Long-Term (24-Year) Effects of Harvest Disturbances on Ecosystem Productivity and Carbon Sequestration in Tupelo-Cypress Swamps in the Mobile-Tensaw River Delta

by

Scott E. McKee

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Committee Members:
W. Michael Aust, Co-Chair
John R. Seiler, Co-Chair
Brian D. Strahm
Erik B. Schilling

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Long-Term (24-Year) Effects of Helicopter and Skidder Harvest Disturbances on Ecosystem Productivity and Carbon Sequestration Patterns in Tupelo-Cypress Swamps in the Mobile-Tensaw River Delta

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ABSTRACT

Due to the paucity of long-term harvest impact data, the primary goals of this study were to quantify the long-term effects of different harvest disturbances twenty-four years after harvest on two major wetland functions: stand productivity and C storage. This study evaluated the effects of three harvest types that were originally applied in 1986 to a tupelo (*Nyssa aquatic*)-cypress (*Taxodium distichum*) forested wetland in the Mobile-Tensaw River Delta of southwestern Alabama. Treatments were: 1. Helicopter harvest (HELI), 2. Skidder simulation where 50% of the site was rutted to a depth of 30 cm (SKID), and 3. Helicopter harvest followed by glyphosate herbicide removal of all sprouts and seedbank regeneration for two years following harvest (GLYPH). An adjacent mature stand (94 years old) within the same original composition represented mature forest or pre-harvest reference conditions (REF). Above- and belowground plant biomass, belowground woody debris, soil C, and soil CO_2 efflux were measured. Twenty-four years after treatments were applied, forest C levels were higher in SKID treatments (206.1 Mg C ha^{-1}) than in HELI treatments (168.7 Mg C ha^{-1}). GLYPH treatments are holding less (144.2 Mg C ha^{-1}) while REF areas hold 332.6 Mg C ha^{-1}. SKID treatments are also holding the most biomass of all treatments with 243.2 Mg ha^{-1} of overstory biomass. Ecosystem C and biomass patterns indicate HELI and SKID are becoming similar to the original site conditions

represented by the REF areas. The resiliency of these highly disturbed stands are explained by the frequent inputs of non-compacted sediments, presence of species well adapted to very poorly drained and aerated conditions, high rates of coppice regeneration, shrink-swell ameliorative properties of the soil and creation of more complex microtopography within SKID treatments.

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Chapter 1. Background and Literature Review

1.1 Introduction

Forested wetlands, such as bottomland hardwoods and riparian forests, are important forest communities because of their numerous ecological functions that translate into socially valued ecosystem services. Riparian forests perform functions such as filtration of sediment, nutrient uptake and transformations, flood moderation, streambank protection, and creation of wildlife habitat (Walbridge 1993, Daniels and Gilliam 1996, Klapproth 1996, Welsch 1996, Kellison and Young 1997, Sheridan et al. 1999, Brady and Weil 2002, Aust et al. 2006). Bottomland forested ecosystems have been harvested for timber products since the 18th century, yet they remain productive systems (Stine 2008). However, legislation and regulation of wetlands, primarily through the 1972 Federal Water Pollution Control Act and subsequent amendments, requires better understanding of harvesting influence on forest wetland regeneration and productivity (Mitsch and Gosselink 2007, Stine 2008).

An understanding of the effects of forest harvesting may also be beneficial for restoration of forested wetlands previously converted to agriculture. Agricultural conversions were especially high in the 1960s and 1970s (Kellison et al. 1998). Kellison and Young (1997) found the loss of bottomland hardwoods in the southern United States to be approximately 2.6 million ha between 1952 and 1985, over half of which was converted to agriculture. Currently, government programs such as the Conservation Reserve Enhancement Program and Wildlife Habitat Incentive Programs assist landowners in restoration efforts that target riparian forests (Bradburn et al. 2010).

1.2 Harvesting in Wetlands and Forest Productivity

Forested wetlands have traditionally been important for timber production because of their high productivity (Stine 2008). For example, logging for cypress timber has been practiced since the 18th century (Stine 2008). In some instances, the effects from previous harvest methods, such as pull-boat yarding, are still readily evident after a century. Therefore, long-term data quantifying the effects of timber harvesting are critical for avoiding and minimizing undesirable impacts (Gellerstedt and Aust 2004). Unfortunately, there are few studies tracking long-term productivity within forested wetlands (Aust et al. 2006).

Forested wetlands in the southeastern US have numerous colloquial names including red river bottoms, black river bottoms, muck swamps, peat swamps, pocosins, minor bottoms, piedmont bottomlands (Kellison and Young 1997), yet they can be more simply and accurately categorized into alluvial and non-alluvial forested wetlands. Alluvial or floodplain forests of the southeast are greatly impacted by upstream erosion (Kellison et al. 1998) and subsequent sediment deposits. Watershed area, climate, land use, and stream gradients influence sediment and nutrient deposition patterns (Schilling and Lockaby 2006). Nutrient rich sediment inputs can influence overall productivity of these forests and increase their capacity to naturally ameliorate disturbance (Gellerstedt and Aust 2004, Aust et al. 2006).

In the continental US there are roughly 21 M ha of forested wetlands, 65% of which are located in the southeastern states (Stine 2008). As the current study site, bald-cypress (*Taxodium distichum* L. Rich.) and water tupelo (*Nyssa aquatica* L.) comprise the most common type of forested wetland because both species are well adapted to poorly drained soil conditions (Krinard and Johnson 1987, Dicke and Toliver 1990). Adaptations that commonly favor these species include abundant lenticels, aerenchymous tissue, and rapid growth of sprouts (Kozlowski 1986).

Harvesting has the potential to affect soil properties and subsequent regeneration. Greacen and Sands (1980) evaluated the existing research on wet site harvesting and concluded that trafficking of sites under very wet conditions can puddle soils and potentially cause increased bulk density, reduced aeration porosity, soil water movement, and gas exchange, and potentially shift species toward those that are adapted to wetter sites. Aust et al. (1998) evaluated a range of drainage classes on non-alluvial wetlands and found that very poorly drained sites had smaller changes in aeration and water movement than moderately well drained sites simply because the poorly drained sites already had less desirable soil aeration properties due to soil texture. Gellerstedt and Aust (2004) evaluated the current research site at stand-age 16 (helicopter logging and skidder simulation logging) and similar results to those at stand-age two were found with skidder treatments favoring tupelo. They speculated that the wetter site conditions caused by ground-based harvests acted as competition control for species that are not as flood tolerant as bald-cypress or water tupelo [e.g., Carolina ash (*Fraxinus caroliniana* P. Mill.)].

Poor aeration is responsible for the dominance of flood tolerant cypress and tupelo in poorly drained soils (Dickson and Broyer 1972). Harvesting on wet sites, like forested wetlands, has the potential to increase soil compaction and/or reduce soil aeration and water movement by churning, a process that homogenizes soil structure and reduces porosity (Miwa et al. 2004). Soil aeration is a common problem in undisturbed forested wetlands since flooded soils reduce gas exchange and growth for many plant species (Kozlowski 1986). Some sites are more resilient and more resistant to long-term harvest traffic effects (Miwa et al. 2004). For example, soils with mixed or montmorillonitic clays have shrink swell properties that can act as ameliorating forces for compaction on sites with fluctuating hydrology (Aust et al. 2006).

During the late 1800's and early 1900's specialized barge mounted cable yarding harvesting systems (i.e., pull boats) were used extensively in tupelo-cypress swamps associated with large navigable streams. After a century later, the canals created by the cable corridors are still evident and provide a visible reminder of the extent of disturbance associated with legacy harvest (Stine 2008). Evans et al. (2008) found pull-boat runs every 20-50 m on the study site of this project on the Mobile-Tensaw River Delta. The soil had been so heavily disturbed that channels from 30-150 cm in depth remained after 90 years. These channels, while not active for over nine decades, are still evident on an adjacent site that was not harvested (Evan et al. 2008). The slow recovery of such harvest practices indicates the importance of long-term studies focused on disturbances.

The annual influx of nutrient rich soil can affect the ability for alluvial wetlands to recover (Aust et al. 2006). As streams and rivers overflow their banks floodwater velocity slows and sediments deposit (Hodges 1997). Aust et al. (2006) measured sediment inputs for each harvesting treatment over a fifteen year period. Non-harvested reference stands accumulated an average of 13.6 cm of soil while the helicopter and skidder harvested area accumulated averages of 24.6 and 19.9 cm of sediment, respectively, indicating that the quantity of sediment deposited in floodplains by overbank flooding is influenced by harvesting system (Aust et al. 2006, Evans et al. 2008).

Due to the potential negative water quality and site productivity impacts from wet site harvests, Scott Paper Company began harvesting trials in 1984 to determine the most effective harvest system for wetland logging with minimal visual impacts to the site. Ground-based and cable systems were considered, but helicopter logging systems were ultimately chosen for operations in the Mobile-Tensaw Delta (Willingham 1988). This system increased the overall efficiency of logging crews, and helicopter logging is often considered to have reduced impacts on soil physical properties (Stokes and Schilling 1997). However, Aust and Lea (1992) found no difference in the mechanical resistance of soils, a measure of soil strength or the ability of the soil to resist penetration, from helicopter and skidder logged sites. While harvesting systems may not affect the mechanical resistance of the soil, it did influence the sites species composition. Wetter conditions in the skidder logged areas led to higher densities of water tupelo compared to areas harvested by helicopter (Aust et al. 2006).

Fine roots are important for water and nutrient uptake by trees, and root biomass can serve as an index of forest productivity. Generally stands that are periodically flooded will put more energy into growing larger root systems than stands that are continuously flooded (Powell and Day 1991, Megonigal and Day 1992). Hook and Brown (1973) found that secondary roots of water tupelo usually die under flooded conditions, but more succulent and less branched roots will grow back. Flooding of roots may also cause an increase in soil carbon (C) through increased root turnover (Megonigal and Day 1992). Megonigal and Day (1992) also found greater aboveground biomass three years after harvesting a site which was continuously flooded.

1.3 Forest Carbon

According to the US Department of Energy Carbon Dioxide Information Analysis Center, there has been a 30% increase in the atmospheric concentration of CO_2 over the past century (Birdsey et al. 2006). Current concerns about climate change have increased interest in management strategies to lower greenhouse gas levels. Forests have been shown to be significant sinks for atmospheric C (Stainback and Alavalapati 2005). Forest C sequestration could become a component of evolving C credit markets causing a need for additional information regarding the C pools and fluxes of forest ecosystems, including those within forested wetlands, and how they may respond to disturbance. Forested wetlands, due to their high productivity and/or slow decomposition rates (Mitsch and Gosselink 2007), have the potential to store large quantities of C, yet the effects of harvesting on C sequestration is not well documented.

C pools vary in forested systems and understanding cycling rates in response to disturbance is critical to our overall understanding of wetland functions. Forest fires and deforestation have increased forest C emissions in recent years since soil organic matter can release C to the atmosphere following these events (Johnson 1992, Trettin et al. 1996, Worrell and Hampson 1997). The flux of C into and out of the soil is a major factor determining C storage of deep bottomland soils (Armentano and Menges 1986). Fine litter can be incorporated into the soil, decompose and subsequently act as a C source for soil microbial populations (Mulholland 1981). Once incorporated into the soil, the C will be stored until it further aerobically decomposes and releases CO_2 (Gaudinski et al. 2000) or anaerobic decomposition releases methane (Segers 1998). Logging debris can also contribute to soil C and may decompose very slowly in poorly aerated soils (Lockaby et al. 2005).

In general the annual inputs of C from vegetation residues are approximately equal to the C lost through decomposition (Schlesinger and Lichter 2001). However, disturbances, both natural and anthropogenic, can alter this balance. Factors influencing C residence time in soils include aeration, microbial populations, C sources and quality (e.g. leaves versus limbs), and species (Lal 2005). Leaves due to their high surface area and chemical ratios (e.g., lignin content) decompose more rapidly than branches (Lal 2005). Soil aeration influences organic matter decomposition where anaerobic soil conditions result in lower decomposition rates because anaerobic microorganisms decompose C more slowly than aerobic organisms (Brinson

1977, Davidson and Janssens 2006). Bottomland systems are often flooded for large parts of the year, so anaerobic conditions are common. Submerged or buried logging debris has the potential to remain on these sites much longer (Lockaby et al. 2005). Further, one major bottomland species, bald-cypress has decay resistant heartwood and decomposes slower than many bottomland species (Stine, 2008).

High rates of net primary productivity in wetlands may also allow these forests to store greater amounts of belowground C (Giese et al. 2003). Increased productivity rates are due to nutrient availability related to annual inputs of nutrient rich sediment deposits in flood water (Mitsch and Gosselink 2007, Schilling and Lockaby 2006) and adequate soil moisture supplies. Productive sites produce more roots and root turnover may result in more C storage in the soil (Symbula and Day 1988). Cypress and tupelo have been found to produce more belowground biomass when periodically flooded (Megonigal and Day 1992) and fine root turnover may in fact add more organic matter to the soil than the leaf litter (Symbula and Day 1988, Conner and Buford 1998). Brinson et al. (1980) found an average litter fall of 6,428 kg ha^{-1} yr^{-1} after two years with 65.7% coming from foliage in a tupelo-cypress alluvial swamp in North Carolina. The rest of the organic matter consisted of reproductive parts (15.6%), woody parts (14.1%), miscellaneous (4.4%), and epiphytes (0.2%).

Soil CO_2 efflux is a measure of CO_2 released from soil into the atmosphere. Soil CO_2 efflux can be compartmentalized into heterotrophic (the respiration of soil active microbes) and autotrophic respiration rates (respiration from roots alone) (Kuzyakov 2006). The heterotrophic rate largely dictates the balance between soil C inputs from fresh litter versus soil organic matter content (Kuzyakov 2006). Oxygen availability also influences autotrophic respiration rates. Anaerobic conditions cause roots to switch to anaerobic functions in order to survive

(Vartapetian and Jackson 1997). Pezeshki's (1991) findings suggest that flood tolerant species increase their anaerobic respiration rates when flooded in order to compensate for the decreased oxygen levels. While these anaerobic conditions may be favorable to holding C in the soil due to decreased decomposition rates (Reddy and Patrick 1975), they may increase the overall rate of soil CO_2 efflux through increased root respiration (Pezeshki 2001).

1.4 Project Goals

The literature indicates that forested wetlands provide numerous ecosystem services, including C storage, production of wood fiber, and filtration of sediment (Lowrance et al 1986, Kellison and Young 1997, Megonigal et al. 1997). Harvest disturbances may negatively impact subsequent stand productivity along with soil and stand C storage and fluxes (Lal 2005). Hydrologic, soil, and vegetative variables have the potential to increase the resiliency and/or resistance of a particular forested wetland to harvesting (Aust et al. 1997). However, little information exists regarding the long-term effect of harvesting on either stand productivity or C storage and release patterns. Specifically, this study was designed to evaluate the long-term (24 year old) effects of three disturbance types (helicopter logging, skidder traffic logging, and helicopter logging followed by the removal of all seed and sprout regeneration sources using repeated glyphosate application) as compared to an adjacent 94-year-old reference area. More specifically we will evaluate the veracity of the following alternative hypotheses:

HA_1: Helicopter, skidder, glyphosate disturbances and non-disturbed reference areas have different above and belowground ecosystem productivity 24 years after disturbance.

HA_2: Helicopter, skidder, glyphosate disturbances and non-disturbed reference areas have different C storage and release patterns 24 years after disturbance.

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Chapter 2. Long-Term Site Productivity of a Tupelo-Cypress Swamp 24-Years After Harvesting Disturbances

Abstract

Long-term research regarding harvesting in bottomland hardwood forests is important, yet scarce, as these forests can be some of the most ecologically and economically important forest types. This study was conducted to determine the long-term impact of different timber harvest types on a tupelo (*Nyssa aquatica* L.)-cypress (*Taxodium distichum* L. Rich.) wetland located in the Mobile-Tensaw river delta in southern Alabama. Specifically, clearcutting followed by 1. Helicopter extraction (HELI), 2. Skidder simulation of ground based extraction (SKID), and 3. Complete removal of coppice and seedbank regeneration with glyphosate herbicide (GLYPH) were compared 24 years after original treatment installation. The goal was to determine long-term treatment effects on biomass accumulation patterns in the regenerating stands. An adjacent portion of the original forest stand provided a reference condition (REF). Studies on this site at stand ages 7 and 16 years indicated that SKID treatment areas had the largest aboveground biomass accumulations while HELI treatments had greater species diversity. Twenty four years after disturbance, results followed the same pattern with SKID treatments having more above and belowground biomass accumulation (242.6 Mg ha^{-1}) while HELI treatments had less biomass (173.6 Mg ha^{-1}) and more woody species diversity. GLYPH treatments are slowly recovering (86.8 Mg ha^{-1}) and are progressing through an herbaceous-shrub-scrub stage of succession. SKID treatments (60% tupelo) appear to be progressing towards original stand conditions (REF = 85% water tupelo). Species in HELI treatments were more diverse (42% tupelo) and similar to species found on the more aerated natural levee, which is a reflection of

the reduced aeration caused by the SKID treatment. Annual inputs of nutrient-rich sediments and the shrink-swell nature of the clay mineralogy appear to be serving as natural amelioration mechanisms for stand recovery.

