Doctoral Dissertations   Graduate School

8-2002

Conversion from a sycamore biomass crop to a no-till corn system : soil effects and management implications

Warren Downe Devine

Follow this and additional works at: https://trace.tennessee.edu/utk_graddiss

To the Graduate Council:

I am submitting herewith a dissertation written by Warren Downe Devine entitled "Conversion from a sycamore biomass crop to a no-till corn system : soil effects and management implications." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant, Soil and Environmental Sciences.

<div align="right">Donald D. Tyler, Major Professor</div>

We have read this dissertation and recommend its acceptance:

Michael D. Mullen, Allan E. Houston, John D. Joslin, Donald G. Hodges

<div align="right">Accepted for the Council:</div>
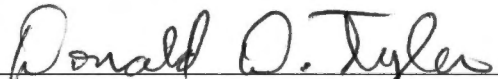
<div align="right">Carolyn R. Hodges</div>

<div align="right">Vice Provost and Dean of the Graduate School</div>

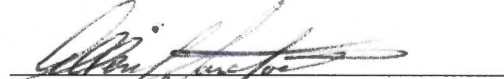(Original signatures are on file with official student records.)

To the Graduate Council:
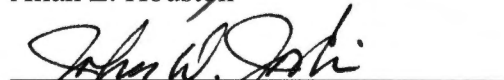
I am submitting herewith a dissertation written by Warren Downe Devine, III entitled "Conversion from a Sycamore Biomass Crop to a No-till Corn System: Soil Effects and Management Implications." I have examined the final paper copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Plant and Soil Sciences.
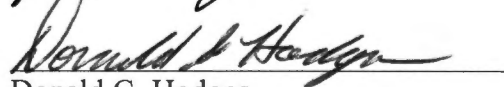
Donald D. Tyler, Major Professor

We have read this dissertation
and recommend its acceptance:

Michael D. Mullen

Allan E. Houston

John D. Joslin

Donald G. Hodges

Acceptance for the Council:

Vice Provost and Dean of Graduate
Studies

CONVERSION FROM A SYCAMORE BIOMASS CROP TO A NO-TILL CORN
SYSTEM: SOIL EFFECTS AND MANAGEMENT IMPLICATIONS

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Warren Downe Devine, III
August 2002

Acknowledgments

I would first like to express gratitude to my advisors, Dr. Don Tyler and Dr. Mike Mullen for all of their support, guidance, and encouragement during my doctoral work. I thank my committee members, Dr. Allan Houston, Dr. Dev Joslin, and Dr. Don Hodges for their assistance and their valuable insights throughout this research. I also would like to thank Dr. Virginia Tolbert and Dr. Marie Walsh for their work with this project. I thank Dr. Arnold Saxton for his continuing help with statistical analyses.

I would like to thank Jennifer Reaves and Janet Gibson for collecting and processing numerous and diverse samples as well as keeping track of records and data. I thank James Morrow and Larry Teague for all of their work in the field during my five years of research at The Ames Plantation. I would like to thank the students in Dr. Mullen's soils lab: Lori Boettcher, David Mathis, Laura Brock, Laura Franks, Curt McDaniel, and Katie Simmons, for performing much of the lab work for this study.

I thank the Trustees of the Hobart Ames Foundation and The UT Agricultural Experiment Station at The Ames Plantation for providing the study site and the field operations for the project. Partial funding for this research was provided by a USDA National Research Initiative competitive grant.

Finally, I would like to thank my wife Kathryn for putting up with me during this research project which has spanned the duration of our relationship. I also want to thank my parents who have put up with me for even longer.

Abstract

It is not known if a short-rotation woody crop (SRWC), grown on an agricultural site, will affect subsequent row crops if the site is returned to agricultural production after harvest of the SRWC. In this study, a woody biomass crop was integrated with an annual row crop system in a row crop-woody crop-row crop rotation. The objectives were to: *i*) document the post-harvest effects of a woody crop rotation on soil C, N, and aggregate stability, *ii*) determine the woody crop's impact on future row crop production and N fertilization efficacy, and *iii*) measure changes in C and N fluxes due to the woody crop rotation. The study was in southwestern TN on a Memphis-Loring silt loam intergrade (Typic Hapludalfs – Oxyaquic Fragiudalfs). Soybean [*Glycine max* (L.) Merr.] was followed by four-year (SY4C) and five-year (SY5C) rotations of American sycamore (*Platanus occidentalis* L.), followed by no-till corn (*Zea mays* L.). Continuous row crops (soybean converted to corn) served as a control (SBC). Four rates of broadcast NH_4NO_3 were applied to corn (0, 73, 146, and 219 kg N ha^{-1}).

Four- and five-year sycamore rotations significantly affected soil properties and post-sycamore corn grain production. During three years of corn production immediately following sycamore harvest, increases in total soil C and N concentrations below a 2.5 cm depth were attributed to the sycamore rotation, specifically to sycamore roots. Soil inorganic N concentrations were higher in the SBC than the SY4C system at a depth of 0 to 2.5 cm. Soil aggregate stability, at depths from 2.5 to 15 cm, was greater in the SY4C than the SBC system. No mechanical problems were encountered when planting no-till corn over sycamore stumps. Significant increases in N were observed in decomposing sycamore roots and stumps. Microbial immobilization of soil inorganic N during

decomposition of woody sycamore residues was suspected to have reduced the amount of N available to corn plants during the first two years following sycamore harvest. First- and second-year corn after sycamore harvest required a 50% higher rate of N fertilization to maximize yield than corn in the SBC system.

Table of Contents

List of Tables

List of Figures

Nomenclature

g	grams
ha	hectares
cm	centimeters
m	meters
mm	millimeters
Mg	megagrams or metric tones
Pg	petagram (one billion metric tones)
μm	micrometers

Abbreviations

Al	aluminum
ANOVA	analysis of variance
C	carbon
CO_2	carbon dioxide
DBH	diameter at breast height (137 cm above ground level)
Fe	iron
GLD	groundline diameter (5 cm above ground level)
K	potassium
MWD	mean weight diameter
N	nitrogen
NH_4^+	ammonium
NO_3^-	nitrate
P	phosphorus
P	probability level of significance of statistical test
SBC	soybean to no-till corn cropping sequence
SOC	soil organic carbon
SRWC	short-rotation woody crops
SY4C	four years of sycamore to no-till corn cropping sequence
SY5C	five years of sycamore to no-till corn cropping sequence
WSA	water-stable aggregate

CHAPTER 1

Introduction and Background

Introduction

Humans have used wood as an energy source since prehistoric times. Only in the last two centuries have other sources of energy, primarily fossil fuels, become more important than wood. In the USA, wood as a fuel was surpassed by coal between 1850 and 1870 (Tillman, 1978). Although this trend was likely facilitated by improvements in transportation, coal also produces approximately 55% more energy per unit mass than dry hardwood (Ince, 1979; Tillman, 1978). By 1960, use of petroleum, which produces more than 130% more energy than wood per unit mass, was twice that of coal in the USA. But with the oil embargoes and energy shortages of the 1970s, wood was reexamined as a potential energy source.

The U.S. Department of Energy and Tennessee Valley Authority, in addition to numerous other public and private institutions, have studied the production of fuel wood through fast-growing bioenergy crops during the past two decades. Many tree species and a variety of plantation establishment practices have been tested. These woody bioenergy crops consist of closely-spaced hardwood forest plantations grown for periods of approximately 3 to 12 years before harvest. They are commonly known as short-rotation woody crops (SRWCs). Upon harvest the wood can be burned in a biomass-fueled power plant, co-fired with coal in a standard power plant, or converted to gas.

Bioenergy crops are viewed as an environmentally-friendly alternative to fossil fuels. Upon combustion, fossil fuels release formerly earth-bound C to the atmosphere as

CO_2. This is a concern because CO_2 is a greenhouse gas that has increased in concentration by 31% since the beginning of the industrial revolution (IPCC, 2001). Although the combustion of bioenergy crops also releases CO_2, the C in the bioenergy crops is former atmospheric CO_2 incorporated into the plants during the process of photosynthesis. Thus, bioenergy crops cycle C to and from the atmosphere while fossil fuels simply transfer C to the atmosphere.

Large-scale production of biomass fuel from SRWCs would require a significant landbase. A 25-megawatt biomass-fueled power facility, capable of providing electricity for approximately 25,000 people, would require 10,000 hectares of land devoted to SRWCs (BFDP, 2001). A potential source of land for SRWC production is former agricultural land. Several studies have demonstrated that establishing SRWCs on agricultural land significantly improves soil properties such as erosion, bulk density, organic matter content, and runoff quality (Mann and Tolbert, 2000; Tolbert et al., 2000; Kort et al., 1998; Thornton et al., 1998).

Woody crops are typically regenerated soon after harvest, but when they are grown on agricultural sites, situations could arise in which it is more profitable to convert the site back to row crops than to regenerate the harvested SRWC. This may result from market fluctuations or even improvements in soils created by the SRWC. For example, the organic matter input from the tree residues may lead to improvements in infiltration rate, water holding capacity, and fertility of soils (Mann and Tolbert, 2000). This may subsequently increase the yields and profitability of row crops that are grown after a SRWC.

Objectives

This study was initiated to test the feasibility of integrating a SRWC with an annual row crop system. This was accomplished through a row crop to woody crop to row crop sequence. A soybean field located in southwestern TN was planted with American sycamore (*Platanus occidentalis* L.) in 1995. Portions of this sycamore plantation were harvested after four and five years of growth, and the site was subsequently converted to a no-till corn (*Zea mays* L.) system. This dissertation examines the latter half of the rotation process: the conversion from sycamore to corn. The post-harvest effects of the sycamore plantation on soils and subsequent corn production are the primary focus.

The objectives of the study were to *i*) document the effects of one rotation of a woody crop on soil C and N, *ii*) understand the woody crop's effect on soil physical properties through analysis of aggregate stability, *iii*) determine the woody crop's impact on future row crop production and N fertilization efficacy, and *iv*) measure changes in C and N fluxes due to the woody crop rotation.

This dissertation contains three chapters that describe various aspects of the research (Chapters numbered 2 through 4). Chapter 2 is devoted to the belowground effects of the harvested sycamore plantation. Changes in soil C, N, aggregate stability, and the decomposition of sycamore roots in the former plantation are discussed. Chapter 3 focuses on the effects of the sycamore crop on subsequent corn grain yields. The decomposition of the sycamore stumps and availability of soil mineral N are included in this chapter. Chapter 4 describes the roots of living and decomposing sycamore root systems and includes estimates of C and N pools and fluxes associated with the cropping

systems investigated. Preliminary results from this study were reported in Devine (2002a and 2002b).

Literature Review

<u>Short-Rotation Woody Crops</u>

The idea of SRWCs for fiber production was conceived in 1965 at the Eighth Southern Forest Tree Improvement Conference in Savannah, Georgia (Herrick and Brown, 1967). American sycamore was selected as the ideal species for a SRWC because prior research indicated it resists many insects and diseases, adapts to a wide range of sites, and sprouts vigorously. Early SRWC studies involved two- to three-year sycamore rotations. Trees were planted at close spacings, and coppice regeneration was used (McAlpine et al., 1966). The close spacings were designed to make use of the complete site, optimizing yield on a spatial basis. The short rotation lengths optimized fiber yield on a temporal basis since the trees grew fastest in the early years after planting. Coppice regeneration made use of existing root systems, "recycling" them in future crops (McAlpine et al., 1966).

Hybrid poplars (*Populus* sp.) and willows (*Salix* sp.) are the most frequently planted SRWC in the USA, but other species including American sycamore, black locust (*Robinia pseudoacacia* L.), and sweetgum (*Liquidambar styraciflua* L.) have also been tested. Rotation lengths for SRWCs are typically 3 to 12 years (Cox, 1996). A variety of cultural treatments including irrigation, fertilization, herbicides, and pesticides are applied to optimize growth rates by improving resource availability and reducing weed competition (Coleman, 1996).

In response to the energy shortages of the 1970s, woody biomass crops were investigated as a renewable energy source. Woody biofuels could be gasified or burned with coal to generate electricity in power plants. The production, economic feasibility, and environmental effects of producing SRWCs were studied for more than two decades by the U.S. Department of Energy's Bioenergy Feedstock Development Program (BFDP). From 1978 to 2002 the BFDP researched both woody and herbaceous energy crops on sites throughout the USA. Many organizations have been involved in numerous aspects of biomass research including genetics, environmental effects, stand establishment, nutrient cycling, and fuel conversions. In addition to the U.S. Department of Energy, examples of organizations that conducted biomass research are educational institutions such as The State University of New York which began a SRWC bioenergy research program in 1986 (Adegbidi et al., 2001), regional power providers such as Tennessee Valley Authority, and forest products companies including Weyerhaeuser Company and Boise Corporation.

Today, many agricultural sites in Tennessee, including some which are currently only marginally profitable (land capability class III to VI), are potential sites for SRWC establishment (Fribourg et al., 1989). Planting SRWCs for the production of fiber or biofuels is an alternative to traditional agriculture on these sites. In recent years, SRWCs in southern USA were most frequently established on plantations less than 40 hectares in size on land farmed within the past 10 years (Coleman, 1996).

In addition to their role as a fuel or fiber source, woody biomass crops improve a variety of environmental parameters. Bandaranayake et al. (1996) examined the soils of 1- and 12-year-old sycamore plantations and of corn and soybean row crops. Soil bulk

density was lower for the 12-year-old plantations than for the row crops and the 1-year-old sycamore plantation. Soil surface residue cover was significantly greater under the 12-year-old plantation than under the first-year plantation or the row crops. Thus, improvements in soil physical properties likely occur sometime between the 1st and the 12th year of SRWC growth.

