USE OF PYROLYSIS CHAR AS AN AMENDMENT IN SOILS OF THE
SOUTHEASTERN UNITED STATES

by

ROBERT ADAM SPEIR

(Under the Direction of Lawrence A. Morris)

ABSTRACT

Pyrolysis is an energy production process involving the thermal decomposition of biomass in the absence of oxygen. Char, a byproduct of the pyrolysis process, has been suggested as a beneficial soil amendment. Instances of charcoal discovered in otherwise infertile soils have shown soil fertility improvements in highly weathered soils through an increase in cation exchange capacity (CEC), pH, and availability of nutrients such as N, P, Ca, and K. Several studies were conducted to determine if char from pyrolysis, produced at 400°C with steam from peanut hull and pine chip feedstocks, would provide similar benefits by improving plant growth, nutrient availability, soil moisture retention, and carbon sequestration. Overall, results show that char from peanut hull and pine chip feedstocks increase available nutrients, although this increase did not lead to significant increases in plant growth or yield. Amendment of pyrolysis char also increased soil moisture during dry greenhouse conditions. Studies of soil respiration and carbon mineralization indicate pyrolysis char resists decomposition and is stable in the soil profile.

INDEX WORDS: Pyrolysis, Char, Corn, Loblolly Pine, Volumetric Water Content, Soil Respiration, Carbon Mineralization, Carbon Sequestration
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SOUTHEASTERN UNITED STATES

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DEDICATION

I dedicate this thesis to my dad, Roy Speir, my mom, Carol Speir, and the rest of my family that have taught me what it means to work hard, how to respect the world around me, and how to appreciate the blessings in my life. I also dedicate this to my future bride, Kellie Sapp, who has been my *ezer kenegdo* ever since God placed her in my life. Thank you, for who you are, and what you mean to me.
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CHAPTER I
INTRODUCTION

Soils in the southeastern United States are characterized by low natural fertility, low soil organic carbon (SOC), and low activity clays (Jenny, 1930). Climate and a history of poor soil management in the region have resulted in increased rates of organic decomposition and significant loss of SOC (Franzluebbers, 2005; Bruce et al., 1995). SOC affects the biological, chemical, and physical properties of soil and is the energy source for microbial processes that facilitate nutrient cycling (Reeves, 1997; Bruce et al., 1995; Bauer and Black, 1994; Nandwa, 2001). To help overcome the effects of climate and poor management on decomposition, increasing the recalcitrant fraction of SOC has been suggested to maintain soil fertility (Rastogi et al., 2002).

Pyrolysis is the thermal decomposition of biomass in the absence of oxygen (Yaman, 2004) and produces char, liquid, and gaseous products (Maschio et al., 1992). The use of pyrolysis has been suggested as a means of energy production from biomass, focusing mainly on the liquid and gaseous products. However, use of pyrolysis char as a soil amendment has been suggested based upon research on the benefits of naturally produced charcoal; instances of anthropogenic charcoal in otherwise infertile soils have shown beneficial impacts on soil quality (Glaser et al., 2001). Research has shown soil fertility can be improved in highly weathered soils due to the presence of charred materials (Glaser et al., 2002a) which leads to an increase in cation exchange capacity.
(CEC), pH, and availability of nutrients such as P, Ca, and K (Liang et al., 2006; Glaser et al., 2001).

Charcoal has been shown to improve retention of soil water and result in more moisture available to plants (Hudson, 1994; Tryon, 1948; Briggs, 2005). However, more research is needed specifically in the ability of pyrolysis char to retain soil moisture, as most research has been conducted using activated charcoal.

Sequestering atmospheric carbon dioxide (CO$_2$) has become a global concern, with concentrations of CO$_2$ increasing 30% since 1750 (IPCC, 2001). In agricultural soils, subject to practices that increase decomposition of organic matter, char application could ultimately lead to an increase of SOC and be may be more efficient in sequestering atmospheric C than other organic amendments.

The purpose of this study was to quantify the effects of pyrolysis char from two biomass feedstocks on plant growth, soil moisture, and carbon sequestration. To answer these questions, three studies were conducted. To evaluate the short term value of char as an agricultural amendment, a two-year field study measuring soil moisture, soil respiration, and grain yield was conducted with corn (Zea mays L). A greenhouse study was conducted to quantify the effects of pyrolysis char amendments on loblolly pine (Pinus taeda L.) seedling growth and soil water retention. Finally, a soil incubation study was conducted in the lab to determine the stability of char amendments by evaluating its effect on C mineralization.
LITERATURE REVIEW

Impact of Soil Organic Carbon on Soil Quality

Soils in the southeastern United States are characterized by low natural fertility, low soil organic carbon (SOC), and low activity clays (Jenny, 1930). Climate and a history of poor soil management in the region have also resulted in increased rates of organic decomposition and significant loss of SOC (Franzluebbers, 2005; Bruce et al., 1995). SOC includes plant, animal, and microbial residues in all stages of decomposition and is regarded as an integral indicator of soil quality and productivity (Post and Kwon, 2000; Reeves, 1997; Jenny, 1980; Doran and Parkin, 1994). SOC affects the biological, chemical, and physical properties of soil and is the energy source for microbial processes that facilitate nutrient cycling (Reeves, 1997; Bruce et al., 1995; Bauer and Black, 1994; Nandwa, 2001). SOC has also been shown to increase plant available water (Hudson, 1994; Tilman et al., 2002), CEC (Wolf and Snyder, 2003), improve infiltration (Franzluebbers, 2002), reduce erosion and leaching of nutrients (Tilman et al., 2002), improve soil structure and stability (Batjes and Sombroek, 1997), and buffer temperature and pH change (Wolf and Snyder, 2003).

The decline of SOC in the Southeast has been attributed to cultivation, particularly soil tillage, in agricultural practices (Post and Kwon, 2000). Tinker et al. (1996) described several factors that contribute to SOC loss during cultivation: soil erosion, increased oxidation due to tillage, and higher surface temperatures increasing
decomposition. In the Georgia Piedmont, 50% of SOC found to a depth of 20 cm was lost after 10 years of disturbance (Franzluebbers, 2005). Fifty years of disturbance was also shown to result in a loss of 65% of SOC compared to native conditions. These rates of decomposition are higher than other regions of the country due to a combination of relatively high precipitation and temperature that exacerbate SOC losses due to tillage and soil disturbance. To help overcome the effect of climate and poor management on decomposition, increasing the recalcitrant fraction of SOC has been suggested as means to maintain soil fertility (Doran and Parkin, 1994; Rastogi et al., 2002).

*Pyrolysis of Biomass*

Pyrolysis is a thermal degradation process performed by heating in the absence of oxygen (Yaman, 2004). Pyrolysis of biomass results in the production of char, liquid, and gaseous products (Maschio et al., 1992). Products from pyrolysis have been used dating back to the Egyptians (Mohan et al., 2006), with present day uses including chemicals, fuels, and solvents (Yaman, 2004). More recently, pyrolysis has become a means of biomass conversion for energy production (Lehmann et al., 2006; Maschio et al., 1992). Pyrolysis, in conjunction with other thermal degradation processes such as liquefaction and gasification, are considered to be the most promising and most efficient means of energy production using renewable biomass (Mohan et al., 2006; Bridgewater and Cottam, 1992).

Pyrolysis can be divided into three classes: conventional pyrolysis, fast pyrolysis, and flash pyrolysis (Demirbaş and Arin, 2002). These three types are distinguished by differences in operating temperature, heating rates, residence times, and feedstock
particle size (Maschio et al., 1992; Yaman, 2004), with the resulting yields of pyrolysis products dependent upon these parameters (Lehmann et al., 2006). The largest char yield is typically associated with conventional pyrolysis that uses operating temperatures less than 600°C and a slow heating rate (Maschio et al., 1992; Bridgewater and Cottam, 1992). A combination of increasing operating temperature and heating rate while reducing residence time generally reduces the percentage of char produced while increasing liquid and gaseous product yield (Maschio et al., 1992; Zanzi et al., 2002).

Many biomass feedstocks have been tested using pyrolysis processes, including hardwood and softwood tree species, manures, crops, and agricultural residues (Yaman, 2004). There is large variability in the yields of pyrolysis products from these feedstocks under standard conditions (Di Blasi, 1999). Generally, yields depend on the organic components of the feedstock used, most importantly hemicellulose, cellulose, and lignin (Yaman, 2004; Maschio et al., 1992; Demirbaş and Arin, 2002). These three structural components decompose at different temperatures and at different temperature ranges (Bridgewater and Cottam, 1992). Cellulose and hemicellulose break down at lower temperatures (200-350°C) while lignin is more structurally complex and therefore more thermally stable, pyrolyzing at temperatures of 280-500°C (Chum, 1991). Biomass with higher lignin composition, such as agricultural residues, will therefore lead to higher char yields with correspondingly lower liquid and gas yields (Di Blasi et al., 1999; Zanzi et al., 2002). Biomass from wood and agricultural wastes have the highest yields of char using conventional pyrolysis procedures (Zanzi et al., 2002; Lehmann et al., 2006).

The liquid bio-oil component of pyrolized biomass has been studied as a substitute for petroleum based fuel-oil and the gaseous components could also be used for
energy production. However, several problems currently limit the economic effectiveness of the liquid and gaseous pyrolysis products (Yaman, 2004; Maschio et al., 1992). Heating values for the liquid products are comparable to methanol or ethanol, but much lower than petroleum products; and the heating values of the gaseous components are much lower than natural gas (Raveendran and Ganesh, 1996). Further refinement and continued research is needed in order to make these components of pyrolysis more economically competitive with petroleum products (Bridgewater and Cottam, 1992).

Currently, limitations exist in the transportation and use of liquid and gaseous pyrolysis products (Maschio, et al., 1992); however, char shows potential as a viable product (Lehmann et al., 2006; Maschio et al., 1992). It has been suggested that char can be used as a fuel source or as an activated charcoal (Maschio et al., 1992). However, another potential use is as a soil amendment (Glaser et al., 2002a; Chidumayo, 1994; Steiner et al., 2007; Topoliantz et al., 2005).

Use of Pyrolysis Char to Improve Soil Quality and Productivity

The literature makes a distinction between the terms “charcoal” and “char” and this distinction is important to mention. Charcoal is the general term for any biomass that has undergone carbonization due to forest fires, controlled burning, or commercial production in hearths or earthen pits (Tryon, 1948; Oguntunde et al., 2004). Other terms are often used interchangeably with charcoal, including “black carbon” and “bio-char” (Schmidt and Noack, 2000; Lehmann et al., 2006), but all of these terms generally refer to biomass charred by natural processes or ancient anthropogenic techniques with unknown parameters such as original feedstock, temperature, or duration. Char generally
refers to carbonization that occurs due to pyrolysis, gasification, or some other controlled chemical process (Bridgewater and Cottam, 1992; Di Blasi et al., 1999; Yaman, 2004). The parameters of char production, such as feedstock, particle size, temperature, and heating rate are often known, and production of char following those parameters could be repeated (Maschio et al., 1992). Char produced from pyrolysis is not presumed to be similar or analogous to naturally produced charcoal, although the terminology used is similar and can be misleading.

Most studies depicting the benefits of charred biomass on soil quality involves the presence of charcoal (Oguntunde et al., 2004; Tryon, 1948; Steiner, et al., 2007; Lima et al., 2002; Glaser et al., 2001; Topoliantz et al., 2005). The charcoal used in these studies comes from various sources produced under varying, sometimes unknown conditions which likely affects the properties of the charcoal. It is unknown how char produced from pyrolysis under controlled conditions compares to the charcoals used in past studies. However, based upon these charcoal studies, the use of pyrolysis char as a soil amendment should be studied to determine its affects.

Application of pyrolysis char has the potential to improve soil quality by improving the physical, chemical, and biological properties of soil (Lehmann et al., 2006; Lehmann and Rondon, 2005; Lehmann et al., 2003; Glaser et al., 2002b). Sites in Germany, Australia, Japan, Central America, and North America where instances of historic fire and anthropogenic management led to an increase of carbon (C) that is still present today indicates charcoal can constitute a large portion of soil C in agricultural soils that has been shown to improve soil characteristics and is resistant to most microbial activity (Schmidt and Noack, 2000; Skjemstad et al., 2002). If amendments of pyrolysis
Charcoal affects soil fertility through the direct addition of nutrients and the indirect retention of nutrients (Lehmann et al., 2003; Briggs, 2005). Although the addition of charcoal generally increases soil fertility and productivity through the increase of available cations, other studies have shown growth depressions due to charcoal application (Tryon, 1948; Mikan and Abrams, 1996). These instances of negative impacts are generally attributed to high rates of charcoal amendment, resulting in high alkalinity and nitrogen (N) immobilization (Lehmann et al., 2003; Tryon, 1948).

Yamato et al. (2006), in a study of charcoal from *Acacia mangium* bark on corn, cowpea, and peanut yield, showed that charcoal amendments with fertilization led to a significant increase in corn and peanut yield. The study showed charcoal application significantly increased the positive effects of fertilization over controls. On one site, which was more fertile, charcoal amendment alone did not significantly increase yield. Bark charcoal also increased nutrient retention, as indicated by higher CEC, as well as total N and phosphorus (P).

Other studies have shown that charcoal alone significantly increases crop yield when compared to unfertilized plots, and is comparable to yields of fertilized plots without char (Oguntunde et al., 2004). Results of Steiner et al., (2007) suggest that charcoal would be most beneficial if combined with organic or inorganic amendments, as the nutrient availability of charcoal itself was not sufficient for crops.
Instances of anthropogenic charcoal in otherwise infertile soils have shown beneficial impacts on soil quality (Glaser et al., 2001). Studies of Terra Preta de Indio, found in the Brazilian Amazon (Glaser et al., 2002a), show that soils high in charcoal contain an average of 250 Mg ha\(^{-1}\) C compared to 100 Mg ha\(^{-1}\) in adjacent soils and also have a higher CEC and pH (Lima et al., 2002). Soils in the humid tropics are typically low in fertility due to weathering and low activity clays (Sombroek, 1966), yet Terra Preta soils, influenced by Pre-Columbian indigenous people, have persisted to present-day and continue to maintain soil productivity (Glaser et al., 2001). The exact source and composition of this charcoal is not exact, and the benefits may be dependent upon these conditions. However, examples such as Terra Preta have shown soil fertility can be improved in highly weathered soils through the presence of charcoal (Glaser et al., 2002a) which leads to an increase in CEC, pH, and availability of nutrients such as N, P, Ca, and K (Liang et al., 2006; Glaser et al., 2001).

Char and Water Retention

The amount of water between field capacity (33 kPa) and permanent wilting point (1500 kPa) is considered available for plant use (Cassel and Nielsen, 1986). Charcoal has been shown to improve retention of soil water and result in greater moisture availability to plants (Hudson, 1994; Tryon, 1948; Briggs, 2005). The amount of retention is somewhat dependent upon the nature of the parent material, method of charring, charring temperature, and age of char (Tryon, 1948). Work by Kishimoto and Sugiura (1985) showed that charcoal was able to improve porosity and water holding capacity in soils, which resulted in better plant and root growth; several mechanisms have been suggested.
to explain the absorptive properties of charcoal, including high surface area and capillary action (Tryon, 1948). Research is needed to determine the ability of pyrolysis char to retain soil moisture, as most research has been conducted using activated charcoal.