2.1 Introduction

Sustainable forest management requires understanding harvesting influences on future site productivity. Long-term data that quantify the effects of timber harvesting on soil physical and chemical properties and subsequent effects on overall site quality are necessary to evaluate ecosystem response and sustainability, yet long-term studies of harvesting responses in forested wetlands are few (Cairns 1990, Gellerstedt and Aust 2004). It is important that land managers have long-term quantitative data to inform management decisions in these forest types (Gellerstedt and Aust 2004). Many riparian wetland sites that provide multiple society-desired ecosystem services (Kellison and Young 1997) have also historically been important resources for timber production because of their high productivity (Stine 2008). For example, logging cypress timber in bottomland riparian forests has been practiced since the 18th century (Stine 2008) and repeated harvests in bottomlands have caused little apparent loss of ecosystem services (Aust et al. 1997). However, previous harvest methods, such as pull boat logging used during the late 1800's to early 1900's, have resulted in long-term changes to soils and hydrology of some sites (Evans et al. 2008). The continuing legacy of these abusive harvest methods emphasizes the necessity to understand the potential impacts of current harvest practices and their ability to remain sustainable.

2.2 Forest Productivity

Forested wetlands in the United States range from nonalluvial peatlands, pocosins, bogs, wet flats, and alluvial forests also known as riparian forests, bottomland hardwoods, river bottoms, and swamps (Kellison and Young 1997). These forested wetlands all have different hydroperiods, soils, climate, and vegetation, thus all respond to harvesting differently (Hodges 1997, Miwa et al. 2004, Aust et al. 2006). Floodplain forested wetlands associated with the major and minor river systems of the southeastern US are strongly influenced by upstream erosion processes (Kellison et al. 1998). Landscape position and watershed characteristics have a strong but variable influence on wetland forest productivity and biogeochemical processes (Schilling and Lockaby 2006). The amount of nutrient rich sediment entering these systems can play a large role in forest productivity and their ability to naturally ameliorate disturbances (Wharton et al. 1976, Aust et al. 2006).

Forested wetlands are valued for the many goods and services they provide, such as their influence on hydrology (e.g. duration and level), water quality (e.g. sediment filtering and deposition), nutrient cycling (e.g. nutrient uptake and transformation), wildlife habitat, shoreline protection, and goods (e.g. timber, berries, and fish) (Walbridge 1993, Daniels and Gilliam 1996, Klapproth 1996, Welsch 1996, Sheridan et al. 1999, Brady and Weil 2002, Aust et al. 2006). Understanding the recovery processes within these critical areas following harvesting is important for future sustainable management. Importantly not all forested wetlands are equal in their ability to recover following harvest (Gellerstedt and Aust 2004).

In the continental US there are about 21 M ha of forested wetlands, 65 percent of which are located in the Southeast (Stine 2008) making it important to understand how harvesting influences productivity given the broad range these wetland types cover across the landscape. Bald-cypress (*Taxodium distichum* L. Rich.) and water tupelo (*Nyssa aquatica* L.) comprise the most common type of forested wetland because both species are well adapted to poorly drained soil conditions (Krinard and Johnson 1987, Dicke and Toliver 1990). Adaptations that commonly favor these species include abundant lenticels, aerenchymous tissue, and rapid growth of sprouts (Kozlowski 1986).

Harvesting can influence species composition in forested wetlands (Lockaby et al. 1997). Aust et al. (2006) looked at the impacts of helicopter and skidder simulation logging on stand composition regeneration with soil properties in South Alabama. At stand-age two the skidder treatment tended to favor tupelo with wetter sites caused by skidder traffic increasing microtopography which helped to control competition of other species such as Carolina ash (*Fraxinus caroliniana* P. Mill.). At age 16, stands were not influenced by harvesting type as both helicopter and skidder treatments were measured to have approximately 20 percent of the volume found in uncut reference stands, which appear to be a reasonable rate for these stands to recover by age 70 (Aust et al. 2006). Perison et al. (1997) found skidder and helicopter harvesting to have similar biomass volumes in a blackwater bottomland forest in South Carolina two years after harvest.

An early logging practice that has impacted wetlands in the southeast was the use of pull-boats which created large corridor channels across several bottomland sites (Stine 2008) that are still visible today. Evans et al. (2008) found pull-boat runs every 20-50 meters on a site on the Mobile-Tensaw River Delta where soil has been so heavily disturbed that channels from 30-150 cm deep still exist after 90 years.

Roots are important for water and nutrient uptake by trees and serve as an index of productivity. Several studies have found that periodically flooded stands will put more energy into growing larger root systems compared to stands that are continuously flooded (Powell and Day 1991, Megonigal and Day 1992). Hook and Brown (1973) found that the secondary roots of water tupelo usually die due to flooding, but more succulent and less branched larger roots will grow back. Megonigal and Day (1992) found greater aboveground biomass three years after harvesting on a site that was continuously flooded as compared to a site that was periodically flooded. This can affect overall site productivity because of increased inputs into root biomass over time.

Harvesting in saturated or flooded soil conditions has the potential to negatively impact soil physical properties (Aust et al. 2004). Soil aeration in these forests is often already problematic due to flooding and can be further influence by harvesting (Kozlowski 1986). Poor soil aeration is one reason that these forests are dominated by cypress and tupelo (Dickson and Broyer 1972), species well adapted to saturated soil conditions. Harvesting methods that increase soil compaction limit gas exchange and can adversely affect tree growth for many sites (Kozlowski, 1986). Soil properties, such as shrink-swell potential, however, can act as ameliorating forces and help soils recover (Aust et al. 2006). Aust et al. (2006) also found that the annual inputs of nutrient rich sediment assisted the site recover from harvesting. Hodges (1997) speculated that shrink-swell soil minerals and sediment inputs allowed bottomland hardwoods to be resilient to disturbances caused by harvesting. As streams and rivers overflow the banks and encounter increased frictional drag, water slows and deposits sediment (Hodges 1997). Aust et al. (2006) measured sediment inputs for harvesting treatments over a fifteen year period and found that mature tupelo-cypress stands accumulated an average of 13.6 cm of sediment while the helicopter and skidder harvested sites accumulated 24.6 cm and 19.9 cm of sediment, respectively. Increases in sediment deposition following harvest have the potential to improve downstream water quality and serve as a natural ameliorative factor by adding non-compacted sediment to harvested stands (Evans et al. 2008).

Due to environmental concerns, Scott Paper Company began a series of harvesting trials in 1984 to determine the most efficient system for wetland logging that would minimize visual site disturbances. The company evaluated numerous tracked and wide tire ground based systems, a cable yarding system, and helicopter systems. The helicopter system was adopted as the preferred logging system due to increased operational productivity, lower costs and fewer visual symptoms of disturbance (Willingham 1988). In 1986, Scott Paper Company supported an investigation to experimentally examine impacts of helicopter vs. ground-based systems (Aust 1989). Aust and Lea (1992) found no difference in the mechanical resistance of soils from helicopter logged sites and skidder logged sites. While ground-based harvesting systems may not affect the mechanical resistance of the soil they may influence species composition by affecting other soil properties (Dickson and Broyer 1972, Kozlowski 1986). Aust et al. (2006) noted that the wetter soil conditions in the skidder logged areas led to higher densities of water tupelo than in areas harvested by helicopter.

This study was initiated by Scott paper company in 1986 is still intact, although the ownership has changed four times during the past 24 years. Today the property belongs to the State of Alabama and is primarily managed for wildlife habitat by the Alabama Department of Game and Fisheries. The objective of the current study is to determine the long-term (24-year) effects of the original harvesting treatments on forest productivity and species composition.

2.3 Study Site

The study site is in the deltaic plain formed by the Mobile, Tensaw, and Middle Rivers in southwestern Alabama. The low gradient and braided river channels of the Delta are within the watersheds of the Tombigbee and Alabama River Basins (Figure 2.1). The site is located at 30°57’45” N and 87°53’20 W approximately 50 km north of the Mobile Bay. At this location the river has fresh water but is influenced by a semidiurnal tide. The Mobile-Tensaw River Delta is the second largest river delta in the United States and the Alabama and Tombigbee river basins have a combined watershed of approximately 11.6 million ha (Smith 1988). This watershed extends into four states and five physiographic provinces (Figure 2.1) (Aust et al. 2006). The delta contains approximately 105,000 ha of wetlands, 89,000 ha of which are forested (Aust et al. 2006). The study site is located on the western bank of the Tensaw River about 4.5 km southwest of Stockton, AL and approximately 1 km upstream of Live Oak Landing (Evans et al. 2008). Climate is subtropical with a mean annual air temperature of 20°C, 250 frost-free days, and less than three weeks below freezing. Average annual precipitation is 1600 mm year^{-1} evenly distributed throughout the year (Riccio et al. 1973, Aust et al. 2006). The site floods annually and frequently. Very poorly drained soils from the Levy series are found across the entire study site (fine, mixed, superactive, acid, thermic typic hydraquents) (Soil Survey Staff 2003).

Species composition is primarily water tupelo and bald-cypress with a smaller component of Carolina ash, pumpkin ash (*Fraxinus profunda* (Bush) Bush), water elm (*Planera aquatica* J.F. Gmel.) and black willow (*Salix nigra* Marsh.). The site has been harvested at least twice prior to the 1986 harvest based on local historical records and on-site spring-board stumps and pull-boat channels (Aust et al. 2006). In 1986, preharvest measurements were conducted in order to ensure that hydroperiods, soils, stand ages and composition, and disturbance histories were similar across the entire proposed study site (Aust 1989). During the fall of 1986 the 25 ha disturbance area was clearcut using chainsaws and stems were transported to riverbank landings via helicopter (Aust 1989). An adjacent portion of the original mature stand remained intact to serve as a reference area (REF) although it could not be incorporated into the disturbance experimental design due to safety concerns expressed by helicopter pilots. Following the clearcut harvest, three disturbance treatments were installed. One treatment represented the clearcut with helicopter transport (HELI). Skidder transport (SKID) was simulated by skidding logs across designated treatment areas within the clearcut with a cable skidder equipped with wide tires (86 cm) until over 50% of the area was rutted to a depth of at least 30 cm. The third treatment consisted of removal of all coppice and seed regeneration for both woody and herbaceous species during the first and second growing seasons with glyphosate herbicide (GLYPH). GLYPH treatments were intended to allow investigation of the importance of coppice and seedbank sources of regeneration to recovery and the treatment resulted in conversion to a freshwater marsh dominated by herbaceous species. The third treatment did not represent an operational silvicultural treatment; rather it was intended to represent a more severe disturbance that would remove on-site regeneration sources.

All disturbance treatments were installed on 60 x 60 m plots within the harvest area. Each treatment was replicated nine times within the study area in a 3 x 3 Latin square design (Figure 2.2). A now 94-year-old reference area (REF) was established adjacent to the treatment plots. Based on pretreatment data from Aust and Lea (1991), soil and forest properties were the same in the disturbance and REF areas prior to treatment installation.

2.4 Methods

2.4.1 Overstory Productivity

Measurements of overstory trees were repeated in 2009 and 2010. In the first year all treatments in the first row (3 replicates, 4 treatments = 12 experimental units) were measured. One year later all 36 plots (9 replicates, 4 treatments = 36 experimental units) were measured. Growth rate calculations were based only on the first row and calculations of total aboveground biomass used all treatment plots. For disturbance treatments, 135-m^2 circular plots were measured for overstory biomass. Because of density differences, 405-m^2 circular plots were measured in REF areas. For each plot species, diameter at 1.3 m (DBH) (≥6.6 cm), and total height where recorded. Heights were measured using a Trupulse laser height finder (Laser Technology, Inc., Centennial, CO). Biomass values (Mg green biomass ha^{-1}) were calculated using species-specific allometric equations (Table 2.1). Many of the willows were leaning so severely that height measurements would lead to a bias in their volumes; therefore allometric equations were chosen that utilized only DBH to estimate volumes for this species (Table 2.1).

2.4.2 Belowground Productivity

A 6.5 cm diameter saw-toothed soil auger was used to sub-sample belowground biomass and woody debris at three locations and four depths (0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm) in the first row and the first upstream replication of the second row (4 replicates, 4 treatments = 16 experimental units). The three sub-sample locations in each plot were located approximately 5 meters from plot center and spaced 120˚ from each other with the first plot located due south. Sub-samples for each depth were combined to reduce plot-level heterogeneity. Samples were washed over 2 mm screens to remove soil and allow for sorting into three categories: fine roots (< 3mm), coarse roots (> 3mm) (Aber et al. 1985), and belowground coarse woody debris. Samples were dried in an oven to a constant weight at 65˚C and weighed. Correction for mineral soil contamination was performed by combustion in a muffle furnace. Dry weight was then expressed as Mg ha^{-1}.

2.4.3 Sediment Deposition

Nine sediment pins made of 12 mm diameter, 1 m length rebar were installed in each plot in 1986 immediately after harvest (Gellerstedt and Aust 2004). These pins had washers welded

30 cm from one end of the rebar and during the last re-measurement in 2002 the washers were relocated at ground level. Log transport during floods and falling trees have removed some pins, but at least five pins per treatment plot were relocated, measured and repositioned at the soil surface in 2010 for continued future measurements.

2.4.4 Bulk Density

Bulk density cores were collected with a double-cylinder hammer-driven bulk density corer as described by Grossman and Reinsch (2002). In each plot along the first row and the first upstream repetition of the second row (4 replicates, 4 treatments = 16 experimental units) bulk density cores were collected at three soil depths (0-10 cm, 15-25 cm, and 25-35 cm) in three locations in each plot. The three depths were sampled to detect differences in soil bulk density between the surface A horizon and deeper Cg_1 and Cg_2 horizons. Cylindrical soil cores were 5 cm in diameter and 10 cm in length. After the surface samples were collected, a bucket auger was used to excavate to desired depth so that the second and third bulk density samples could be collected. Soil cores were subsequently dried for 24 hours at 105°C and weighed. Bulk density values were calculated based on the following equation from Hillel (1998):

Bulk Density = Mass of solid / Volume of soil (BD = Ms/Vt).

2.4.5 Differential Leveling

Differential leveling using a transit, tripod and Philadelphia rod was performed to obtain elevations at the sediment pins within each treatment (McCormac 1999). Originally the study site was slightly higher at the upstream end and sloped down as it moved away from the river, although total variation across the entire site was less than 60 cm. Differential leveling allowed calculation of treatment elevation, which was subsequently compared to the original elevation calculated before harvest using total accumulated sediment data.

At time zero, a survey of the site was taken using well locations (4 per treatment area) and depth of the water table above or below the surface was used to indicate relative surface elevations (Aust 1989). This site is tidally influenced so the water table measurements were taken within one and a half hours to minimize tidal effects. Elevations collected in year 24 used different methodology and the original well locals are missing, but the sediment pins represent similar locations in the treatment plots. Sediment accumulation data were used to interpret elevation differences between the two surveys. While this comparison is for slightly different locations, it allowed visual representation of the elevations on the site as temporal changes occurred.

2.4.6 Statistical Analysis

Statistical analysis was performed using either a completely randomized design (CRD) or a Latin Square design (LS) with three disturbance treatments depending upon number of replicates used. Due to site conditions, measurements were replicated 4-9 times depending on water levels at time of data collection. A Tukey HSD mean separation was performed with SAS v9.2 statistical software at alpha level 0.05 to determine significance (SAS Institute 2008). Treatment plots were compared to REF areas using a t-test at $\alpha = 0.05$.

2.5 Results and Discussion

2.5.1 Aboveground productivity

SKID treatments contained more biomass than HELI treatments ($p < 0.001$) at stand age 24-years, similar to the results of Gellerstedt and Aust (2004) at stand age 15 years. Current results found SKID treatments contain 243.2 Mg ha^{-1} of green biomass while HELI treatments contain 174.0 Mg ha^{-1} of green biomass in the overstory (Table 2.2). Currently woody vegetation in GLYPH treatments are transitioning from shrub-scrub wetlands to bottomland hardwood forests and currently contain an average of 87.0 Mg ha^{-1} of green biomass (Table 2.2). SKID and HELI treatments are presently about one quarter the age of the reference stand (94 years) and contain approximately one quarter of the biomass the REF areas (839.3 Mg ha^{-1} green biomass, Table 2.2).

Higher biomass in SKID relative to HELI treatments has several potential explanations, including differences in microtopography after harvest, coppice regeneration, and species differences which may alter interspecific competition (Battaglia et al. 2000, Goelz et al. 2001, Lockhart et al. 2006). Water tupelo comprises over 50% of the overstory in SKID treatments with 1482 stems ha^{-1} (Tables 2.2 and 2.3). HELI treatments have 889 stems ha^{-1} of tupelo making up approximately 42% of the overstory. Carolina and pumpkin ash make up 47% of tree species with 988 stems ha^{-1} in HELI treatments (Tables 2.2 and 2.3). On poorly drained sites Carolina and pumpkin ash are commonly smaller mid-story species. Tupelo is a flood tolerant species that is well adapted to wet soil conditions (Keeland et al. 1997). For example, Megonigal and Day (1992) found that tupelo will sometimes produce more aboveground biomass when the site is continuously flooded. SKID treatments were originally much wetter than other treatments due to trafficking effects (Gellerstedt and Aust 2004). Increased biomass in SKID treatments, therefore, may be due to enhanced tupelo growth from the initially wetter soil conditions combined with the reduced species competition compared to HELI treatments (Goelz et al. 2001, Lockhart et al. 2006).