Because frequent harvests, equivalent to as much as 20 Mg dry biomass ha^{-1} yr^{-1}, may remove significant amounts of nutrients from a site, there has been concern that SRWC production may eventually reduce a site's fertility (Blackmon, 1979). Significant variation exists among estimates of nutrient contents of sycamore biomass plantations (Table 1-1); however, Wood et al. (1977) found that, for a three-year sycamore rotation, N removed in harvesting approximated the natural N input estimates. On an annual basis, 30 kg N ha^{-1} were removed through harvesting, and it was estimated that 22 to 34 kg N ha^{-1} entered the system through mineralization of organic matter and other inputs.

Wood et al. (1977) found that foliage, which is often removed with the woody biomass in SRWC harvests, contained more N than any other tree component. On unfertilized plots, foliage contained 30.9 kg N ha^{-1}, while bole wood, bole bark, and branches contained 15.5, 6.1, and 8.0 kg N ha^{-1}, respectively. Researchers have suggested that if foliage and/or small branches were not removed in the harvest operation, nutrient removals from the site would be significantly less (Heilman and Norby, 1998; Wittwer and Stringer, 1985; Wood et al., 1977; Blackmon, 1979). Wittwer and Stringer (1985) found that sycamore aboveground biomass contained less N than several other SRWC species. This indicated that a sycamore biomass crop may result in less N

Table 1-1. Cumulative aboveground nutrient content (stem, branches, bark, and foliage) of unfertilized American sycamore.

Site	Stocking	Age	Nutrient						Source
			N	P	K	Ca	Mg	Mn	
	trees ha^{-1}	years	------------------- kg ha^{-1} -------------------						
Terrace	12,346	3	24.2	4.3	15.9	16.7	8.3	0.19	Wood et al., 1977
Floodplain	12,346	3	60.5	14.3	42.6	43.1	16.8	0.23	Wood et al., 1977
Floodplain	11,111	4	146.4	31.6	94.1	100.6	18.9	0.29	Blackmon, 1979
Floodplain	5,556	4	144.0	35.6	89.7	95.5	21.5	0.35	Blackmon, 1979
Floodplain	18,519	5	63	17.3	40	39	12.7	0.22	Wittwer and Stringer, 1985
Floodplain	3,333	4	112-197	-	-	-	-	-	van Miegroet et al., 1994

removal than other SRWC species. The belowground components of sycamore plantations have been studied less than the aboveground fraction. Steinbeck and Nwoboshi (1980) reported that the average belowground dry mass of several sycamore plantation studies was 21.3 Mg ha^{-1}.

Biofuels and the Global Carbon Cycle

The earth's C is distributed among four major pools: oceanic, terrestrial, atmospheric, and geologic. Although significant amounts of C cycle annually among the former three pools (e.g. approximately 100 Pg C are transferred annually between the atmospheric and terrestrial pools), the geologic pool remains relatively inactive unless it is disturbed (Johnson, 1995). The burning of fossil fuels is a major disturbance of the geologic C pool that results in the annual release of approximately 5.3 Pg C to the atmosphere (Sundquist, 1993). This release of C is a concern because the primary atmospheric form of C is CO_2, a greenhouse gas.

Biofuels, specifically woody and herbaceous biomass crops, represent a potential means of reducing the net transfer of C from the geological pool to the atmospheric pool. They accomplish this through several pathways (Batjes, 1998). First, biofuels can be directly substituted for fossil fuels in generating power, reducing fossil fuel consumption. Second, CO_2-C is removed from the atmosphere in photosynthesis during the growth of biomass crops. Although this photosynthesized, or 'fixed,' C is released back into the atmosphere when it is combusted as fuel, this does not create a net increase in atmospheric C. Finally, the production of biomass crops stores fixed C in the form of aboveground plant residues and increased soil C (Tolbert et al., 2000). The reduction in

fossil fuel use and the sequestration of C in plant residues and soils theoretically reduces the net rate of atmospheric C increase.

Agricultural practices leading to increases in soil C storage, or soil C sequestration, have been studied extensively in recent years (Metting et al., 1999). However, there is a limited amount of data on soil C sequestration associated with woody biomass crops. Furthermore, most of these data were collected in experiments that were conceived years after the biomass crops were established. Ideal documentation of soil C changes associated with biomass crops would include baseline soil data gathered before crop establishment.

Based on soil samples taken from poplar plantations in Minnesota and adjacent states, Hansen (1993) reported that soil C was increased under plantations. This increase in C did not occur until the plantations had reached an age of 6 to 12 years, perhaps because some soil C was mineralized, or released as CO_2, in the first years after plantation establishment. The soil C increase attributed to tree roots was significant after approximately 12 years of plantation growth. Grigal and Berguson (1998) sampled soils of five poplar plantations in Minnesota and found no difference in soil C between the plantations and adjacent non-plantation sites. Mehdi et al. (1999) found no difference in soil C at a depth of 0-60 cm between crops of willow and conventionally tilled corn at two sites in southwestern Quebec. Three study sites in the southeastern USA showed increased soil C under three- and four-year-old woody biomass crops (Tolbert et al., 2000). In one of these studies a fescue cover crop, grown between tree rows, had a significant positive effect on the amount of soil C after four years of plantation growth.

The ability of biomass crops to increase soil C likely depends on a variety of environmental factors, many of which have not yet been quantified.

Management of Soil Organic Carbon

Carbon is the most common element in soil organisms and the energy source for the majority of soil biota. On a global basis, it is estimated that the mass of SOC (1400 to 1500 Pg) is approximately 50% greater than the mass of soil inorganic C (800 to 1000 Pg) (Schlesinger, 1995). Most current research on soil C focuses on the factors that determine the amount of organic C in soils. In many managed ecosystems SOC levels are closely related to soil quality. Soil organic C contributes significantly to a soil's cation exchange capacity and increases fertility by increasing the ability of a soil to hold nutrients and water. Soil organic C improves soil structure by increasing soil aggregation and porosity which in turn lead to improved infiltration rates and aeration. Management practices including conservation tillage, cover crops, afforestation, agroforestry, and use of scientifically-sound agricultural systems result in increased SOC and land sustainability (Lal et al., 1995; Schlesinger, 1999). Continued use of non-sustainable management practices such as deforestation, tillage of erosive soils, overgrazing, and intensive use of sensitive lands result in soil C losses and long-term declines in productivity (Lal et al., 1995).

Tillage practices affect the concentration and distribution of organic C in the soil profile. Tillage mixes the soil and exposes organic C to oxygen, increasing the likelihood of microbially-mediated mineralization. In a Texas corn field, 5 tillage treatments were applied continuously for 16 years (Salinas-Garcia et al., 1997). Under no-till, SOC levels

in the top 5 cm of soil were 39 to 105% higher than for tillage treatments. This was attributed to slower decomposition of residue, which, under no-till, was not incorporated into the soil where the majority of microbial decomposers reside. Moldboard plowing resulted in the least SOC after 16 years. It was concluded that reduced tillage was the most efficient way to increase SOC. Reduced tillage, when combined with fertilization, provided the greatest increase in total soil organic matter.

Van Veen and Kuikman (1990) proposed that physical barriers were the primary cause for the slowing of organic matter decomposition by soil microbes. The authors cited two major mechanisms which limited organic matter decomposition in soils: adsorption of organic matter to clays and incorporation of organic matter into soil aggregates. Both processes prevented microorganisms from metabolizing SOC. Positive correlations between clay content and SOC supported the assertion that C can thus be immobilized and made unavailable to decomposers. Organics may be adsorbed to clay surfaces or be immobilized by complexation. Van Veen and Kuikman (1990) also stated that the total soil surface area is largely uninhabited by microbes. Soils high in clay content have much more surface area for OM adsorption, a large portion of which is largely inaccessible to microbes due to the relatively large size of the microbes compared to the size of the pores. Thus, finer-textured soils present an increased opportunity for storage of SOC.

In north-central Alberta, a study was conducted in which barley was grown for 11 years under various combinations of tillage, residue disposal, and N fertilization (Nyborg et al., 1995). Zero-tillage, as opposed to conventional tillage, increased the mass of C in the top 15 cm of soil. However, when crop residues were removed and fertilizer was not

added, zero-tillage did not differ from conventional tillage in the amount of C added to the soil. Therefore, tillage practice did not affect soil C concentration unless crop residues were left on the site. It was noted that soil C levels changed little during the course of the study under conventional tillage without N fertilization.

A study conducted in the Southern Great Plains assessed the effects of ten years of crop rotation, tillage, and fertilization on soil C sequestration (Potter et al. 1997). In the top seven cm of soil, no-till resulted in higher SOC concentrations than stubblemulch tillage, but tillage practice did not affect soil C concentrations below seven cm. Fertilization had no effect on soil C in the study. Rotations with fallow resulted in lower soil C concentrations than continuous cropping. When total SOC on a per hectare basis was calculated to a depth of 20 cm, no-till systems increased C for continuous wheat (*Triticum aestivum* L.) and continuous sorghum [*Sorghum bicolor* (L.) Moench] but not for rotation crops.

Many studies have demonstrated that the application of N fertilizer can increase SOC (Table 1-2). Salinas-Garcia et al. (1997) concluded that a significant increase in SOC accompanying N fertilization was likely due to the increase in crop biomass (and thus residue) production. Halvorson et al. (1999) stated that practices that maintain adequate N fertility help to sequester atmospheric CO_2 in soil organic matter.

N'dayegamiye and Angers (1993) conducted a study in which three rates of wood residue (25, 50, and 100 Mg ha^{-1}) were applied to a sandy loam soil on a biennial basis. A four-year crop rotation (wheat, barley-clover, corn, corn) with conventional tillage was used. The effect of N fertilizer (100, 150, and 200 kg ha^{-1}) applied in addition to the wood residue was examined. With all three rates of wood application, SOC and N were

Table 1-2. Effect of N fertilization on soil organic carbon (SOC).

N fertilization rate	Years of application	Result	Source
kg N ha^{-1}			
22 to 134	11	Increased SOC with increased N at 0 to 7.5 cm depth	Halvorson et al., 1999
45 to 200	12 to 36	All N rates increased SOC	Robinson et al., 1996
90 and 180	8	Both N rates increased total soil C and N	Varvel, 1994
252	8	Slight increase in SOC	Havlin et al., 1990

increased, while the soil C:N ratio decreased slightly. However, N fertilizer in conjunction with wood residue had no added effect on SOC or soil N levels. It was concluded that the application of woody residue could have directly increased SOC and/or it could have increased crop production and thus increased soil C through the increase in crop residues.

Carbon input from fine and coarse tree roots is important in both organic and mineral soil horizons of forests and SRWCs. Root C enters the soil C pool through root senescence, respiration, and exudation (Vogt et al., 1991). Fine root turnover constitutes a significant input of C to the soil. The lifespan of fine tree roots ranges from weeks to over a decade depending on genetic and environmental factors (Vogt et al., 1991). Friend et al. (1991) reported that total root biomass of a two-year-old poplar plantation was 6.3 Mg ha^{-1}, of which 2.3 Mg ha^{-1} were fine roots. This represents a significant contribution of organic C to the soil.

To model the effects of SRWCs or traditional row crops on soil C storage, the many fluxes of C within the soil ecosystem must be understood. Numerous scientists have attempted to model the flow of C and organic matter in terrestrial ecosystems (Falloon and Smith, 2000). Conceptual C pools, identified by their turnover rates, have often been used in these models. Carbon turnover rates vary from rapid to essentially inert (refractory C pools). Factors such as soil water, temperature, N availability, tillage, and depth below the surface have been used to model rates of organic matter decomposition. A better understanding of the refractory C pool is vital to research on soil C sequestration. Currently, difficulties in measuring refractory SOC limit the

effectiveness of models in predicting future changes in this C pool (Falloon and Smith, 2000).

Soil Nitrogen and the C:N Ratio

Nitrogen in the soil matrix exists in organic, inorganic, and gaseous forms. Organic N exists in a variety of compounds in plants, living soil biota, and non-living organic matter. Nitrogen is a component of amino acids and thus proteins and enzymes. Although a significant fraction of organic N is in amino acids, many of the N-containing compounds in soils are still unidentified or poorly understood (Stevenson and Cole, 1999). The most important types of soil inorganic N are ammonium and nitrate, the forms available for plant uptake. Soil gaseous N (N_2) is important because it may be fixed by N-fixing bacteria to ammonia via the nitrogenase enzyme complex. Soil nitrogen-fixing bacteria may be free-living or symbiotic. The most commonly-known examples are of the symbiotic *Rhizobium* genus associated with the roots of leguminous plants (Stevenson and Cole, 1999).

The mineralization of organic matter and its nitrogenous components by soil organisms yields inorganic N in the form of ammonium. This release of inorganic N, termed ammonification, is a byproduct of the catabolism of N-containing organic compounds by soil heterotrophs (Myrold, 1999). The degradation of the organic compounds is facilitated first by extracellular enzymes and then by intracellular enzymes. Following ammonification, ammonium may be taken up by plants, adsorbed to soil organic or mineral matter, immobilized by soil microorganisms, or oxidized by nitrifying bacteria (Tisdale et al., 1993).

Nitrifying bacteria oxidize ammonium to nitrate in a process known as nitrification. Nitrification is a two-phase process: ammonium is first oxidized to nitrite and then nitrite is oxidized to nitrate (Tisdale et al., 1993). Soil nitrate may be assimilated by plants or microbes, but must first be reduced to ammonium in an energy-consuming process. Alternatively, nitrate may be reduced to ammonium by bacteria without assimilation in anaerobic process known as dissimilatory nitrate reduction (Myrold, 1999).