Much research has been conducted determining the general impacts of SOC on soil moisture retention. Hudson (1994) suggested that a 1-3% increase in SOC doubled the plant available water over three textural groups (sand, silt loam, and silty clay loam). In the sand textural class, SOC caused a greater increase in water content at field capacity than at permanent wilting point. More water would be available to plants at a lower tension, allowing easier use of soil water between rainfall or irrigation events (Hudson, 1994). Work by Briggs, (2005) indicated that application of wildfire charcoal amendments at rates up to 50 g kg soil\(^{-1}\) may linearly increase soil water content. This increase of SOC likely has direct and indirect affects on water retention. The organic matter has higher absorbency and amendments generally improve soil physical characteristics such as bulk density and porosity (Briggs, 2005; Tester, 1990).

Use of Char in Carbon Sequestration

Sequestering atmospheric carbon dioxide (CO\(_2\)) has become a global concern, with concentrations of atmospheric CO\(_2\) increasing 30% since 1750 (IPCC, 2001). Most of this increase has been attributed to combustion of fossil fuels over the last 50 years, yet the large pool of potentially mineralizable C in soils is nearly 10 times the amount of CO\(_2\) released from fossil fuels (Raich and Tufekcioglu, 2000). Therefore, the greatest potential for C sequestration is in soil and SOC (Causarano et al., 2006; Franzluebbers, 2005; West and Post, 2002). The soil C pool has a profound impact on the global C
cycle, with nearly twice as much C stored in SOC than in the atmosphere (Parker et al., 2001). With such a significant influence on global C cycling and increased pressure to reduce atmospheric C concentrations, soil management focusing on C sequestration is essential (Barnwell et al., 1992).

The amount of SOC present is the long-term balance of C inputs and C losses from the soil (Gregorich et al., 1998; Follett, 2001). In undisturbed systems, this balance is in a state of quasi-equilibrium, with soil C losses equaling C input from plants (Follett, 2001). Soil C losses are a result of erosion and soil respiration, which results from microbial, root, and faunal activity (Rastogi et al., 2002). Agricultural practices and land-use change have led to large amounts of erosion and C efflux over the course of many years (Franzluebbers, 2005; Lal, 2004). However, agricultural practices can also maintain or increase SOC, thus increasing rates of C sequestration (Reeves, 1997; Follett, 2001; Rosenberg and Izaurralde, 2001; Causarano et al., 2006). Techniques such as reduced tillage and intensive cropping systems can increase C sequestration as much as 30 to 105 million metric tons of carbon (MMTC) yr\(^{-1}\) in the United States (Follett, 2001).

West and Post (2002), analyzing several long term experiments (n=93), showed no-till treatments can sequester 48 ± 13 g C m\(^{-2}\) yr\(^{-1}\) over an average of 15 years compared to conventional tillage. Results also showed sequestration rates were higher for crop rotation systems than continuous monocultures.

The application of organic amendments and crop residues has been proven to increase SOC in the Southeast (Follett, 2001; Edmeades, 2003; Franzluebbers, 2005). However, application of conventional organic matter, such as manure or crop residues, often results in only a short-term increase of SOC before mineralization releases carbon
into the atmosphere (Johnson et al., 2004), and may also lead to poor water quality
(Edmeades, 2003). Buyanovsky and Wagner (1987) reported that 80% of a crop residue
left on a field was mineralized and returned to the atmosphere within 2 years.
Amendments of organic matter to agricultural fields have also been shown to actually
increase CO$_2$ efflux by providing an immediate source of food for microbial activity
(Rastogi et al., 2002).

The recalcitrance of charcoal to microbial decomposition sets it apart from fresh
organic amendments in terms of sequestering C, especially in humid regions with high
decomposition rates (Sombroek et al., 1993). The residence time of charcoal in the soil
profile is still uncertain, with estimated times ranging from hundreds to thousands of
years (Bird et al., 1999; Shindo, 1991). The variability in recalcitrance is due to charcoal
characteristics, including type of original biomass and charcoal production techniques.
Residence time may also vary due to climate and soil properties (Schmidt and Noack,
2000; Masiello, 2004). Despite uncertainty in the stability of charcoal, evidence shows
an overall ability of charcoal to reside in soils for centuries, if not longer (Lehmann and
Rondon, 2005; Pessenda et al., 2001). Non-charred material, such as manure or compost,
releases C slowly over time, with only 10-20% of the original biomass C remaining after
5-10 years. Charring of biomass results in an immediate release of approximately 50%
C, with the remaining C being more resistant to microbial activity (Lehmann and
Rondon, 2005). In agricultural soils, application of pyrolysis char could ultimately lead
to a greater amount of SOC over the long term and be more efficient in sequestering
atmospheric C than organic amendments.
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CHAPTER II

THE EFFECT OF PYROLYSIS CHAR ON SOIL MOISTURE, SOIL RESPIRATION, GRAIN YIELD, AND BIOMASS OF CORN (ZEA MAYS L.)

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\[\text{1} \text{ Speir, R.A., Morris, L., Gaskin, J., Ogden, L., and K. Harris. 2008. To be submitted to Soil Science Society of America Journal} \]
Abstract

Soils in the southeastern United States are characterized by low natural fertility, low soil organic carbon (SOC), and low activity clays. Climate and a history of poor soil management in the region have also resulted in increased rates of organic decomposition and significant loss of soil organic matter. Pyrolysis, the thermal decomposition of biomass in the absence of oxygen, results in a char byproduct. Application of pyrolysis char to soil has the potential to improve soil quality by improving the physical, chemical, and biological properties of soil, as well as increasing soil moisture retention. Char may also be a recalcitrant source of soil carbon that may increase carbon sequestration. The objectives of this study were to determine the effects of char, produced at 400°C with steam, from peanut hull and pine chip feedstocks on soil moisture, soil respiration, and yield of corn (Zea mays L.) in a Tifton loamy sand over two growing seasons in the southeastern Coastal Plain. Overall, char amendments did not significantly affect soil moisture content during either growing season. Soil respiration varied seasonally over the two years (P<0.0001) but there was no significant differences in respiration due to char amendment. This research demonstrated no gain in corn yields or biomass over two growing seasons due to char amendments. Also, yield and biomass decreased during the 2007 season due to drought conditions and nutrient depletion evident in controls and fertilizer checks. It is suggested from this research that char may be applied to agricultural soils as a stable C source without significantly decreasing crop yields.

INDEX WORDS: Zea mays L., Volumetric Water Content, Carbon Sequestration, Soil Respiration, Pyrolysis, Char, Yield, Biomass, Coastal Plain
Introduction

Impact of Soil Organic Carbon on Soil Quality

Soils in the southeastern United States are characterized by low natural fertility, low soil organic carbon (SOC), and low activity clays (Jenny, 1930). Climate and a history of poor soil management in the region have also resulted in increased rates of organic decomposition and significant loss of SOC (Franzluebbers, 2005; Bruce et al., 1995). SOC includes plant, animal, and microbial residues in all stages of decomposition and is regarded as an integral indicator of soil quality and productivity (Post and Kwon, 2000; Reeves, 1997; Jenny, 1980; Doran and Parkin, 1994). SOC affects the biological, chemical, and physical properties of soil and is the energy source for microbial processes that facilitate nutrient cycling (Reeves, 1997; Bruce et al., 1995; Bauer and Black, 1994; Nandwa, 2001). SOC has also been shown to increases plant available water (Hudson, 1994; Tilman et al., 2002), CEC (Wolf and Snyder, 2003), improve infiltration (Franzluebbers, 2002), reduce erosion and leaching of nutrients (Tilman et al., 2002), improve soil structure and stability (Batjes and Sombroek, 1997), and buffer temperature and pH change (Wolf and Snyder, 2003).

The decline of SOC in the Southeast has been attributed to cultivation, particularly soil tillage, in agricultural practices (Post and Kwon, 2000). Tinker et al. (1996) described several factors that contribute to SOC loss during cultivation: soil erosion, increased oxidation due to tillage, and higher surface temperatures increasing decomposition. In the Georgia Piedmont, 50% of SOC found to a depth of 20 cm was lost after 10 years of disturbance (Franzluebbers, 2005). Fifty years of disturbance was also shown to result in a loss of 65% of SOC compared to native conditions. These rates
of decomposition are higher than other regions of the country due to a combination of relatively high precipitation and temperature that exacerbate SOC losses due to tillage and soil disturbance. To help overcome the effect of climate and poor management on decomposition, increasing the recalcitrant fraction of SOC has been suggested as means to maintain soil fertility (Doran and Parkin, 1994; Rastogi et al., 2002).

*Pyrolysis of Biomass*

Pyrolysis is a thermal degradation process performed by heating in the absence of oxygen (Yaman, 2004). Pyrolysis of biomass results in the production of char, liquid, and gaseous products (Maschio et al., 1992). Products from pyrolysis have been used dating back to the Egyptians (Mohan et al., 2006), with present day uses including chemicals, fuels, and solvents (Yaman, 2004). More recently, pyrolysis has become a means of biomass conversion for energy production (Lehmann et al., 2006; Maschio et al., 1992).

Currently, limitations exist in the transportation and use of liquid and gaseous pyrolysis products (Maschio, et al., 1992); however, char shows potential as a viable product (Lehmann et al., 2006; Maschio et al., 1992). It has been suggested that char can be used as a fuel source or as an activated charcoal (Maschio et al., 1992). However, another potential use is as a soil amendment (Glaser et al., 2002a; Chidumayo, 1994; Steiner et al., 2007; Topoliantz et al., 2005).
Use of Pyrolysis Char to Improve Soil Quality and Productivity

The literature makes a distinction between the terms “charcoal” and “char” and this distinction is important to mention. Charcoal is the general term for any biomass that has undergone carbonization due to forest fires, controlled burning, or commercial production of charcoal in hearths or earthen pits (Tryon, 1948; Oguntunde et al., 2004). Other terms are often used interchangeably with charcoal, including “black carbon” and “bio-char” (Schmidt and Noack, 2000; Lehmann et al., 2006), but all of these terms generally refer to biomass charred according to natural processes or ancient anthropogenic techniques with unknown production conditions such as original feedstock, temperature, or duration. Char generally refers to carbonization that occurs due to pyrolysis, gasification, or some other controlled chemical process (Bridgewater and Cottam, 1992; Di Blasi et al., 1999; Yaman, 2004). The parameters of char production, such as feedstock, particle size, temperature, and heating rate are often known, and production of char following those parameters could be repeated (Maschio et al., 1992). Char produced from pyrolysis is not presumed to be similar or analogous to naturally produced charcoal, although the terminology used is similar and can be misleading.

Most studies depicting the benefits of charred biomass on soil quality involves the presence of charcoal (Oguntunde et al., 2004; Tryon, 1948; Steiner, et al., 2007; Lima et al., 2002; Glaser et al., 2001; Topoliantz et al., 2005). The charcoal used in these studies comes from various sources produced under varying, sometimes unknown conditions, which likely affects the properties of the charcoal. It is unknown how char produced from pyrolysis under controlled conditions compares to the charcoals used in past studies.
However, based upon these charcoal studies, the use of pyrolysis char as a soil amendment should be studied to determine its affects.

Application of pyrolysis char has the potential to improve soil quality by improving the physical, chemical, and biological properties of soil (Lehmann et al., 2006; Lehmann and Rondon, 2005; Lehmann et al., 2003; Glaser et al., 2002b). Sites in Germany, Australia, Japan, Central America, and North America where instances of historic fire and anthropogenic management led to an increase of C that is still present today indicates charcoal can constitute a large portion of soil C in agricultural soils that has been shown to improve soil characteristics and is resistant to most microbial activity (Schmidt and Noack, 2000; Skjemstad et al., 2002). If amendments of pyrolysis char resulted in similar improvements, the relative stability of char would prevent quick turnover of C pools due to decomposition or soil disturbance (Lehmann and Rondon, 2005).

Charcoal affects soil fertility through the direct addition of nutrients and the indirect retention of nutrients (Lehmann et al., 2003; Briggs, 2005). Although the addition of charcoal generally increases soil fertility and productivity through the increase of available cations, other studies have shown growth depressions due to charcoal application (Tryon, 1948; Mikan and Abrams, 1996). These instances of negative impacts are generally attributed to high rates of charcoal amendment, resulting in high alkalinity and N immobilization (Lehmann et al., 2003; Tryon, 1948).
**Char and Water Retention**

Much research has been conducted determining the general impacts of SOC on soil moisture retention. Hudson (1994) suggested that a 1-3% increase in SOC doubled the plant available water over three textural groups (sand, silt loam, and silty clay loam). In the sand textural class, SOC caused a greater increase in water content at field capacity than at permanent wilting point. More water would be available to plants at a lower tension, allowing easier use of soil water between rainfall or irrigation events (Hudson, 1994). Work by Briggs, (2005) indicated that application of wildfire charcoal amendments at rates up to 50 g kg soil\(^{-1}\) may linearly increase soil water content. This increase of SOC likely has direct and indirect affects on water retention. The organic matter has higher absorbency and amendments generally improve soil physical characteristics such as bulk density and porosity (Briggs, 2005; Tester, 1990).

**Use of Char in Carbon Sequestration**

The recalcitrance of charcoal to microbial decomposition sets it apart from fresh organic amendments in terms of sequestering C, especially in humid regions with high decomposition rates (Sombroek et al., 1993). The residence time of charcoal in the soil profile is still uncertain, with estimated times ranging from hundreds to thousands of years (Bird et al., 1999; Shindo, 1991). The variability in recalcitrance is due to charcoal characteristics, including type of original biomass and charcoal production techniques. Residence time may also vary due to climate and soil properties (Schmidt and Noack, 2000; Masiello, 2004). Despite uncertainty in the stability of charcoal, evidence shows an overall ability of charcoal to reside in soils for centuries, if not longer (Lehmann and...
Rondon, 2005; Pessenda et al., 2001). Non-charred material, such as manure or compost, releases C slowly over time, with only 10-20% of the original biomass C remaining after 5-10 years. Charring of biomass results in an immediate release of approximately 50% carbon with the remaining carbon more resistant to microbial activity (Lehmann and Rondon, 2005). In agricultural soils, application of pyrolysis char could ultimately lead to a greater amount of SOC over the long term and be more efficient in sequestering atmospheric C than organic amendments.

The objective of this study was to determine the effects of pyrolysis char from peanut hull and pine chip feedstocks on characteristics of a Tifton loamy sand. Specifically, a 2-year field study was conducted to determine the effects of pyrolysis char amendment on growth and yield of corn (Zea mays L.), soil moisture retention, and soil CO$_2$ efflux. Based upon research into charcoal as a soil amendment, we hypothesized that char amendments would increase grain and biomass yields in corn. We also hypothesized that char amendments would increase soil moisture retention and nutrient availability, as well as not contribute to soil respiration and remain stable in the soil profile.