SKID, HELI, and GLYPH treatments averaged 2487, 2108 and 1021 stems ha^{-1}, respectively (Table 2.2). Height and DBH in SKID treatments averaged 12.0 m and 13.8 cm similar to 12.0 m and 12.3 cm in HELI treatments (Table 2.2). GLYPH treatments had significantly lower heights (9.4 m, $p = 0.003$), but DBH in the relatively open GLYPH treatment was greater numerically, but not significantly, (14.3 cm) compared to other disturbance treatments (Table 2.2). Increased DBH growth in GLYPH treatments is likely due to the significantly lower stem density (1021 stems ha^{-1}, Table 2.2). Decreased height growth may be due to the fact that many of the willow stems in the GLYPH treatments were falling over and growing at an acute angle. Height was measured to the highest point rather than along the stems, thus reducing average height and requiring allometric equations relying on DBH for volume calculations (Table 2.1). When compared to other species, black willows are the tallest trees in HELI and SKID treatments, though are not as tall in GLYPH treatments reflecting their growth pattern. Heights in GLYPH treatments are also lower due the younger tree age compared to those found in SKID and HELI treatments. Establishment of GLYPH woody regeneration was delayed by at least two years due to the removal of initial regeneration sources with herbicide, followed by the abundant herbaceous vegetation that competed with seedlings at establishment.

For the 2009-2010 growing season SKID and HELI treatments had similar rates of aboveground net primary productivity (ANPP): 12.42 Mg ha^{-1} yr^{-1} and 12.08 Mg ha^{-1} yr^{-1}, respectively. ANPP rates in GLYPH treatments are double of those in SKID and HELI treatments at 24.64 Mg ha^{-1} yr^{-1}. This rate is probably related to the lower density in GLYPH treatments which allowed trees to grow at approximately 4x the rate of those found in SKID and HELI treatments. Results similar to SKID and HELI were found in a study by Conner and Day (1976) for a Louisiana bottomland hardwood swamp with an ANPP of approximately 22 Mg ha^{-1} yr^{-1}. A comparison to REF was unable to be made with this data due to a plot size measurement error in 2009, but in 1988 the productivity of the mature stands was 13.24 Mg ha^{-1} yr^{-1} at age 70 (Mader 1990). Average ANPP rates over 24 years for SKID treatments (10.1 Mg ha^{-1} yr^{-1}) are higher than those found in HELI and GLYPH treatments (7.23 and 3.62 Mg ha^{-1} yr^{-1}, respectively, based on data from Table 2.2). Average ANPP rate over 94 years in REF areas is 8.91 Mg ha^{-1} yr^{-1} based on data from Table 2.2.

It was assumed that ground based skidding would more negatively affect site and soil properties as compared to helicopter extraction due to increased compaction, churning, rutting and reduced aeration and drainage (Stokes and Schilling 1997). However, in this study SKID treatments have been more productive than HELI treatments. The wetter conditions in SKID treatments have likely favored the tupelo by reducing woody competition during the initiation of this study in 1986 as compared to HELI treatments (Gellerstedt and Aust 2004). Aust and Lea (1992) found a six-fold reduction in soil water movement compared to REF areas and a decrease in soil O_2 as compared to HELI treatments. Another explanation behind this is the increased microtopography after harvest in SKID treatments. By simulating a ground-based harvest, skidders trafficked across an average of 50% of the of these treatment areas (Aust and Lea 1992). Traffic caused soils to be rutted creating areas above the water and below the water creating microsites for vegetation to become established and a range of soil moisture condition that roots could exploit. HELI treatments did have greater species diversity than the SKID, but both treatments contain the species found in the original stands which were 85% water tupelo, 10% cypress, and 5% pumpkin ash, water elm, Carolina ash, and a few minor species (Aust and Lea 1992). The largest species difference between the REF areas and disturbance treatments is the presence of black willow in the disturbed treatments. Black willow commonly becomes established on disturbed wetland sites, but it is a short lived pioneer species (Hodges 1997) that has become noticeably reduced during the past decade.

2.5.2 Belowground Productivity

Belowground biomass results generally parallel the trends of aboveground biomass. SKID treatments had greater belowground biomass (p = 0.07, marginally significant) to a depth of 60 cm while HELI treatments had the least (25.65 Mg ha^{-1} and 13.71 Mg ha^{-1}, respectively, Table 2.4). GLYPH treatments had the highest average biomass in the top 15 cm (approximately 8.0 Mg ha^{-1}); however at the lower three depths the total amount of belowground biomass is lower than other treatment totals (Table 2.4). Belowground biomass follows a similar trend in HELI treatments but, the pattern is not as prominent as observed in GLYPH treatments. SKID treatments had consistent belowground biomass at all depths and belowground biomass increases in the deepest sample (45-60 cm) to 6.5 Mg ha^{-1} from 5.7 and 5.8 Mg ha^{-1} in the preceding depths (15-30 cm and 30-45 cm, respectively, Table 2.4). This may be due to the amount of logging debris buried on the site. With the combination of wet conditions and annual inputs of sediment, much of the logging debris from past harvests has been buried on the site. This has caused an increase in organic material on the site at depth, from an average of 4.4 Mg ha^{-1} of woody debris from 15-45 cm to an average of 15.4 Mg ha^{-1} from a depth of 45-60 cm and coarse roots may have taken advantage of this deep nutrient source (Chapter 3, Table 3.6). GLYPH treatments have high amounts of fine roots in the upper soil depth which is to be expected due to the dense herbaceous ground cover on these treatments (2.8 Mg ha^{-1} of dry biomass, Table 3.4). There are few coarse roots in GLYPH treatments primarily due to the low density of trees on these treatments. As trees continue to develop and the GLYPH transitions into a bottomland hardwood forest, a change in root biomass patterns may become similar to SKID or HELI treatments.

SKID treatments have the highest total coarse roots (20.7 Mg ha^{-1}) and belowground biomass (Table 2.4). This suggests that disturbance from skidder traffic on these sites was not necessarily detrimental to the regeneration of these stands. Furthermore, disturbance initially increased microtopography on the site which may have resulted in different belowground habitats for tree roots to exploit.

2.5.3 Sediment Deposition

The herbaceous dominated GLYPH treatments accumulated the greatest amount of sediment, a total of 38.5 cm (2156 Mg ha^{-1}) over the 24 years (Table 2.5). Herbaceous vegetation has increased surface roughness and sediment filtering capabilities in these plots (Figure 2.3). The increased surface roughness slows the water and allows sediment to settle out of water (Sheridan et al. 1999). HELI, SKID and REF treatments accumulated 30.0, 25.4 and 18.1 cm (1680, 1422, and 1014 Mg ha^{-1}) of sediment respectively (Table 2.5). Patterns of disturbances causing higher sedimentation rates has also been found by Perison et al. (1997) where skidder and helicopter harvested areas in a South Carolina bottomland hardwood forest collected more sediment compared to mature stands.

Since measurement in 2002 at age 16 (Gellerstedt and Aust 2004), GLYPH treatments have averaged 11.6 cm (649.6 Mg ha^{-1}) of sediment accumulation while HELI, SKID and REF treatments averaged 8.4, 7.7 and 6.2 cm (470.4, 431.2, and 347.2 Mg ha^{-1}), respectively (Table 2.5). Over this eight year period average yearly sediment accumulation ranged from 0.8 cm and 1.4 cm a year (44.8-78.4 Mg ha^{-1} yr^{-1}) for all treatments and results are similar to those found by Gellerstedt and Aust (2004) (Table 2.5). Sedimentation rates in a coastal plain watershed studied by Lowrance et al. (1986) were found to be within this same range with an average of 52 Mg ha^{-1} yr^{-1}. Rates of soil accumulation have remained consistent since the last measurement period and values have fallen closer to those found in the REF stands. Of course, these sediment rates vary with flood length and intensity. For example, in the winter of 2009-2010 an upstream hydrograph indicated that the site was continually submerged for approximately seven months beginning in September (USGS stream gauge 02470630, Figure 2.4). However, in previous years the site has been flooded less frequently.

Sediment inputs to this floodplain also vary due to the nature of land use and climate in the watershed. Large amounts of development and agriculture in the watershed can increase sedimentation rates (Pimentel and Kounang 1998). Similarly, if the watershed receives lower than average precipitation in that same year, sedimentation rates would likely decrease due to lower flood waters for a shorter period (Nearing et al. 2005). Annual inputs of these nutrient rich sediments are very important in this system and have acted as a natural amelioration factor over the period of this study.

2.5.4 Bulk Density

Bulk density values were generally low due to the recent deposition of sediment (Gellerstedt and Aust 2004). Bulk density values increased with soil depth ranging from 0.56 Mg m^{-3} in the A horizon to 0.83 Mg m^{-3} in the Cg2 horizon at the lowest depth, 25 cm to 35 cm. Treatment effects for bulk density were only significant for 25 cm to 35 cm soil depth ($p = 0.03$) where HELI treatments had significantly greater bulk density than REF stands (0.85 and 0.74 Mg m^{-3}, respectively, Table 2.6). While bulk densities found here are lower than those of Messina et al. (1997) for a Texas bottomland hardwood swamp they follow a similar pattern of increased bulk density with increased soil disturbance.

Major differences were not expected in soil bulk density due to findings in year two by Aust and Lea (1992) where soil mechanical resistance had already almost returned to that of REF areas. Comparing bulk density values at different depths provides some insight into soil recovery potential. Initially compaction had occurred in SKID treatments due to skidder traffic which covered an average 50% of the treatment and bulk density values indicate that the soil has recovered from the skidder traffic. Recovery is likely due to a combination of the shrink-swell nature of the Levy series soils, input of non-compacted sediments, exploration of root biomass and old root channels (McKee 2001, Gellerstedt and Aust 2004).

2.5.5 Differential Leveling

Changes in elevation due to sediment accumulation are important since small changes in elevation can have dramatic influences on hydroperiod and the rooting environment. Original survey data found an average difference in elevation across the study area of 12.2 cm (Aust 1989). Results from this survey show the change in elevation across the study area being 54.9 cm. Within treatments, the average difference in elevation was 9.14 cm in 1986 (Aust 1989) and this increased to 30.48 cm in 2010. These results show that the sediment accumulation over time has affected the overall microtopography of the site.

Figure 2.5 represents the change in elevation over time for each row as distance from the river increases. This survey was referenced to the original survey data using sediment deposition data from the first treatment row. Row 1 of the study shows an interesting pattern that is less apparent in the second and third rows (Figure 2.5). Changes in topography seem to be driven more by location rather than by treatment. At the far right (upstream) of row 1 is a GLYPH treatment (Figure 2.2), sedimentation begins to occur more as flood waters come out of the undisturbed forest adjacent to the study. As the flood waters continue across the floodplain they slow and more sediment settles out from the water column. Finally as the flood waters enter the

REF areas they begin to speed back up due to a lack of surface roughness and less sedimentation occurs. This pattern is also evident for rows 2 and 3 (Figure 2.5).

2.6 Conclusions

Twenty-four years after harvest, the treatments have similar species composition and growth rates relative to REF conditions. The presumably more disruptive SKID treatment seems to be recovering more quickly than the HELI treatment. HELI treatments contain less overstory biomass than SKID treatments, probably caused by initial harvest soil effects in SKID treatments. The more rutted, wetter, and less aerated SKID treatments favored tupelo establishment. The changed microtopography of SKID treatments from traffic has also allowed for the water tolerant species such as water tupelo and bald-cypress to become established on these treatments before other competitors such as Carolina ash and black willow could become established. In turn, this has allowed for the tupelo and cypress to grow much faster than in other treatments. These results indicate that soil and site disturbance caused by skidder traffic has no negative long-term impact on timber production and may actually increase overall biomass growth in these ecosystems.

Annual inputs of sediment have also helped to speed stand recovery. Accumulation of non-compacted sediment not only allows for soil aeration, but also brings nutrients into the system annually. Further, the shrink-swell clays that are on the site have naturally ameliorated compaction that may have been caused by heavy machinery on the site, such as a skidder. While these conditions do not apply to all wetland sites, on similar sites these results do demonstrate that the negative impacts associated with skidder traffic tend to be naturally ameliorated.

Long-term studies are important for understanding ecosystem recovery. Continued management of wetland forests may become increasingly important in the future as more wood is grown on a decreasing land base. Fertile and self-healing sites such as this may be the key to being able to manage timber on limited areas with an increasing demand.

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Chapter 2 Table and Figure Captions

Table 2.1 Volume equations and sources used to estimate aboveground biomass. Other species include the following: *Nyssa aquatic, Fraxinus caroliniana, Fraxinus profunda, Acer rubrum, Planera aquatica,* and *Platanus occidentalis.*

Table 2.2 Overstory stand characteristics by species and treatment including diameter at 1.3m (DBH), average height, stems per hectare and volume per hectare (green weight basis). Other species include *Cephalanthus occidentalis, Planera aquatica* and *Platanus occidentalis*. Values with different letters within a row are significantly different from each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 2.3 Major species composition percentage as affected by harvesting treatments. Other species include *Cephalanthus occidentalis*, *Planera aquatica* and *Platanus occidentalis*. SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 2.4 Belowground biomass measurement (megagrams per hectare) for four soil depths as influenced by harvesting treatments. Total measurements calculated in Mg ha^{-1} to a depth of 60 cm. Values with different letters within a row are significantly different from each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 2.5 Sediment deposition metrics across the study site as influenced by harvesting treatment. Values with different letters within a column are significantly different from each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 2.6 Bulk density of the soil at depths 0-10 cm, 15-25 cm and 25-35 cm by harvesting treatment. Values with different letter within a row differ statistically (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

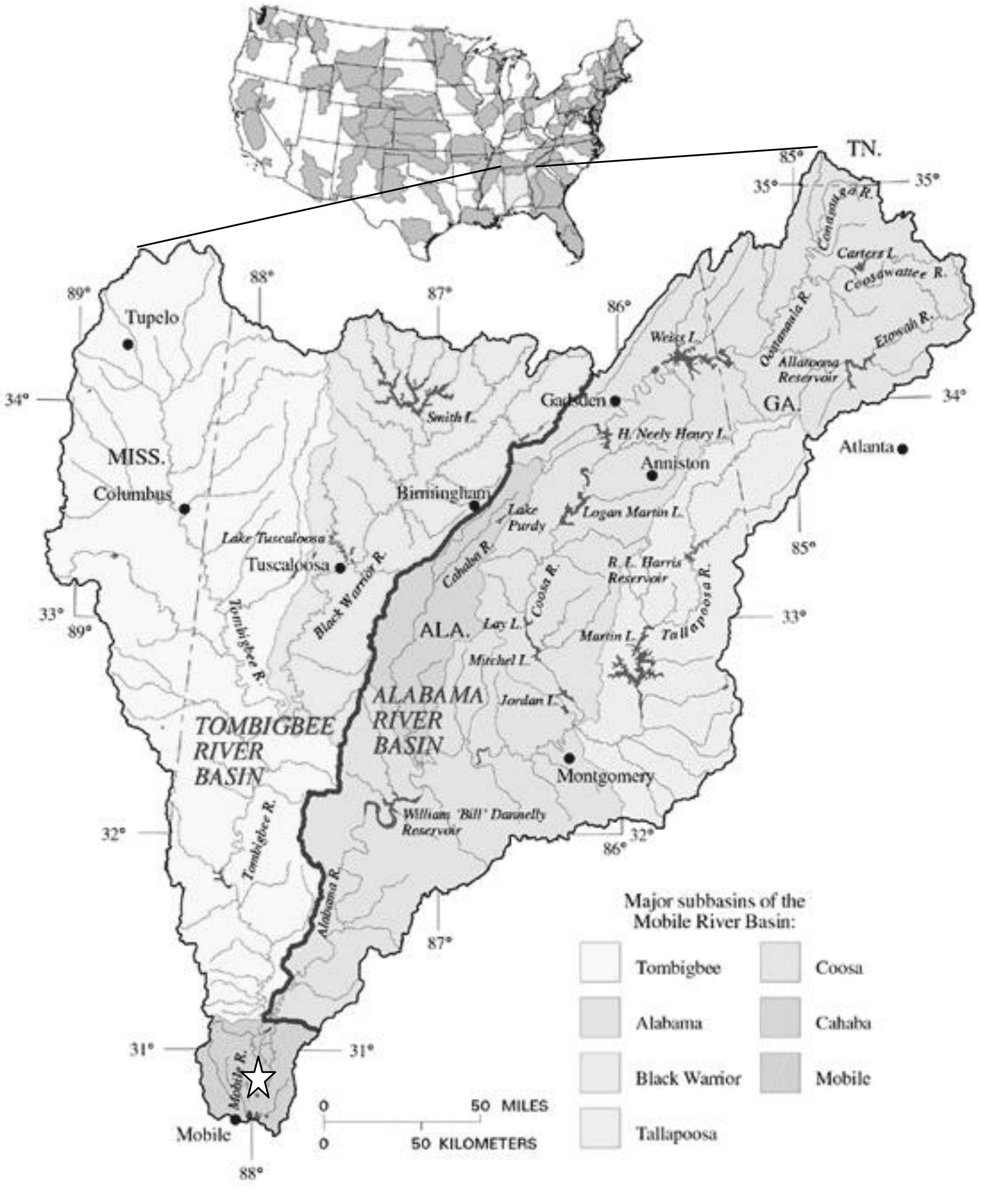
Figure 2.1 The Mobile-Tensaw River Delta below the Alabama and Tombigbee River Basins. Approximate location of the study site indicated by star. Adapted from Dillon (2009).