Immobilization is the removal of nutrients from the plant-available pool by their assimilation by soil organisms for cell synthesis. Immobilization of N is important in agricultural systems because it reduces the amount of inorganic N available to crop plants. Plant-available N may also be lost through leaching. While the positive charge of the ammonium ion leads to retention in the predominately negatively-charged soil profile, nitrate's negative charge repels the soil and makes it susceptible to downward movement with water. Another loss of plant-available N occurs through denitrification in which nitrate is reduced by bacteria to gaseous N (Tisdale et al., 1993). Denitrification occurs in anaerobic conditions when nitrate is used by denitrifying bacteria in place of oxygen as a terminal electron acceptor. Denitrification is an enzyme-assisted process that involves a series of reduction reactions. Nitrate is first converted to nitrite, then to nitric oxide, nitrous oxide, and finally to N_2 gas (Myrold, 1999).

Nitrogen has been applied to agricultural soils in a variety of forms for nearly three millennia (Hairston, 1990). Since N is the most frequently limiting nutrient in crop growth, the N cycle and N fertilization have been studied exhaustively. The earliest

known N fertilizer recommendations are attributed to Theophrastus (372-287 BC) who prescribed varying rates of manure for different soils (Hairston, 1990).

The cycles of C and N, two of the most important and most studied elements in the soil, are closely related. Because soil organisms require specific amounts of C and N for growth and energy, the ratio of soil C to N is important to soil biota and soil fertility. Early observations on the soil C:N ratio were made by Dyer (1902) on soils that had been in long-term wheat production. Dyer observed a progressively smaller C:N ratio with increasing soil depth, to a minimum of 5:1 at which point the C:N ratio remained constant with increasing depth. He concluded that at a depth of approximately 1.1 to 1.4 m and deeper, there was no longer a significant influence of crop residues on soil C and N. Read (1921) examined 37 different soils and found that yields of corn were not related to the soil C:N ratio.

Prior to the 1920s, it was understood that the addition of different soil amendments affected different fractions of the soil microbial community. Waksman and Starkey (1924) found that while dextrose stimulated growth of bacteria, cellulose selectively stimulated fungal growth. The authors believed that the N requirement of fungi was much higher than that of bacteria. This belief was based on the observation that fungal growth increased more than bacterial growth when high-C residues were supplemented with $NaNO_3$. Waksman and Starkey (1924) did not attempt to analyze the C and N content of the microorganisms themselves.

Salter (1931) studied the effect of the C:N ratio on accumulation of soil organic matter. Residues were combined with ammonium nitrate to create soil amendments with C:N ratios ranging from 15:1 to 1:1. The 15:1 ratios resulted in the net release of very

little mineral N, while the 1:1 ratios released the equivalent of 2,800 kg ha^{-1} nitrate. In a

typical agricultural system much of this nitrate would be lost through leaching. Salter

(1931) also observed that addition of residues with C:N ratios of less than 20:1 did not

cause soil nitrate losses while residues with wider C:N ratios did lead to nitrate losses.

These nitrate losses observed after the residue additions were temporary and were due to

immobilization.

Today it is recognized that when plant residues with C:N ratios between 20:1 and

30:1 are added to a soil, there is usually little change in soil mineral N (Stevenson and

Cole, 1999). Residues with C:N ratios larger than 30:1 cause immobilization of soil

mineral N by microorganisms, and residues with ratios less than 20:1 lead to N

mineralization. The basis of these trends is the N requirement for structural growth by

the soil biota. If a residue substrate contains insufficient N relative to C, microbes must

draw on, or immobilize, soil mineral N for their growth. If a substrate contains excess N

relative to C, the N not needed for microbial structural growth is mineralized during

decomposition and thus becomes available for plant uptake.

Since bacteria have an average C:N ratio of 4:1 and fungi have an average C:N

ratio of 10:1, it is not surprising that bacteria require approximately twice as much N per

unit mass of structural growth than do fungi (Wagner and Wolf, 1999). The disparity

between the C:N ratio of a typical substrate (i.e. 25:1) and that of the average microbial

biomass (i.e. 8:1 for fungi plus bacteria) can be explained by microbial efficiency.

Microbial efficiency, the percent of total substrate C that is incorporated into microbial

biomass, is often between 30 and 50% in aerobic soils (Wagner and Wolf, 1999). The

remaining substrate C is released as CO_2 or is not used by the microbial community. For

example, with a substrate C:N ratio of 25:1 and a microbial efficiency of 35%, the C:N ratio of the substrate fraction which is incorporated into microbial biomass becomes 8.75:1.

Different types of plant residues contain vastly different ratios of C:N. Composts and legume residues both have C:N ratios in the range of 15:1 to 20:1 while cereal and straw residue have C:N ratios of 60:1 to 80:1 (Stevenson and Cole, 1999). Woody residues from the aboveground portions of trees have C:N ratios ranging from 150:1 to 500:1. In forest plantations, residues from harvested trees such as stumps, roots, and dead limbs all have a high C:N ratio. The high C:N ratios of the woody residues in SRWC systems have not yet been proven to cause N immobilization, but studies of woody amendments in agricultural systems have shown immobilization. Lalande et al. (1998) conducted a study in which chopped wood from twigs was added to a loamy soil at a rate of 600 m^3/ha for two years. Nitrogen immobilization was observed in the first year, and a significant increase in total soil C and N was observed in the second year.

Beauchemin et al. (1990) examined the effects of wood residues on N fertilizer availability. Fifty Mg ha^{-1} of either fresh or humified woody residues with a C:N ratio between 50:1 and 175:1 were applied to a potato crop that was fertilized with N. In the same year that the wood residues were applied, 46 kg N ha^{-1} was immobilized. It was calculated that, to compensate for the N lost through immobilization due to the wood residue, 1.9 kg N would have to be added for each ton of wood residue. However, in the second year after wood residue application, N immobilization was significantly less. When wood residues were allowed to decompose for one year prior to application, there

was no decrease in crop yields compared to treatments with no wood residues. A significant increase in water retention was observed for soils after addition of residues.

In 1986, N'dayegamiye and Dube investigated the effects of bark application on crop yields and soil chemical properties. In the first year of bark application, yields and N uptake by plants were very low due to N immobilization resulting from the bark application. But during the following three years, yields and N uptake improved significantly. Soils that were amended with bark also had higher C:N ratios (21:1) than soils without bark (19:1). When pig manure, as a N source, was applied with bark, soil organic matter (SOM) content increased slowly but significantly. Cation exchange capacity of the soil did not change after soil amendments.

Risasi et al. (1998) conducted a study in which the fine roots of four tree species and those of corn plants were added to soil in which corn was grown. The objective was to determine what effect the decomposing roots would have on soil N availability. Roots with a low C:N ratio (13:1 to 14:1) increased N uptake by corn plants, while the addition of decomposing corn roots, which had a C:N ratio of 40:1, reduced N uptake by corn plants. Incubation of decomposing roots in soil prior to the planting of corn increased N uptake by corn. The authors concluded that although N immobilization occurred after the addition of high C:N roots, a period of incubation prior to planting could reduce this negative effect on plant-available soil N.

Soil Aggregate Stability

Kemper and Rosenau (1986) defined a soil aggregate as "a group of primary particles that cohere to each other more strongly than to other surrounding soil particles."

Soil aggregates provide structure in the soil that is essential for infiltration, drainage, aeration, and plant growth. The aggregation of soil particles into water-stable aggregates with a porous structure reduces the likelihood of erosion (Tisdall and Oades, 1982).

In 1946, Kroth and Page proposed that there were two types of binding agents involved in aggregation of soil particles: i) polar organic substances and ii) Fe and Al oxides, fats, waxes, and resins. The polar organic substances were reported to be either soil humus or the recent organic products of microbial metabolism. These substances were believed to bind clay particles through chemical bonds, while the Fe and Al oxides, fats, waxes, and resins bound particles strictly through physical mechanisms. Kroth and Page (1946) found that soil aggregates were not coated or surrounded by binding agents; instead, the binding agents were evenly distributed throughout the inside of the aggregates.

Tisdall and Oades (1982) classified organic soil binding agents as *transient*, *temporary*, or *persistent* according to their rate of decomposition. Transient binding agents were part of the labile C pool and consisted primarily of polysaccharides from microorganisms and plant roots. Temporary binding agents consisted of plant roots and fungal hyphae that lasted for periods of months to years. Binding agents classified as persistent included complexes of clay particles and humic substances. Tisdall and Oades (1982) identified microaggregates, defined as aggregates less than 250 μm in diameter, as clusters of smaller aggregates, 2-20 μm in diameter, held together by persistent binding agents. Macroaggregates (>250 μm in diameter) were formed mainly by temporary binding agents such as roots and fungal hyphae.

Aggregate stability is measured by applying disintegrating forces to a sample of soil aggregates of a known size fraction and then measuring the proportions of aggregates broken down into one or more smaller size fractions (Kemper and Rosenau, 1986). The disintegrating forces are designed to simulate the effects of cultivation, wind and water erosion, and wetting. In the wet-sieving technique, pioneered by Yoder (1936), a soil sample is sieved underwater through a nest of sieves with various opening sizes (Kemper and Rosenau, 1986). The larger soil aggregates are eventually broken down by water movement into smaller, water-stable aggregates (WSA). In multi-sieve procedures, the proportion of water-stable aggregates in each size class is measured, and a mean weight diameter (MWD) of aggregates is calculated (Kemper and Chepil, 1965).

Scientists have debated whether air-drying of samples prior to wet-sieving affects aggregate stability measurements. Rapid wetting of air-dry soils results in substantial slaking as air bubbles are forced out during the swelling of moistened soil (Dickson et al., 1991). Haynes (2000) stated that soils rarely reach an air-dried state in the field. Thus, analysis of field-moist samples would provide a more realistic measure of wet aggregate stability than would air-dried samples. However, Haynes (2000) found a significant linear correlation ($r = 0.90$) between the MWD of samples that were prepared using the field-moist and air-dry techniques. Perfect et al. (1990) and Raimbault and Vyn (1991) found that wet aggregate stability increased during summer months when soil moisture content was lowest. Ellsworth et al. (1991) also found a small but significant increase in MWD when soil moisture was lowest. However, a number of earlier studies reported that soils higher in moisture were also higher in wet aggregate stability (Harris et al., 1966). The effects of wetting or drying on soil aggregate stability is variable. Factors such as

soil texture, initial moisture, and the type of wetting treatment affect results (Harris et al., 1966).

Because soil organic matter and living microorganisms are largely responsible for soil aggregation, soil C concentration often is positively correlated with the degree of aggregation. Haynes (2000) found a positive, curvilinear relationship between SOC and stable aggregate size for samples from a silt loam soil. The relationship was strong between 20 and 30 g kg^{-1} SOC but became weak when SOC concentrations were higher than 30 g kg^{-1}. The authors hypothesized that this weakening trend was likely due to the fact the soil highest in organic C came from a pasture with abundant microbes, roots, and earthworms. These organisms raised soil aggregation to a maximum level that could not be further increased by additional amounts of humic materials.

Although soil macroaggregation is often correlated with soil C, it is not always obvious whether the source of that C is above- or belowground plant litter. In a laboratory study designed to simulate a no-till system, Gale et al. (2000a) determined that the C derived from plant roots was more important than C derived from surface residues in stabilizing macroaggregates. Carbon originating from surface residues, which entered the soil through fungal hyphae and particles of organic matter, was associated with relatively less stable macroaggregates. In a related study, Gale et al. (2000b) examined the formation process of soil microaggregates. Prior investigations had supported one of two hypotheses: that microaggregates were precursors to macroaggregates, or microaggregates formed inside already-existing macroaggregates. Gale et al. (2000b) made observations of macroaggregate stability and particulate organic matter origin that

indicated microaggregates formed as a result of biological activity (and C turnover) inside of macroaggregates.

Bossuyt et al. (2001) found that fungi, but not bacteria, had a significant positive effect on the formation of soil macroaggregates. Fungal growth was stimulated by additions of high C:N residues without supplemental mineral N but not after additions of high C:N residues with supplemental mineral N. Furthermore, low C:N residues did not increase fungal growth. These trends indicate that woody residues, with their inherently low levels of organic N (relative to C), are conducive to fungal growth and subsequent soil aggregation while mineral N may actually hinder these processes.

In agricultural systems, soil macroaggregation is often a function of management practices. Strickling (1950) examined the effects of various crop rotations on soil aggregation and organic matter and determined that soybean [*Glycine max* (L.) Merr.] and corn crops had approximately the same effect on soil aggregate stability. In a study that examined the effect of root growth on soil aggregate stability, Monroe and Kladivko (1987) found no significant difference in aggregate stability among corn, soybean, and wheat crops on a silt loam soil. Although root length densities differed among crops, there was no evidence that these differences were enough to affect aggregate stability. There was a significant difference in aggregate stability between crop soils and fallow soils, and this was attributed to root entanglement of soil particles and root exudates and their positive effect on microbial activity.

Lalande et al. (1998) found that two annual applications of chopped woody twigs to a loamy soil significantly increased soil microbial populations, most notably fungi. This increase was accompanied by a significant increase in water-stable

macroaggregates. However, in a study that involved the long-term application of woody residues, N'dayegamiye and Angers (1993) found that these residues did not increase macroaggregate stability. The authors suggested that the high lignin content and high C:N ratio of the woody residues resulted in very slow decomposition and had only a minimal effect on soil microbes. Given the high sand content (65%) of the soil in this study, the fungal growth may not have been sufficient to significantly increase soil aggregation. Formation of water-stable aggregates in sandy soils is less likely than in finer-textured soils.