Materials and Methods

Site Location

A 2-year field study was established in March 2006 on Field #533 of the Lang Farm at The Coastal Plain Experiment Station, University of Georgia near Tifton, GA (31°30'N, 83°32'W). The study area was a 0.04 ha section of a 0.20 ha field. The farm has a history of intensive farming practices, growing several commodity crops of the
Southeast using conventional tillage and resulting in frequent soil disturbance. This site is typical of agricultural fields in the lower Coastal Plain, located on a Tifton soil (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) and contains low organic matter (0.4%) and low cation exchange capacity (CEC) (5 cmol kg$^{-1}$).

**Design and Installation**

Pyrolysis char was produced by EPRIDA$^\text{®}$ from pelletized peanut hull and pine chip feedstocks in a pyrolysis reactor at 400°C with steam. These pelletized chars were ground using a roller mill and were applied at three rates (0, 11.2 Mg ha$^{-1}$, 22.4 Mg ha$^{-1}$) in factorial combination with fertilizer treatment (standard fertilization vs. initial fertilizer only). Each treatment combination was replicated four times in a completely randomized design (24 plots for each char feedstock).

Treatments in this factorial experiment for each feedstock included: no char with initial fertilizer only (C), no char with standard fertilizer (F), char at 11.2 Mg ha$^{-1}$ with initial fertilizer only (L), char at 11.2 Mg ha$^{-1}$ with standard fertilizer (L+F), char at 22.4 Mg ha$^{-1}$ with initial fertilizer only (H), and char at 22.4 Mg ha$^{-1}$ with standard fertilizer (H+F).

Prior to plot establishment, the section of field used for the experiment was disk harrowed to a depth of approximately 15 cm and fertilized with an initial application of 10.4 kg N, 49.55 kg P$_2$O$_5$ (21.8 kg elemental P), and 67.8 kg K$_2$O (56.28 kg elemental K). Each plot, 2.23 x 1.82 m (7.3 x 6.0 ft) in size, was delineated by stakes and a wooden frame was used to delineate each char application plot and prevent mixing of treatments with adjacent plots. Char was applied to assigned plots by hand and mixed into the soil.
with a yard rake. Plots designated for additional fertilization (F, L+F, and H+F) received NH$_4$NO$_3$ (10.4 kg ha$^{-1}$ N) which was hand applied as starter fertilizer at 9.07 g row$^{-1}$. At around the six-leaf corn growth stage (V6), these same plots received NH$_4$NO$_3$ (34-0-0) (86.2 kg ha$^{-1}$ N) hand applied as side-dressing at 101 g row$^{-1}$. These fertilization rates were recommended to achieve grain yields of 12,552.5 kg ha$^{-1}$ (200 bushels ac$^{-1}$).

After the 2006 growing season, a cover crop of rye (*Secale cereale*) was planted. This cover crop did not receive any fertilization, nor did the field receive an initial fertilization at the start of the 2007 growing season. Only those plots designated as fertilizer plots (F, L+F, and H+F) received NH$_4$NO$_3$ side-dressing (224 kg ha$^{-1}$ N) at approximately 136 g row$^{-1}$. More fertilizer was applied as side-dressing in 2007 than 2006 to offset fertilizer not applied to the rye cover crop.

Each plot had two rows of Pioneer 33M53 No. 2 corn (*Zea mays L.*) planted at a 91 cm (36 in) spacing at a density of 69,187 seeds ha$^{-1}$ (28,000 seeds acre$^{-1}$). The next row outside of each plot served as a buffer row, leaving two rows between each plot. Within each plot, a 46 cm (18 in) buffer was used to establish the sampling area of each plot to reduce edge effect of different treatments (Figure 2.1).

The site was watered weekly by a lateral irrigation system which applied approximately 2 cm water per use. This rate of irrigation was set for irrigating other nearby experimental plots with other crops. The area also received less than average rainfall during the 2006 and 2007 growing seasons and crops were drought stressed during both seasons (Figure 2.2).
Measurements

Volumetric soil moisture was estimated monthly during the 2006 and 2007 growing seasons and periodically between seasons for a total of 15 dates using a Riser Bond Model 1205CXA coaxial metallic time domain reflectometer (TDR) (Radiodetection, Bridgton, ME). In each plot, soil moisture at 0-15 cm depth was measured with a pair of 30-cm steel rods installed parallel at a 30° angle to the soil surface. A second pair of parallel 30-cm steel rods was installed vertically to measure soil moisture at the 0-30 cm depth. These pairs of rods were located along the second row (first measurement row) in each plot. Topp’s equation was used to convert TDR readings to a volumetric soil moisture percentage (Topp and Davis, 1985).

Soil respiration ($F_c$) was measured in conjunction with soil moisture measurements (14 dates) using a LI-COR 6400 portable infrared gas analyzer (IRGA) with an attached soil respiration chamber (LI-COR Inc. Lincoln, NE). For each plot measurement, the soil chamber was placed in proximity to the TDR rods near the plants in the same row and allowed to make two consecutive cycles of respiration measurements (Scala Jr. et al., 2005). Soil temperature at 5 cm was concurrently measured. An average soil temperature was calculated for each measurement day and used to standardize soil respiration values:

Soil temperature between 0-15°C: $F_c \times 4^{[(25-T)/10]}$
Soil temperature between 15-35°C: $F_c \times 2^{[(25-T)/10]}$

Where: $F_c$ = measured soil respiration
T = measured soil temperature
**Harvest**

Prior to sampling at harvest, the interior sampling area of each plot was determined and used as the measurement area for each plot. Total biomass was harvested from each plot at the end of each growing season. Corn ears from each plot were removed from their shucks, bagged, and dried for six days at 49°C (120°F) in a forced-air drying shed. Corn stalks located within the sampling area of each plot were cut at 35.5 cm (14 in.) above ground, shredded, and dried similar to the ears. After drying, ears were mechanically shelled and cob and kernel biomass was determined for each plot. Grain moisture content was calculated using a 2100 Grain Analysis Computer (Dickey-John Corp. Auburn IL). Kernel biomass and grain yield were standardized at 15.5% moisture using the following equation (Beuerlein, 2007):

\[
\text{Standard weight} = \text{kernel weight}^{((100 - \text{kernel moisture})/(100 - 15.5))}
\]

**Statistical Analysis**

Statistical analyses of biomass and yield data were performed using the Statistical Analysis System general linear model (GLM) procedure (SAS Institute, Cary NC) for a two-way factorial experiment (application rate and fertilizer). Separate analyses were conducted for each of the two char types. Tukey’s means separation procedure was used to compare treatment differences (\(\alpha = 0.05\)) when significant differences were indicated by GLM.

Soil moisture and soil respiration data were analyzed using analysis of variance (ANOVA) with repeated measures and evaluated using univariate analysis for within and between subject effects. Significance of factor and time interaction (within subject) was
determined using a Greenhouse-Geisser adjustment at $\alpha=0.05$. This correction adjusts the degrees of freedom in ANOVA to produce a more accurate p value if the assumption of sphericity has been violated. Between subject tests were also evaluated at $\alpha=0.05$.

Results

Soil Moisture

Volumetric soil moisture varied during the two year experiment at each depth, with generally lower values during early spring and late summer due to decreased precipitation and absence of irrigation during fallow periods (Figure 2.3 and Figure 2.4). Soil moisture percentages were slightly higher in the 0-30 cm depth than the 0-15 cm depth for both peanut hull and pine chip char treatments. Among both char feedstocks, measurement date was significant ($P<0.0001$) in determining volumetric soil moisture content in both 0-15cm and 0-30cm ranges.

A time*fertilizer interaction existed in the pine chip treatments at both 0-15 cm ($P=0.0105$) and 0-30 cm ($0.0032$) ranges. A time*fertilizer interaction also existed in the peanut hull char treatments at the 0-30 cm range ($P=0.0208$). Evaluating treatments without time effects resulted in no significant differences among treatments or interactions with fertilizer in peanut hull or pine chip char at either depth (Table 2.1).

Soil Respiration

There were no significant differences in soil respiration among treatments for either char feedstock (Figure 2.5). Measurement date was significant for both char feedstocks, with seasonal variations occurring over the two years ($P < 0.0001$). No
interaction existed among time, char rate, and fertilizer treatments (Table 2.2). When observing the between subject effects (excluding time as a factor), application rate for peanut hull char was nearest to a significant p value at $\alpha = 0.05$ ($P = 0.0546$). However, the interaction between application rate and fertilizer was not significant ($P = 0.7201$).

**Biomass and Yield**

Yield and biomass values were higher in 2006 than 2007, and higher in fertilizer treatments than char-only treatments or controls. Fertilizer caused a significant increase in grain yield (Figure 2.6 and 2.7) and biomass (Figure 2.8 and 2.9) in both 2006 and 2007. There was no statistical difference among char or control treatments within either level of the fertilizer factor. In 2006, high rates of peanut hull char with fertilizer resulted in slightly less total biomass ($20.50 \text{ Mg ha}^{-1} \pm 1.20$) than plots with low rates of char with fertilizer ($23.80 \text{ Mg ha}^{-1} \pm 0.75$). This was also true in 2007, with total biomass averages of $14.69 \text{ Mg ha}^{-1} \pm 1.64$ in H+F and $17.98 \text{ Mg ha}^{-1} \pm 0.41$ in L+F (Figure 2.8). This trend also applied to yield results for plots amended with peanut hull char (Figure 2.6), with high rates of char and fertilizer resulting in less yield compared to the low rate of char with fertilizer in both growing seasons. The opposite held true in peanut hull char treatments without fertilizer, with high rates of char resulting in more biomass than plots with low rates of char or control plots with no char. No differences existed in 2007 in the unfertilized plots. No differences in biomass existed in plots with pine chip char in either year (Figure 2.9).
Discussion

Soil Moisture

Water availability is a major concern in agriculture, as plant-available water can be a limiting factor in production. Even with modern irrigation technology, water retention is a problem in soils with low SOC, such as sandy soils. Rawls et al. (2003) concluded that water retention in sandy soils responds more to increases in SOC than finer textured soils. Rawls et al. (2003) also states the effect of C increases on water retention is dependent on pre-existing soil C contents. The incorporation of char has been shown to increase soil moisture, although differences exist among char production techniques and char characteristics (Tryon, 1948; Briggs, 2005; Hudson, 1994). However, with no previous studies conducted to determine the effects of pyrolysis char on volumetric water content in southeastern soils, little comparable data is available.

Char amendments did not significantly increase volumetric water content at the rates used in our study over two growing seasons (Table 2.1). The time*fertilizer interaction that occurred likely shows the effect of fertilizer on increasing water utilization by the crop. A one time application of char did not show to increase soil moisture at the rates used in this study. However, future applications of char or higher rates should be studied to observe these effects on soil moisture.

Soil Respiration

Studies show that incorporation of fresh or composted organic amendments increases soil respiration due to immediate C availability and subsequent increase in microbial activity (Rastogi et al., 2002; Moore and Dalva, 1993). In order to sequester C,
amendments that are more resistant to microbial decay and essentially removed from the mineralization cycle are required (Rastogi et al., 2002). Char has been suggested as one means of sequestering C due to char’s apparent recalcitrance and longevity in the soil (Lehmann and Rondon, 2005). Two years after incorporating char from two feedstocks in a Tifton soil under agricultural use, no significant difference existed in soil respiration between controls and char amended plots.

Studies show soil respiration is highly dependent upon soil moisture and temperature (Howard and Howard, 1993). Generally, as soil temperature and soil moisture increase, soil respiration increases. However, during July and August of the 2006 growing season, soil moisture and temperature reached their maximum value after the highest measured rates of CO$_2$ efflux. Soil efflux began decreasing while soil temperature and moisture values continued increasing, indicating soil respiration may have been more a result of root respiration rather than affects of soil moisture or temperature (Amos et al., 2005). Martens (1990) reported a decrease in soil respiration as plants matured and root respiration decreased even though soil moisture and temperatures remained high. Qian et al. (1997) also showed roots of corn plants release less C as plants mature. Compared to the first growing season, soil respiration values were lower during the 2007 growing season (Figure 2.5). This is likely due to a reduction in plant productivity caused by drought conditions (Figure 2.2) and nutrient limitations.

Although lengthier studies are necessary to understand the response of soil respiration to char incorporation, initial results show that amendments of char do not significantly contribute to soil respiration. This indicates that char used in this study did not immediately contribute to soil respiration and may remain in the soil profile.
Amendments of charcoal have been shown to be beneficial to plant growth and yield by adding nutrients and improving soil physical and biological properties (Lehmann et al., 2006; Lehmann and Rondon, 2005; Lehmann et al., 2003; Glaser et al., 2002b). However, a review of current research provided no information on the use of char specifically on agricultural field studies in the southeastern United States. Oguntunde et al. (2004), in a study conducted in Ghana, showed that fields located on charcoal kiln sites resulted in much higher corn grain yields than sites adjacent to kiln sites which served as controls. Plots located on the charcoal kiln sites yielded 91% more grain than controls. When amended with mineral fertilizer at 150 kg ha$^{-1}$, the charred plots yielded an increase of 276% compared to the control. Yamato et al. (2006) also showed that char from *Acacia mangium* bark improved corn and peanut yields in an infertile field in Indonesia when used with mineral fertilizer. Yamato et al. (2006) suggests that char alone would also serve to increase crop yields through amelioration of soil properties. Our results do not support this suggestion, as no significant positive effect of char amendment alone or with fertilizer on grain yield (Figure 2.6 and 2.7) or biomass (Figure 2.8 and 2.9) was observed.

Results from Oguntunde et al. (2004) may show the effects of long-term incorporation of char at a site, which may have an additive positive effect over time. Our experiment lasted only two growing seasons with only one application of char at low rates of 11 and 22 Mg ha$^{-1}$. Over time, repeated applications of char may change soil characteristics that could significantly increase grain yields and biomass production.

Our results suggest that peanut hull or pine chip char does not serve as a fertilizer
replacement in intensive agricultural production, especially with nutrient-demanding crops such as corn. Steiner et al. (2007) also indicated the low nutrient content of char prevented it from being a suitable fertilizer replacement in the production of rice (*Oryza sativa* L.) and sorghum (*Sorghum bicolor* L.). Char did perform well in improving grain yield when combined with mineral fertilizer. Gaskin et al. (not published), using the same char feedstocks as this study, concluded that peanut hull char at 22.4 Mg ha\(^{-1}\) significantly contributed to potassium levels in a Tifton loamy sand and corn tissue over the first corn growing season, but potassium levels decreased in the next growing season. During this study, no additional potassium was added as mineral fertilizer. Further studies should be conducted with the use of char with conventional mineral and organic fertilizer application regimes to determine if char retains nutrients in agricultural production systems.

**Conclusions**

We hypothesized that amendments of pyrolysis char would increase the biomass and yield production of corn. This hypothesis was rejected, as char from peanut hull and pine chip feedstocks did not significantly increase grain yields or biomass of corn in a Tifton loamy sand during the 2006 or 2007 growing season. For both soil moisture and soil respiration, results varied significantly by measurement date, but no differences existed between plots with char amendments and controls. Compared to the first growing season, soil respiration values were lower during the 2007 growing season. This is likely due to a reduction in plant productivity caused by drought conditions and nutrient limitations. Although char did not increase grain yields or soil moisture during the 2006
or 2007 growing seasons, it did not seem to decrease yields or soil moisture. Application of char did not show to increase crop production or soil moisture in the short term, but it also did not show to significantly decrease yields or moisture content.