Figure 2.2 Experimental design and plot layout of the study site. R = reference area (REF), S = Skidder simulation treatment (SKID), H = helicopter logged area (HELI), G = glyphosate treatment area (GLYPH). Plots are 60 meters by 60 meters. Adapted from Aust and Lea (1991).

Figure 2.3 The relationship between herbaceous vegetation amount and sediment deposition as influenced by harvesting treatments with overall linear relationship. SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Figure 2.4 Hydrograph of mean daily river stage from Army Corps of Engineers river gauge 02470630 on the Mobile River at Barry Steam Plant, approximately 12 km Northwest of the study site, from August 1, 2009 to August 31 2010. Flood stage of 1.16 m was determined from study site observations and river gauge formerly located at Live Oak Landing approximately 1 km downstream of study site. The dashed line represents the river stage where the majority of the study site is under water.

Figure 2.5 Changes in elevation across the experimental site from 1986 and 2010, row 1 is closest to river and row 3 is farthest from the river. The River flows from the right to left on the x-axis. Elevation measured in meters and not based on mean sea level. GLYPH (Glyphosate plots), SKID (Skidder transport plots), HELI (Helicopter transport plots), and REF (Reference plots).



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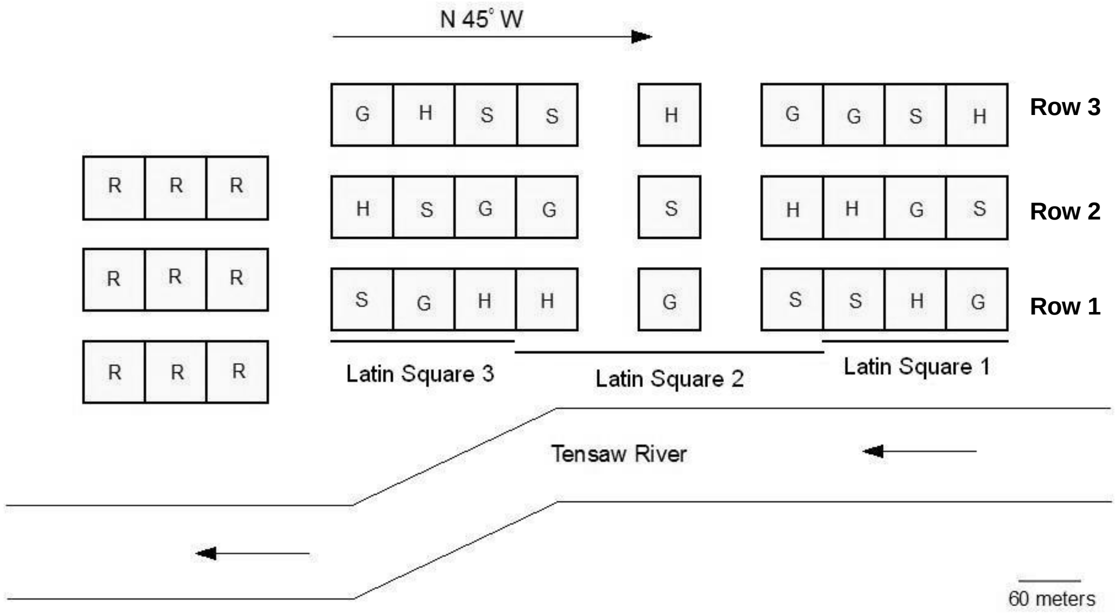

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Table 2.1 Volume equations and sources used to estimate aboveground biomass. Other species include the following: *Nyssa aquatic*, *Fraxinus caroliniana*, *Fraxinus profunda*, *Acer rubrum*, *Planera aquatica*, and *Platanus occidentalis*.

Species	**Equation**	**Units**	**Source**
Taxodium distichum	$Vol = 0.0043*D^{1.78756}*H^{1.00866}$	cubic feet (total tree)	Hotvedt et al. 1985
Other Species (DBH < 11.0 in)	$Vol = 0.16747(D^2H)^{0.95874}$	green weight (lbs)	Clark et al. 1985 (Table 12)
Other Species (DBH > 11.0 in)	$Vol = 0.09201(D^2)^{1.08363}(H)^{0.95874}$	green weight (lbs)	Clark et al. 1985 (Table 12)
Salix nigra	$Vol = 10^{(-1.017+2.07*\log(DBHcm))}$	dry weight (kg)	Muzika et al. 1987
Cephalanthus occidentalis	$Vol = 10^{(-0.712+1.744*\log(DBHcm))}$	dry weight (kg)	Muzika et al. 1987

Table 2.2 Overstory stand characteristics by species and treatment including diameter at 1.3m (DBH), average height, stems per hectare and volume per hectare (green weight basis). Other species include *Cephalanthus occidentalis*, *Planera aquatica* and *Platanus occidentalis*. Values with different letters within a row are significantly different from each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Treatment	*Taxodium distichum*	*Nyssa aquatica*	*Fraxinus caroliniana/ F. profunda*	*Salix nigra*	*Acer rubrum*	Other Spp.	**All Species**
			Average DBH (cm) (+/- Standard Error)				
	$p < 0.001$	**$p < 0.001$**	**$p < 0.001$**	$p = 0.4$	$p = 0.1$	$p = 0.9$	**$p = 0.01$**
SKID	11.0 ± 1.3 b	15.6 ± 0.4 b	8.3 ± 0.1 b	22.9 ± 1.4	7.8 ± 0.0	9.7 ± 0.1	13.8 ± 0.3 b
HELI	12.3 ± 1.4 b	16.0 ± 0.9 b	8.3 ± 0.2 b	25.4 ± 1.4	12.7 ± 0.1	9.1 ± 0.8	12.3 ± 0.5 b
GLYPH	21.0 ± 1.3 ab	15.0 ± 1.8 b	8.8 ± 0.9 ab	18.1 ± 2.4	11.9 ± 0.5	9.5 ± 0.6	14.3 ± 1.1 b
REF	34.3 ± 6.4 a	43.7 ± 1.2 a	11.1 ± 0.4 a	-	-	-	30.9 ± 0.8 a
			Average Height (m) (+/- Standard Error)				
	$p < 0.001$	**$p < 0.001$**	**$p = 0.002$**	**$p < 0.001$**	$p = 0.3$	$p = 0.06$	**$p = 0.003$**
SKID	9.2 ± 0.8 b	13.3 ± 0.2 b	9.5 ± 0.3 ab	15.3 ± 0.8 a	8.3 ± 0.0	6.2 ± 0.1	12.0 ± 0.2 b
HELI	9.9 ± 1.6 b	13.8 ± 0.5 b	10.3 ± 0.2 a	16.9 ± 0.5 a	12.8 ± 0.2	8.5 ± 0.5	12.0 ± 0.3 b
GLYPH	10.9 ± 0.3 b	11.4 ± 1.2 b	8.0 ± 0.6 b	10.3 ± 0.5 b	10.5 ± 0.7	4.5 ± 0.2	9.4 ± 0.5 c
REF	21.3 ± 2.6 a	25.4 ± 0.6 a	9.5 ± 0.3 ab	-	-	-	19.2 ± 0.4 a
			Average stems ha^{-1} (+/- Standard Error)				
	$p = 0.03$	**$p < 0.001$**	**$p = 0.002$**	$p = 0.1$	$p = 0.4$	$p = 0.4$	**$p < 0.001$**
SKID	329 ± 82 a	1482 ± 139 a	478 ± 91 b	132 ± 30	49 ± 21	17 ± 7	2487 ± 141 a
HELI	115 ± 48 ab	889 ± 189 a	988 ± 154 a	66 ± 23	17 ± 9	33 ± 13	2108 ± 227 a
GLYPH	82 ± 34 b	264 ± 146 b	173 ± 54 b	296 ± 114	74 ±39	132 ± 101	1021 ± 166 b
REF	80 ± 16 b	379 ± 26 ab	261 ± 21 b	-	-	-	719 ± 27 b
			Average Mg ha^{-1} (+/- Standard Error)				
	$p < 0.001$	**$p < 0.001$**	**$p = 0.007$**	$p = 0.3$	$p = 0.4$	$p = 0.4$	**$p < 0.001$**
SKID	38.9 ± 20.2 b	175.9 ± 15.1 b	10.1 ± 1.9 ab	17.2 ± 3.4	0.8 ± 0.8	0.3 ± 0.2	243.2 ± 17.7 b
HELI	12.9 ± 4.4 b	126.1 ± 28.9 b	22.6 ± 4.7 a	10.5 ± 4.2	1.1 ± 0.5	0.8 ± 0.4	174.0 ± 26.1 c
GLYPH	25.5 ± 8.7 b	24.9 ± 12.2 c	3.6 ± 1.0 b	27.4 ± 8.5	3.3 ± 2.1	2.2 ± 1.6	87.0 ± 18.6 d
REF	177.2 ± 47.3 a	651.9 ± 32.3 a	10.2 ± 0.9 ab	-	-	-	839.3 ± 50.4 a

Table 2.3 Major species composition percentage as affected by harvesting treatments. Other species include *Cephalanthus occidentalis*, *Planera aquatica* and *Platanus occidentalis*. SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Treatment	*Taxodium distichum*	*Nyssa aquatica*	*Fraxinus caroliniana / F. profunda*	*Salix nigra*	*Acer rubrum*	Other Spp.	**All Species**
SKID	13.2%	59.6%	19.2%	5.3%	2.0%	0.7%	100%
HELI	5.5%	42.2%	46.9%	3.1%	0.8%	1.6%	100%
GLYPH	8.1%	25.8%	16.9%	29.0%	7.3%	12.9%	100%
REF	11.1%	52.7%	36.3%	0.0%	0.0%	0.0%	100%

Table 2.4 Belowground biomass measurement (Mg ha^{-1}) for four soil depths as influenced by harvesting treatments. Total measurements calculated in Mg ha^{-1} to a depth of 60 cm. Values with different letters within a row are significantly different from each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

		Treatment				
		SKID	**HELI**	**GLYPH**	**REF**	
Soil Depth	**Root Class**	Mg ha^{-1} in 15 cm depth classes (+/- Standard Error)				***p-value***
0-15 cm	*Fine*	3.3 ± 1.0	1.8 ± 0.7	4.2 ± 1.7	2.4 ± 1.6	$p = 0.6$
	Coarse	4.4 ± 0.5	4.2 ± 1.6	3.8 ± 1.2	3.7 ± 0.5	$p = 0.9$
	Total	7.6 ± 1.5	6.0 ± 1.4	8.0 ± 1.6	6.1 ± 1.4	$p = 0.7$
15-30 cm	*Fine*	0.7 ± 0.1	1.0 ± 0.6	0.7 ± 0.2	1.0 ± 0.5	$p = 0.9$
	Coarse	5.0 ± 1.7	3.2 ± 1.2	1.5 ± 0.7	3.2 ± 0.9	$p = 0.3$
	Total	5.7 ± 1.7	4.2 ± 1.3	2.2 ± 0.9	4.2 ± 1.4	$p = 0.4$
30-45 cm	*Fine*	0.6 ± 0.0	0.4 ± 0.2	0.3 ± 0.0	0.4 ± 0.2	$p = 0.5$
	Coarse	5.2 ± 1.1 a	0.9 ± 0.6 b	1.5 ± 1.3 ab	1.8 ± 0.8 ab	**$p = 0.04$**
	Total	5.8 ± 1.1 a	1.2 ± 0.8 b	1.8 ± 1.3 ab	2.2 ± 0.8 ab	**$p = 0.04$**
45-60 cm	*Fine*	0.4 ± 0.0	0.2 ± 0.1	0.4 ± 0.1	0.9 ± 0.4	$p = 0.2$
	Coarse	6.1 ± 2.3	2.1 ± 1.6	1.6 ± 0.3	8.3 ± 2.4	$p = 0.07$
	Total	6.5 ± 2.3	2.3 ± 1.7	1.9 ± 0.3	9.2 ± 2.7	$p = 0.07$
		Mg ha^{-1} to a depth of 60 cm (+/- Standard Error)				
Total 60 cm	*Fine*	5.0 ± 1.1	3.4 ± 1.6	5.6 ± 1.8	4.7 ± 2.7	$p = 0.9$
	Coarse	20.7 ± 2.6 a	10.3 ± 2.9 ab	8.4 ± 2.9 b	17.0 ± 2.5 ab	**$p = 0.02$**
	Total	25.7 ± 1.9	13.7 ± 3.9	13.9 ± 2.5	21.7 ± 4.5	$p = 0.07$

Table 2.5 Sediment deposition metrics across the study site as influenced by harvesting treatment. Values with different letters within a column are significantly different from each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Treatment	24 Year Total Deposition	2002-2010 Deposition (*$p < 0.001$*)	Annual Deposition
		cm of soil (Mg ha^{-1})	
SKID	25.4 (1422.4)	7.7 ± 0.5 bc (431.2)	1.0 (56.0)
HELI	30.0 (1680.0)	8.4 ± 0.5 b (470.4)	1.1 (61.6)
GLYPH	38.5 (2156.0)	11.6 ± 0.6 a (649.6)	1.4 (78.4)
REF	18.1 (1013.6)	6.2 ± 0.5 c (347.2)	0.8 (44.8)

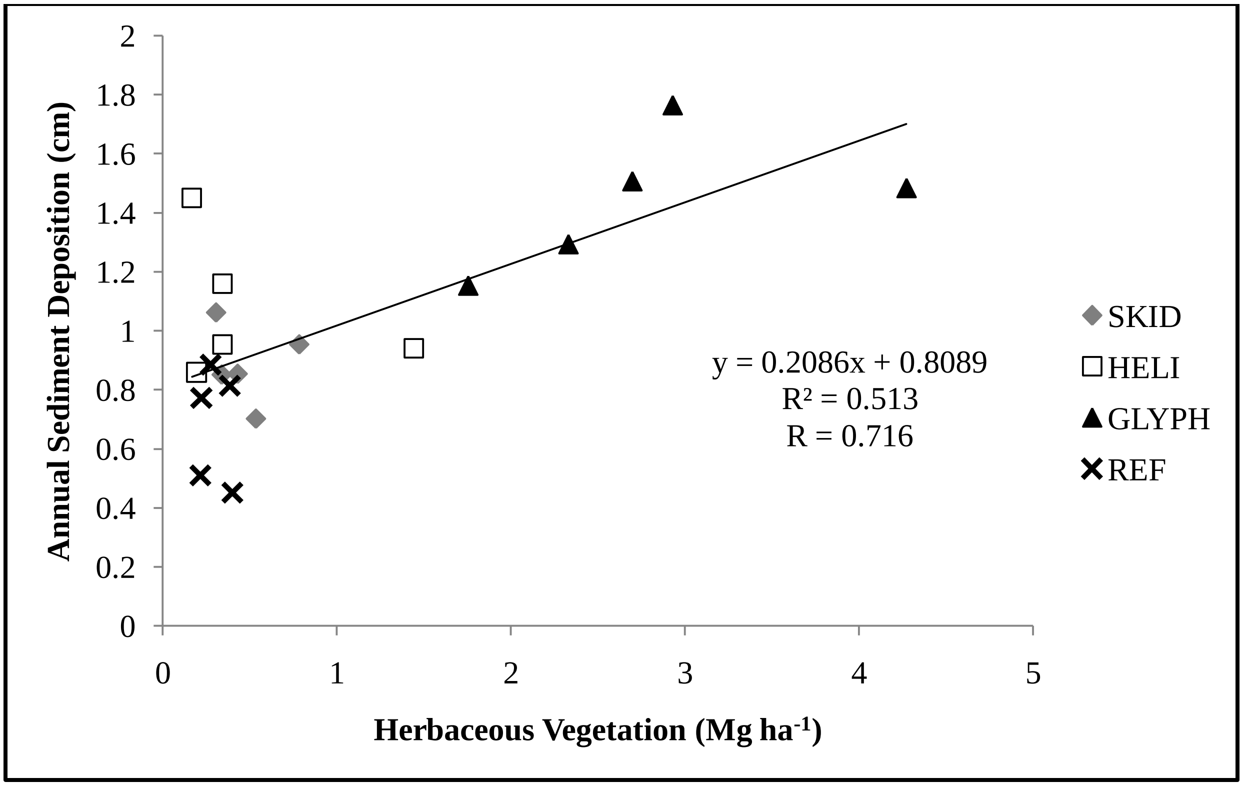

Figure 2.3 The relationship between herbaceous vegetation amount and sediment deposition as influenced by harvesting treatments with overall linear relationship. SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