Soil aggregation can limit SOM decomposition by making SOM physically inaccessible to microbes or by reducing the oxygen supply within soil aggregates. Van Veen and Kuikman (1990) modeled SOM levels following cultivation of a virgin prairie soil and concluded that the rapid decline in SOM was due to an increase in microbial accessibility of formerly aggregate-bound SOM. Six et al. (2000) reported that the increased soil C typical of no-till systems was due in part to the reduction in macroaggregate turnover rate and the increase in C stabilization in microaggregates. When a soil macroaggregate is broken apart in an aerobic environment the organic matter within is exposed to oxygen and the likelihood microbially mediated oxidation is increased.

Site Description

The study site was located on an upland field on the Ames Plantation in Fayette County, TN (35° 08' N, 89° 13' W). The Ames Plantation was purchased in 1901 by Hobart Ames. After his death, his widow Julia Colony Ames created the Hobart Ames

Foundation whose trustees today oversee the operation of the Ames Plantation for education, research, and The National Championship for Field Trialing Bird Dogs. In cooperation with The University of Tennessee, the Ames Plantation has provided resources for numerous environmental, agronomic, forestry, and wildlife research projects since 1954.

Soils on the study site consisted of loess over marine sediments. The sediments were deposited during the Mississippi Embayment, which lasted from the late Cretaceous period to the early Quaternary period (Miller, 1974). During the Mississippi Embayment, sea levels periodically rose and fell, each time depositing a layer of sediment over what is now the Mississippi Valley. The overlying loess is a wind-deposited silt of glacial till origin. From approximately 190,000 to 9,000 years before present, three major deposits of loess covered the Mississippi River Valley region and areas eastward (Krinitzsky and Turnbull, 1967; Rodbell et al., 1997). The depth of the loess deposits decreases eastward; at the study site loess was approximately one meter deep. Loessal soil is highly prone to erosion, and on many historically agricultural sites significant amounts of soil have been lost.

Soils of the study site were a Memphis-Loring silt loam intergrade (fine-silty, mixed, active, thermic Typic Hapludalfs – fine-silty, mixed, active, thermic Oxyaquic Fragiudalfs) with a slope of less than two percent. A variably developed fragipan was reported on the site between a depth of 90 and 150 cm (Kirchner, 1999). Mean annual precipitation was 135 cm (Dickson and Springer, 1964). Soil 1:1 water pH was 6.0 to 6.5. Soil mineralogy of the region has been identified as dominated by hydroxy-interlayered vermiculite, a non-expanding 2:1 clay mineral (M. Essington, personal

communication, 2002). Inman (2000), in soil profile descriptions of a nearby site,

reported approximately one meter of loess over 1.5 meters of alluvium which was

underlain by Tertiary-aged sands. Silt content was 70% to 80% from the surface to a

depth of one meter, declining at depths greater than one meter. Sand content increased

from less than 10% to approximately 50% with increasing depth from one meter to 2.5

meters, while silt content simultaneously declined from 70% to 30% on this same depth

interval. Clay content averaged approximately 20% to a depth of three meters (Inman,

2000).

Prior to the initiation of this study, the site was in soybean. A diagram of the

cropping system treatments appears in Figure 1-1. Detailed descriptions of the treatments

are in the Materials and Methods sections of Chapters 2, 3, and 4.
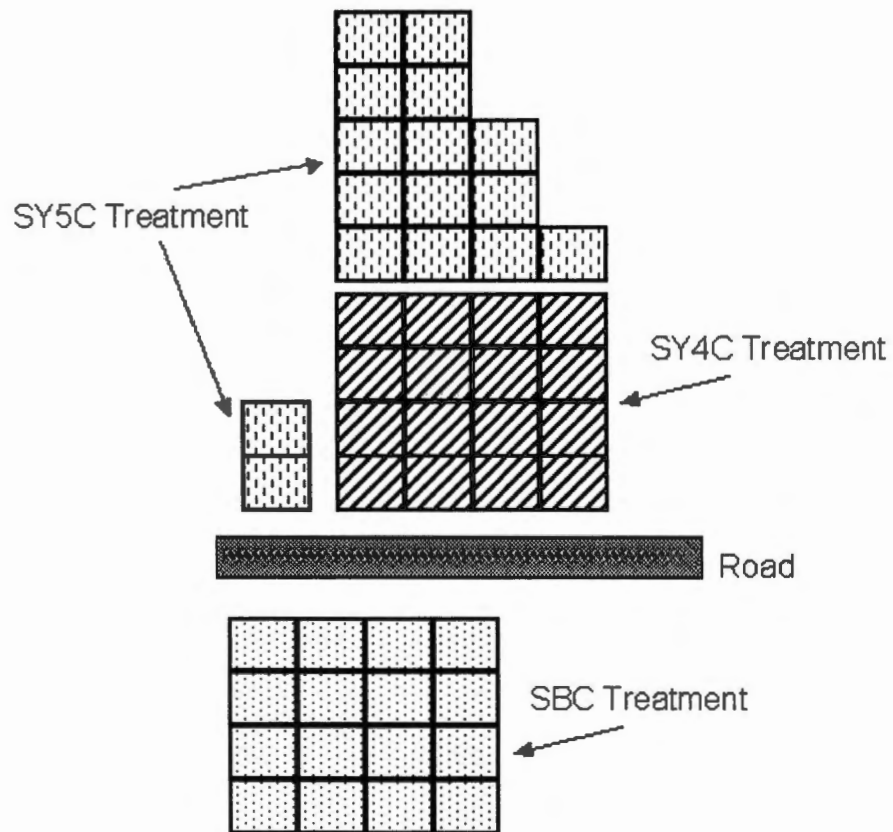
Figure 1-1. Arrangement of cropping system treatments. Five-year sycamore-corn (SY5C), four-year sycamore-corn (SY4C), and soybean-corn (SBC) treatments consisted of 16 plots each.

CHAPTER 2

Conversion from a Sycamore Biomass Crop to a No-till Corn System:

Effects on Soils

Introduction

Biofuels such as herbaceous and woody biomass crops are a renewable alternative to fossil fuels. Because the amount of land required to produce biomass crops for a developed bioenergy industry would be substantial, agricultural land could make up a major portion of this land base (Walsh et al., 2000). In addition to biomass production, establishing perennial crops, such as short-rotation woody crops (SRWCs), on highly-eroded or otherwise degraded agricultural lands increases residue inputs and decreases soil disturbance compared to conventional agricultural practices. Conversion of cropland to SRWCs has been shown to improve soils by lowering bulk density and reducing sediment in runoff (Mitchell, 1997; Thornton et al., 1998; Tolbert et al., 1999). A limited number of studies have examined the effect that converting croplands or grasslands to SRWCs has on soil C sequestration (Hansen, 1993; Grigal and Berguson, 1998; Mehdi et al., 1999; Tolbert et al., 2000). However, there is still a need for further quantification of the aboveground and especially the belowground C fluxes in the SRWC system.

The residue from SRWCs can affect soils differently from residue from annual row crops. A major source of litter in a woody crop system is the turnover of fine roots (Friend et al., 1991). However, the effects of root decomposition in an undisturbed soil environment are difficult to quantify (Waird, 1974; Urquiaga, 1998). The woody root residues from SRWCs have a high C:N ratio and therefore have the potential to cause

immobilization of N during the microbial decomposition process. An increase in root N concentration, likely due to microbial immobilization, was reported during decomposition of fine tree roots (Arunachalam et al., 1996). Nitrogen immobilization after the addition of high C:N plant residues to agricultural soils is well documented (Schomberg et al., 1994), and the addition of woody residues to agricultural soils also has been shown to cause significant N immobilization (Beauchemin et al., 1990; N'dayegamiye and Dubé, 1986; Lalande et al., 1998). The effect of decaying tree roots from a harvested SRWC on soil plant-available N is not well quantified.

Soil aggregate stability, or the ability of soil aggregates to resist breakdown, is a measure of soil structure that affects aeration, infiltration rate, and resistance to erosion (Kemper and Rosenau, 1986). With a few exceptions, increased soil organic C is positively correlated with increased aggregate stability (Tisdall and Oades, 1982). While this correlation may be due to amounts of organic binding agents in the soil, aggregation itself can protect soil organic C from oxidation by making it less accessible to microbes (Van Veen and Kuikman, 1990). Fungi play a major role in decomposition of high-C woody and herbaceous residues (Kaarik, 1974), and fungal hyphae are important in the formation of soil aggregates (Beare et al., 1997; Tisdall and Oades, 1982). In recent years, studies have been established to investigate the effects of SRWCs on soil physical properties including aggregate stability (Thornton et al, 1998; Tolbert et al., 1999; Bandaranayake, et al., 1996).

Although several studies have shown positive effects of establishing SRWCs on former agricultural soils, there is a lack of information on whether these soil improvements endure after a site is converted back to agricultural crop production.

Conversion of land from SRWC production back to traditional row crop production is a realistic possibility given fluctuations in crop prices and uncertain bioenergy markets. Alternatively, a farmer could plan a row crop-SRWC-row crop sequence if there were sufficient evidence that significant improvements in soil quality would result from the SRWC. This study examines such a sequence, focusing on the conversion of a site from a woody biomass crop back to a row crop system. Preliminary results were reported in Devine et al. (2002a, 2002b). The objective of this portion of the study was to document the residual effects of a sycamore biomass crop on soil total C, N, inorganic N, and aggregate stability after the site was converted to a no-till corn system.

Materials and Methods

The study began in 1995 on the Ames Plantation in Fayette County, located in southwestern TN (35° 08' N, 89° 13' W). Soils were a Memphis-Loring silt loam intergrade, formed in aeolian loess. Soil pH was 6.0 to 6.5. The study was analyzed as a completely-randomized, split plot design with a whole-plot factorial treatment arrangement and four replications. The whole-plot treatments were cropping system and N fertilization rate, and the split-plot treatment was sampling depth. The three cropping systems were: *i*) soybean converted to sycamore in 1995 converted to corn in 1999 (SY4C), *ii*) soybean converted to sycamore in 1995 converted to corn in 2000 (SY5C), and *iii*) soybean converted to corn in 1999 (SBC; control treatment). Nitrogen fertilizer, in the form of NH_4NO_3, was broadcast at 4 rates (0, 73, 146, and 219 kg N ha^{-1}). No-tillage systems were used for all row crops.

A 0.6-ha section of a soybean field was planted with one-year-old American sycamore seedlings on a 1.5- x 3.0-m grid (2,222 trees ha^{-1}) in Feb. 1995. Approximately 640 sycamore were harvested in Oct. 1998 after four growing seasons in the field, and equal number were harvested in Oct. 1999 after five growing seasons in the field. At harvest, trees were cut as close to the ground as possible (approximately 2 to 5 cm from the soil) with chainsaws, and stumps were treated with glyphosate to prevent sprouting. After both the SY4C and the SY5C sycamore harvests, the same procedure was used to convert the site to corn production. Wheat (*Triticum aestivum* L.) was planted as a winter cover crop and killed the following April with an application of glyphosate (Roundup®) and atrazine (Bicep II® and AaTrex®). Sixteen plots, each 10.7 by 15.2 m, were then established on the site. Each plot encompassed approximately 35 sycamore stumps. The 16 plots consisted of 4 randomly assigned replications of the 4 N fertilization rates. When the first set of post-sycamore plots (SY4C) was established in April 1999, a set of 16 plots was also established on the adjacent SBC treatment that had been in no-till soybean through 1998. After plots were designated, corn was planted over the sycamore stumps and lime was applied at a rate of 4.5 Mg ha^{-1}. Planting dates were 12 Apr. 1999, 21 Apr. 2000, and 30 Apr. 2001. Ammonium nitrate was broadcast on 3 May 1999, 4 May 2000, and 30 May 2001. Corn grain was harvested 2 Sept. 1999, 15 Sept. 2000, and 25 Sept. 2001. The SY4C and SBC cropping systems remained in corn for three years (1999-2001), while the SY5C system was in corn for two years (2000-2001).

Soil samples for chemical analysis were collected on April 22, June 16, and December 1 of 1999 in the SY4C and SBC systems and on May 2 of 2001 in all three systems. Abnormally dry conditions prevented collection of soil samples in 2000. In

1999, the April samples were collected 11 days before N fertilization, and the June samples were collected 44 days after fertilization. The May 2001 samples were collected 28 days prior to N fertilization. Soil samples for chemical analysis (n=1,920) each consisted of a composite of eight to ten soil cores (1.75 cm diameter) sampled with a steel soil probe. All samples for chemical analysis were collected from four depths (0-2.5, 2.5-7.5, 7.5-15, and 15-30 cm). On SBC plots, these cores were collected from two randomly chosen row middles. On SY4C and SY5C plots, each sample consisted of soil cores collected in a circular pattern around each of two randomly chosen stumps per plot. Two sampling circles per stump with radii of 5 and 37.5 cm were used. An exception was May 2001 when plots fertilized at 146 kg N ha^{-1} also had cores removed in circles with radii of 75 and 150 cm. For this set of samples taken at four distances from the stump, distance was analyzed as an independent variable. For all other analyses, data extracted from the samples taken 5 and 37.5 cm from the stumps were used to represent the SY4C and SY5C systems.

Fine organic particles (<2 mm) were not removed from soil samples prior to analyses. Soil samples were air-dried, ground to pass through a 250-μm sieve, and analyzed for total C and N by the dry combustion method (Matejovic, 1997) using a LECO CNS-2000 elemental analyzer (LECO Corp., St. Joseph, MI). Concentrations of NO_3^- and NH_4^+ were measured by the modified indophenol blue technique described by Sims et al. (1995), following a 1 M KCl extraction.