This short-term study on small plots showed no beneficial effects of char on grain yields or soil moisture. No increases soil respiration rates from addition of char may indicate that char is a stable source of C and may remain in the soil profile for at least two growing seasons. Long term studies are recommended on larger plots to more precisely determine the effects of char amendments on agricultural production and soils of the southeastern United States.
Table 2.1. Summary of statistical significance for volumetric soil moisture response measured in 2006 and 2007 using repeated measures and in response to fertilizer and application of char from peanut hull and pine chip char at 0, 11.2, and 22.4 Mg ha\(^{-1}\) to a Tifton soil in Tifton, GA.

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§ Univariate test for within subject effects over time using Greenhouse-Geisser P-value correction.
Figure 2.1. Schematic of two adjacent plots showing corn sample and buffer rows and time domain reflectometry (TDR) rod locations for field experiment at Field #533 of the Lang Farm, Coastal Plains Experiment Station in Tifton, GA.
Figure 2.2. Average monthly precipitation for 2006, 2007 and 1971-2000 for Tifton, GA.
Figure 2.3. Volumetric water content (± 1 SE) of a Tifton soil in Tifton, GA with SE over two corn growing seasons treated with peanut hull char at 0 Mg ha⁻¹ (C), 0 + fertilizer (F), 11.2 Mg ha⁻¹ (L), 11.2 Mg ha⁻¹ + fertilizer (L+F), 22.4 Mg ha⁻¹ (H), and 22.4 Mg ha⁻¹ + fertilizer (H+F). (n=4)
Figure 2.4. Volumetric water content (± 1 SE) of a Tifton soil in Tifton, GA with SE over two corn growing seasons treated with pine chip char at 0 Mg ha$^{-1}$ (C), 0 + fertilizer (F), 11.2 Mg ha$^{-1}$ (L), 11.2 Mg ha$^{-1}$ + fertilizer (L+F), 22.4 Mg ha$^{-1}$ (H), and 22.4 Mg ha$^{-1}$ + fertilizer (H+F). (n=4)
Figure 2.5. Average soil respiration (± 1 SE) and average daily soil temperature and for a Tifton soil in Tifton, GA over two corn growing season treated with peanut hull (top) and pine chip char (bottom) at 0 Mg ha\(^{-1}\) (C), 0 + fertilizer (F), 11.2 Mg ha\(^{-1}\) (L), 11.2 Mg ha\(^{-1}\) + fertilizer (L+F), 22.4 Mg ha\(^{-1}\) (H), and 22.4 Mg ha\(^{-1}\) + fertilizer (H+F). (n=4)
Table 2.2. Summary of statistical significance for soil respiration response using repeated measures and in response to fertilizer and application of char from peanut hull and pine chip char at 0, 11.2, and 22.4 Mg ha\(^{-1}\) to a Tifton soil in Tifton, GA.

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§ Univariate test for within subject effects over time using Greenhouse-Geisser P-value correction.
Figure 2.6. Grain yield (means ± 1 SE) for a corn crop in 2006 (top) and 2007 (bottom) in a Tifton soil in Tifton, GA amended with pyrolysis char from peanut hull feedstock at 0 Mg ha$^{-1}$ (C), 0 + fertilizer (F), 11.2 Mg ha$^{-1}$ (L), 11.2 Mg ha$^{-1}$ + fertilizer (L+F), 22.4 Mg ha$^{-1}$ (H), and 22.4 Mg ha$^{-1}$ + fertilizer (H+F). (n=4)
Figure 2.7. Grain yield (means ± 1 SE) for a corn crop in 2006 (top) and 2007 (bottom) in a Tifton soil in Tifton, GA amended with pyrolysis char from pine chip feedstock at 0 Mg ha\(^{-1}\) (C), 0 + fertilizer (F), 11.2 Mg ha\(^{-1}\) (L), 11.2 Mg ha\(^{-1}\) + fertilizer (L+F), 22.4 Mg ha\(^{-1}\) (H), and 22.4 Mg ha\(^{-1}\) + fertilizer (H+F). (n=4)
Figure 2.8. Biomass (means ± 1 SE) for a corn crop over two growing seasons in a Tifton soil in Tifton, GA amended with pyrolysis char from peanut hull feedstock at 0 Mg ha⁻¹ (C), 0 + fertilizer (F), 11.2 Mg ha⁻¹ (L), 11.2 Mg ha⁻¹ + fertilizer (L+F), 22.4 Mg ha⁻¹ (H), and 22.4 Mg ha⁻¹ + fertilizer (H+F). (n=4)
Figure 2.9. Biomass (means ± 1 SE) for a corn crop over two growing seasons in a Tifton soil in Tifton, GA amended with pyrolysis char from pine chip feedstock at 0 Mg ha\(^{-1}\) (C), 0 + fertilizer (F), 11.2 Mg ha\(^{-1}\) (L), 11.2 Mg ha\(^{-1}\) + fertilizer (L+F), 22.4 Mg ha\(^{-1}\) (H), and 22.4 Mg ha\(^{-1}\) + fertilizer (H+F). (n=4)
References


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CHAPTER III

A GREENHOUSE STUDY ON THE EFFECT OF PYROLYSIS CHAR ON GROWTH AND NUTRIENT CONCENTRATION OF LOBLOLLY PINE (*PINUS TAEDA L.*) SEEDLINGS AND SOIL MOISTURE OF THREE SOUTHEASTERN SOILS

Abstract

Soils in the southeastern United States are characterized by low natural fertility, low soil organic carbon (SOC), and low activity clays. The U.S. South is also the largest timber producing region in the country, with more land devoted to timber production than all other regions combined. This timber is often grown on sols which are low in plant-available Ca, K, and Mg and are generally unsuited for continuous production at maximum levels without the use of fertilizers. Pyrolysis, the thermal decomposition of biomass in the absence of oxygen, results in the production of char. Application of pyrolysis char has the potential to improve soil quality by improving the physical, chemical, and biological properties of soil, as well as increasing soil moisture retention. The objective of this study was to determine the effects of char from peanut hull and pine chip feedstocks with or without N fertilizer on growth of loblolly pine (P. taeda L.) seedlings, soil nutrient availability, and soil moisture of three soil series that represent major areas of the southeastern United States: Cecil sandy clay loam, Stilson loamy sand, and Tifton loamy sand. Amendment of pyrolysis char increased pH, total C, and nutrient availability in all soils, although this generally did not result in improved seedling growth or nutrient uptake. A char*fertilizer interaction occurred with peanut hull char in Stilson soils, significantly increasing seedling volume. Char increased soil moisture with larger effects in coarse-textured soils and on dates when seedlings were watered less frequently, indicating char amendments may improve water availability during dry periods. Overall, char is recommended as a soil amendment in the planting of loblolly pine.

INDEX WORDS: Pinus taeda, Pyrolysis, Char, Volumetric Water Content, TDR, Seedling Volume Index, Stilson, Tifton, Cecil, Greenhouse
Introduction

Impact of Soil Organic Carbon on Soil Quality

Soils in the southeastern United States are characterized by low natural fertility, low soil organic carbon (SOC), and low activity clays (Jenny, 1930). Climate and a history of poor soil management in the region have also resulted in increased rates of organic decomposition and significant loss of SOC (Franzluebbers, 2005; Bruce et al., 1995). SOC includes plant, animal, and microbial residues in all stages of decomposition and is regarded as an integral indicator of soil quality and productivity (Post and Kwon, 2000; Reeves, 1997; Jenny, 1980; Doran and Parkin, 1994). SOC affects the biological, chemical, and physical properties of soil and is the energy source for microbial processes that facilitate nutrient cycling (Reeves, 1997; Bruce et al., 1995; Bauer and Black, 1994; Nandwa, 2001). SOC has also been shown to increases plant available water (Hudson, 1994; Tilman et al., 2002), CEC (Wolf and Snyder, 2003), improve infiltration (Franzluebbers, 2002), reduce erosion and leaching of nutrients (Tilman et al., 2002), improve soil structure and stability (Batjes and Sombroek, 1997), and buffer temperature and pH change (Wolf and Snyder, 2003).

The decline of SOC in the Southeast has been attributed to cultivation, particularly soil tillage, in agricultural practices (Post and Kwon, 2000). Tinker et al. (1996) described several factors that contribute to SOC loss during cultivation: soil erosion, increased oxidation due to tillage, and higher surface temperatures increasing decomposition. In the Georgia Piedmont, 50% of SOC found to a depth of 20 cm was lost after 10 years of disturbance (Franzluebbers, 2005). Fifty years of disturbance was also shown to result in a loss of 65% of SOC compared to native conditions. These rates
of decomposition are higher than other regions of the country due to a combination of relatively high precipitation and temperature that exacerbates SOC losses due to tillage and soil disturbance. To help overcome the effect of climate and poor management on decomposition, increasing the recalcitrant fraction of SOC has been suggested as means to maintain soil fertility (Doran and Parkin, 1994; Rastogi et al., 2002).

Pyrolysis of Biomass

Pyrolysis is a thermal degradation process performed by heating in the absence of oxygen (Yaman, 2004). Pyrolysis of biomass results in the production of char, liquid, and gaseous products (Maschio et al., 1992). Products from pyrolysis have been used dating back to the Egyptians (Mohan et al., 2006), with present day uses including chemicals, fuels, and solvents (Yaman, 2004). More recently, pyrolysis has become a means of biomass conversion for energy production (Lehmann et al., 2006; Maschio et al., 1992).

Currently, limitations exist in the transportation and use of liquid and gaseous pyrolysis products (Maschio, et al., 1992); however, char shows potential as a viable product (Lehmann et al., 2006; Maschio et al., 1992). It has been suggested that char can be used as a fuel source or as an activated charcoal (Maschio et al., 1992). However, another potential use is as a soil amendment (Glaser et al., 2002a; Chidumayo, 1994; Steiner et al., 2007; Topoliantz et al., 2005).
Use of Pyrolysis Char to Improve Soil Quality and Productivity

The literature makes a distinction between the terms “charcoal” and “char” and this distinction is important to mention. Charcoal is the general term for any biomass that has undergone carbonization due to forest fires, controlled burning, or commercial production in hearths or earthen pits (Tryon, 1948; Oguntunde et al., 2004). Other terms are often used interchangeably with charcoal, including “black carbon” and “bio-char” (Schmidt and Noack, 2000; Lehmann et al., 2006), but all of these terms generally refer to biomass charred according to natural processes or ancient anthropogenic techniques with unknown production conditions such as original feedstock, temperature, or duration. Char generally refers to carbonization that occurs due to pyrolysis, gasification, or some other controlled chemical process (Bridgewater and Cottam, 1992; Di Blasi et al., 1999; Yaman, 2004). The parameters of char production, such as feedstock, particle size, temperature, and heating rate are often known, and production of char following those parameters could be repeated (Maschio et al., 1992). Char produced from pyrolysis is not presumed to be similar or analogous to naturally produced charcoal, although the terminology used is similar and can be misleading.

Most studies depicting the benefits of charred biomass on soil quality involves the presence of charcoal (Oguntunde et al., 2004; Tryon, 1948; Steiner, et al., 2007; Lima et al., 2002; Glaser et al., 2001; Topoliantz et al., 2005). The charcoal used in these studies comes from various sources produced under varying, sometimes unknown conditions, which likely affects the properties of the charcoal. It is unknown how char produced from pyrolysis under controlled conditions compares to the charcoals used in past studies.
However, based upon these charcoal studies, the use of pyrolysis char as a soil amendment should be studied to determine its affects.

Application of pyrolysis char has the potential to improve soil quality by improving the physical, chemical, and biological properties of soil (Lehmann et al., 2006; Lehmann and Rondon, 2005; Lehmann et al., 2003; Glaser et al., 2002b). Sites in Germany, Australia, Japan, Central America, and North America where instances of historic fire and anthropogenic management led to an increase of C that is still present today indicates charcoal can constitute a large portion of soil C in agricultural soils that has been shown to improve soil characteristics and is resistant to most microbial activity (Schmidt and Noack, 2000; Skjemstad et al., 2002). If amendments of pyrolysis char resulted in similar improvements, the relative stability of char would prevent quick turnover of C pools due to decomposition or soil disturbance (Lehmann and Rondon, 2005).

Charcoal affects soil fertility through the direct addition of nutrients and the indirect retention of nutrients (Lehmann et al., 2003; Briggs, 2005). Although the addition of charcoal generally increases soil fertility and productivity through the increase of available cations, other studies have shown growth depressions due to charcoal application (Tryon, 1948; Mikan and Abrams, 1996). These instances of negative impacts are generally attributed to high rates of charcoal amendment, resulting in high alkalinity and N immobilization (Lehmann et al., 2003; Tryon, 1948).
Char and Water Retention

The amount of water between field capacity (33 kPa) and permanent wilting point (1500 kPa) is considered available for plant use (Cassel and Nielsen, 1986). Charcoal has already been shown to improve retention of soil water and result in greater moisture availability to plants (Hudson, 1994; Tryon, 1948; Briggs, 2005). The amount of retention is somewhat dependent upon the nature of the parent material, method of charring, charring temperature, and age of char (Tryon, 1948). Work by Kishimoto and Sugiura (1985) showed that charcoal was able to improve porosity and water holding capacity in soils, which resulted in better plant and root growth; several mechanisms have been suggested to explain the absorptive properties of charcoal, including high surface area and capillary action (Tryon, 1948). Research is needed to determine the ability of pyrolysis char to retain soil moisture, as most research has been conducted using activated charcoal.

Much research has been conducted determining the general impacts of SOC on soil moisture retention. Hudson (1994) suggested that a 1-3% increase in SOC doubled the plant available water over three textural groups (sand, silt loam, and silty clay loam). In the sand textural class, SOC caused a greater increase in water content at field capacity than at permanent wilting point. More water would be available to plants at a lower tension, allowing easier use of soil water between rainfall or irrigation events (Hudson, 1994). Work by Briggs, (2005) indicated that application of wildfire charcoal amendments at rates up to 50 g kg soil\(^{-1}\) may linearly increase soil water content. This increase of SOC likely has direct and indirect affects on water retention. The organic
matter has higher absorbency and amendments generally improve soil physical characteristics such as bulk density and porosity (Briggs, 2005; Tester, 1990).

The objective of this study was to determine the effects of pyrolysis char from peanut hull and pine chip feedstocks on growth and nutrient concentrations of loblolly pine, soil moisture, and soil extractable nutrients of three soils series common in the southeastern United States. This study was conducted in a greenhouse over a six month period. It was hypothesized that amendments of char would increase nutrient availability in soils, as well as increase soil moisture and pine seedling growth.

**Materials and Methods**

*Experimental Design*

A greenhouse study of pyrolized char from two feedstocks was conducted at Whitehall Forest, Athens, GA to compare growth and nutrient responses of loblolly pine (*Pinus taeda L.*), as well as volumetric soil moisture response to char addition on three soils of the southeastern United States. Chars were produced by EPRIDA® from pelletized peanut hulls and pine chip feedstocks in a pyrolysis reactor at 400° C with steam. The pelletized char was roller milled prior to use in this study.