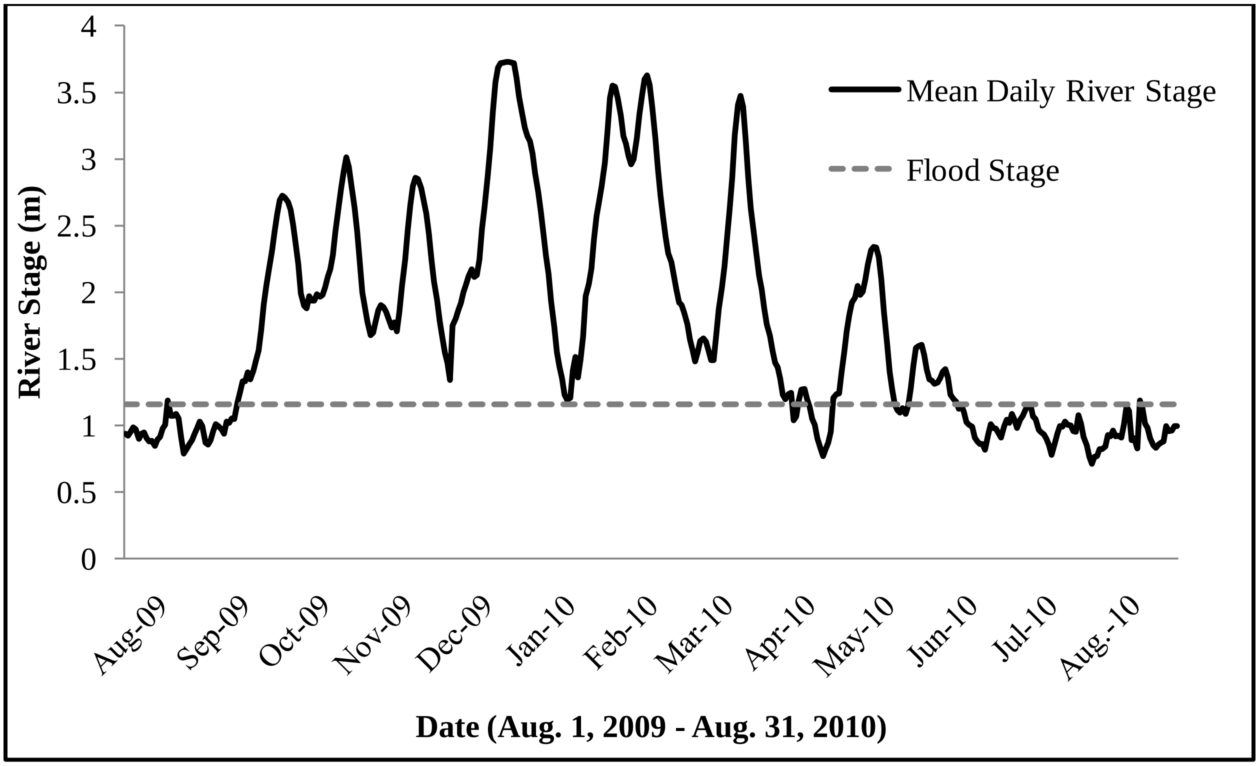

Figure 2.4 Hydrograph of mean daily river stage from Army Corps of Engineers river gauge 02470630 on the Mobile River at Barry Steam Plant, approximately 12 km Northwest of the study site, from August 1, 2009 to August 31 2010. Flood stage of 1.16 m was determined from study site observations and river gauge formerly located at Live Oak Landing approximately 1 km downstream of study site. The dashed line represents the river stage where the majority of the study site is under water.

Table 2.6 Bulk density of the soil at depths 0-10 cm, 15-25 cm and 25-35 cm by harvesting treatment. Values with different letter within a row differ statistically (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Depth	**Treatment**			
Increment	**SKID**	**HELI**	**GLYPH**	**REF**
	(Mg m^{-3} ± Standard Error)			
0-10 cm (*p = 0.5*)	0.57 ± 0.01	0.56 ± 0.01	0.55 ± 0.03	0.54 ± 0.02
15-25 cm (*p=0.6*)	0.72 ± 0.04	0.75 ± 0.04	0.73 ± 0.02	0.69 ± 0.03
25-35 cm **(*p = 0.03*)**	0.84 ± 0.02 ab	0.85 ± 0.02 a	0.79 ± 0.03 ab	0.74 ± 0.04 b

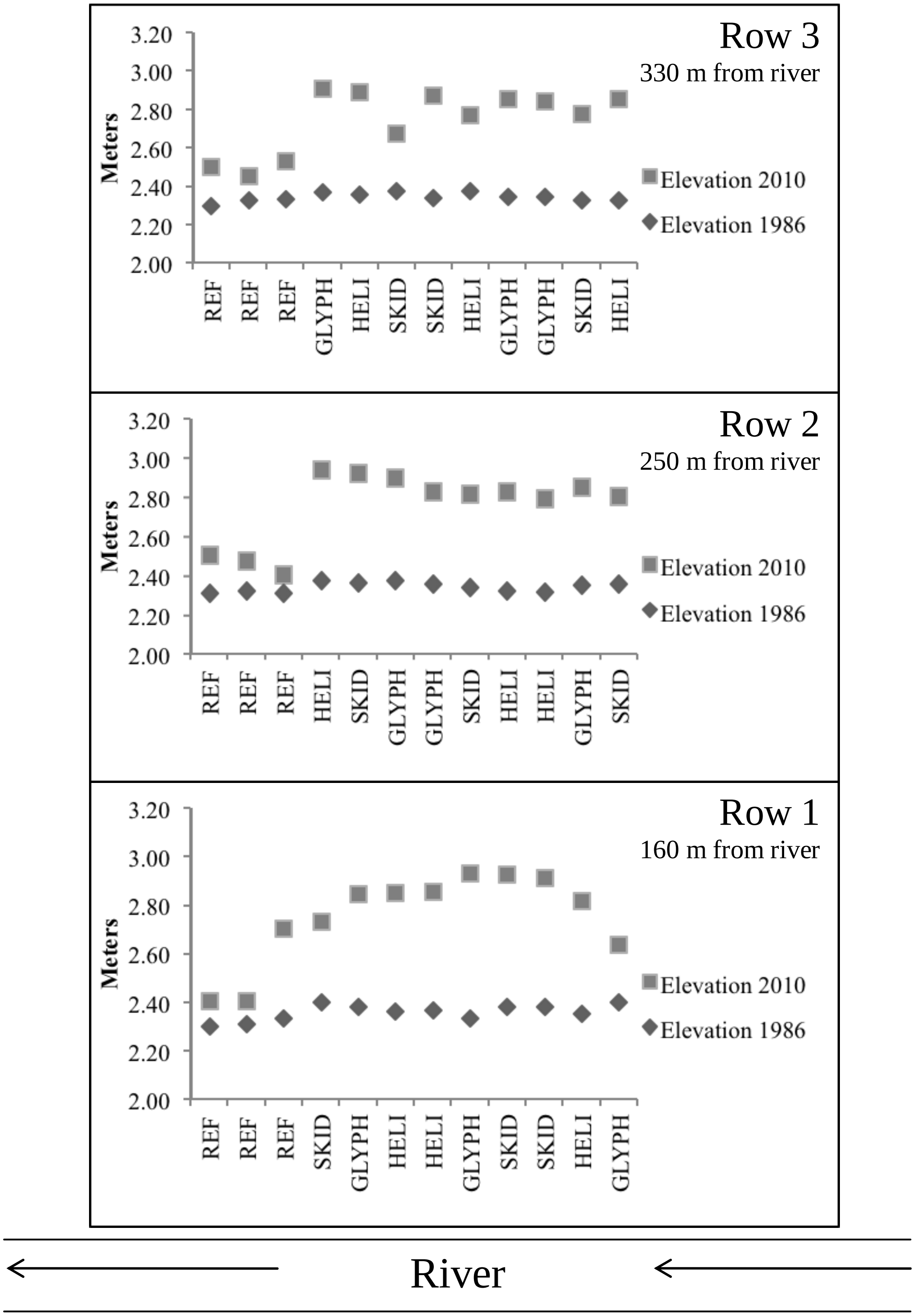

Figure 2.5 Changes in elevation across the experimental site from 1986 and 2010, row 1 is closest to river and row 3 is farthest from the river. The River flows from the right to left on the x-axis. Elevation measured in meters and not based on mean sea level. GLYPH (Glyphosate plots), SKID (Skidder transport plots), HELI (Helicopter transport plots), and REF (Reference plots).

Chapter 3. Carbon Pools and Fluxes in a Tupelo-Cypress Swamp 24-Years after Harvest Disturbances

Abstract

Bottomland forests are productive timberlands that possess large quantities of above- and belowground carbon (C), yet long-term research projects relating to harvest effects in bottomland hardwood forests are few. This project evaluated the long-term (24-years after harvest) influence of three harvest treatments on the C budget of a bottomland hardwood forest. The study site, a tupelo-cypress swamp in southwestern Alabama, was clearcut in 1986 and timber removed by helicopter. Treatments compared were: 1. Helicopter alone (HELI) 2. Skidder-simulation (SKID) harvesting practices and 3. Complete vegetation removal following harvesting with herbicide during years one and two (GLYPH). An adjacent non-harvested reference stand (REF) was maintained. Measurements included aboveground biomass, belowground biomass, soil C, soil CO_2 efflux and estimates of buried coarse woody debris on the site. SKID treatments had the highest aboveground biomass (73.9 Mg C ha^{-1}) and total C storage (206.1 Mg C ha^{-1}) of the three treatments. GLYPH treatments had the lowest C storage (144.2 Mg C ha^{-1}) and lower aboveground woody biomass (26.4 Mg C ha^{-1}). HELI and SKID treatments were similar, but have slightly less in total forest C (168.7 Mg C ha^{-1}). Belowground biomass pools indicate that SKID treatments possess the highest amount of C in their roots. Belowground coarse woody debris storage increased C storage on these sites with an additional 8-13 Mg C ha^{-1} being stored. GLYPH treatments had the highest total soil CO_2 efflux followed by HELI and SKID treatments, respectively. Higher biomass and C storage of SKID treatments is explained by a combination of factors: flood tolerant species such as tupelo, diverse microtopography from harvest by

skidder trafficking, and decreased soil aeration of skidder-rutted areas after harvest which favored tupelo coppice have all favored increased C storage of SKID treatments.

3.1 Introduction

Potential climate change as a result of increasing greenhouse gas emissions has focused attention on the role forests play in sequestering atmospheric C (Stainback and Alavalapati 2005). According to the US Department of Energy Carbon Dioxide Information Analysis Center, a 30% increase in the atmospheric concentration of carbon dioxide (CO_2) has occurred during the past century (Birdsey et al. 2006). The ability of forests to sequester C has promoted interests in forest C credit trading markets. Therefore, accurate estimates of C pools and fluxes, particularly from soils, that occur in different forest types are needed.

3.2 Forest Carbon

Understanding C pools within different forest cover types is critical when managing wetland forests. Components of aboveground C pools consist of overstory, mid-story and understory vegetation, and the forest floor consisting of leaf litter and woody debris. Turner et al. (1995) stated that mature planted pine forests in the southeast US hold approximately 130-150 Mg C ha^{-1} in the aboveground biomass pools. Turner et al. (1995) also estimate that about half of the total C held in forests in the US is in aboveground biomass pools. Current rates of deforestation and forest fires result in annual net losses of soil C from a combined loss of soil organic matter and/or O horizon after harvesting or fire (Johnson 1992, Trettin et al. 1996, Worrell and Hampson 1997).

Belowground C pools account for approximately half of forest C in floodplain forests (Megonigal and Day 1988, Schilling et al. 1999). Forested wetland soils can hold greater amounts of C belowground because of their extended saturation and reduced decomposition

(Aust and Lea 1991). Aust and Lea (1991) found that decomposition in bottomlands can be influenced by soil temperature. The authors found that increased soil temperature decreased soil organic matter content on a wetland site causing C to be released to the atmosphere. Increased productivity in these wetlands may also help these forests store greater C belowground (Giese et al. 2003). Increased productivity is due in part to the annual inputs of nutrient and mineral rich deposits from flood water (Wharton et al. 1976, Aust et al. 2006). Soil C content is also related to root production since root turnover releases C to the soil (Symbula and Day 1988). Roots from wetland species such as cypress and tupelo generally produce more belowground biomass when periodically flooded (Megonigal and Day 1992) and fine root turnover may in fact add more organic matter to the soil than the leaf litter (Symbula and Day 1988, Conner and Buford 1998). Litterfall can be another C input to soils when not transported from the site by flood waters. In a tupelo-cypress alluvial swamp in North Carolina Brinson et al. (1980) found an average litter fall of 6,428 kg ha^{-1} yr^{-1} with 65.7% coming from foliage. The rest of the organic matter consisted of reproductive tree parts (15.6%), woody parts (14.1%), miscellaneous (4.4%), and epiphytes (0.2%).

Carbon pools in forested systems fluctuate in response to harvesting (Lal 2005). Balancing C flux in the soil ultimately determines storage capacity of bottomland forests (Armentano and Menges 1986). Carbon accumulates in forest soils when plant litter or logging debris is deposited and incorporated into the soil (Lockaby et al. 2005). Fine litter can decompose, be incorporated into the soil and eventually store C belowground (Mulholland 1981). Once incorporated into the soil, C will be stored until it further decomposes and is transformed into CO_2 (Gaudinski et al. 2000). In bottomlands, logging debris may contribute to soil C if buried by overbank flood sediment or churning of soil that occurs as a result of harvesting operations (Aust and Lea 1992, Lockaby et al. 2005).

As plants decompose, CO_2 is released from the soil (Gaudinski et al. 2000). In general, annual inputs of C from vegetation residues are equal to C lost through decomposition (Schlesinger and Lichter 2001). However, harvesting can alter this balance, favoring net increases or decreases in soil C. Many different factors influence C storage: soil oxygen availability, microbial biomass and activity, C quality (e.g. leaves versus limbs), and species composition (Lal 2005). Under anaerobic conditions decomposition is reduced (Brinson 1977) a common occurrence in bottomland systems since they can be flooded for weeks or months at a time. Furthermore, buried logging debris has the potential to remain much longer (Lockaby et al. 2005) and many wetland species are naturally decay resistant. Cypress, for example, takes longer to decompose than many bottomland species (Stine, 2008).

Soil CO_2 efflux is the amount of CO_2 being released from the soil and is an index of soil respiratory activity. This biological process is comprised of heterotrophic (the respiration of active soil microbes) and autotrophic respiration (respiration from roots alone). The heterotrophic rate largely dictates the relationship between soil C inputs from litter and soil C content (Kuzyakov 2006).

The objective of this study was to measure total forest C in a bottomland hardwood forest and assess differences associated with three logging treatments. Measurements of total aboveground C, belowground biomass C, soil C, below ground woody debris and soil CO_2 efflux were taken.

3.3 Study Site

The study site is located within the alluvial deltaic plain formed by Mobile, Tensaw, and Middle Rivers in southwestern Alabama and is located at 30°57’45” N and 87°53’20 W. The Mobile-Tensaw River Delta is the second largest river delta in the United States and is formed below the confluence of the Alabama and Tombigbee river basins with a total watershed of approximately 11.6 million ha (Smith 1988). This watershed extends into four different states, (Figure 3.1), and five physiographic provinces (Aust et al. 2006). The Delta contains approximately 105,000 ha of wetlands, 89,000 ha of which are forested (Aust et al. 2006). The study site is located on the western bank of the Tensaw River about 4.5 km southwest of Stockton, AL and approximately 1 km north of Live Oak Landing (Evans et al. 2008). Climate is subtropical with a mean annual air temperature of 20°C, 250 frost-free days, and less than three weeks below freezing. Average annual precipitation is 1600 mm year^{-1} evenly distributed throughout the year (Riccio et al. 1973, Aust et al. 2006). Annual overbank floods are frequent throughout the year.

Species composition in the frequently flooded Delta is primarily water tupelo (*Nyssa aquatica* L.) and bald-cypress (*Taxodium distichum*) with a smaller component of Carolina ash (*Fraxinus caroliniana* P. Mill.), pumpkin ash (*Fraxinus profunda* (Bush) Bush), water elm (*Planera aquatica* J.F. Gmel.) and black willow (*Salix nigra* Marsh.). The site has been harvested at least twice before the 1986 harvest as evidenced by local historical records and site features, such as old springboard notches, stumps and pull-boat runs (Aust et al. 2006). Three disturbance treatments were installed on the site in 1986 following clearcut harvests with chainsaw felling and helicopter removal. One treatment was simply the helicopter logging (HELI). Skidder logging (SKID) was simulated by skidding logs across the sites until over 50%

of the area was rutted to a depth of 30 cm. The third disturbance treatment consisted of the helicopter harvest followed by removal of all coppice and seed source regeneration with glyphosate herbicide (GLYPH) for two years following harvest. The third treatment did not represent an operational silvicultural treatment; rather it was intended to represent a more severe disturbance that would remove on-site regeneration sources. All disturbance treatments were installed on 60x60 meter plots within the harvest area. Each disturbance treatment was originally replicated nine times in three 3x3 Latin Squares to create a total of 27 experimental units for disturbance treatments (Figure 3.2). Nine pseudo replications were created for the reference area (REF) which was established adjacent to the treatment plots and is now 94 years old. Due to helicopter pilot safety it was not feasible to include REF areas with disturbance treatments. Preharvest measures of soil, hydrology, vegetation, and previous disturbance data collected within the 36 treatment plots indicated that disturbance treatments and REF areas were created within the same stand (Aust and Lea 1991).