Soil aggregate stability samples (n=192) were collected on June 16, 1999 from SY4C and SBC treatments. Samples were taken at two randomly selected locations per plot at three depths (0-2.5, 2.5-7.5, and 7.5-15 cm). Mean weight diameter (MWD) of

water-stable aggregates was determined by wet sieving after samples were wetted at atmospheric pressure (Kemper and Chepil, 1965). Sieve screen sizes were 2000, 1000, 500, and 250 µm.

The intact sycamore stumps and first-order roots that were impossible to sample with a soil probe were sampled by excavating one randomly chosen stump per plot (n=16 for SY4C; n=16 for SY5C) on May 16, 2001. A backhoe was used to excavate the stump as well as the soil within an approximate one-meter radius of the stump. The depths of these excavations were determined by the rooting depth and state of decomposition of the individual stump but were generally about one meter. Intact root and stump fragments were sorted by hand from the excavated soil in the field. These fragments were cleaned, dried, weighed, sub-sampled, and analyzed for total C and N concentration by dry combustion (Matejovic, 1995).

Treatment effects at each sampling date were evaluated with analysis of variance (ANOVA) using Proc Mixed in SAS (SAS Institute, 1997). Repeated measures analysis was not used due to within-subject variation from the uneven root distribution around each stump. Post-ANOVA mean separations were performed with single degree of freedom contrasts (Steel and Torrie, 1980). A minimum confidence level of α=0.05 was used in all analyses.

Results

Soil total C, N, and inorganic N concentrations were not affected by sampling distance from sycamore stump, nor were there interactions between distance from stump and sampling depth or cropping system (Table 2-1). Estimates and data pertaining to the

Table 2-1. Analysis of variance for treatments affecting soil total C, N, and inorganic N (NO_3^- + NH_4^+) concentrations for a Memphis-Loring silt loam intergrade in southwestern TN, May 2001. Data represent only plots fertilized at 146 kg N ha⁻¹.

Source of variation	Degrees of freedom	Total C	Total N	Inorganic N
Cropping system (C)	1	NS	*	NS
Stump distance (S)	3	NS	NS	NS
C * S	3	NS	NS	NS
Depth (D)	3	***	***	***
C * D	3	NS	NS	NS
S * D	9	NS	NS	NS
C * S * D	9	NS	NS	NS

*, *** Significant at the 0.05 and 0.001 probability levels, respectively.

sycamore stumps and extractable roots appear in Table 2-2. Large differences between the 84- and 136-week-old stump and root residues were observed for all parameters other than C concentration. These data were not used in conjunction with the soil data to estimate C and N pools since an undetermined fraction of the roots were extracted from a greater depth than the soil samples (below 30 cm).

At each of the three sampling dates in 1999 (27 to 58 weeks after sycamore harvest) total soil C concentration was significantly greater in the SY4C system than in the SBC system (Table 2-3). Soil C concentration varied significantly by depth at every sampling date, and in April 1999 and May 2001 there also was a significant cropping system x depth interaction. This was due to higher concentrations of soil C at the lower sampling depths (especially 7.5-30 cm) for SY4C and SY5C systems compared to the SBC system (Figure 2-1). The only significant difference in soil C between cropping systems at the 0-2.5 cm depth occurred in June 1999. Nitrogen fertilization rate did not affect total soil C concentration.

Total soil N concentration was significantly affected by sampling depth at each sampling date. Cropping system affected total N at all dates except June 1999. There also was a significant cropping system x depth interaction at each date. In April 1999 the SBC treatment had a higher total N concentration than SY4C at depths from 0 to 7.5 cm (Figure 2-2). By December 1999 the SY4C system had higher total N than the SBC system from depths of 2.5 to 30 cm. In May 2001 the SBC system had more total N than the sycamore cropping systems from 0 to 2.5 cm, but not at the lower depths. Nitrogen fertilization rate did not affect total soil N, although there were two interactions involving

Table 2-2. Properties of 84-week-old (SY5C) and 136-week-old (SY4C) extractable sycamore roots and stumps on a Memphis-Loring silt loam intergrade in southwestern TN.

Parameter	Cropping system	
	SY5C	SY4C
C concentration, g kg^{-1}	428.3a†	422.1a
N concentration, g kg^{-1}	5.3a	9.3b
C:N ratio	85.3:1b	48.8:1a
Estimated dry mass, Mg ha^{-1}	4.95b	1.50a
Estimated C content, Mg ha^{-1}	2.12b	0.63a
Estimated N content, kg ha^{-1}	26b	14a

† Within each row, values followed by the same letter are not significantly different ($P > 0.05$).

Table 2-3. Analysis of variance for treatments affecting soil total C, N, and inorganic N ($NO_3^- + NH_4^+$) concentrations for a Memphis-Loring silt loam intergrade in southwestern TN.

Sampling Date	Source of variation	Degrees of freedom	Total C	Total N	Inorganic N
April, 1999	Cropping system (C)	1	***	***	**
	N fertilization (N)	3	NS	NS	NS
	C * N	3	NS	NS	NS
	Depth (D)	3	***	***	***
	C * D	3	***	***	NS
	N * D	9	NS	NS	NS
	C * N * D	9	NS	NS	NS
June, 1999	Cropping system (C)	1	***	NS	NS
	N fertilization (N)	3	NS	NS	***
	C * N	3	NS	NS	NS
	Depth (D)	3	***	***	***
	C * D	3	NS	***	***
	N * D	9	NS	*	***
	C * N * D	9	NS	NS	NS
Dec., 1999	Cropping system (C)	1	***	***	NS
	N fertilization (N)	3	NS	NS	NS
	C * N	3	NS	NS	NS
	Depth (D)	3	***	***	***
	C * D	3	NS	***	***
	N * D	9	NS	NS	NS
	C * N * D	9	NS	NS	NS
May, 2001	Cropping system (C)	2	NS	*	NS
	N fertilization (N)	3	NS	NS	NS
	C * N	6	NS	*	NS
	Depth (D)	3	***	***	***
	C * D	6	***	***	NS
	N * D	9	NS	NS	NS
	C * N * D	18	NS	NS	NS

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.
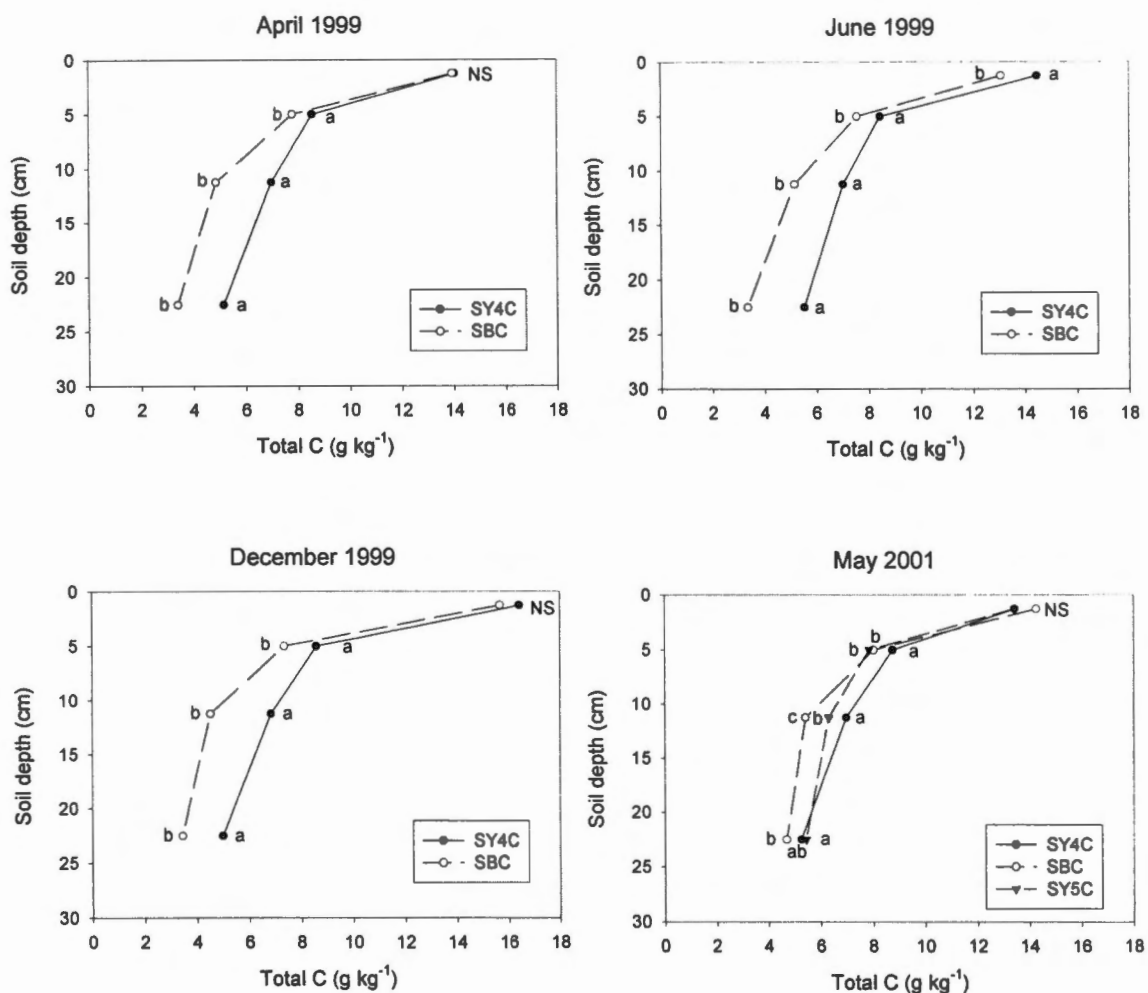
Figure 2-1. Soil total C concentrations for soybean-corn (SBC), four-year sycamore-corn (SY4C), and five-year sycamore-corn (SY5C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN. SY4C sycamore were harvested in October 1998 and SY5C sycamore were harvested in October 1999. Within each depth, points with different letters are significantly different ($P < 0.05$).
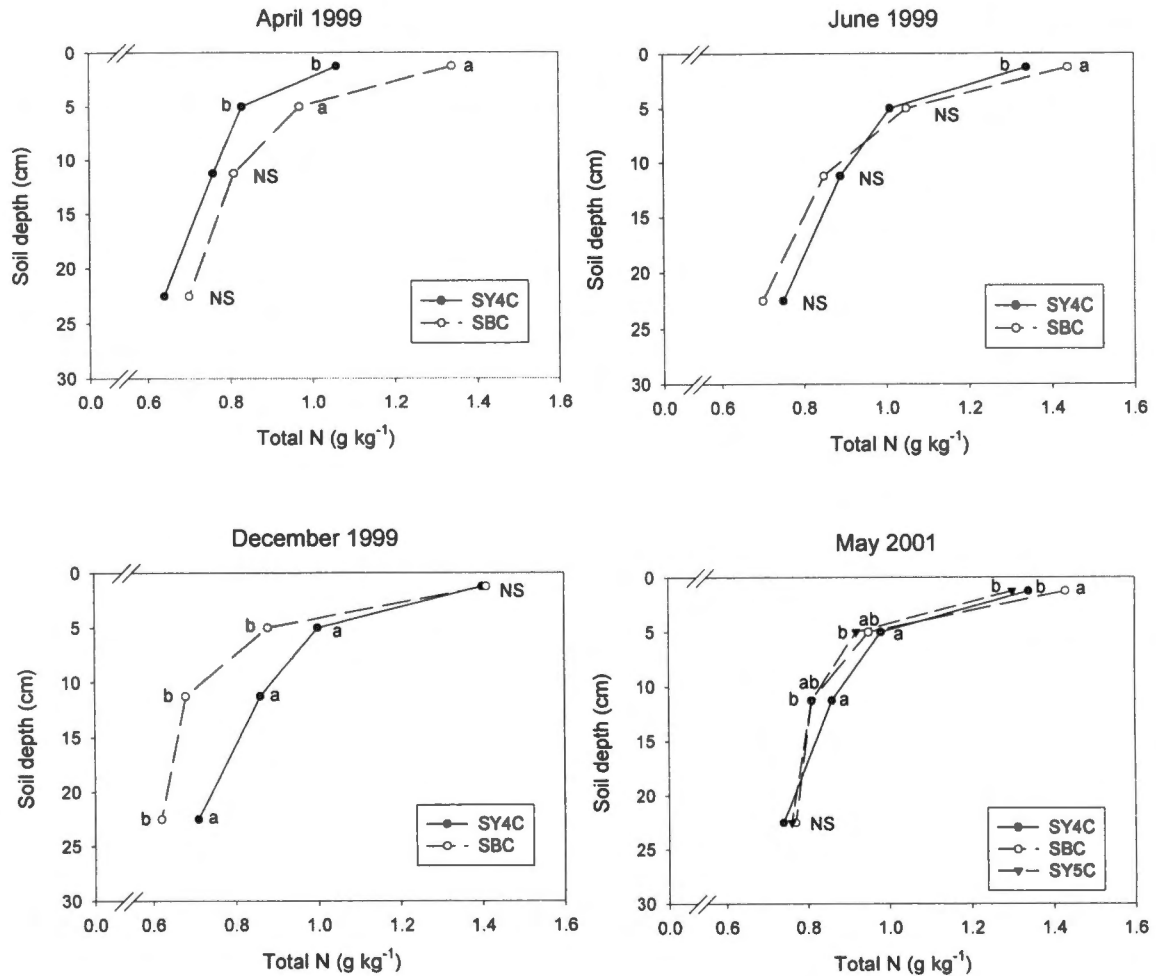
Figure 2-2. Soil total N concentrations for soybean-corn (SBC), four-year sycamore-corn (SY4C), and five-year sycamore-corn (SY5C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN. SY4C sycamore were harvested in October 1998 and SY5C sycamore were harvested in October 1999. Within each depth, points with different letters are significantly different ($P < 0.05$).