Treatments consisted of a factorial combination of feedstock (peanut hull or pine chip), application rate (0, 22.4 or 44.8 Mg ha⁻¹ equivalent), and soil type (Cecil, Stilson, or Tifton). Treatments were replicated in randomized complete blocks with four clonal families of *P. taeda* serving as blocks. Each experimental unit was replicated within each block (Figure 3.1). Clones used were from four families (Q7766, Q3802, O3621, and
L3791) and donated by International Forest Company in Moultrie, GA. The use of clones as blocks was to reduce variation within each block.

**Materials**

Surface soils from three series were used in the study: Cecil sandy clay loam (fine, kaolinitic, Thermic Typic Kanhapludult), Stilson loamy sand (loamy, siliceous, subactive, Thermic Arenic Plinthic Paleudult), and Tifton loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult). The Tifton soil was collected on October 26, 2006 at the Gibbs Farm, University of Georgia Coastal Plains Experiment Station in Tifton, GA. The site had recently been cropped in corn and was recently harrowed. The Stilson soil was collected in Valdosta, GA from a naturally regenerated slash pine (*P. elliottii*) stand owned by Langdale Forest Products. The Cecil soil was collected on November 16, 2006 at Whitehall Forest from a grass-covered field. At all sites, surface soils were removed from the top 15 cm and sieved through a 6 mm screen.

The amount of char needed for each treatment was determined by using a ratio of the volume of the seedling pot to the volume of an acre furrow slice (AFS). This ratio (8.01 x 10^{-6}) was multiplied by each application rate to determine the weight of char needed for each pot. To achieve a field application rate of 22.4 Mg ha\(^{-1}\), 72.7 g of char was applied to soil for each pot. This amount of char was doubled and added to each pot to achieve a rate of 44.8 Mg ha\(^{-1}\). The char treatments were uniformly incorporated at the specified rates (22.4 or 44.8 Mg ha\(^{-1}\)) by adding the necessary amount of char to five gallons of soil and thoroughly mixing it in a cement mixer for several minutes. This five
gallon mix was enough to fill approximately four pots, with the mixing process repeated until all pots were filled with the assigned treatment.

Seedlings were planted in the pots on February 13, 2006. To simulate tillage depth in the field, each pot was filled to a depth of 2.54 cm with unamended soil of the designated soil type (Cecil, Stilson, or Tifton), then filled with respective treatments to a total depth of approximately 18 cm. One block (family) of seedlings was planted at a time, starting with Block 1 and continuing in sequential order. Each seedling was randomly chosen from the selected family and hand-planted in each pot. Seedlings were kept moist during planting and were watered after planting. Seedlings were watered weekly during the first four weeks of the study, and twice weekly for the remainder of the six-month study using tap water.

Four months into the study, seedlings began displaying signs of chlorosis, which indicated a possible N deficiency. One of the two replicates of each treatment in each block was randomly selected to receive fertilization, totaling four replicates of each treatment. For each selected pot, 1.35 g (0.14 Mg ha\(^{-1}\)) of ammonium nitrate (NH\(_4\)NO\(_3\)) fertilizer was hand applied evenly over the pot. To prevent salt-shock to roots, this amount was split over two applications two weeks apart and all pots were watered before and after each fertilization. Prior to the first fertilization treatment, needles were collected from the upper 2/3 of each seedling and by treatment and block for nutrient analysis.
Measurement and Analysis

Seedling height (Ht) and ground line diameter (GLD) were measured every two weeks for the duration of the six-month study. Initial measurements were made four days after planting. Height from soil surface to tip of apical bud was measured with a meter stick to the nearest 0.1 cm. GLD was measured to the nearest 0.01 mm using digital calipers. Seedling volume was defined by determining the stem volume increment (SVI) in cm³ and calculated using the equation (Wheeler et al., 2002):

$$SVI = Ht \times GLD^2.$$  

Soil moisture was measured weekly using a Riser Bond Model 1205CXA coaxial metallic time domain reflectometer (TDR) (Radiodetection, Bridgton, ME). In each pot, soil moisture at 0-10 cm was measured with a pair of parallel 10 cm steel rods installed vertically to the soil surface. Topp’s equation was used to convert TDR readings to a volumetric soil moisture percentage (Topp and Davis, 1985).

Soil samples were collected at establishment and at harvest for each treatment. Soil pH was determined using a 0.01 M calcium chloride (CaCl₂) solution with 1 soil:solution ratio. Total carbon was determined using a LECO CNS 2000 Carbon Analyzer (LECO Corporation, St Joseph, MI, USA). Ammonium (NH₄) and nitrate (NO₃) N were extracted using a 1M potassium chloride (KCl) solution and analyzed using a Perstorp EnviroFlow 3000 AutoAnalyzer. Extractable nutrients, P, Ca, K, and Mg were extracted using a Mehlich solution (Mehlich, 1953) and Enviro I inductively coupled plasma (ICP) mass spectrometer (Thermo Jarrel-Ash, Franklin, MA).
Harvest and Analysis

Seedlings were harvested on August 21, 2007. Stems were cut at ground level and needles removed. Stems and needle biomass was separated, dried at 65° C, and weighed to determine biomass for each seedling.

Foliage was ground by Wiley mill and passed through a 2 mm screen prior to elemental analysis (Bremmer and Mulvaney, 1982). Total C and N were determined using an automatic elemental analyzer on the NC 2100 Soil Analyzer (CE Instruments, USA) following the Dumas dry combustion technique (Dumas, 1831). Foliage was also digested following the Kjeldahl method and measured for total P, Mg, Ca, and K using an ICP mass spectrometer (Kirk, 1950).

Statistical Analysis

Data were analyzed using the Statistical Analysis System (SAS) general linear model (GLM) procedure (SAS Institute, Cary NC) for a 3 x 3 x 2 factorial experiment. Main effects (soil, char type, rate) were treated as main plots which were split by fertilizer treatment within a randomized complete block (RCB) design. In the analysis, control treatments were treated as a third char type (control, pine, and peanut). Tests for normality were conducted using the univariate procedure in SAS and were transformed if assumptions of normality were violated. Soil moisture data were adjusted using a square root transformation and SVI data were adjusted using a logarithmic transformation.

For data collected prior to fertilization, data were analyzed for a three-way factorial design with randomized complete blocks. For data collected after fertilization, the fertilizer split-plot factor was included in the analysis. An adjusted error term (whole
unit remainder) was used to analyze the effect of block, char type, rate, and soil on results. Soil moisture data were analyzed with a repeated measures analysis of variance (ANOVA) and evaluated using a univariate analysis for within and between subject effects. Final Ht, GLD, and SVI data were analyzed using analysis of covariance (ANCOVA) with split-plot; initial Ht, GLD, and SVI were used as the covariate in the analysis. Differences among treatments and fertilizer effects were evaluated using Tukey’s means separation procedure when significant differences ($\alpha=0.05$) were indicated by SAS procedures.

**Results**

*Seedling Growth*

For Ht, GLD, and SVI, the main factor effect of soil type was significant (Table 3.1). Seedling SVI was lowest in the Stilson soil, with an average of $27.10 \pm 3.28$ cm$^3$ and $34.66 \pm 1.91$ cm$^3$ in control and fertilized treatments, respectively (Table 3.2). A soil*char interaction ($P<0.0001$) existed, with peanut hull char contributing more to seedling growth than pine chip char in the Stilson soil; an interaction also occurred in Cecil soil, with peanut hull char negatively affecting seedling growth (Table 3.2). A soil*char*rate interaction also existed in Ht, GLD, and SVI (Table 3.1).

Fertilizer had an overall significant effect on Ht, GLD, and SVI (Table 3.1), but did not significantly increase Ht, GLD, or SVI in control treatments of the three soils (Table 3.2). Fertilizer did have an effect on soils with char treatments. In Stilson soil, fertilizer increased SVI by 43%, 38%, and 37% in peanut hull L, H, and pine chip L treatments, respectively, while only a 22% SVI increase occurred in the fertilized control.
This effect seemed to indicate a char*soil*fertilizer interaction, which was not statistically significant in SVI, but was in Ht (Table 3.1). Fertilizer and char also led to increases in seedling Ht and GLD in the Stilson soil and also in the Tifton soil, with no instances found in the Cecil soil (Table 3.2).

Stem and needle biomass was affected by soil type (P<0.0001) as well as by a soil*char (P<0.0001) and soil*char*rate interaction in both stem (P=0.0031) and needle (P=0.0014) (Table 3.3). Fertilizer also affected both stem and needle biomass (P<0.0001). Stem and needle weight were significantly lower in Tifton soils with pine chip char at 22.4 Mg ha\(^{-1}\) + fertilizer compared to fertilized control. Peanut hull char combined with fertilizer increased biomass at both low and high rates in the Stilson soil. Similar to results of seedling volume, stem and needle weight were significantly lower in seedlings treated with peanut hull char at 22.4 Mg ha\(^{-1}\) in the Cecil soil (Table 3.3).

**Nutrient Concentration**

Foliar Elemental Analysis

Prior to fertilization, amendment with peanut hull char resulted in higher foliar Ca concentration than amendment with pine chip char (P=0.01). Concentrations of K for treatments varied slightly by soil type and also by treatment. Peanut hull char amendments slightly increased K concentration in seedlings grown in Stilson soil compared to pine chip char, while K was lower in seedlings in amended Cecil soil compared to the control, and all char treatments increased foliar K compared to the control in the Tifton soil (Figure 3.2). Magnesium varied by soil type (P=0.0003), with seedlings grown in Stilson soil having a higher foliar concentration than those grown in
Cecil or Tifton soils. Char type had a significant (P=0.01) affect on foliar Mg.

Concentrations were higher in Stilson soil with peanut hull char than most other treatment combinations. Char*soil interaction due to peanut hull char and Stilson soil significantly increased foliar P concentrations (P=0.02) compared to pine chip char, but had no similar effects in other soils (Figure 3.2).

Analyses of samples collected at harvest showed similar results to pre-fertilized samples, with peanut hull char resulting in higher foliar Ca concentrations than pine chip char (P=0.03). No general trends existed that would explain any main effects on K or Mg concentrations (Figure 3.3), although a four-way interaction existed within the effects of char, soil, rate, and fertilizer for both K (P=0.005) and Mg (P=0.03). Rate of char application affected foliar P concentration (P=0.0067). In unfertilized treatments, phosphorus was 17% lower in seedlings in Cecil soils treated with peanut hull char at 44.8 Mg ha\(^{-1}\) compared to 22.4 Mg ha\(^{-1}\) and 19% lower in Tifton soil (Figure 3.3). Total foliar N was increased by fertilizer (P<0.0001) and also affected by soil type (P<0.0001). Seedlings in Stilson soil responded most favorably to fertilizer, although char treatments with fertilizer were significantly lower compared to the control (Figure 3.4). In unfertilized conditions, neither char improved foliar N concentration compared to controls.

Soils Analysis

In general, nutrient concentrations varied by soil, with the Tifton and Cecil soils having higher concentrations in every element measured compared to Stilson soil (P<0.0001). Initial soils analysis indicated a pre-existing fertilizer effect in the Tifton
soil, with amounts of NH$_4$ N, P, and Ca much higher in the Tifton control than Cecil and Stilson controls (Table 3.4). This effect is most likely from agricultural fertilization prior to soil collection for this experiment. The Cecil control had higher amounts of K and Mg than Tifton and Stilson controls. A soil*char interaction existed in the analysis for every element except NH$_4$ N. A soil*char*rate interaction also existed in nearly all instances (Table 3.5).

Char amendments from both feedstocks increased total soil C with increases in rate of application (Table 3.4 and 3.5). Pine chip char at 44.8 Mg ha$^{-1}$ resulted in a slightly higher percentage of total C than equal rates of peanut hull char. Peanut hull char significantly increased availability of cations P, K, Mg (P<0.0001) and Ca (P=0.0002) when compared to pine chip char (Table 3.4). The addition of char, and increasing rates of char amendment, generally resulted in higher initial nutrient concentration for each soil (Table 3.4); however, this was not true at 44.8 Mg ha$^{-1}$ of pine chip char in Tifton soil, which resulted in lower Ca (P=0.0329) or at either rate of pine chip char which resulted in lower Mg (P=0.0014) compared to the control soil (Table 3.4).

Analyses of soils collected at harvest indicated concentrations of P, K and Mg were significantly higher in soils amended with pine chip char than peanut hull char (Table 3.6 and Table 3.7). This contrasts with results from initial soils analyses, which showed peanut hull char significantly improved availability of these nutrients compared to pine chip char (Table 3.4 and Table 3.5). In each soil type, fertilizer increased amounts of NH$_4$ N and NO$_3$ N compared to the control (P<0.0001). Char treatments with fertilizer had higher concentrations of NH$_4$ N and NO$_3$ N compared to unfertilized char treatments; however, these concentrations were generally lower than the fertilized
controls (Table 3.6). A soil*char*fertilizer interaction also existed, which affected total C, NH$_4$ N, NO$_3$ N, and K (Table 3.7).

When observing the differences between final and initial soil analyses, an obvious contrast existed in the concentrations of K, P, and Mg for peanut hull and pine chip chars (Table 3.8). Initially, soils with peanut hull char amendments had higher concentrations of extractable K, P, and Mg than soils amended with pine chip chars across all soil types (Table 3.4). At harvest, differences showed that pine chip char amended soils had higher concentrations of extractable K, P, and Mg while peanut hull char amended soils had drastically lower concentrations. In Cecil soil alone, pine chip char at 44.8 Mg ha$^{-1}$ resulted in an increase of 4.6, 325 and 65.2 kg ha$^{-1}$ in P, K, and Mg respectively; equivalent rates of peanut hull char resulted in decreases of 12.7, 568, and 92.3 kg ha$^{-1}$ of P, K, and Mg (Table 3.8).

**Volumetric Water Content**

Soil moisture varied by soil type over the six months of measurement (P<0.001), with values in the Cecil soil generally higher than Stilson or Tifton soils (Figures 3.5a,b,c). Time was also significant (P<0.0001), with volumetric water content generally decreasing over time, indicating increasing water demand by seedlings. Analyses of data from the three measurements after fertilization showed no significant fertilizer effect on soil moisture. Therefore, values presented in Figures 3.5a,b,c for the final three dates were averaged by treatment and removed fertilizer treatments.

Rate of application affected soil moisture over all measurement dates (P=0.0008); however, a time*char*soil*rate interaction (P=0.0004) occurred, indicating that the effect
of application rate was not consistent by char type or soil type. In Cecil soil, volumetric water content was increased in treatments with both high and low rates of peanut hull char while only the high rate of pine chip char consistently resulted in higher volumetric water content compared to the control (Figure 3.5a).

Water content of Stilson soil was increased by char amendments on a few measurement dates, but there were many measurement dates where no difference existed between char treatments and the control (Figure 3.5b). One trend was observed during the first four weeks of measurements, char amendments resulted in increased soil moisture at low moisture percentages (< 30%). This trend coincided with watering schedule, with seedlings watered only once weekly during the first four weeks.