3.4 Methods

3.4.1 Vegetation Sampling

An inventory of aboveground biomass was conducted across all 36 plots (9 replicates, 4 treatments = 36 experimental units). Trees (>1.3m height) were subdivided by overstory (≥6.6 cm diameter at 1.3 meters (DBH)) and lower story (a combination of midstory and understory < 6.6 cm DBH) strata. All overstory trees were sampled within one 135-m^2 circular plots in the center of each treatment plot and 405-m^2 circular plots in REF areas. Differences in plot size were due to stand age and density differences between REF areas and treatment plots. All lower story (mid- and understory trees) trees were sampled within 81-m^2 circular plots in all disturbance treatments and REF areas. Data collected for all overstory and lower story trees included species, total height, and DBH. Heights were measured with a Trupulse laser height finder (Laser Technology, Inc., Centennial, CO). Biomass values (dry Mg ha^{-1}) were calculated using existing species-specific allometric equations (Tables 3.1 and 3.2). Many of the willows were leaning so severely that height measurements would lead to a bias in their volumes. Therefore, allometric equations were chosen that utilized only DBH to estimate volumes for this species (Table 3.1 and 3.2).

Ground flora were sampled using three 0.5x0.5 m clip plots per treatment plot. The three sub-samples were taken from each plot along the front row and the entire third Latin Square (Figure 3.2) (5 replicates, 4 treatments = 20 experimental units). The three sub-samples were spaced 15 meters from plot center on azimuths of 120°, 240°, and 360°. All aboveground herbaceous and woody material (<1.3 m height) within the frame was clipped at ground level and bagged. Vegetation samples were subsequently oven dried at 65° C and weighed. Dry herbaceous biomass values were expressed as Mg ha^{-1} and subsequently converted to C contents (Mg C ha^{-1}) by assuming that 50% of the dry weight was C (Buol et al. 1980). The overstory, lower story, and herbaceous C values were combined to estimate total aboveground C.

3.4.2 Belowground Biomass and Woody Debris

A 6.5 cm diameter saw-tooth soil auger was used to sub-sample belowground biomass at three locations and four depths (0-15 cm, 15-30 cm, 30-45 cm, and 45-60 cm) in each plot along the first row and the first upstream replicate in the second row (4 replicates, 4 treatments = 16 experimental units). The three sub-sample locations in each plot were located approximately five meters from plot center and spaced 120˚ from each other with the first plot located due south. Sub-samples at each depth were combined to reduce plot-level heterogeneity. Samples were washed over 2 mm screens to remove soil and allow for sorting into three categories: fine roots (< 3mm), coarse roots (≥ 3mm) (Aber et al. 1985) and woody debris. The woody debris likely resulted in the burial of logging slash by skidder traffic and sediment over time. Samples were dried to a consistent weight at 65˚ C and weighed. Corrections for mineral soil contamination were performed by combustion in a muffle furnace. Corrected weight was expressed as Mg C ha^{-1} by assuming half the dry weight was C (Buol et al. 1980).

3.4.3 Bulk Density

Bulk density cores were taken with a double cylinder hammer bulk density corer as described by Grossman and Reinsch (2002). Within each plot along the first row and the first upstream replicate of the second row (4 replicates, 4 treatments = 16 experimental units) bulk density was sampled at three depths (0-10 cm, 15-25 cm, and 25-35 cm) in three random locations in each plot. Cylindrical soil cores measured 5 cm in diameter and 10 cm in length. After the surface core samples were taken, a bucket auger was used to excavate to 15 cm depth and the second depth of bulk density samples were taken. A 25-35 cm depth was similarly collected. These samples were brought back to a lab to be dried for 24 hours at 105°C and weighed. Bulk density values were calculated based on the following Hillel (1998) equation:

$$\text{Bulk Density} = \text{Mass of solid} / \text{Volume of soil} \ (BD = Ms/Vt)$$

3.4.4 Soil C

Soil C samples were collected in the first row and the first upstream replicate of the second row (4 replicates, 4 treatments = 16 experimental units) at 4 sub-samples and 4 depths (0-15, 15-30, 30-45, and 45-60 cm). The four sub plots were established in each plot at a distance of approximately 5 m from plot center in the four cardinal directions. Samples from each depth were combined and homogenized for C analysis. After air drying to a constant weight, samples were sieved through a 2mm screen. Samples were then analyzed with an Elementar CNS Max (Elementar, Hanau, Germany) C-N dry combustion gas analyzer to determine C percentage.

3.4.5 Soil CO_2 Efflux

Measurements of total soil efflux of CO_2 were obtained with a Li-Cor LI-6200 infrared gas analyzer (IRGA) (Li-Cor, Lincoln, NE) in each plot along the first two rows (6 replicates, 4 treatments = 24 experimental units) in July 2009. Measurements were not able to be taken in the third row due to high water. Measurements were taken as described by Gough and Seiler (2004) to obtain total CO_2 efflux, soil moisture, and soils temperature with the exception of the cuvette size. A Li-Cor model 6000-09S cuvette was used with a volume of 926.0 cm^3 covering 71.5 cm^2 of soil surface. Three randomly located sub-sample measurements were taken in each plot and averaged.

3.4.6 Statistical Analysis

Statistical analysis was performed using either a completely randomized design (CRD) or a Latin Square design (LS) with three disturbance treatments depending upon number of replicates used. Due to site conditions measurements were replicated 4-9 times depending on water levels at time of data collection. A Tukey HSD mean separation was performed with SAS v9.2 statistical software at alpha level 0.05 to determine significance (SAS Institute 2008). Treatment plots were compared to REF areas using a T-test at alpha level 0.05.

3.5 Results and Discussion

3.5.1 Aboveground Biomass

SKID treatments contained more biomass than the other treatments ($p < 0.001$) and averaged 2487 stems ha^{-1} while HELI and GLYPH treatments average 2108 and 1021 stems ha^{-1}, respectively (Table 3.3). Average height and DBH in SKID treatments are 12.0 m and 13.8 cm similar to 12.0 m and 12.3 cm in HELI treatments (Table 3.3). GLYPH treatments had significantly lower heights ($p = 0.003$) and the largest DBH, though not significant, averaging 9.4 m tall and 14.3 cm in DBH (Table 3.3). Lower heights within GLYPH treatments are due to later stand establishment and reliance on seed regeneration rather than coppice. The lower tree density and resulting reduced competition in GLYPH treatments favored faster diameter growth.

Measurements found SKID treatments had the most Overstory C with 73.9 Mg C ha^{-1}. HELI treatments had significantly less C than SKID treatments (52.8 Mg C ha^{-1}, $p < 0.001$) and GLYPH treatments had the lowest averaging 26.4 Mg C ha^{-1} (Table 3.3). Growth rates from 2009 to 2010 were used to estimate annual additions of C to the overstory. Current growth rates in SKID and HELI treatments were similar with 3.1 and 3.0 Mg C ha^{-1} yr^{-1}, respectively. The GLYPH treatment added significantly more C averaging 6.2 Mg C ha^{-1} yr^{-1} and is likely due to reduced density and competition allowing trees within GLYPH to capture C at a faster rate. These rates are similar to NPP rates found by Conner and Day (1976) which were measured to be 5.7 Mg C ha^{-1} yr^{-1} in a tupelo-cypress swamp. These growth rates are also similar to many other studies of NPP in other wetland studies (Conner and Day 1976).

SKID treatments had the greatest lower story density (4021 stems ha^{-1}, $p < 0.001$) followed by HELI and GLYPH treatments (3568 stems ha^{-1} and 1208 stems ha^{-1}, respectively, Table 3.4). SKID and HELI treatments had similar average values for DBH and height with SKID treatments averaging 4.1 cm and 5.6 m. HELI treatments averaged 4.1 cm DBH and 5.8 m heights (Table 3.4). Although trees in HELI treatments were larger, the greater stem density in SKID treatments offset the larger stems in HELI treatments. SKID treatments had greater lower story C with 3.0 Mg C ha^{-1} while HELI treatments were 2.6 Mg C ha^{-1}, though not significant

(Table 3.4). The GLYPH treatment has significantly less C in the lower story with 0.5 Mg C ha^{-1} ($p < 0.001$, Table 3.4).

GLYPH treatments had significantly greater herbaceous biomass values than either the SKID or HELI treatments. As a result, more C was stored in the herbaceous vegetation of GLYPH treatments (1.40 Mg C ha^{-1} versus 0.24 and 0.25 Mg C ha^{-1} in the SKID and HELI treatments, respectively; Table 3.4). Giese et al. (2003) found a similar pattern where mature stands had less herbaceous vegetation than younger stands with no crown closure. The original herbicide treatments removed the seedbank and coppice for woody regeneration and converted GLYPH treatments into freshwater herbaceous marshes that are gradually going through early bottomland forest succession. At stand-age 24 years, only 2229 total woody stems ha^{-1} (over and lower story) were in GLYPH treatments compared to 6508 and 5676 total stems ha^{-1} in SKID and HELI treatments, respectively (Table 3.3 and 3.4).

3.5.2 Belowground Biomass and Woody Debris

Belowground biomass results follow trends observed for aboveground biomass. SKID treatments had the highest belowground C to a depth of 60 cm stored in roots while HELI treatments has the least (12.8 Mg C ha^{-1} and 6.9 Mg C ha^{-1}, respectively; Table 3.5). GLYPH treatments had the greatest amount of biomass in the top 15 cm of soil with approximately 4.0 Mg C ha^{-1}. However, at greater depths the amount of C contained in the belowground biomass declined (Table 3.5). Carbon in belowground biomass follows a similar trend in HELI treatments but this pattern is not as pronounced as in GLYPH treatments. SKID treatments had a relatively constant amount of C in belowground biomass at all depths. Belowground biomass C in SKID treatments increased at the greatest depth to 3.2 Mg C ha^{-1} (45-60 cm) from 2.9 Mg C ha^{-1} in depths 15-30 and 30-45 cm (Table 3.5), potentially due to the amount of buried woody debris on the site. The combination of trafficking under wet conditions and annual inputs of sediment caused a portion of logging debris has been buried on the site resulting in an increase in organic material on the site at a depth of 45-60 cm. This may have allowed roots to take advantage of a deep nutrient source. Old root channels may have also promoted growth of in the lower depth (45-60 cm) by providing pools of nutrients for roots to exploit.

Many large pieces of debris were found at the deepest sample depth (45-60 cm). Based on sediment rates this debris is likely from the 1986 logging; however with the rot resistance of cypress and the anaerobic conditions of the soil this debris could be from older harvests (i.e., the 1916 pull-boat logging). Lockaby et al. (2005) found an association between sedimentation levels and decomposition with 0.2 cm year^{-1} of sediment causing a decline in decomposition rates.

Buried logging debris added to the total amount of C storage in this forest. Most of this material has partially decomposed, but it was assumed that the C to organic matter ratio is still the same at 2.0 (Buol et al. 1980). Approximately 8.2 to 13.8 Mg C ha^{-1} of debris was found on the site to a depth of 60 cm contributing to 3.4-9.6% of the total C pool (Tables 3.6 and 3.10). The GLYPH treatment had the greatest buried debris pools at 13.8 Mg C ha^{-1} which was unexpected since these treatments were not trafficked by skidders, though this may be explained because of their increased sedimentation rate (Tables 2.5 and 3.6). While no significant treatment effects were found, SKID treatments had more debris at the 45-60 cm depth (7.7 Mg C ha^{-1}) suggesting that skidder traffic may have churned slash from the 1986 harvest into the soil or pushed existing debris deeper into the soil profile (Table 3.6).

3.5.3 Bulk Density

As would be expected, bulk density values increased with depth from an average of 0.56 Mg m^{-3} at 0-10 cm to 0.81 Mg m^{-3} at 25-35 cm (Table 3.7). Treatment effects for bulk density were also not statistically significant until the greatest depth (25 cm to 35 cm, $p = 0.03$) where bulk density was greater in HELI treatments compared to REF areas (0.84 and 0.74 Mg m^{-3}, respectively, Table 3.7). Major differences were not expected in soil bulk densities due to findings in year two (Aust and Lea 1992). Aust and Lea (1992) found after two years of growth, mechanical resistance of the site had almost returned to that of the REF areas.

3.5.4 Soil C

SKID treatments had the highest soil C with a total of 103.6 Mg C ha^{-1} to a depth of 60 cm followed by HELI and GLYPH treatments with 97.9 and 95.1 Mg C ha^{-1}, respectively (Table 3.8). Soil C decreased with depth; though, in all treatment plots soil C values were higher in the 45-60 cm depth class (2.1% C) than the 30-45 cm depth classes (1.8% C, Table 3.8). REF areas followed the same pattern with the total soil C content being 100.9 Mg C ha^{-1} to a depth of 60 cm (Table 3.8). Soil C in REF areas makes up 30% of the total C held in the plots (Table 3.10). This is approximately half the amount of C held in overstory biomass in REF areas (63% of total C), the same ratio found by Megonigal and Day (1988) in a cypress stand in the Great Dismal Swamp.

Patterns of increased soil C at depth is likely due to large amounts of organic debris found at depth across this site. Buried woody debris may have increased soil C levels in the deeper soil horizons. Anaerobic soil conditions have also contributed to this build up of soil C at depth providing a nutrient rich soil which also can hold much more C than may have been expected.

3.5.5 Soil CO_2 Efflux

Soil CO_2 efflux measurements were difficult to obtain on this site due to saturated soil conditions. Measurements were taken on multiple site visits; however, results were variable and obtaining consistent samples was difficult. Only one suitable set of measurements were taken and reported in this paper, while three other measurements were taken in saturated conditions. Saturated soils created anaerobic conditions and limited soil CO_2 efflux. Results of the dry site measurements show that GLYPH treatments had significantly higher total soil CO_2 efflux averaging 12.8 µM CO_2 m^{-2} s^{-1} ($p = 0.01$, Table 3.9). HELI and SKID treatments followed with total soil CO_2 efflux levels of 9.6 and 8.8 µM CO_2 m^{-2} s^{-1}, respectively (Table 3.9). REF areas had a rate of 7.5 µM CO_2 m^{-2} s^{-1} which was not significantly different from HELI and SKID treatments. Soil temperature and moisture measurements were similar averaging 29.2°C and 67.3% moisture for all measurements (Table 3.9). While it was expected that GLYPH treatments would have higher soil temperatures from the lack of overstory trees, temperatures were found to be similar to those of the other treatments and REF areas. This was explained by Perison et al. (1997) where following harvest short woody and herbaceous cover lowered soil temperatures on a blackwater bottomland in South Carolina. The higher efflux rates in GLYPH treatments were likely due to the dense herbaceous understory similar to results found by Schilling et al. (1999). As stated previously GLYPH treatments had the most belowground biomass in the top 15 cm compared to all of the treatments (4.0 Mg C ha^{-1}, Table 3.5). The high fine root density likely caused higher amounts of root respiration causing overall higher soil CO_2 efflux rates. The high turnover of fine roots likely also contributes to the higher efflux rate in these treatments. If measurements of heterotrophic respiration and autotrophic respiration had been possible one might expect to have observed higher levels of autotrophic respiration in GLYPH treatments.

3.5.6 Total Forest C

Carbon pools were consolidated to calculate total forest C. Total C pools revealed that SKID treatments had the highest total C of the three treatments with 206.1 Mg C ha^{-1} (Table 3.10). HELI and GLYPH treatments followed with 168.7 and 144.2 Mg C ha^{-1}, respectively (Table 3.10). REF areas were found to contain 332.6 Mg C ha^{-1} ($p < 0.001$, Table 3.10). The most important variable for determining differences in total C in the forest appeared to be overstory biomass. These results follow a similar trend to those found by Giese et al. (2003) from other disturbed riparian wetlands where C pools were higher in mature forests and differences were mainly caused by aboveground woody biomass. The other large contributor was soil C. Soil C makes up 50-66% of total forest C in treatment plots. All treatments were found to be similar, differing only by 5.7 Mg C ha^{-1}, likely from sedimentation rates and the amount of buried debris on the site (HELI versus SKID, Table 3.10). Other above- and belowground C pools in the system are relatively insignificant to the total C pool due to their small proportions (6.8-15.7% of total C Figure 3.3, Table 3.10).

3.6 Conclusions

SKID treatments are holding more total forest C than HELI treatments. Differences in total forest C values are mainly due to differences in overstory biomass, thus HELI and SKID treatments (31.3% and 35.9% total C pool, respectively) stored more C than GLYPH (18.3% of total C pool) (Table 3.10). While GLYPH treatments had a dense herbaceous understory, this vegetation has relatively low biomass and C content (1.0% of total C pool, Table 3.10) compared to the greater woody biomass found in SKID, HELI, and REF treatments. Lower story tree biomass components were smaller contributors to C capital of the system (0.3-1.5% of total C, Table 3.10). The lower story component is growing into overstory canopy positions and is expected to contribute more significantly to total C pools during the coming stages of stand development.

Soil C represents the majority of C in this bottomland system (50-66% of total C pool in treatment plots, Table 3.10) but there were no treatment effects on soil C. This may be partially explained by sediment deposits since harvest which may have partially masked treatment effects on soil C by bringing C into the system. With 45-78 Mg ha^{-1} of soil deposited annually (Table 2.5), and an average soil C content of 2.4% (Table 3.8), 1-1.9 Mg C ha^{-1} yr^{-1} are potentially being added to the system. Anaerobic soils reduce decomposition, therefore organic material remains for much longer periods of time, increasing the residence time of organic material in the system.

Buried debris on the site added 8-13 Mg C ha^{-1} to belowground C pools. These levels of buried debris accounted for 3.4-9.8% of the total C pool (Table 3.10). While this debris is slowly decomposing it has a longer residence time when in the anaerobic soil conditions of this site than if on the soil surface. Storage of buried woody debris on the site helps hold more C in the system. While the age of this buried debris is unknown it may be possible that decomposition has slowed so much that it is from a previous harvest in 1916. Multiple large stumps exist on the site, remnants of previous harvests indicating how long debris decay resistant material may stay on the site in aerobic conditions. Many stumps exhibit marks from where springboards were used indicating they are 94-years old. Buried logs were also found while taking root samples indicating that subsurface coarse woody debris decay in this system could take at least 100 years and likely longer. The ability to store C in buried debris could cause this system to hold much more C than is currently projected.

