents. Within the first 20 cm, C contents are autocorrelated at distances between 500 and 600 m; by 50 cm, however, spatial autocorrelation had decreased to ~250 m. For the Georgia Coastal Plain, sampling for soil C is necessary every 500-600 m at the surface; for depths >20 cm, one must sample every 250 m in order to stay in the predictive range. In addition, sampling based on genetic horizons (A, E, B, and C) versus generic horizons as used in this study (0-5, 5-20, and 20-50 cm) may further reduce variance.

The effects of hardwood removal on soil C contents is limited; total C for both reference longleaf pine-wiregrass stands and hardwood removal plots have no significant difference. Hardwood removal is not a strong predictor to use when accounting for soil C as root decay five years post harvest did not increase soil C stocks. Increased bulk soil C found in agricultural fields may be due to soil mixing associated with tillage.

Black carbon (BC) is a sink for carbon dioxide and has the potential to sequester large amounts of $CO_2$ for many years given its recalcitrant nature.  Land management regimes, specifically prescribed fire, aids in the deposition of charcoal and/or soot particles into the soil. Data indicate significant differences in BC and soot C when compared across land management regimes and soil type gradients.  As with total soil C, there is greater variation among land management regimes than among soil great groups.  BC contents were greatest in areas that are subjected to prescribed fire (i.e. reference longleaf pine-wiregrass) and contributed ~14% to the total C stock in the study area.

With these results in mind, I am confident that soil C prediction will benefit from this analysis.  The recommendations for sampling will lead to more efficient and accurate estimations of soil C contents across landscapes; this will in turn save time, money and effort for all parties involved.  The input of black carbon in soils is minimal when compared to bulk organic C and C from litter inputs.  Even though prescribed fire does add significant amounts of charcoal to the system, these do not compare to the C inputs from bulk C and litter in fire suppressed areas.

As BC work is limited in longleaf pine dominated ecosystems, this work will benefit the scientific community and aid in the general understanding of BC in Coastal Plain soils.