Results in the Tifton soil were similar to those of the Cecil soil with high rates of peanut hull and pine chip char resulting in higher moisture content compared to the control over most measurements (Figure 3.5c). Results were also similar to those in the Stilson soil in that char amendments increased soil moisture over the first two months of measurements when soil moisture was low.

Discussion

Seedling Growth and Nutrient Concentrations

The U.S. South is the largest timber producing region in the country, with more land devoted to timber production than all other regions combined (Haynes, 2002). This timber is often grown on relatively infertile Ultisols, which are low in plant-available Ca, K, and Mg and are generally unsuited for continuous production without the use of fertilizers (McDaniel, 2007). Due to the native infertility of southeastern soils, nutrient
deficiencies in N and P are a major limiting factor on tree growth in the southeastern United States and fertilizers are required to maximize growth (Allen, 1987).

Studies have shown that soils high in charcoal and black carbon produced by fires are more fertile than adjacent soils absent of charcoal (Schmidt and Noack, 2000). In unfertilized soils, charcoal amendments alone generally increased availability of nutrients in each soil; however, these results did not result in increased seedling height, diameter, or volume (Table 3.2). Char amendments also increased the effectiveness of fertilizer addition by increasing seedling height, diameter, and volume. These results are similar to findings from Yamato et al. (2006) which showed that a combination of charcoal and mineral fertilizer resulted in better growth of agronomic crops than crops treated with only fertilizer.

Char from each feedstock was shown to increase availability of soil nutrients at establishment (Table 3.4). Peanut hull char increased the availability of these macronutrients compared to pine chip char, although both chars increased these nutrients compared to the controls. Gaskin et al. (2007), using char from pine chip and peanut hull feedstocks created under the same production conditions as chars in this experiment, showed that peanut hull char was higher in available K, P, and Ca. Gaskin et al. (2007) also showed that peanut hull char had a cation exchange capacity (CEC) of 44 cmol kg$^{-1}$ compared to a 27 cmol kg$^{-1}$ capacity in pine chip char. Although CEC was not measured in this study, it can be assumed that char would increase the charge capacity of soils in the Southeast with typically low CEC’s, such as Tifton and Stilson soils (Perkins, 1987).

Results of soils analyses at the end of six months provided unexpected results given the nature of peanut hull char and initial chemical analysis (Table 3.6). Soils
amended with pine chip char had higher concentrations of several cations compared to soils amended with peanut hull char at the end of this study (Table 3.6). A full understanding of this response is not available without total nutrient concentrations from soil digestions or analysis of leachate waters. In an experiment comparing pine chip and peanut hull feedstocks in a field experiment located on a Tifton soil series, available P levels decreased for both feedstocks after two years (Gaskin, not published). Foliar digestions also did not show any significant difference in nutrient concentrations between pine chip and peanut hull char, removing the possibility of increased plant uptake of these nutrients in soils treated with peanut hull char (Figure 3.3). Other reasons for this difference may be a result of increased leaching of nutrients from the peanut hull char compared to pine chip char or differences between plant-available concentrations shown by Mehlich extraction and total soil concentrations which would be explained through soil digestion.

N and P are the two elements most often deficient in forested sites (Leaf, 1968). This is especially true in southeastern soils, which are most often fertilized with N and P at site establishment (Allen, 1987). In the southeastern Coastal Plain, responses to early P-fertilization may last well into a stand’s development, with responsive sites averaging 3.5 m³ ha⁻¹ year⁻¹ for 15-20 years (Pritchett and Comerford, 1982) and site index increases of 2.4-4.5 meters or more at 25 years (Allen, 1987). Application of N has been shown to increase growth by 2.8-3.5 m³ ha⁻¹ year⁻¹, similar to P application, but the duration of the response lasts only 5-8 years depending on site characteristics (Allen, 1987). Typical rates of application on southeastern Coastal Plain sites average 45-56 kg ha⁻¹ of P at establishment and 170-225 kg ha⁻¹ N on established stands (Allen, 1987).
Chemical analyses of soils at establishment indicated that char application did not increase available P to this recommended application rate. Concentration of available P was above the 45 kg ha\(^{-1}\) recommended rate in the Tifton soil, but this was due to previous fertilizer effects as indicated by the high concentration of P in the control soil (Table 3.4). Concentrations of N were also below the recommended rate at both establishment and harvest. Fertilized seedlings, which were treated with approximately 140 kg ha\(^{-1}\) NH\(_4\)NO\(_3\), generally did not show an increase in seedling growth with or without char amendment (Table 3.2). However, an increase in seedling growth may have been noticed if more than two months after fertilization had been allowed for measurement.

Sites that are often too dry or too wet for agriculture are still often used in forest production (Pritchett and Fisher, 1987). Kishimoto and Sugiura (1985) showed application of charcoal increased porosity and soil moisture, which improved crop response. Work by Tryon (1948) showed that charcoal was only beneficial in increasing available moisture in sandy soils. In our study, char was shown to increase soil moisture percentages in all three soil types, which varied in texture from loamy sand to sandy clay loam. These increases were most notable in sandier soils during the first four weeks of measurement (Figures 3.5a,b,c). These measurement dates are important to point out, as seedlings were only watered once weekly, compared to twice weekly after this four week period. These results suggest that drought conditions are ameliorated by char amendments in sandy soils, likely due to the high surface area of char attributing to adsorption and retention of low amounts of water against gravity (Tryon, 1948; Kishimoto and Sugiura, 1985).
Soil moisture was generally higher in the Cecil soil than the two courser-textured soils (Figures 3.5a,b,c). The observed increases in soil moisture in the Cecil soil may be also result from decreased seedling growth. Soil moisture was consistently higher with low rates of peanut hull char amendment (Figures 3.5a). This coincides with significantly decreased seedling growth compared to the control or high rate of peanut hull char (Table 3.2). This relationship indicates that higher moisture contents may partly result from reduced transpiration from seedlings rather than a char affect.

**Conclusions**

Our hypotheses were that amendment of pyrolysis char would increase the nutrient availability of soils and increase growth of loblolly pine. Overall, amendment of pyrolysis char increased pH, total C, and improved nutrient availability in Cecil, Stilson, and Tifton soils. However, this increase in nutrient availability did not result in significant growth increases in most cases. Exceptions occurred with seedlings planted in Stilson soils, where amendments of peanut hull char increased seedling height and volume in fertilized and unfertilized conditions. Application of peanut hull char at rates of 10 Mg ha\(^{-1}\) did cause a decrease in seedling growth in Cecil soils. A char*fertilizer interaction occurred with peanut hull char in Stilson soils, significantly increasing seedling volume.

We also hypothesized that char amendment would increase moisture content. Results were not consistent among all soil types, but char did increase soil moisture in coarse-textured soils, especially when seedlings were watered less frequently. This
indicates that char amendments may have the greatest chance of increasing soil moisture availability during dry periods.

Application of char showed to ameliorate soil conditions by increasing nutrients and total C. Based upon results from this greenhouse study on three different soil types, char amendment may be most beneficial in soil types of the lower Coastal Plain, such as the Stilson soil series. Fertilization would also be required in these sites to best meet production potential. With the application of char only showing negative effects in one instance in this study, it would be recommended that char application can be beneficial.
Figure 3.1. Block schematic of design for greenhouse experiment using pyrolysis char from peanut hull (PN) and pine chip (PC) feedstocks at 0 (C), 22.4 Mg ha\(^{-1}\) (L), and 44.8 Mg ha\(^{-1}\) (H) on Cecil (C), Stilson (S), and Tifton (T) soil series with duplicated treatments.
Table 3.1. Summary of statistical significance (P< F) for average height (Ht), ground line diameter (GLD), and stem volume index (SVI) of loblolly pine response to soil type, char type, application rate, fertilizer, and interaction of soil type, char type, and application rate after six months in a greenhouse study.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Ht</th>
<th>GLD</th>
<th>SVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil type£</td>
<td>2</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>char type§</td>
<td>1</td>
<td>0.2712</td>
<td>0.6997</td>
<td>0.6969</td>
</tr>
<tr>
<td>app. rate*</td>
<td>1</td>
<td>0.1027</td>
<td>0.1825</td>
<td>0.0211</td>
</tr>
<tr>
<td>fertilizer</td>
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<td>0.0001</td>
<td>0.0004</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>soil*char</td>
<td>2</td>
<td>&lt;0.0001</td>
<td>0.0005</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>char*rate</td>
<td>1</td>
<td>0.0275</td>
<td>0.4966</td>
<td>0.0512</td>
</tr>
<tr>
<td>soil<em>char</em>rate</td>
<td>2</td>
<td>0.0293</td>
<td>0.0237</td>
<td>0.0168</td>
</tr>
<tr>
<td>soil<em>char</em>fert</td>
<td>8</td>
<td>0.0224</td>
<td>0.4201</td>
<td>0.2696</td>
</tr>
</tbody>
</table>

£ Cecil, Stilson, and Tifton soil series
§ Peanut hull and pine chip feedstocks
* 0, 22.4, and 44.8 Mg ha⁻¹
Table 3.2. Average height (Ht), ground line diameter (GLD), and stem volume index (SVI) of loblolly pine after six months in a greenhouse study using pyrolysis char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 Mg ha\(^{-1}\) (L), and 44.8 Mg ha\(^{-1}\) (H) with N fertilizer treatment (F) and without (NF).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Treatment</th>
<th>Ht (cm)</th>
<th>GLD (mm)</th>
<th>SVI* (cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NF</td>
<td>F</td>
<td>NF</td>
</tr>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>£§67.26(^{a,c})</td>
<td>62.85(^{a,c})</td>
<td>9.30(^{a,c})</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull L</td>
<td>52.88(^{a,d})</td>
<td>49.45(^{a,d})</td>
<td>6.73(^{a,d})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>61.73(^{a,c})</td>
<td>59.50(^{a,c})</td>
</tr>
<tr>
<td></td>
<td>Pine Chip L</td>
<td>66.83(^{a,c})</td>
<td>67.53(^{a,c})</td>
<td>9.50(^{a,c})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>64.95(^{a,c})</td>
<td>67.73(^{a,d})</td>
</tr>
<tr>
<td>Stilson</td>
<td>Control</td>
<td>52.21(^{a,c})</td>
<td>57.89(^{a,c})</td>
<td>7.13(^{a,c})</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull L</td>
<td>59.03(^{a,c})</td>
<td>64.23(^{a,d})</td>
<td>7.55(^{a,c})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>64.43(^{a,d})</td>
<td>73.93(^{b,d})</td>
</tr>
<tr>
<td></td>
<td>Pine Chip L</td>
<td>51.40(^{a,c})</td>
<td>63.73(^{b,c})</td>
<td>6.95(^{a,c})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>51.03(^{a,c})</td>
<td>56.45(^{a,c})</td>
</tr>
<tr>
<td>Tifton</td>
<td>Control</td>
<td>69.11(^{a,c})</td>
<td>75.10(^{a,c})</td>
<td>9.09(^{a,c})</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull L</td>
<td>74.48(^{a,c})</td>
<td>69.35(^{a,c})</td>
<td>8.98(^{a,c})</td>
</tr>
<tr>
<td></td>
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<td>69.13(^{a,c})</td>
<td>71.95(^{a,c})</td>
</tr>
<tr>
<td></td>
<td>Pine Chip L</td>
<td>61.20(^{a,c})</td>
<td>66.90(^{a,c})</td>
<td>8.20(^{a,c})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>64.38(^{a,c})</td>
<td>74.53(^{a,c})</td>
</tr>
</tbody>
</table>

* SVI = Ht (cm)\*ground line diameter (cm\(^2\))

£ Means with dissimilar first letters are significantly different between fertilizer treatments at the 0.05 level using Tukey’s means separation procedure.

§ Means with dissimilar second letters are significantly different among char treatments at the 0.05 level using Tukey’s means separation procedure.
Table 3.3. Stem and needle biomass of loblolly pine after six months growth in a greenhouse study using pyrolysis char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 Mg ha$^{-1}$ (L), and 44.8 Mg ha$^{-1}$ (H) with N fertilizer treatment (F) and without (NF).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Treatment</th>
<th>Stem Wt. (g)</th>
<th>Needle Wt. (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NF F</td>
<td>NF F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>8.14$^{a,c}$</td>
<td>8.50$^{a,c}$</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>4.38$^{a,d}$</td>
<td>4.10$^{a,d}$</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6.85$^{a,c}$</td>
<td>8.93$^{b,c}$</td>
</tr>
<tr>
<td></td>
<td>Pine Chip</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>10.13$^{a,c}$</td>
<td>9.50$^{b,c}$</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>9.43$^{a,c}$</td>
<td>10.33$^{a,c}$</td>
</tr>
<tr>
<td></td>
<td>Stilson</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>3.48$^{a,c}$</td>
<td>4.59$^{a,c}$</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>5.10$^{a,c}$</td>
<td>7.38$^{a,d}$</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>4.93$^{a,c}$</td>
<td>9.03$^{b,d}$</td>
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<td></td>
<td>Pine Chip</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>3.58$^{a,c}$</td>
<td>6.80$^{b,c}$</td>
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<td></td>
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<td>3.43$^{a,c}$</td>
<td>5.58$^{a,c}$</td>
</tr>
<tr>
<td></td>
<td>Tifton</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>8.19$^{a,c}$</td>
<td>10.33$^{b,c}$</td>
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<tr>
<td></td>
<td>Peanut Hull</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>9.13$^{a,c}$</td>
<td>9.63$^{a,c}$</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6.98$^{a,c}$</td>
<td>8.38$^{a,c}$</td>
</tr>
<tr>
<td></td>
<td>Pine Chip</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>5.10$^{a,d}$</td>
<td>7.83$^{a,d}$</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>6.48$^{a,c}$</td>
<td>9.60$^{b,c}$</td>
</tr>
</tbody>
</table>

£ Means with dissimilar first letters are significantly different between fertilizer treatments at the 0.05 level using Tukey’s means separation procedure. § Means with dissimilar second letters are significantly different among char treatments at the 0.05 level using Tukey’s means separation procedure.
Figure 3.2. Concentrations (means ± 1 SE) of Ca, K, Mg, and P in plant tissue of loblolly pine prior to fertilization in a greenhouse study using char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 Mg ha$^{-1}$ (L), and 44.8 Mg ha$^{-1}$ (H) across three soil types. (n=4)
Figure 3.3. Concentrations (means ± 1 SE) of Ca, K, Mg, and P in plant tissue of loblolly pine after six months in a greenhouse study using pyrolysis char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 Mg ha⁻¹ (L), and 44.8 Mg ha⁻¹ (H) ± N fertilizer treatment across three soil types. (n=4)
Figure 3.4. Foliar nitrogen (N) percent (means ± 1 SE) of loblolly pine after a six month greenhouse study with three soil types amended with char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 (L), and 44.8 (H) Mg ha$^{-1}$ ± N fertilizer treatment across three soil types. (n=4)
Table 3.4. Analyses of pH, total C, KCl extracted NH₄ N and NO₃ N, and Mehlich I nutrients of surface soils from Cecil, Stilson, and Tifton series at the establishment of a six month greenhouse study using char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 Mg ha⁻¹ (L), and 44.8 Mg ha⁻¹ (H).