N fertilization. The interaction between N fertilization rate and depth that occurred in June 1999 reflected a higher total soil N from 0 to 2.5 cm on the plots receiving 219 kg N ha^{-1} fertilizer (data not shown). The May 2001 interaction between cropping treatment and N fertilization rate is due to a low total N concentration that occurred in the SY5C system at 73 kg N ha^{-1}.

Before the application of N fertilizer in the first season of corn, soil inorganic N was significantly greater under the SY4C system than the SBC system at a depth of 2.5 to 7.5 cm (Figure 2-3). At the next three (post-fertilization) sampling dates there was no overall effect of cropping system on soil inorganic N, although there were interactions between cropping system and sampling depth in June and December of 1999. On these dates, SBC systems had higher inorganic N concentrations at the 0-2.5 cm depth only (Figures 2-4 and 2-5). In May 2001, soil inorganic N did not differ among cropping systems at any fertilization rate or depth (Figure 2-6). Rate of N fertilization affected soil inorganic N concentration only at the June 1999 sampling date. There also was a significant fertilization rate x depth interaction at this time as N fertilization increased soil inorganic N to a greater extent at 0-2.5 cm than at lower depths.

While MWD of water-stable soil aggregates did not differ between cropping systems at a depth of 0-2.5 cm, the SY4C system had a larger MWD than the SBC system at depth intervals both of 2.5 to 7.5 and of 7.5 to 15 cm (Table 2-4). The difference was reflected by a greater fraction of macroaggregates larger than 2 mm under the SY4C system and a greater fraction of microaggregates (<0.25 mm) under the SBC system.
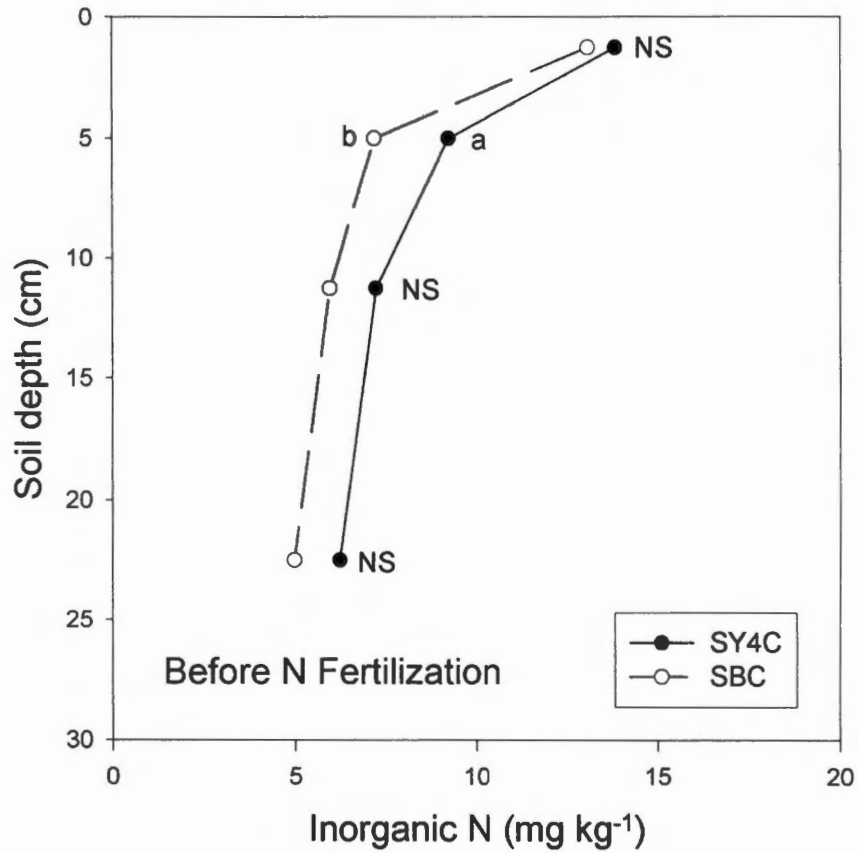
Figure 2-3. Soil inorganic N (NO_3^- + NH_4^+) concentrations for soybean-corn (SBC) and four-year sycamore-corn (SY4C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN, 22 April 1999. Sycamore were harvested in October 1998.
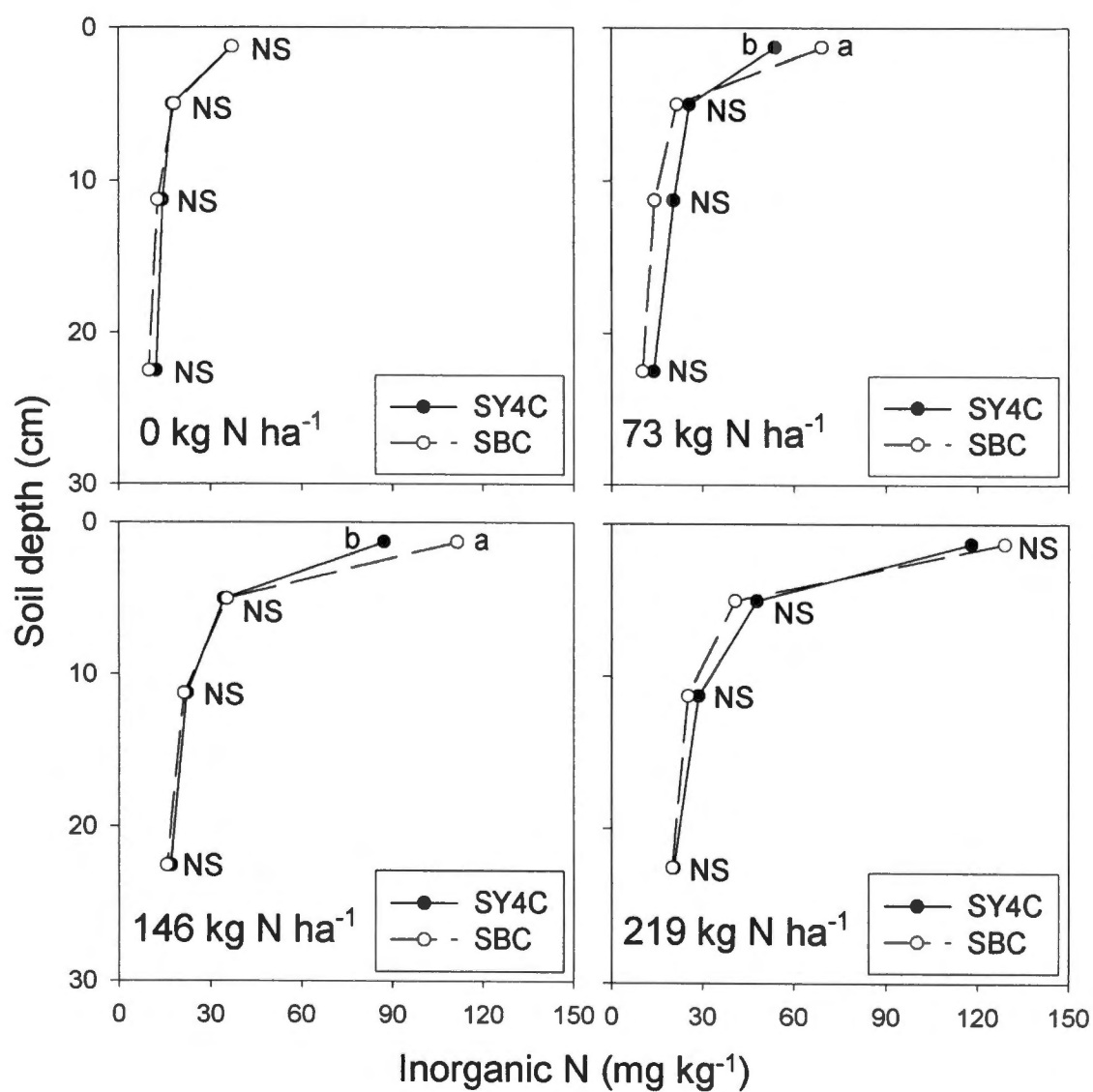
Figure 2-4. Soil inorganic N ($NO_3^- + NH_4^+$) concentrations for soybean-corn (SBC) and four-year sycamore-corn (SY4C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN, 16 June 1999. Sycamore were harvested in October 1998.
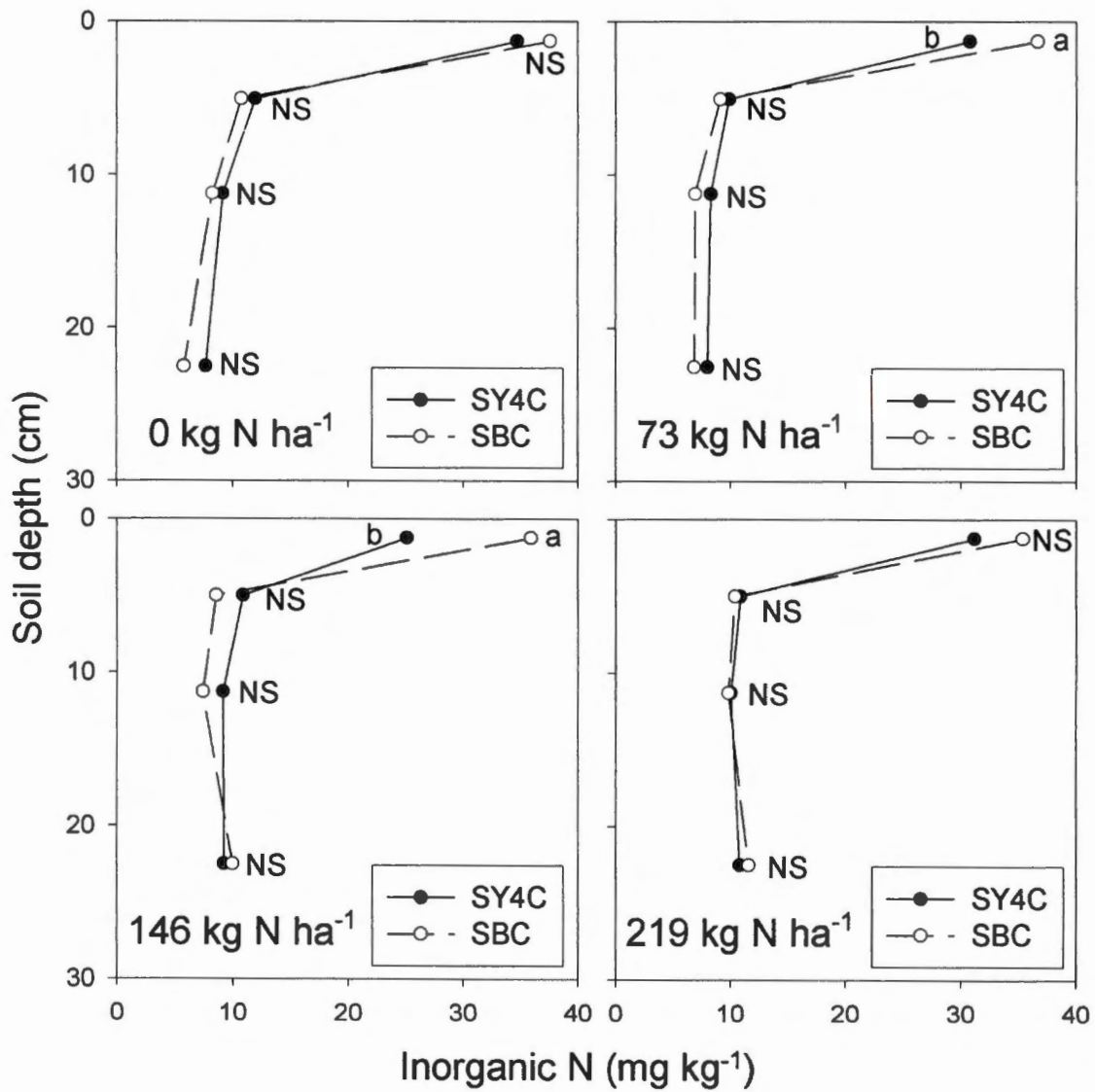
Figure 2-5. Soil inorganic N ($NO_3^- + NH_4^+$) concentrations for soybean-corn (SBC) and four-year sycamore-corn (SY4C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN, 1 December 1999. Sycamore were harvested 1998.
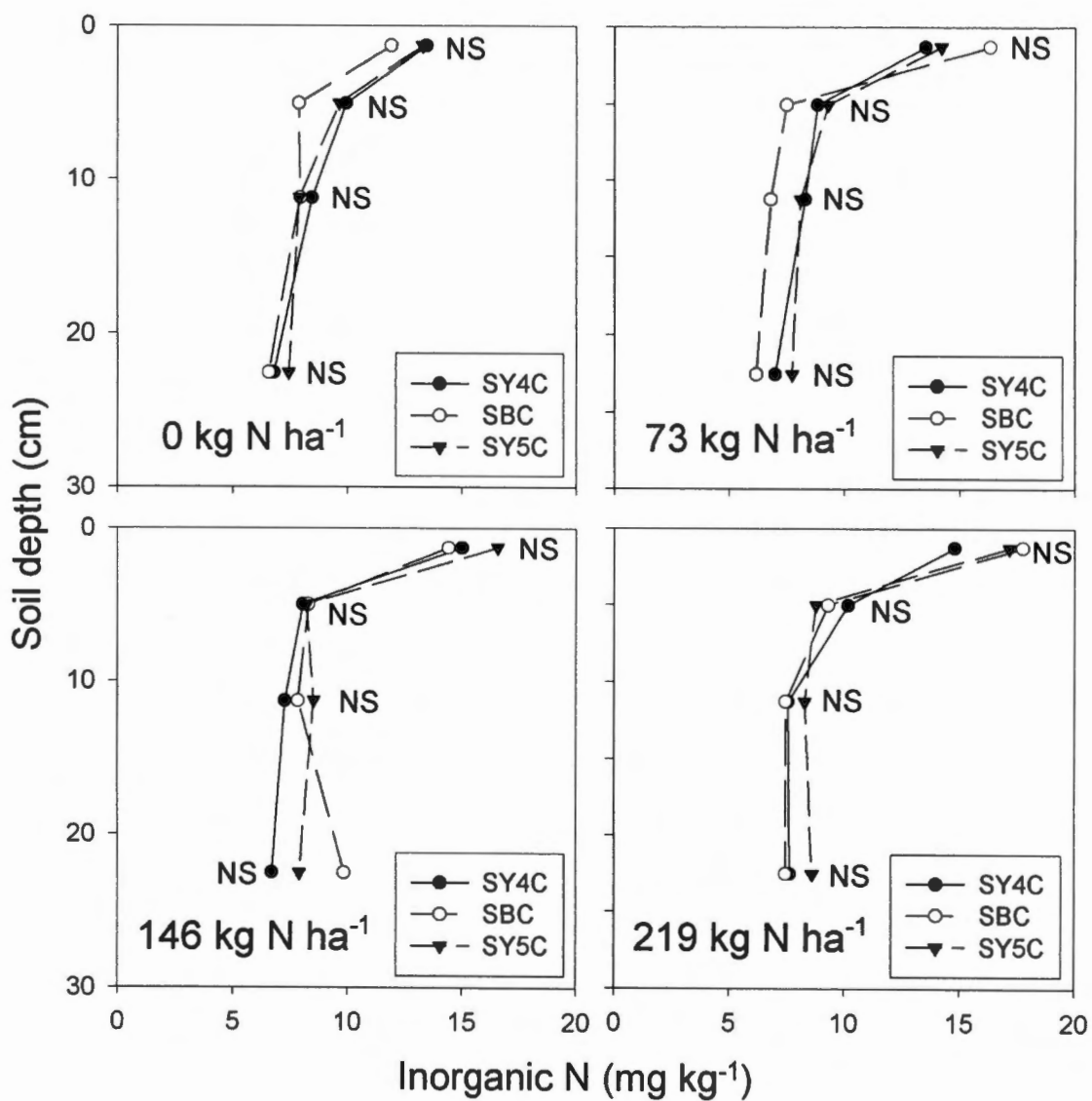
Figure 2-6. Soil inorganic N ($NO_3^- + NH_4^+$) concentrations for soybean-corn (SBC) and four-year sycamore-corn (SY4C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN, 2 May 2001. Sycamore were harvested in October 1998.