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Chapter 3 Table and Figure Captions

Table 3.1 Volume equations for overstory trees by species. Other species include the following: *Nyssa aquatic, Fraxinus caroliniana, Fraxinus profunda, Acer rubrum, Planera aquatica,* and *Platanus occidentalis*.

Table 3.2 Volume equations from Mader (1990) for lower story trees by species.

Table 3.3 Overstory stand characteristics by harvesting treatment including trees per hectare, average diameter at 1.3m (DBH) and height and Mg C ha^{-1} in overstory (+/- Standard Error). Values with different letters within a column are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 3.4 Lower story characteristics by harvesting treatment including trees per hectare, average diameter at 1.3 m (DBH) and height and Mg C ha^{-1} in lower story and herbaceous vegetation (+/- Standard Error). Values with different letters within a column are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 3.5 Belowground biomass measurement (Megagrams of C per hectare) at 4 soil depths as influenced by harvesting treatments. Total measurements converted to Mg C ha^{-1} to a depth of 60 cm. Values with different letters within a row are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 3.6 Estimates of belowground debris biomass in Megagrams of C per hectare at 4 soil depths as influenced by harvesting treatment. Total estimates expressed as Mg C ha^{-1} to a depth of 60 cm. No significant differences were found (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 3.7 Average bulk density of the soil at 3 soil depths as influenced by harvesting treatments. Values with different letters within a row differ statistically (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 3.8 Soil C measurements in Mg ha^{-1} and % C at 4 soil depths as influenced by harvesting treatment. Total measurement to a depth of 60 cm and no significant differences were found (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

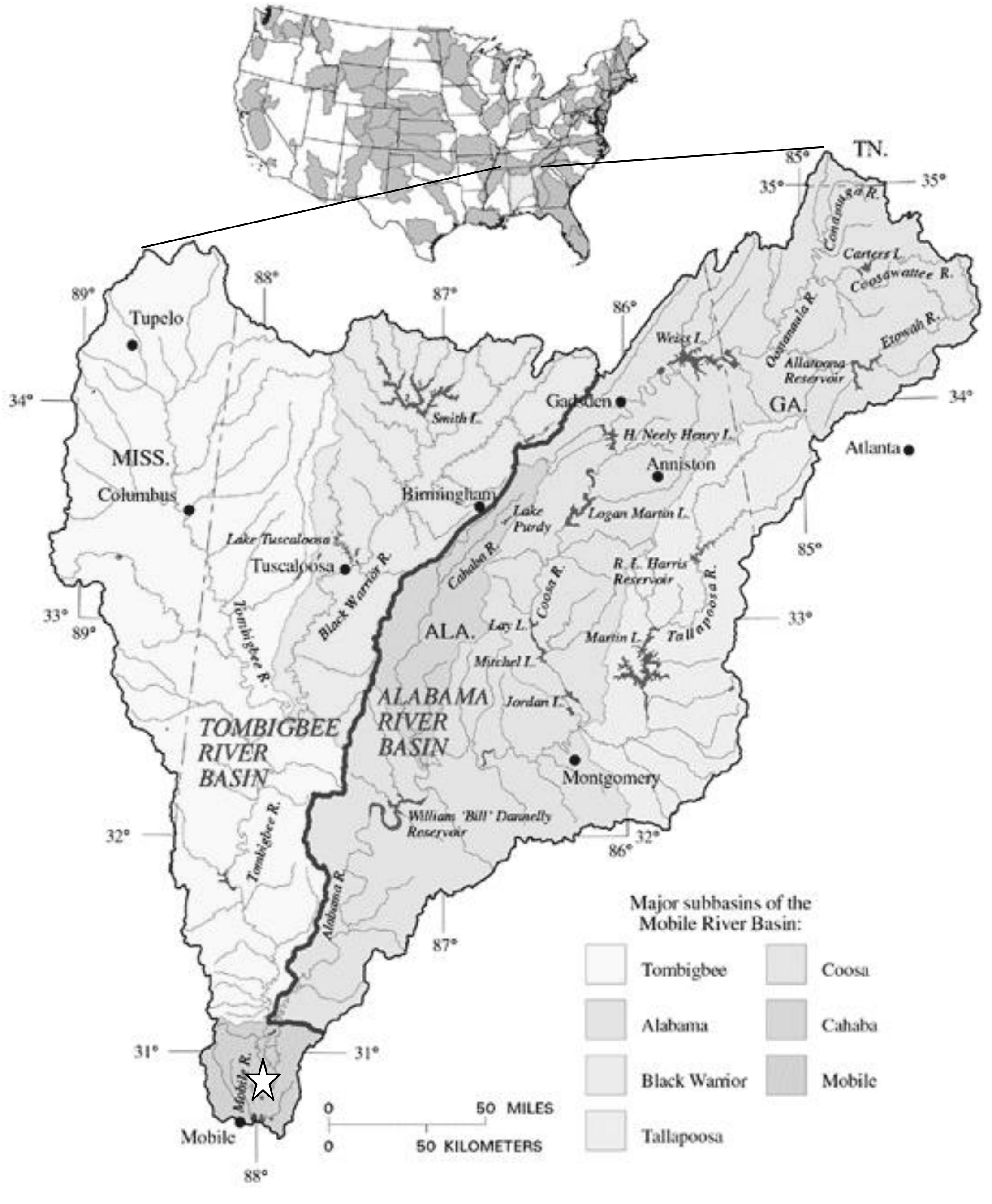
Table 3.9 Total soil CO_2 efflux, temperature, and moisture as influenced by harvesting treatment (+/- Standard Error). Values with different letters within a row are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Table 3.10 Measurements of forest C by harvesting treatment and pool. Values with different letters within a row are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Figure 3.1 The Mobile-Tensaw River Delta below the Alabama and Tombigbee River Basins. Approximate location of the study site indicated by star. Adapted from Dillon (2009).

Figure 3.2 Experimental design and plot layout of the study site. R = reference area (REF), S = Skidder simulation treatment (SKID), H = helicopter logged area (HELI), G = glyphosate treatment area (GLYPH). Plots are 60 meters by 60 meters. Adapted from Aust and Lea (1991).

Figure 3.3 C pools as influenced by harvesting treatments. Those marked with asterisk (*) are belowground carbon pools to a depth of 60 cm. Total carbon indicated in graph a. Graph b represents other aboveground C and other belowground C pools. SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.



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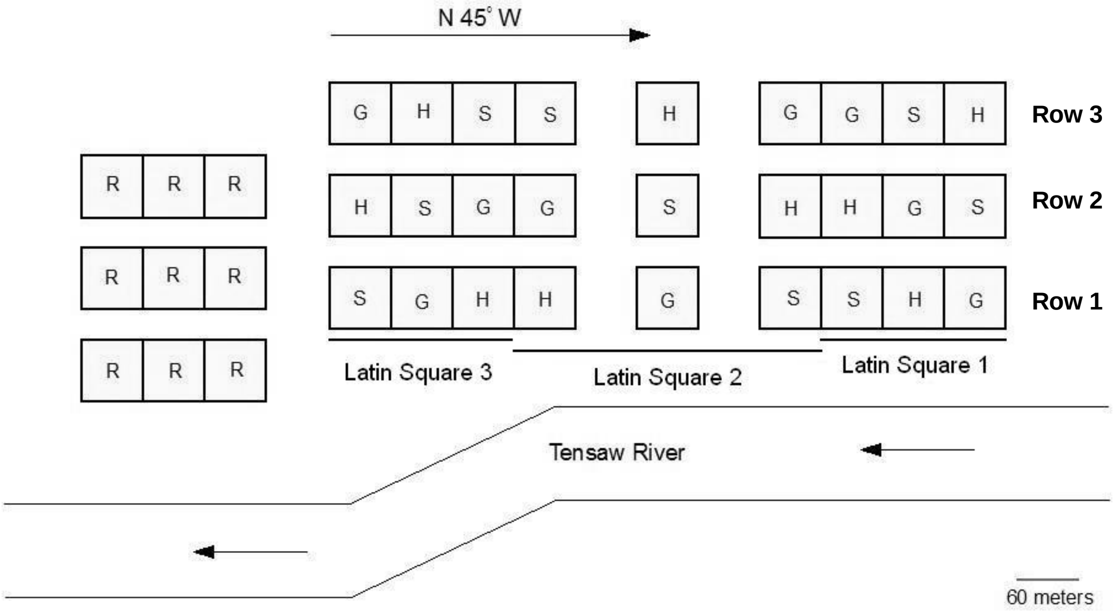

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Table 3.1 Volume equations for overstory trees by species. Other species include the following: *Nyssa aquatic, Fraxinus caroliniana, Fraxinus profunda, Acer rubrum, Planera aquatica,* and *Platanus occidentalis*.

Species	Equation	Units	Source
Taxodium distichum	$Vol = 0.0043*D^{1.78756}*H^{1.00866}$	cuft (total tree)	Hotvedt et al. 1985
Other Species (DBH < 11.0 in)	$Vol = 0.10538(D^2H)^{0.93657}$	dry weight (lbs)	Clark et al. 1985 (Table 12)
Other Species (DBH > 11.0 in)	$Vol = 0.07004(D^2)^{1.02176}(H)^{0.93657}$	dry weight (lbs)	Clark et al. 1985 (Table 12)
Salix nigra	$Vol = 10^{(-1.017+2.07*\log(DBHcm))}$	dry weight (kg)	Muzika et al. 1987
Cephalanthus occidentalis	$Vol = 10^{(-0.712+1.744*\log(DBHcm))}$	dry weight (kg)	Muzika et al. 1987

Table 3.2 Volume equations from Mader (1990) for lower story trees by species.

Species	**Equation**	**Units**
Taxodium distichum	$\mathrm{Vol} = \exp(4.247+(2.144*\ln(\mathrm{DBH}_{cm}))+(0.243/2))$	dry weight (grams)
Nyssa aquatic	$\mathrm{Vol} = \exp(3.892+2.417*\ln(\mathrm{DBH}_{cm})+(0.0814/2))$	dry weight (grams)
Fraxinus caroliniana and Fraxinus profunda	$\mathrm{Vol} = \exp(4.149+(2.203*\ln(\mathrm{DBH}_{cm}))+(0.074/2))$	dry weight (grams)
Salix nigra	$\mathrm{Vol} = \exp(4.008+2.373*\ln(\mathrm{DBH}_{cm})+(0.036/2))$	dry weight (grams)
Acer rubrum	$\mathrm{Vol} = \exp(4.169+2.243*\ln(\mathrm{DBH}_{cm})+(0.063/2))$	dry weight (grams)
Cephalanthus occidentalis	$\mathrm{Vol} = \exp(3.202+2.986*\ln(\mathrm{DBH}_{cm})+(0.053/2))$	dry weight (grams)
Planera aquatica	$\mathrm{Vol} = \exp(4.440+1.976*\ln(\mathrm{DBH}_{cm})+(0.071/2))$	dry weight (grams)
Platanus occidentalis	$\mathrm{Vol} = \exp(4.008+2.373*\ln(\mathrm{DBH}_{cm})+(0.036/2))$	dry weight (grams)

Table 3.3 Overstory stand characteristics by harvesting treatment including trees per hectare, average diameter at 1.3m (DBH) and height and Mg C ha^{-1} in overstory (+/- Standard Error). Values with different letters within a column are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Treatment	**Average Stems ha^{-1}**	**Average Overstory Height (m)**	**Average Overstory DBH (cm)**	**Mg C ha^{-1} in Overstory**
	p < 0.001	***p = 0.003***	***p = 0.01***	***p < 0.001***
SKID	2487 ± 141 a	12.0 ± 0.2 b	13.8 ± 0.3 b	73.9 ± 4.4 b
HELI	2108 ± 227 a	12.0 ± 0.3 b	12.3 ± 0.5 b	52.8 ± 6.5 c
GLYPH	1021 ± 166 b	9.4 ± 0.5 c	14.3 ± 1.1 b	26.4 ± 4.7 d
REF	719 ± 27 b	19.2 ± 0.4 a	30.9 ± 0.8 a	209.4 ± 12.6 a

Table 3.4 Lower story characteristics by harvesting treatment including trees per hectare, average diameter at 1.3 m (DBH) and height and Mg C ha^{-1} in lower story and herbaceous vegetation (+/- Standard Error). Values with different letters within a column are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Treatment	**Average Stems ha^{-1}**	**Average Lower Story Height (m)**	**Average Lower Story DBH (cm)**	**Mg C ha^{-1} in Lower Story**	**Mg C ha^{-1} in herbaceous vegetation**
	$p < 0.001$	***$p < 0.001$***	***$p < 0.001$***	***$p < 0.001$***	***$p < 0.001$***
SKID	4021 ± 457 a	5.6 ± 0.2 a	4.1 ± 0.1 a	3.0 ± 0.2 a	0.24 ± 0.03 bc
HELI	3568 ± 424 a	5.8 ± 0.2 a	4.1 ± 0.1 a	2.6 ± 0.2 a	0.25 ± 0.09 b
GLYPH	1208 ± 239 b	3.8 ± 0.4 b	3.2 ± 0.5 ab	0.5 ± 0.1 b	1.40 ± 0.16 a
REF	302 ± 88 b	2.5 ± 0.4 b	1.7 ± 0.4 b	0.1 ± 0.0 b	0.15 ± 0.01 c

Table 3.5 Belowground biomass measurement (Megagrams of C per hectare) at 4 soil depths as influenced by harvesting treatments. Total measurements converted to Mg C ha^{-1} to a depth of 60 cm. Values with different letters within a row are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

		Treatment				
		SKID	**HELI**	**GLYPH**	**REF**	
Soil Depth	**Root Class**	Mg C ha^{-1} in 15 cm depth classes (+/- Standard Error)				*p-value*
0-15 cm	*Fine*	1.6 ± 0.5	0.9 ± 0.4	2.1 ± 0.9	1.2 ± 0.8	*p = 0.6*
	Coarse	2.2 ± 0.3	2.1 ± 0.8	1.9 ± 0.6	1.9 ± 0.3	*p = 0.9*
	Total	3.8 ± 0.8	3.0 ± 0.7	4.0 ± 0.8	3.1 ± 0.7	*p = 0.7*
15-30 cm	*Fine*	0.3 ± 0.1	0.5 ± 0.3	0.3 ± 0.1	0.5 ± 0.3	*p = 0.9*
	Coarse	2.5 ± 0.9	1.6 ± 0.6	0.8 ± 0.4	1.6 ± 0.5	*p = 0.3*
	Total	2.9 ± 0.9	2.1 ± 0.7	1.1 ± 1.5	2.1 ± 0.7	*p = 0.4*
30-45 cm	*Fine*	0.3 ± 0.0	0.2 ± 0.1	0.2 ± 0.0	0.2 ± 0.1	*p = 0.5*
	Coarse	2.6 ± 0.6 a	0.5 ± 0.3 b	0.8 ± 0.7 ab	0.9 ± 0.4 ab	***p = 0.04***
	Total	2.9 ± 0.6 a	0.6 ± 0.4 b	0.9 ± 0.7 ab	1.1 ± 0.4 ab	***p = 0.04***
45-60 cm	*Fine*	0.2 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.5 ± 0.2	*p = 0.2*
	Coarse	3.1 ± 1.2	1.0 ± 0.8	0.8 ± 0.2	4.1 ± 1.2	*p = 0.07*
	Total	3.2 ± 1.2	1.1 ± 0.9	1.0 ± 0.2	4.6 ± 1.4	*p = 0.07*
		Mg C ha^{-1} to a depth of 60 cm (+/- Standard Error)				
Total 60 cm	*Fine*	2.5 ± 0.6	1.7 ± 0.8	2.8 ± 0.9	2.3 ± 1.4	*p = 0.9*
	Coarse	10.4 ± 1.3 a	5.2 ± 1.5 ab	4.2 ± 1.5 b	8.5 ± 1.3 ab	***p = 0.02***
	Total	12.8 ± 1.0	6.9 ± 2.0	7.0 ± 1.3	10.8 ± 2.3	*p = 0.07*

Table 3.6 Estimates of belowground debris biomass in Megagrams of C per hectare at 4 soil depths as influenced by harvesting treatment. Total estimates expressed as Mg C ha^{-1} to a depth of 60 cm. No significant differences were found (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

	Treatment				
Soil Depth	**SKID**	**HELI**	**GLYPH**	**REF**	
	Mg C ha -1 of debris 15 cm depth classes (+/- Standard Error)				*p-value*
0-15 cm	2.6 ± 0.6	3.2 ± 1.2	2.7 ± 1.0	3.0 ± 1.0	*p = 0.9*
15-30 cm	0.7 ± 0.3	1.3 ± 0.5	2.1 ± 1.4	1.1 ± 0.4	*p = 0.7*
30-45 cm	1.5 ± 1.1	0.9 ± 0.2	3.4 ± 2.6	2.3 ± 2.0	*p = 0.8*
45-60 cm	7.7 ± 2.9	2.8 ± 1.6	5.6 ± 2.0	4.8 ± 2.7	*p = 0.5*
	Mg C ha -1 of debris to 60 cm (+/- Standard Error)				
Total 60 cm	12.5 ± 3.6	8.2 ± 2.0	13.8 ± 3.2	11.2 ± 5.1	*p = 0.7*