<table>
<thead>
<tr>
<th>Soil</th>
<th>Treatment</th>
<th>pH</th>
<th>Total C %</th>
<th>NH₄-N</th>
<th>NO₃-N</th>
<th>P kg ha⁻¹</th>
<th>K kg ha⁻¹</th>
<th>Ca kg ha⁻¹</th>
<th>Mg kg ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>4.62</td>
<td>0.90</td>
<td>4.48</td>
<td>1.68</td>
<td>6.88</td>
<td>103.25</td>
<td>506.46</td>
<td>148.29</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull L</td>
<td>5.05</td>
<td>2.73</td>
<td>4.48</td>
<td>4.98</td>
<td>13.08</td>
<td>383.94</td>
<td>632.74</td>
<td>199.08</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>5.60</td>
<td>4.62</td>
<td>4.48</td>
<td>8.96</td>
<td>22.65</td>
<td>708.23</td>
<td>707.20</td>
<td>228.09</td>
</tr>
<tr>
<td></td>
<td>Pine Chip L</td>
<td>4.74</td>
<td>3.08</td>
<td>5.04</td>
<td>1.12</td>
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Table 3.5. Summary of statistical significance (P< F) for response of nutrient concentrations to soil type, char type, application rate, and interactions of soil, char, and rate at the establishment of a six month greenhouse study.

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<th>Ca</th>
<th>Mg</th>
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£ Cecil, Stilson, and Tifton soil series
§ Peanut hull and pine chip feedstocks
* 0, 22.4, and 44.8 Mg ha$^{-1}$
Table 3.6. Analyses of pH, total C, KCl extracted NH$_4$ N and NO$_3$ N, and Mehlich I nutrients of surface soils (0-15 cm) from Cecil, Stilson, and Tifton series at the end of a six month greenhouse study using char from peanut hull and pine chip feedstocks at 0 (Control), 0 + fertilizer (Cont. + Fertilizer), 22.4 Mg ha$^{-1}$ (L), 22.4 Mg ha$^{-1}$ + fertilizer (L+F), 44.8 Mg ha$^{-1}$ (H), and 44.8 Mg ha$^{-1}$ + fertilizer (H+F).

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Table 3.7. Summary of statistical significance (P< F) for response of nutrient concentrations to soil type, char type, application rate, fertilizer, and interactions of soil, char, rate, and fertilizer at the end of a six month greenhouse study.

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Table 3.8. Difference (Final - Initial) between final and initial soil analyses of pH, total C, KCl extracted NH$_4$ N and NO$_3$ N, and Mehlich I nutrients of surface soils from Cecil, Stilson, and Tifton series using char from peanut hull and pine chip feedstocks at 0 (Control), 22.4 Mg ha$^{-1}$ (L) and 44.8 Mg ha$^{-1}$.

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<td>Pine Chip L</td>
<td>0.33</td>
<td>-0.15</td>
<td>0.84</td>
<td>-0.75</td>
<td>9.09</td>
<td>163.66</td>
<td>180.12</td>
<td>67.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.50</td>
<td>-1.14</td>
<td>0.07</td>
<td>-0.41</td>
<td>18.34</td>
<td>308.91</td>
<td>196.98</td>
</tr>
<tr>
<td>Tifton</td>
<td>Control</td>
<td>-0.79</td>
<td>-0.08</td>
<td>0.13</td>
<td>-15.10</td>
<td>-5.58</td>
<td>-18.28</td>
<td>109.41</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull L</td>
<td>0.23</td>
<td>0.05</td>
<td>-1.07</td>
<td>-13.08</td>
<td>-26.20</td>
<td>-154.97</td>
<td>19.99</td>
<td>-18.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>-0.27</td>
<td>0.66</td>
<td>-9.99</td>
<td>-11.54</td>
<td>-34.95</td>
<td>-334.32</td>
<td>-26.74</td>
</tr>
<tr>
<td></td>
<td>Pine Chip L</td>
<td>0.31</td>
<td>-0.51</td>
<td>-0.82</td>
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<td>5.53</td>
<td>94.14</td>
<td>130.68</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>0.28</td>
<td>-0.14</td>
<td>-3.31</td>
<td>-13.89</td>
<td>9.20</td>
<td>154.91</td>
<td>127.06</td>
</tr>
</tbody>
</table>
Figure 3.5a. Volumetric water content (means ± 1 SE) of a Cecil soil control and soil amended with 22.4 (L) and 44.8 (H) Mg ha⁻¹ of pyrolysis char from peanut hull and pine chip feedstocks over a six month greenhouse study. (n=8)
Figure 3.5b. Volumetric water content (means ± 1 SE) of a Stilson soil control and soil amended with 22.4 (L) and 44.8 (H) Mg ha$^{-1}$ of pyrolysis char from peanut hull and pine chip feedstocks over a six month greenhouse study. (n=8)
Figure 3.5c. Volumetric water content (means ± 1 SE) of a Tifton soil control and soil amended with 22.4 (L) and 44.8 (H) Mg ha\(^{-1}\) of pyrolysis char from peanut hull and pine chip feedstocks prior to fertilization over a six month greenhouse study. (n=8)


Jenny, H. 1930. A study on the influence of climate upon the nitrogen and organic matter content of the soil. Research Bulletin 152, Missouri Agricultural Experiment Station, Columbia, Missouri, USA.


Perkins, H. 1987. Characterization data for selected Georgia soils. The Georgia Agricultural Experiment Stations Spec.Publ.43. The University of Georgia, Athens, GA.


CHAPTER IV

THE EFFECT OF PYROLYSIS CHAR ON CARBON MINERALIZATION IN THREE SOUTHEASTERN SOILS

3


105
Abstract

Sequestering atmospheric carbon dioxide (CO\textsubscript{2}) has become a global concern, with concentrations of CO\textsubscript{2} increasing 30% since 1750. The pool of soil carbon (C) has a profound impact on the global C cycle, with nearly twice as much C stored in soil organic carbon (SOC) than in the atmosphere. With such a large influence on global carbon cycling and increased pressure to reduce atmospheric C concentrations, soil management focusing on carbon sequestration is essential. The application of organic amendments and incorporation of crop residues has been proven to increase SOC in Southeast U.S. soils. However, application of conventional organic matter, such as manure or crop residues, often only causes a short-term increase of SOC before mineralization releases carbon into the atmosphere. The recalcitrance of pyrolysis char sets it apart from fresh organic amendments in terms of C sequestration potential, especially in humid regions with high decomposition rates. To determine the potential of pyrolysis char to sequester soil C, a 24-day laboratory incubation experiment was conducted using three soils representative of the southeastern United States. Carbon mineralization was affected by soil type, with higher rates of carbon loss in a Cecil sandy clay loam compared to Stilson and Tifton loamy sands. Rates of mineralization were highest during the first three days of incubation across each soil type. Amendment of pyrolysis char did not significantly increase or decrease carbon mineralization during any time interval during the 24-day incubation experiment. This indicates that amendments of pyrolysis char would result in C sequestration in southeastern soils.

INDEX WORDS: Incubation, Carbon, Mineralization, Pyrolysis, Char, Titration
Introduction

Sequestering atmospheric carbon dioxide (CO$_2$) has become a global concern, with concentrations of atmospheric CO$_2$ increasing 30% since 1750 (IPCC, 2001). Most of this increase has been attributed to combustion of fossil fuels over the last 50 years, yet the large pool of potentially mineralizable C in soils is nearly 10 times the amount of CO$_2$ released from fossil fuels (Raich and Tufekcioglu, 2000). Therefore, the greatest potential for C sequestration is in soil and SOC (Causarano et al., 2006; Franzluebbers, 2005; West and Post, 2002). The soil C pool has a profound impact on the global C cycle, with nearly twice as much C stored in SOC than in the atmosphere (Parker et al., 2001). With such a significant influence on global C cycling and increased pressure to reduce atmospheric C concentrations, soil management focusing on C sequestration is essential (Barnwell et al., 1992).

The amount of SOC represents a long-term balance between C inputs and C losses from the soil (Gregorich et al., 1998; Follett, 2001). In undisturbed systems, this balance is in a state of quasi-equilibrium, with soil C losses equaling C input from plants (Follett, 2001). Soil C losses are a result of erosion and soil respiration, which results from microbial, root, and faunal activity (Rastogi et al., 2002). Agricultural practices and land-use change have led to large amounts of erosion and increased C efflux over the course of many years (Franzluebbers, 2005; Lal, 2004). However, agricultural practices can also maintain or increase SOC, thus increasing rates of C sequestration (Reeves, 1997; Follett, 2001; Rosenberg and Izaurralde, 2001; Causarano et al., 2006). Techniques such as reduced tillage and intensive cropping systems can increase C sequestration as much as 30 to 105 million metric tons of carbon (MMTC) yr$^{-1}$ in the
United States (Follett, 2001). West and Post (2002), analyzing several long term experiments (n=93), showed no-till treatments can sequester 48 ± 13 g C m$^{-2}$ yr$^{-1}$ over an average of 15 years when compared to conventional tillage. Results also showed sequestration rates were higher for crop rotation systems than continuous monocultures.

Application of organic amendments and crop residues has been shown to increase SOC in the Southeast (Follett, 2001; Edmeades, 2003; Franzluebbers, 2005). However, application of conventional organic matter, such as manure or crop residues, often results in only a short-term increase of SOC before mineralization releases carbon into the atmosphere (Johnson et al., 2004), and may also lead to poor water quality (Edmeades, 2003). Buyanovsky and Wagner (1987) reported that 80% of a crop residue left on a field was mineralized and returned to the atmosphere within 2 years. Amendments of organic matter to agricultural fields have also been shown to actually increase CO$_2$ efflux by providing an immediate source of food and stimulating microbial activity (Rastogi et al., 2002).

The recalcitrance of charcoal to microbial decomposition sets it apart from fresh organic amendments in terms of sequestering C, especially in humid regions with high decomposition rates (Sombroek et al., 1993). The residence time of charcoal in the soil profile is still uncertain, with estimated times ranging from hundreds to thousands of years (Bird et al., 1999; Shindo, 1991). The variability in reported residence times is due, in part, to charcoal characteristics, including type of original biomass and charcoal production techniques. Residence time may also vary due to climate and soil properties (Schmidt and Noack, 2000; Masiello, 2004). Despite uncertainty in the stability of charcoal, most evidence shows an overall ability of charcoal to reside in soils for
centuries, if not longer (Lehmann and Rondon, 2005; Pessenda et al., 2001). In contrast, non-charred material, such as manure or compost, releases C more rapidly, with only 10-20% of the original biomass C remaining after 5-10 years. Charring of biomass results in an immediate release of approximately 50% C with the remaining carbon more resistant to microbial activity (Lehmann and Rondon, 2005). In agricultural soils, application of pyrolysis char could ultimately lead to a greater amount of SOC and, over the long term, be more efficient in sequestering atmospheric C than organic amendments.

The objective of this study was to determine if pyrolysis char added to surface soils from three southeastern soils would increase C mineralization. A 24-day laboratory incubation experiment was conducted which measured CO$_2$ evolution. The soils and chars used in this study had undergone six months of weathering in a recently completed greenhouse study. We hypothesized that char amendments would not significantly increase soil C mineralization compared to controls.

**Materials and Methods**

*Study Design*

A laboratory incubation study was conducted using a 3 x 3 x 2 factorial design. Factors in the experiment were surface soil type (Cecil, Stilson, Tifton), char (no addition, peanut hull, pine chip), and N fertilizer addition (fert/no fert). Treatments used in the experiment were the same treatments taken from a recently completed six month greenhouse study of pyrolysis char on loblolly pine seedlings. Soils used in the study were: Cecil sandy clay loam (fine, kaolinitic, Thermic Typic Kanhapludult), Stilson loamy sand (loamy, siliceous, subactive, Thermic Arenic Plinthic Paleudult), and Tifton
loamy sand (fine-loamy, kaolinitic, thermic Plinthic Kandiudult). These treatments underwent six months of watering and plant growth in the seedling pots during the greenhouse experiment. At the end of the greenhouse experiment, soils were collected from each pot, air dried, and stored at room temperature in plastic bags.

Treatments consisted of soil with no char amendment (control) or char from peanut hull and char from pine chip feedstocks at a field application rate equivalent to 44.8 Mg ha\(^{-1}\). In the greenhouse experiment, the amount of char needed for each treatment was determined by using a ratio of the volume of the seedling pot to the volume of an acre furrow slice (AFS). This ratio (8.01 \times 10^{-6}) was multiplied by the rate of char to determine the weight of char needed. To achieve a field application rate of 44.8 Mg ha\(^{-1}\), 145.4 g of char was applied to soil for each pot, equal to 439.7 g per liter of soil. During the greenhouse experiment, half of the duplicated treatments received ammonium nitrate fertilizer at a rate equivalent to 0.14 Mg ha\(^{-1}\).

The incubation experiment was replicated in four complete blocks. The treatments used in these four blocks followed a factorial design with soil (Cecil, Stilson, and Tifton series), char type (no application, peanut hull, or pine chip) and N fertilizer (fert/no fert). This factorial design resulted in 24 treatments, which were duplicated in each block. Four blanks were also included in each block, totaling 52 units per block (Table 4.1).

**Incubation and Analysis**

Potential soil C mineralization (CMIN) was determined using the aerobic laboratory incubation method of Anderson and Domsch, (1982). Soils from the control
and 44.8 Mg ha\textsuperscript{-1} treatments in the previous greenhouse experiment were collected from each pot and kept air dry until the incubation experiment. Soils were passed through a 4 mm sieve to remove roots and other material which may have remained from the greenhouse experiment. For each treatment, 40.0 g of soil was placed in a 50 ml beaker and wet to 55% water-filled pore space for each soil type with deionized water.

Each experimental unit consisted of a beaker of soil placed in a mason jar along with a vial filled with 10 ml of 1M sodium hydroxide (NaOH) and a vial filled with 10 ml of deionized water. In each block, four jars contained empty beakers along with 1M NaOH vials water vials to serve as blanks. Blocks were individually incubated in a refrigerator-sized incubation chamber at 25 ± 1\degree C for 24 days. On days 3, 10, 21, and 24 of each incubation run, jars were removed from the incubation chamber long enough to remove and replace NaOH. Vials containing NaOH were capped and refrigerated until analysis. Fresh vials were filled with NaOH using a repipetor and placed back in each mason jar. Jars were returned and randomly placed in the incubator and undisturbed until the next measurement date.