Table 2-4. Mean weight diameter (MWD) and distribution among size classes of water-stable soil aggregates from soybean-corn (SBC) and sycamore-corn (SY4C) cropping sequences on a Memphis-Loring silt loam intergrade in southwestern TN, June 1999.

Depth	MWD		>2 mm		1 - 2 mm		0.5 - 1 mm		0.25 – 0.5 mm		<0.25 mm	
	SBC	SY4C	SBC	SY4C	SBC	SY4C	SBC	SY4C	SBC	SY4C	SBC	SY4C
cm	------ mm ------		--- % ---									
0 - 2.5	2.42a†	2.49a	44.6a	46.1a	4.9a	5.0a	6.4a	6.9a	10.1a	9.8a	35.0a	33.7a
2.5 - 7.5	1.13a	1.56b	17.9a	26.7b	6.1a	5.9a	7.7a	8.1a	9.9a	10.4a	59.8b	49.9a
7.5 - 15	0.96a	1.30b	13.8a	20.8b	6.4a	6.6a	8.9a	8.9a	10.7a	10.9a	61.1b	54.1a

† Within each row and size class heading, values followed by the same letter are not significantly different ($P > 0.05$).

Discussion

The spatial uniformity of soil C and N concentrations observed in 2001 indicates that the effect of the woody crop rotation on the top 30 cm of soils was evenly distributed across the plantation. There was no evidence that the corn rows that coincided with the tree stump rows were subjected to different soil conditions than the corn rows located between the stump rows. The uniformity of the soil indicates that randomly located soil samples are adequate for similar SRWC studies. In contrast, Kaur et al. (2000) found that soil C and N decreased to a horizontal distance of three meters from six-year-old hardwoods in a agroforestry system on a semiarid site in India. A higher initial concentration of soil C and N and closer tree spacing in our study may explain the difference in results.

Estimates of belowground C and N must include the tree stumps and intact first-order roots, which, unless substantially decomposed, are unlikely to be sampled representatively by a soil probe. A three-fold difference in intact belowground dry biomass between the 84- and the 136-week-old residues was clearly due in part to time since harvest but was also affected by the differences in stump size and root system development between the four-and five-year-old trees. The decomposition process was considerably more advanced in the 136-week-old root residues than in the 84-week-old residues. This was evidenced by the higher N concentration and lower C:N ratio of the 136-week-old SY4C roots. Although the estimated amount of N contained in tree roots was quite small, this was likely due to the fact that many small roots and some larger ones were in advanced stages of decomposition and were not extractable. Decomposed

roots such as these were sampled by the soil probe and thus contributed to soil C and N concentrations.

Soil and vegetation disturbance have been suggested to cause soil C oxidation in the first years after establishment of SRWCs (Hansen, 1993; Grigal and Berguson, 1998). A study conducted in Minnesota and adjacent states that compared hybrid poplar (*Populus* sp.) plantations to grasslands and row crops documented net soil C losses among four- to six-year-old plantations presumably due to the increased oxidation of organic C near the surface of the soil (Hansen, 1993). Another study in Minnesota found no significant change in soil C attributable to poplar plantations with an average age of 7 to 8 years (Grigal and Berguson, 1998). The significant soil C increases associated with the SRWC in our study were probably due in part to a relatively low initial soil C concentration of <8 g C kg^{-1} at a depth of 0 to 30 cm (Tolbert et al., 2000). Thus, the relative loss of soil organic matter due to disturbance was substantially lower in our study than in Hansen's study, where soil C concentration was approximately 25 g C kg^{-1} (0 to 30 cm depth), and Grigal and Berguson's study where average soil C concentration was >37 g C kg^{-1} (0 to 25 cm depth). Alternatively, the relative contribution of root residues to total soil C may have been higher in our study than in either Hansen's study or Grigal and Berguson's study. Three studies conducted on low-C soils (<10 g C kg^{-1}) in the southeastern USA found increases in soil C three to four years after establishment of SRWCs (Tolbert et al., 1999). Garten (2002) observed a significant soil C increase at a depth of 10 to 30 cm but not at 0 to 10 cm for an 11-year-old sweetgum (*Liquidambar styraciflua* L.) plantation in TN.

Since the April 1999 soil C concentration at a depth of 0 to 2.5 cm was similar for SY4C and SBC soils, the effect of four years of aboveground sycamore residue on soil C concentration was no different than that of four years of residue from a no-tillage soybean system. A significant litter layer did not accumulate in the sycamore plantation until the end of the third year after planting. By this point there was sufficient litterfall and enough dropped limbs to trap abscised leaves, preventing them from being blown away during winter. Cottonwood (*Populus deltoides* Bartr. ex Marsh.) plantations have shown significant surface litter accumulation, sufficient to affect soil hydrologic properties, in their second growing season (Mitchell, 1997). However, Hansen (1993) found no evidence of C accumulation from the trapping of wind-blown detritus in plantations of hybrid poplar (*Populus* sp.). The fact that most of the C increases observed in SY4C and SY5C soils occurred at the lower soil depths (2.5 to 30 cm) indicates that sycamore roots were a more important source of soil C than aboveground residues including leaves and dropped limbs. Although the soil C increases 134 weeks after sycamore harvest (relative to the SBC system) were not as large as those observed in the first year after harvest, their significance suggests that the effect of a SRWC on soil C lasts at least two and a half years, and perhaps much longer. The use of a no-till system in this study after the harvest of the SRWC likely helped to minimize oxidation of accumulated soil C. Since N fertilization rate had no effect on soil C in the SY4C system during the first two and a half years after sycamore harvest, any significant effect of repeated fertilization on the microbially-mediated oxidation of sycamore roots will likely be either long-term or nonexistent. Halvorson et al. (1999) found a significant positive relationship between N

fertilization rate and soil organic C, but this was due to cumulative increases in aboveground plant residues at higher N rates.

Higher total N concentrations for SBC than for SY4C soils at shallow depths (0 to 7.5 cm) in April 1999 suggest greater N inputs under no-till soybeans than under four years of sycamore. The observed increase in total N for SY4C soils relative to SBC soils during 1999 is due to both an increase in SY4C soil N and a slight decrease in SBC soil N. The cause of this phenomenon is not known. The differences in total N found in the upper 15 cm of soils in May 2001 are small and may have no practical significance.

The higher level of inorganic N under the SY4C system in April 1999 may have been a result of increased microbial activity close to tree stumps. Samples taken 5 cm from stumps had a higher inorganic N content than those taken 37.5 cm away (data not shown). Kaur et al. (2000) found increased soil N mineralization rates in an agroforestry system compared to an agricultural system, possibly due to the organic inputs of tree litter. Slightly lower post-fertilization (June and December 1999) inorganic N at a depth of 0 to 2.5 cm under the SY4C system may have been due to immobilization of N during decomposition of shallow sycamore roots. Nitrogen immobilization was not detected in preliminary results from this study (Devine et al., 2002b). Effects of the lower inorganic N in the SY4C system on corn grain production are discussed in Chapter 3.

In June 1999, the significant increases in soil C for the SY4C system relative to the SBC system were accompanied by significant increases in soil aggregate stability at the same depths. The improved aggregate stability may have been due in part to the high C:N ratio of the decomposing sycamore root residues. Seventy-six weeks after trees were harvested, the sycamore roots in this study had a C:N ratio of 80:1 (unpublished data).

Addition of high-C residues to soil has been shown to cause increases in fungal populations and soil aggregate stability (Bossuyt et al., 2001; Lalande et al., 1998). In mostly undisturbed soil environments such as no-tillage systems, or the woody crop systems of this study, plant root C plays a much larger role than surface residue C in the formation of stable soil macroaggregates (>250 µm) (Gale et al., 2000). Since the increases in aggregate stability under the sycamore cropping system occurred at deeper sampling depths (2.5-15 cm) and not at the surface (0-2.5 cm), it is likely that the C from sycamore roots, rather than that from surface residues, was responsible for this trend.

The time required for a woody biomass crop to improve soil structure has not yet been conclusively determined, although this study suggests that it may take as little as four years. Mitchell (1997) found that soil aggregate stability three years after cottonwood (*Populus deltoides* Bartr. ex Marsh.) establishment was greater than that of a conventionally tilled cotton (*Gossypium hirsutum* L.) system. However, Houston et al. (1997) found no increase in soil aggregate stability at a depth 0 to 15 cm after three years of sycamore growth on a site adjacent to the present study. Twelve-year-old sycamore had lower soil bulk density and a much increased infiltration rate compared to no-till row crop systems and one-year-old sycamore (Bandaranayake et al., 1996). An important factor in the improvement of soil structure under SRWCs is the formation of a perennial litter layer composed of leaves and fallen tree limbs. A seven-year-old sycamore plantation adjacent to this study exhibited a thick litter layer which was beginning to form an O horizon. Although the sycamore crop in the present study did not improve aggregation in the soil fraction prone to erosion (0 to 2.5 cm below the surface), other studies have shown significant reductions in erosion after establishment of woody crops

(Mann and Tolbert, 2000; Kort et al., 1998; Thornton et al., 1998; Mitchell, 1997). Most of these reductions occurred after the woody crop had become established on the site, usually two or more years after planting. Erosion is decreased under SRWCs not only by improved soil aggregation and infiltration but also by the thick litter layer that reduces the impact of raindrops on the soil and slows overland flow. This effect can also be achieved by growing cover crops between tree rows during the establishment of SRWCs (Tolbert et al., 2000).

Conclusions

Two and a half years after a field was converted from a sycamore biomass plantation to a no-till corn system, increases in soil C from the sycamore plantation were still present. The source of this added C appeared to be from tree roots rather than aboveground residues. Soil aggregate stability also was improved by the sycamore plantation, but not at the shallowest sampling depth. Plant-available N after fertilization was not affected by the sycamore residues at lower soil depths, but N immobilization may have occurred near the surface. For soils initially low in organic matter, it is possible for a sycamore biomass crop with a rotation length as short as four years to increase soil C concentrations and improve soil structure. Longer rotation lengths would likely lead to greater increases in soil C and aggregate stability and perhaps improvements in erosion resistance and infiltration rates. This could, in turn, benefit subsequent row crop production.

CHAPTER 3

Conversion from a Sycamore Biomass Crop to a No-till Corn System: Management and Yields

Introduction

Crop rotation has been used to increase agricultural production for centuries (Grigg, 1974). Some agroforestry practices use crop rotation systems such as shifting cultivation and managed tree fallows that combine trees and crops (Smith, 1986). These systems alternate periods of unmanaged or managed forest growth with food crops, using the forests to improve soil fertility that is depleted during cultivation (Young, 1997). In much of the USA, a history of wind and water erosion has resulted in loss of surface soil and soil fertility on row-cropped lands (Miller et al., 1985). Where forests regenerate on such lands, increases in soil organic matter and soil fertility occur (Kimmins, 1987). With the advent of SRWCs in the USA for fiber (1960s) and fuel (1970s) production, historically eroded agricultural lands became a potential site for establishment of fast-growing tree plantations. Carefully managed SRWCs and herbaceous biomass crops can lead to reductions in soil erosion (Kort et al., 1998; Thornton et al., 1998), increases in soil organic matter, and improvements in soil physical properties (Mann and Tolbert, 2000; Bandaranayake et al., 1998; Mitchell, 1997).