Table 3.7 Average bulk density of the soil at 3 soil depths as influenced by harvesting treatments. Values with different letters within a row differ statistically (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Bulk Density by Soil Depth	**Treatment** **SKID**	 **HELI**	 **GLYPH**	 **REF**
	(Mg m^{-3} ± Standard Error)			
0-10 cm (*p = 0.5*)	0.57 ± 0.01	0.56 ± 0.01	0.55 ± 0.03	0.54 ± 0.02
15-25 cm (*p = 0.6*)	0.72 ± 0.04	0.75 ± 0.04	0.73 ± 0.02	0.69 ± 0.03
25-35 cm **(*p = 0.03*)**	0.84 ± 0.02 ab	0.85 ± 0.02 a	0.79 ± 0.03 ab	0.74 ± 0.04 b

Table 3.8 Soil C measurements in Mg ha^{-1} and % C at 4 soil depths as influenced by harvesting treatment. Total measurement to a depth of 60 cm and no significant differences were found (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

		Treatment			
Soil Depth		**SKID**	**HELI**	**GLYPH**	**REF**
		Mg C ha^{-1} (+/- Standard Error)			
0-15 cm	Average	33.6 ± 4.2	28.9 ± 7.3	28.3 ± 3.7	28.3 ± 2.8
	%C	3.9%	3.4%	3.4%	3.5%
15-30 cm	Average	24.1 ± 3.8	22.8 ± 4.8	21.6 ± 1.5	22.8 ± 1.3
	%C	2.2%	2.0%	2.0%	2.2%
30-45 cm	Average	21.8 ± 1.8	21.7 ± 2.6	21.2 ± 1.4	23.0 ± 1.1
	%C	1.7%	1.7%	1.8%	2.1%
45-60 cm	Average	24.2 ± 1.4	24.5 ± 2.8	24.0 ± 3.1	26.8 ± 1.4
	%C	1.9%	1.9%	2.0%	2.4%
		Mg C ha^{-1} to 60 cm (+/- Standard Error)			
Total 60 cm	Average	103.6 ± 10.7	97.9 ± 17.4	95.1 ± 8.3	100.9 ± 5.7
	%C	2.5%	2.3%	2.3%	2.5%

Table 3.9 Total soil CO_2 efflux, temperature, and moisture as influenced by harvesting treatment (+/- Standard Error). Values with different letters within a row are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

	Treatment			
	SKID	**HELI**	**GLYPH**	**REF**
Soil Efflux (µM CO2 m^{-2} s^{-1}) (***p = 0.01***)	8.8 ± 1.1 b	9.6 ± 1.3 b	12.8 ± 0.8 a	7.5 ± 0.8 b
Soil Temperature (^{0}C) (*p = 0.4*)	28.7 ± 0.5	29.2 ± 0.3	29.3 ± 0.6	29.7 ± 0.1
Soil Moisture (%) (*p = 0.4*)	68.3% ± 1.7%	70.8% ± 3.1%	62.8% ± 5.2%	67.4% ± 2.1%

Table 3.10 Measurements of forest C by harvesting treatment and pool. Values with different letters within a row are significantly different than each other (alpha = 0.05). SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

	Treatment			
Component	**SKID**	**HELI**	**GLYPH**	**REF**
Aboveground C Pools (Mg C ha^{-1}) (% of total C)				
Overstory ($p < 0.001$)	73.9 b (35.9%)	52.8 c (31.3%)	26.4 d (18.3%)	209.4 a (63.0%)
Lower Story ($p < 0.001$)	3.0 a (1.5%)	2.6 a (1.5%)	0.5 b (0.3%)	0.1 b (0.03%)
Herbaceous ($p < 0.001$)	0.2 bc (0.2%)	0.3 b (0.2%)	1.4 a (1.0%)	0.2 c (0.06%)
Total	77.1 (33.0%)	55.7 (33.1%)	28.3 (19.6%)	209.7 (63.0%)
Belowground C Pools (Mg C ha^{-1}) (% of total C)				
Coarse Roots ($p = 0.02$)	10.4 a (5.0%)	5.2 ab (3.1%)	4.2 b (2.9%)	8.5 ab (2.6%)
Fine Roots	2.5 (1.2%)	1.7 (1.0%)	2.8 (1.9%)	2.3 (0.7%)
Buried Debris	12.5 (6.1%)	8.2 (4.9%)	13.8 (9.6%)	11.2 (3.4%)
Soil C	103.6 (50.3%)	97.9 (58.0%)	95.1 (66.0%)	100.9 (30.3%)
Total	129.0 (62.6%)	113.0 (67.0%)	115.9 (80.4%)	122.9 (37.0%)
Grand Total **($p < 0.001$)**	**206.1 b**	**168.7 b**	**144.2 b**	**332.6 a**

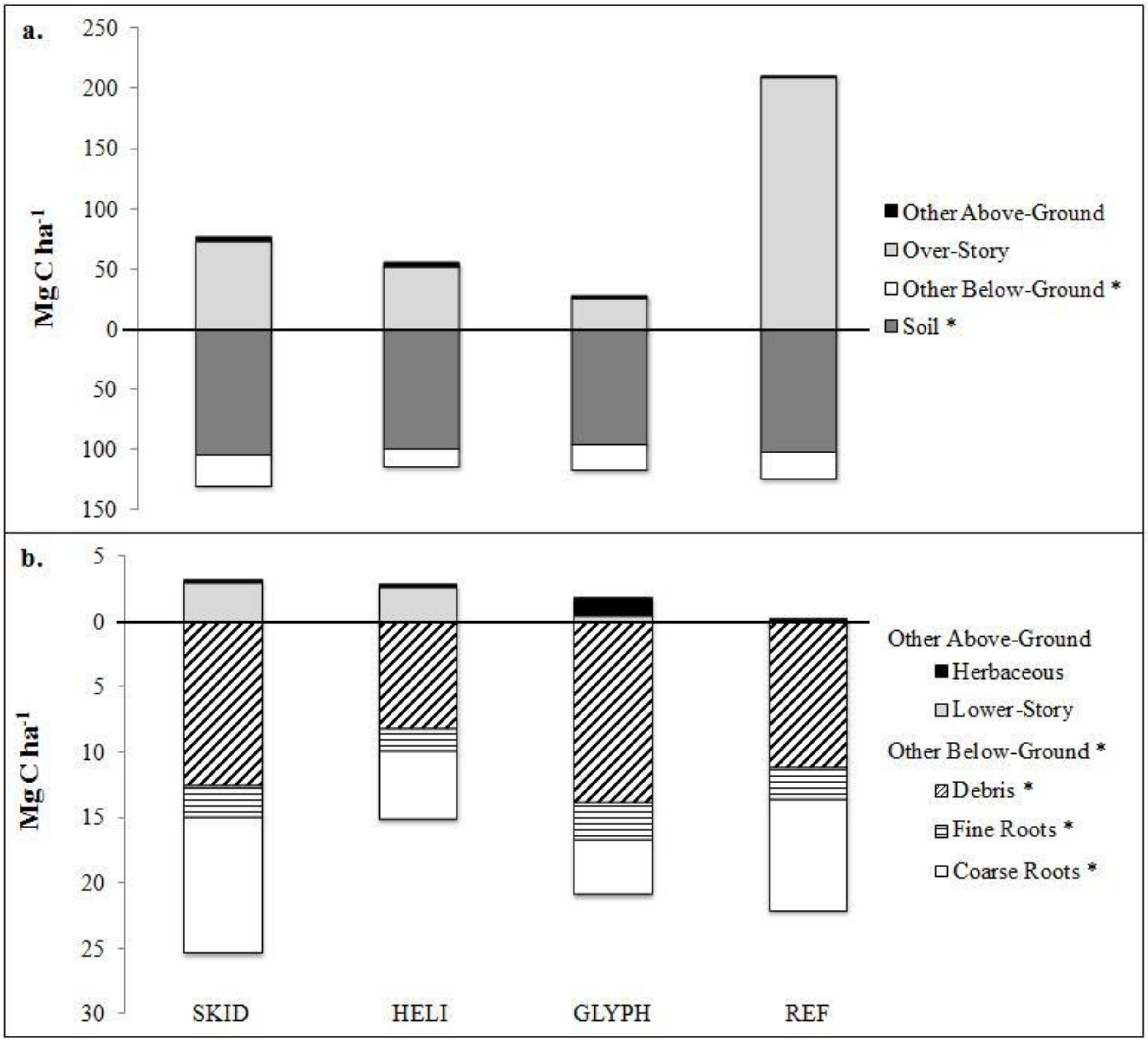

Figure 3.3 C pools as influenced by harvesting treatments. Those marked with asterisk (*) are belowground carbon pools to a depth of 60 cm. Total carbon indicated in graph a. Graph b represents other aboveground C and other belowground C pools. SKID = Skidder simulation treatment, HELI = helicopter logged treatment, GLYPH = glyphosate treatment, and REF = reference area.

Chapter 4. Summary and Conclusions

4.1 Study Objectives

This study was designed to evaluate any long-term (24 year) effects of harvest on above and belowground site biomass productivity and carbon (C) storage in a tupelo-cypress wetland located in the Mobile Tensaw River Delta of southwestern Alabama. Three harvest treatments were applied to a 70 year old tupelo cypress swamp in 1986 following clearcut harvesting with chainsaw felling and helicopter transport. The disturbance treatments were: 1. Helicopter removal of stems (HELI), 2. Skidder simulation which trafficked over 50% of the sites (SKID), and 3. Glyphosate herbicide application to control all regeneration during the first two years following harvest (1987, 1988) (GLYPH). An intact portion of the original stand (94 years old in 2010) was retained to serve as a reference condition (REF).

4.2 Objective 1 – Evaluation of Long-Term Forest Productivity

At age 24, HELI and SKID treatments have species and biomass storage levels that indicate these stands are moving in a similar trajectory that will eventually match the REF stands. SKID treatments produced more overall biomass than any other treatments. Helicopter logging is widely accepted as a low impact logging (Stokes and Schilling 1997); but, HELI treatments produced less biomass than SKID treatments on this site. This apparent paradox is best explained by a combination of the site hydroperiod and soils, buried debris on the site, species adaptations, and treatment effects on soil properties and elevations. First, this site floods frequently and deposits sediment, which enhances the nutritional status of the site and provides a non-compacted soil. During the past 24 years, overbank flood events have deposited 25-38 cm of sediments in all treatments. Secondly, the soil is dominated by the Levy soil series, which has mixed mineralogy that indicates and shrink-swell clays. During dry times the shrinking cracks are obvious and this process has been shown to naturally ameliorate soil compaction (Miwa et al. 2004). Soil cation exchange capacity is classified as superactive, which implies that this is a fertile site that can adequately supply plant nutritional demands. Aust et al. (1998) and Eisenbies et al. (2005) found fertile site conditions increased site resiliency to harvest disturbances. While these conditions exist across the site they have helped SKID treatments by naturally ameliorating the effects of the skidder traffic helping to fill in ruts and increase soil aeration (Table 4.1).

Species adaptations provide additional explanation of the treatment recovery. Tupelo is capable of producing abundant coppice (Kennedy 1982) and coppice is a widely accepted regeneration advantage on sites that flood (Gardiner et al. 2000). Tupelo is also a flood tolerant species (Hook and Brown 1973) and SKID conditions in years 1 and 2 reduced hydraulic conductivity and soil aeration (Aust and Lea 1992) which seems to have been beneficial for tupelo growth. Belowground productivity of SKID treatments indicates more growth than HELI as flooding has been shown to favor tupelo root growth (Powell and Day 1991, Megonigal and Day 1992). Tupelo from coppice was able to survive and thrive and the wetter conditions reduced competing species relative to HELI treatments (Aust et al. 1997).

Differences in microtopography provide another explanation of the SKID response (Table 4.1). SKID treatments were severely rutted with local procurement foresters rating the traffic level on this site as severely disturbed (Aust 1989). While SKID treatments where wetter overall, the enhanced microtopography created both wetter and drier areas as compared to the HELI. In effect, the ruts created areas similar to those seen by natural windthrow pits and mounds or bedding site preparation. These treatments have been shown to improve aeration in elevated areas (Patterson and Adams 2003), thus SKID treatments created many diverse areas that may have provided habitat for root exploration in small mounds of soil adjacent to skidder ruts (Jones et al. 1996).

GLYPH treatments are in the transition from herbaceous marshes to shrub-scrub wetlands. Trees in GLYPH treatments had high growth rates, compared to SKID and HELI, due to their low stem density and lack of competition other than dense understory herbaceous vegetation. These trees are growing approximately four times as fast as trees in the other two treatment plots. Goelz et al. (2001) found similar results in a study where five years after thinning tupelo coppice, thinned stands were not significantly different in total volume from non-thinned stands indicating growth rates in thinned stands were higher than rates found in unthinned stands. Though they have a higher growth rate, there are only a fraction of the trees growing in these treatments leading to less total C storage. It is likely GLYPH treatments will turn into young bottomland hardwood forests in the coming years as the existing trees continue adding shade to these treatments and allow seedlings to compete with the dense herbaceous vegetation.

While soil disturbance during harvest is generally considered to negatively influence growth, in this instance a twenty four year old bottomland hardwood forest which was trafficked on approximately 50% of the site (Aust and Lea 1992) is growing better than sites with no skidder traffic. These results indicate that, depending on management objectives, disturbance effects can be transitory or even beneficial. Several site factors have favored resilience, yet this may not be the case on all bottomland hardwood sites (Table 4.1). Caution should be used when disturbing bottomland hardwoods as harvest type can influence regeneration responses (Lockaby et al 1997). It is important to note that evidence of previous logging disturbances, in the form of pull boat runs, remain on these sites a century later.

4.3 Objective 2 – Understanding Carbon Pools and Fluxes in Bottomland Hardwood Forests

Forests are widely recognized as being very efficient at C storage (Giese et al. 2003). Differences in C pools on this site are primarily driven by the differences in woody biomass in each treatment. GLYPH treatments are currently storing the lowest amount of C of all the treatments, resulting from less aboveground woody biomass.

Soil C contents were similar across all treatments, likely due to the large amount of debris left on the site after harvest which has been buried by a combination of traffic and annual sediment inputs. Also, high soil moisture levels and reduced soil conditions have slowed decomposition of buried material and these factors have helped homogenize soil C values across the site (Brinson 1977, Lockaby et al. 2005). Evaluation of soil C change does not indicate any treatment effects on soil C by depth. However soil C levels increased at the lowest depth (45-60 cm), possibly due to the large amounts of logging debris or past O horizons that have been buried by sediment.

C fluxes in this system are difficult to measure, temporally variable, and often difficult to interpret. Measurements of total soil CO_2 efflux were possible on only one date and site conditions were too flooded in 2009 and 2010 when we planned to differentiate autotrophic and heterotrophic respiration rates. It is speculated that higher soil CO_2 efflux rates in GLYPH treatments result from higher root respiration and turnover of understory herbaceous vegetation, however this could not be measured.

4.4 Future Research Needs

This research project is relatively unique in that it has been periodically measured, it has maintained some continuity in researchers, and is the longest term harvest impact study on forested wetlands in the southern US. The continuation of this study is desirable and appears to be logistically feasible. Due to current land owner objectives (The State of Alabama) this site will not likely be harvested. Because of this, re-measurement of this site is feasible at relatively frequent intervals to assure the understanding of how this site has recovered at a mature age.

In addition to the continued study of this current site, other studies on similar sites would be helpful to see how other sites may react to harvest. Questions to be answered with additional sites would be:

1. How does sediment accumulation relate to watershed size?

   Annual sediment accumulation affected site productivity. However, do these accumulations of sediment compare to other watersheds?

2. What are typical soil CO_2 efflux rates in these systems?

   A better method for measuring soil CO_2 efflux in these systems should be developed.

3. How are soil CO_2 efflux rates affected by site saturation?

   In this study, soil CO_2 efflux seemed to be decreased by soil saturation. When the soil was saturated little or no CO_2 was moving from the soil, at what saturation level does CO_2 begin or stop exchanging?

4. What are heterotrophic and autotrophic respiration rates in these systems?

   The separation of autotrophic and heterotrophic respiration rates was not able to be measured during this study. Understanding these rates is important for a better understanding of soil microbe and root respiration in these ecosystems.

5. Can these results truly be applied throughout the southeast or are they just for larger watersheds?

Expanding this study to look at other sites which are similar will ensure these findings can be applied throughout the southeast United States.

Currently there are few long-term studies based on forest productivity in southeastern wetland systems. With the continuation of this study to maturity more information about long-term effects of harvesting these wetlands will become available. Continuing to measure this site will allow for a much better understanding of long-term effects and may allow for more detailed management prescriptions to be made.

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Chapter 4 Table Captions

Table 4.1 List of factors that helped the site recover following harvest. Factors only seen from SKID treatment denoted with asterisks (*).

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Species	Soils	Site Manipulation
Coppice	Shrink-swell	Microtopography*
Flood tolerance	Sediment	Sun light
Desirable species	Nutrients	Pioneer species
	Aeration	Traffic
	Fill ruts*	Wetter*
	Debris*	Harvest
	Nutrients	Wetter
	Aeration	Competition control*