To quantify soil CMIN during each incubation, a Metrohm 751 GPD Titrino titrator with 730 automatic sample changer (Metrohm Ltd., Switzerland) was used to back titrate excess alkali from each NaOH vial to an endpoint of pH 7.0 using 1 N hydrochloric acid (HCl) after excess CO\textsubscript{2} was precipitated with 2 ml of 3 N barium chloride (BaCl\textsubscript{2}). Exact normality of the acid used in titrations was determined by standardizing against a primary standard base, tris-hydroxymethyl-aminomethane (THAM) using a bromocresol green indicator (AOAC, 1990). The auto-titrator recorded
the amount of HCl needed to titrate each 10 ml NaOH sample. This titrated amount was used to calculate mineralized C using the following equation (Stotzky, 1965):

$$\text{CMIN} = (\text{ml}_{\text{blank}} - \text{ml}_{\text{sample}}) \times N \text{HCl} \times 6 \times 1000/ (\text{g oven dry (OD) soil})/k_c$$

Where: $\text{ml}_{\text{blank}} =$ amount of 1N HCl used to titrate blank NaOH vials to an endpoint of pH 7.0

$\text{ml}_{\text{sample}} =$ amount of 1 N HCl used to titrate treatment vials of NaOH to an endpoint of pH 7.0

$k_c =$ efficiency factor (0.41) (Voroney and Paul, 1984)

Titration of blanks was problematic with several blanks requiring less titrant than the samples. When used in calculating CMIN, the equations yielded negative values, indicating that C had been incorporated back into the soil during the incubation. In an attempt to address this issue, five unincubated NaOH blanks were analyzed to calculate an average blank value which would be used as the standard blank value for all samples. This new blank average still resulted in some samples with negative mineralization values. Samples with these negative CMIN values were dropped from the analysis, reducing the total samples collected in the experiment by 4%.

**Statistical Analysis**

Mineralization data was analyzed using the Statistical Analysis System (SAS) general linear model (GLM) procedure (SAS Institute, Cary NC). The fertilizer main effect initially included in the experiment did not result in any statistically significant differences in C mineralization and results were averaged across fertilization treatment. Differences were evaluated using Tukey’s mean separation procedure at $\alpha=0.05$. 
Mineralization results were adjusted using a log_{10} transformation to prevent violations of normality.

**Results**

CMIN differed with soil type (P<0.0001), with more C released from the Cecil surface soil than Stilson or Tifton surface soils, and no difference between Stilson and Tifton (Table 4.2). There were no significant differences in daily CMIN among treatments within each soil type (Figure 4.1). Amounts of CMIN differed among measurement dates (3, 10, 21, and 24) (P<0.0001), but no statistical difference existed between the two char treatments or controls in any soil type by sample day (Table 4.3).

After 24 days of incubation, no statistical differences existed in cumulative CMIN among char treatments in any soil type (Figures 4.2a,b,c); however, Cecil soils amended with peanut hull char released 15% more C than the control (Figure 4.2a) and pine chip char amended soil released 7% more C than the control. In the Stilson surface soil, char amendment resulted in a slight decrease of CMIN after 24 days compared to the control; peanut hull char amendment resulted in a 5% decrease in CMIN and pine chip char amendment resulted in a 12% decrease (Figure 4.2b). CMIN was increased by 8% in Tifton surface soils amended with pine chip char compared to the control and Tifton surface soil amended with peanut hull char (Figure 4.2c).

Generally more C was mineralized during the first three days of the incubation than other time periods for each soil (Figure 4.3a,b,c). This was not true in one instance when daily mineralization averaged across all treatments and controls during days 21-24 in the Tifton soil was slightly higher than the days 0-3 (Figure 4.3c). There was no
difference between char treatments and controls during any of the four measurement periods.

**Discussion**

Most soils found in the Southeast are low in SOC and the benefits of maintaining or increasing SOC are well documented (Franzluebbers, 2005). Charcoal is presumed to be recalcitrant in the soil profile and should contribute to long-term maintenance of soil C (Glaser et al., 2002). A previous greenhouse study of pyrolysis char amendments showed that total C may be increased by up to 5% (Speir et al., in review). Despite the increase in total C, results from the 24-day incubation study of surface soil from three representative soils of the Southeast show that neither peanut hull nor pine chip char increased soil respiration or C mineralization (Figure 4.1). This suggests that char would increase C sequestration in soils by providing a recalcitrant form of C in the soil profile.

Differences in the amount of SOC and rates of CMIN are affected by soil texture, specifically the clay fraction (Franzluebbers and Arshad, 1997). Soils with finer texture generally have greater amounts of SOC compared to coarse texturized soils due to differences in soil moisture and available nutrients (Wolf and Synder, 2003). The amount of SOC in finer-textured soils is also affected by soil aggregation and the physical protection of C from microbial decomposition afforded by aggregate structure (Balesdent et al., 2000; Craswell and Waring, 1972; van Veen et al., 1984). Soils used in this study were ball-mill ground and sieved prior to incubation, breaking soil aggregates and presumably exposing protected C to mineralization (Elliot, 1986; Franzluebbers et al., 1999). The Cecil soil, with finer texture and more structured aggregates than the
Stilson or Tifton soils, had generally higher rates of mineralization and larger amounts of mineralized C than either the Stilson or Tifton surface soils. These higher rates of CMIN may be a result of the C protection theory proposed by Cranswell and Waring (1972) and affected by the clay fraction (Franzluebbers et al., 1996a).

Higher rates of mineralization occurred during days 0-3 and 21-24 compared to days 3-10 and 10-21 (Figures 4.3a,b,c). Previous studies of microbial activity in soils and effects of organic amendments on CMIN show that rates of mineralization are usually highest within the first 3-10 days of incubation (Franzluebbers et al., 1998; Jenkinson and Powlson, 1975; Franzluebbers et al., 1996b). This abundant mineralization early in the incubation may be attributed to decomposition of more readily available C in the soil and soil-char treatments; however, there is no trend among the three soils to indicate if this is a result of char decomposition or other sources of soil C. The increased flux of CMIN during the last three days of the incubation is not generally supported by other studies (Bernal et al., 1998; Boyle and Paul, 1989). During a 70-day incubation of soils amended with several organic wastes, Bernal et al. (1998) reported mineralization decreased after 2 weeks and remained low during the rest of the study for all treatments. It could be reasoned that, because the organic wastes used in the Bernal study are more readily available sources of C, most mineralization would occur early. If char is more recalcitrant than these types of organic amendments, mineralization may occur later in the incubation, however there were no consistent trends indicating that char was decomposing during the last days of incubation.
Conclusions

The application of pyrolysis char has been shown to increase the percent of total C in surface soils. We hypothesized that the incorporation of pyrolysis char would not significantly increase C mineralization. Results from a 24-day incubation experiment of three soils amended with char taken from a six month greenhouse study failed to reject this hypothesis, by showing that rates of mineralization in char amended soils are not statistically different from soils with no char amendments.

Mineralization was affected by soil type, with higher rates of C loss in the Cecil surface soil compared to Stilson or Tifton surface soils. Mineralization was also dependent upon time, with the highest rates occurring during the first three and final three days of incubation across each soil type. Despite these differences, no statistical difference was noticed between controls and char amended soils. This indicates that char amendments in soils results in an increase of soil C that is stable and may serve to sequester C.
Table 4.1. Treatments for one block in a randomized complete block design used in a 24-day incubation experiment for three soils amended with pyrolysis char from peanut hull and pine chip feedstocks at 0 (control) and 44.8 Mg ha$^{-1}$ ± N fertilizer at 0.14 Mg ha$^{-1}$.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Char Type</th>
<th>Fertilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>N</td>
</tr>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>N</td>
</tr>
<tr>
<td>Cecil</td>
<td>Peanut Hull F</td>
<td>F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Peanut Hull F</td>
<td>N</td>
</tr>
<tr>
<td>Cecil</td>
<td>Peanut Hull N</td>
<td>F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Peanut Hull N</td>
<td>N</td>
</tr>
<tr>
<td>Cecil</td>
<td>Pine Chip</td>
<td>F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Pine Chip</td>
<td>F</td>
</tr>
<tr>
<td>Cecil</td>
<td>Pine Chip</td>
<td>N</td>
</tr>
<tr>
<td>Cecil</td>
<td>Pine Chip</td>
<td>N</td>
</tr>
<tr>
<td>Stilson</td>
<td>Control</td>
<td>F</td>
</tr>
<tr>
<td>Stilson</td>
<td>Control</td>
<td>F</td>
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<tr>
<td>Stilson</td>
<td>Control</td>
<td>N</td>
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<tr>
<td>Stilson</td>
<td>Control</td>
<td>N</td>
</tr>
<tr>
<td>Stilson</td>
<td>Peanut Hull F</td>
<td>F</td>
</tr>
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<tr>
<td>Stilson</td>
<td>Peanut Hull N</td>
<td>N</td>
</tr>
<tr>
<td>Stilson</td>
<td>Pine Chip</td>
<td>F</td>
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<tr>
<td>Stilson</td>
<td>Pine Chip</td>
<td>F</td>
</tr>
<tr>
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</tr>
<tr>
<td>Stilson</td>
<td>Pine Chip</td>
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<tr>
<td>Tifton</td>
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<tr>
<td>Tifton</td>
<td>Pine Chip</td>
<td>N</td>
</tr>
</tbody>
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Blank

Blank

Blank

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Table 4.2. Mineralized carbon (C) on days 3, 10, 21, and 24 of a 24-day incubation study of three soils of the southeastern United States amended with pyrolysis char at 44.8 Mg ha\(^{-1}\) from peanut hull and pine chip feedstocks.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Treatment</th>
<th>Mineralized Carbon (mg C kg OD Soil(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample Day</td>
<td>3</td>
</tr>
<tr>
<td>Cecil</td>
<td>Control</td>
<td>41.15</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull</td>
<td>39.05</td>
</tr>
<tr>
<td></td>
<td>Pine Chip</td>
<td>47.68</td>
</tr>
<tr>
<td>Stilson</td>
<td>Control</td>
<td>28.08</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull</td>
<td>28.35</td>
</tr>
<tr>
<td></td>
<td>Pine Chip</td>
<td>26.35</td>
</tr>
<tr>
<td>Tifton</td>
<td>Control</td>
<td>32.89</td>
</tr>
<tr>
<td></td>
<td>Peanut Hull</td>
<td>26.83</td>
</tr>
<tr>
<td></td>
<td>Pine Chip</td>
<td>25.15</td>
</tr>
</tbody>
</table>

Table 4.3. Summary of statistical significance (P<F) of C mineralization response to soil type and char type for four time frames of a 24-day incubation study.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Day 0-3</th>
<th>Day 3-10</th>
<th>Day 10-21</th>
<th>Day 21-24</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil type(^{§})</td>
<td>2</td>
<td>0.0003</td>
<td>0.0001</td>
<td>&lt;0.0001</td>
<td>0.3711</td>
</tr>
<tr>
<td>char type(^{£})</td>
<td>2</td>
<td>0.494</td>
<td>0.3015</td>
<td>0.1444</td>
<td>0.3652</td>
</tr>
<tr>
<td>soil*char</td>
<td>4</td>
<td>0.6472</td>
<td>0.3973</td>
<td>0.8034</td>
<td>0.1363</td>
</tr>
</tbody>
</table>

\(^{§}\) Cecil, Stilson, and Tifton soil series  
\(^{£}\) Control (no char), peanut hull, and pine chip feedstocks  
* Interaction term
Figure 4.1. Daily (means ± 1 SE) mineralized carbon (Cumulative CMIN at day 24 divided by 24) after a 24-day incubation experiment for three soils of the southeastern United States amended with pyrolysis char at 44.8 Mg ha\(^{-1}\) from peanut hull and pine chip feedstocks. (n=16)
Figure 4.2a. Cumulative carbon mineralization (means ± 1 SE) for a Cecil sandy clay loam during a 24-day incubation experiment amended with pyrolysis char at 44.8 Mg ha$^{-1}$ from peanut hull and pine chip feedstocks. (n=16)

Figure 4.2b. Cumulative carbon mineralization (means ± 1 SE) for a Tifton loamy sand during a 24-day incubation experiment amended with pyrolysis char at 44.8 Mg ha$^{-1}$ from peanut hull and pine chip feedstocks. (n=16)
Figure 4.2c. Cumulative carbon mineralization (means ± 1 SE) for a Stilson loamy sand during a 24-day incubation experiment amended with pyrolysis char at 44.8 Mg ha$^{-1}$ from peanut hull and pine chip feedstocks. (n=16)

Figure 4.3a. Mineralized carbon per day (means ± 1 SE) for each measurement time frame in a Cecil sandy clay loam during a 24-day incubation experiment amended with pyrolysis char at 44.8 Mg ha$^{-1}$ from peanut hull and pine chip feedstocks. (n=16)
Figure 4.3b. Mineralized carbon per day (means ± 1 SE) for each measurement time frame in a Stilson loamy sand during a 24-day incubation experiment amended with pyrolysis char at 44.8 Mg ha\(^{-1}\) from peanut hull and pine chip feedstocks. (n=16)

Figure 4.3c. Mineralized carbon per day (means ± 1 SE) for each measurement time frame in a Tifton loamy sand during a 24-day incubation experiment amended with pyrolysis char at 44.8 Mg ha\(^{-1}\) from peanut hull and pine chip feedstocks. (n=16)
References


CHAPTER 5

CONCLUSIONS

This study examined the effects of pyrolysis char from peanut hull and pine chip feedstocks on three representative soils of the southeastern United States. We examined the effects of char on growth of agronomic (corn) and timber (loblolly pine) species commonly grown on these soils, on soil volumetric water content, and on soil respiration. A field study was conducted in Tifton, GA observing the biomass and grain production of corn over two growing seasons. A six-month greenhouse study was also conducted to determine the effects of char on loblolly pine seedling growth in three soils commonly found in the southeast. Finally, a laboratory incubation experiment was conducted using the same three soils as the greenhouse experiment.

Results from the Tifton field study show that char amendments did not have an overall affect on soil moisture over the two growing seasons. There were no significant differences in soil respiration among treatments in either char feedstock. For both soil moisture and soil respiration measurements, date was significant for both char feedstocks, with seasonal variations occurring over the two years (P < 0.0001). Neither char feedstock significantly increased grain yields or biomass production. Yield and biomass decreased during the 2007 season, but this is likely due to severe drought conditions.

Overall, results from the greenhouse study show amendment of pyrolysis char improved initial nutrient availability in Cecil, Stilson, and Tifton soils. Nutrients concentrations in soils amended with char were still higher than control soils at the end of
six months, although this generally did not result in improved seedling growth or nutrient uptake. A char x fertilizer interaction occurred with peanut hull char in Stilson soils, significantly increasing seedling volume. Char increased soil moisture, more so in coarse-textured soils. Char treatments also seemed to have a greater effect on moisture during the first four measurement dates when seedlings were watered less frequently, which indicated char amendments may improve water availability during severe drought conditions.

In the laboratory incubation, carbon mineralization was affected by soil type, with higher rates of carbon loss in clay-textured soil compared to sandy soils. Rates of mineralization were also highest during the first three days of incubation across each soil type. Amendment with pyrolysis char did not significantly increase or decrease carbon mineralization during any time frame studied in this incubation experiment.

This study is the first to evaluate the effects of pyrolysis char on soils in the southeastern United States. Overall, char may serve to retain soil moisture under dry conditions and marginally improve nutrient availability in commonly infertile soils, although this increase may not directly result in improved plant growth. Char was not shown to be readily mineralized through microbial decomposition based upon soil efflux data and incubation results. The determination of this study is that char may be applied to soils at rates up to 45 Mg ha^{-1} without negatively affecting plant growth or crop yield when accompanied with conventional fertilizer amendments. Long-term studies are necessary to determine the nature of char’s recalcitrance in the soil profile, as well as long-term effects on soil nutrient cycling and moisture retention.