Early SRWC experiments used American sycamore because prior research indicated it was fast-growing, relatively disease resistant, adaptable to a wide range of sites, and suited to coppice (sprout) regeneration (Herrick and Brown, 1967). Pioneer SRWC researchers recognized the importance of close tree spacings, rotations lengths as short as 2 to 3 years, genetic improvement, and increased mechanization in harvesting to

maximize biomass production (McAlpine et al., 1966). When investigation of SRWCs as a renewable energy source began in the late 1970s, American sycamore was again a promising species (Ezell et al., 1983). Since then, hybrid poplars (*Populus* sp.) and willows (*Salix* sp.) have shown the most potential of the SRWC species studied in the USA, but American sycamore and sweetgum (*Liquidambar styraciflua* L.) biomass research continues in some areas, particularly in the southeastern USA.

After harvest, SRWCs are typically regenerated by coppicing or replanting. When SRWCs are established on former agricultural lands, however, multiple rotations may not always be practical. If SRWCs were to become less profitable than an alternative row crop, cropland would likely be converted to that row crop. The effect of a woody crop to row crop conversion on subsequent row crop yields is not known. It has been shown that conversion from the production of the herbaceous biomass crop switchgrass (*Panicum virgatum* L.) to corn has no significant effect on subsequent corn yields at standard N fertilization rates (Anderson et al., 1997). Because stump extraction is practical only in situations of wood shortage (Czereyski et al., 1965), and stump grinding would be prohibitively expensive, stumps from a woody crop must remain in the ground during the ensuing row crop production. No-till systems may be the only way to produce row crops during the years immediately following woody crops since tree stumps prohibit tillage until they decompose.

Decomposition of woody tree litter such as stumps, roots, and dropped branches will likely affect the properties and productivity of an agricultural soil. The low surface area:volume ratio and high polysaccharide and lignin contents of woody residues limit the invasion and activity of decomposing microbes (Brown et al., 1996; Wagner and

Wolf, 1999). This subsequently reduces decomposition rate and may have a different effect on nutrient cycling than typical agricultural residues. Kirchner (1999) reported that sycamore roots had a significantly higher C:N ratio than roots of corn plants. The high C:N ratio of woody residues often leads to the microbial immobilization of N during decomposition (Brown et al., 1996; Fahey and Arthur, 1994). This N immobilization may have a negative effect on crop yields.

In this study we investigated the conversion of a site from SRWC production to a no-till corn system. The objectives of this portion of the study were to determine the feasibility of following a SRWC with a no-till row crop system and to understand the effect of the SRWC on corn grain yields and N fertilizer efficacy.

Materials and Methods

The study was located on a Memphis-Loring silt loam intergrade on the Ames Plantation in southwestern TN (35° 08' N, 89° 13' W). Soils were composed of deep aeolian loess and had a pH of 6.0 to 6.5. The study was analyzed as a completely-randomized design with a factorial treatment arrangement and four replications. The treatments were cropping system and N fertilization rate. Cropping systems were: *i*) soybean converted to sycamore in 1995 converted to corn in 1999 (SY4C), *ii*) soybean converted to sycamore in 1995 converted to corn in 2000 (SY5C), and *iii*) soybean converted to corn in 1999 (SBC) that served as a control treatment. All row crops were no-tillage systems.

In Feb. 1995, a 0.6-ha portion of a soybean field was planted with one-year-old American sycamore seedlings on a 1.5- x 3.0-m grid (2,222 trees ha^{-1}). Sycamore was

fertilized at a rate of 134 kg N ha^{-1} in Apr. 1996 and 67 kg N ha^{-1} in Apr. 1997 and Apr.

1998. Lime was applied at 2.24 Mg ha^{-1} in Apr. 1995 and Apr. 1997 and P was applied

at 56 kg ha^{-1} in Apr. 1997. Approximately 640 sycamore trees were harvested in Oct.

1998 (SY4C), and an equal number were harvested in Oct. 1999 (SY5C). At harvest,

trees were cut as close to ground level as possible (approximately 2 to 5 cm from soil)

with chainsaws, and stumps were treated with glyphosate to prevent sprouting. After

both the SY4C and SY5C sycamore harvests, the same field procedure was applied to

convert the site to corn production (Table 3-1). Wheat (*Triticum aestivum* L.) was

planted as a winter cover crop and killed the following April with an application of

glyphosate (Roundup®) and atrazine (Bicep II® and AaTrex®). Sixteen plots, each 10.7

by 15.2 m and encompassing approximately 35 tree stumps, were established on the

former sycamore plantation. In Apr. 1999, when the SY4C corn plots were established,

another 16 plots (SBC) were established where the field had been in no-till soybean. The

SY5C plots were established in Apr. 2000. No-till corn was planted on plots in April of

each year, at a row width of 76.2 cm. Each set of 16 plots contained four randomly

assigned replications of four rates of NH_4NO_3 (0, 73, 146, and 219 kg N ha^{-1}) broadcast

approximately two weeks after planting. These N rates represented 0%, 50%, 100%, and

150% of the recommended rate for corn production on the study site. Corn grain was

harvested in September. Equipment used in the study included a John Deere no-till drill

(JD 750), a John Deere six-row planter (JD 7000), and a John Deere combine (JD 9500).

The SY4C and SBC cropping systems remained in corn for three years (1999-2001),

while the SY5C system was in corn for two years (2000-2001).

Table 3-1. Treatments and sampling for corn after soybeans and sycamore on a Memphis-Loring silt loam intergrade in southwestern TN, 1998-2001.

Activity	Year				Notes
	1998	1999	2000	2001	
Harvest sycamore	Oct.	Oct.	-	-	
Plant wheat cover crop	Nov.	Nov.	-	-	
Plots established for corn	-	Apr.	Apr.	-	1999 plots were for SBC and SY4C systems; 2000 plots were for SY5C.
Plant corn	-	12 Apr.	21 Apr.	30 Apr.	Pioneer 3335 in 1999 and 2000; Dekalb DK697 in 2001. 76.2 cm row width.
Apply herbicide to cover crop	-	13 Apr.	10 Apr.	-	Glyphosate (Roundup®) and atrazine (Bicep II® and AaTrex®).
Apply lime	-	14 Apr.	-	-	Rate of 4.5 Mg ha^{-1}.
Fertilize with NH_4NO_3	-	3 May	4 May	30 May	Applied to plots at four rates.
Fertilize with P and K	-	-	11 Apr.	-	Applied at recommended rate.
Thin corn plots	-	13 May	19 May	29 May	Thinned to 54,340 plants ha^{-1} in 1999 and 2000; 49,400 plants ha^{-1} in 2001.
Sample corn ear leaves	-	June 29	June 27	Aug. 9	Ten leaves plot^{-1} removed from random plants in center rows.
Harvest corn grain	-	2 Sept.	15 Sept.	25 Sept.	Two rows per plot harvested to measure grain yield.

For each of the harvested trees (n=1,280), total aboveground green weight, total height, and diameter at stump and breast height (5 and 137 cm above the ground, respectively) were measured. A subset of the harvested trees, consisting of 31 trees in 1998 and 16 trees in 1999, were oven dried to constant weight at 65° C and then re-weighed. Using the measured parameters from the dried trees, equations were developed for estimation of individual tree dry biomass for the remaining sycamore. Estimation variables were chosen by stepwise variable selection using Proc Corr in SAS (SAS Institute, 1997). For the 1998 and 1999 sycamore harvests the individual tree dry weight estimation equations used were, respectively,

$$Y = b_0 + b_1W - b_2W^2 - b_3D + b_4D^2$$

$$Y = b_0 + b_1W - b_2H$$

where Y is the estimated harvested dry weight (kg) of the tree, W is the harvested green weight (kg), D is diameter at 137 cm above ground level (cm), H is total height (m), and b coefficients were determined from the data. Harvestable dry sycamore biomass ha^{-1} was calculated using estimated dry biomass of individual trees, survival rate, and number of trees planted ha^{-1}. Foliage was not included in the harvest estimates. Sub-samples from the limbs and stems of the 16 SY5C trees that were dried after harvest in 1999 were analyzed for N concentration by combustion analysis (Matejovic, 1995) using a LECO CNS-2000 analyzer (LECO Corporation, St. Joseph, Michigan, USA). Limb and stem

samples from the SY4C trees harvested in 1998 were lost; thus, N concentration could not be determined.

Corn ear leaves from each plot were sampled at tasseling on 27 June 1999 and 29 June 2000. In 2001 ear leaf samples were inadvertently collected late, on 9 Aug. Corn grain yields for all three years were measured by harvesting two center rows from each plot, for a total of 21.4 m of row per plot. This grain was sub-sampled for N analysis. Ear leaf samples and grain sub-samples were dried at 65° C, ground, and total N concentration was determined by combustion analysis (Matejovic, 1995).

On 30 Oct. 2000, sycamore stump samples were collected from SY4C plots (104 weeks post-harvest), SY5C plots (52 weeks post-harvest), and from living trees in an adjacent study (0 weeks post-harvest). On SY4C and SY5C plots, chainsaws were used to remove the intact aboveground portion of the stump (a cross-section two to three cm thick) from four randomly selected stumps per plot. Six living sycamore trees, planted in 1995 for an adjacent study, were felled and then sampled in the same manner as the SY4C and SY5C stumps. Wood density of all stump samples was calculated by water displacement. Samples were dried at 65° C, ground, and total C and N concentrations were determined by combustion analysis (Matejovic, 1995).

Stump C, N, and density data and corn ear leaf N data were analyzed with analysis of variance (ANOVA) using Proc Mixed in SAS (SAS Institute, 1997). Protected post-ANOVA mean separations were performed with Fisher's least significant difference test (Steel and Torrie, 1980). Linear and quadratic response functions of corn grain yield to N fertilization rate were tested with Proc Mixed and Proc Reg (SAS Institute, 1997). A minimum confidence level of $\alpha=0.05$ was used in all analyses.

Results

Survival rates for four- and five-year sycamore rotations were 97.2 and 98.4 percent, respectively (Table 3-2). These rotations yielded 19.9 and 26.9 Mg ha^{-1} dry aboveground biomass, respectively (excluding foliage). The four-year SY4C rotation yielded an average of 5.0 Mg ha^{-1} yr^{-1} dry aboveground biomass, while the five-year SY5C rotation yielded an average of 5.4 Mg ha^{-1} yr^{-1}. The woody aboveground biomass of the SY5C rotation contained an estimated 77 kg N ha^{-1}.

No mechanical problems were encountered when corn was planted over the 26-week-old tree stumps. Wood density of 52-week-old stumps did not differ significantly from that of freshly-cut stumps, but wood density was significantly greater for 52-week-old than for 104-week-old-stumps (Table 3-3). Concentration of total N was significantly greater for 52-week-old than for fresh stumps, and 104-week-old stumps had a significantly higher N concentration than 52-week-old-stumps. There was a small but significant decrease in C concentration between freshly-cut stumps and both 52-week-old and 104-week-old stumps. The C:N ratio was significantly lower after 52 weeks and continued to significantly decline after 104 weeks. The difference in C:N ratio after 104 weeks was approximately four-fold the initial level (224.9:1 and 55.7:1, respectively). Stump absolute N content (i.e. mass of N expressed on a volumetric basis) was significantly greater for 52-week-old than for fresh stumps but was not greater for 104-week-old stumps than for 52-week-old stumps. Stump absolute C content was significantly less for 104-week-old than for 52-week-old stumps, but there was no

Table 3-2. Attributes of four- (SY4C) and five-year-old (SY5C) sycamore plantations on a Memphis-Loring silt loam intergrade in southwestern TN. Foliage is not included in data.

Parameter	Cropping system	
	SY4C	SY5C
Survival, %	97.2	98.4
Height, m	8.0 ± 0.9†	9.9 ± 1.3
Diameter at 137 cm above ground, cm	5.9 ± 1.1	7.1 ± 1.5
Diameter at 5 cm above ground, cm	10.0 ± 1.9	11.1 ± 2.3
Estimated dry aboveground mass, Mg ha^{-1}	19.9	26.9
Estimated annual dry aboveground biomass production, Mg ha^{-1} yr^{-1}	5.0	5.4
N concentration of harvested sycamore, g kg^{-1}	-‡	2.9
Estimated N removal in harvested sycamore, kg ha^{-1}	-	77

† Standard deviation.

‡ Data unavailable.

Table 3-3. Physical and chemical properties of stumps of short-rotation sycamore on a Memphis-Loring silt loam intergrade in southwestern TN. Absolute C and N content is the mass of the element expressed on a volumetric basis.

Stump age	Wood density	Total C	Total N	C/N ratio	Absolute C content	Absolute N content
weeks	g cm^{-3}	----------- g kg^{-1} -----------			------------ g m^{-3} ------------	
0	0.46b†	482.8b	2.2a	224.9c	$2.2 * 10^5$b	$1.0 * 10^3$a
52	0.45b	468.6a	6.3b	76.0b	$2.1 * 10^5$b	$2.8 * 10^3$b
104	0.34a	468.9a	8.5c	55.7a	$1.6 * 10^5$a	$2.9 * 10^3$b

† Same letter within column denotes no significant difference ($P > 0.05$).

difference between fresh and 52-week-old stumps. Neither stump density nor stump N concentration was significantly affected by N fertilization rate (data not shown).

Corn grain yields differed greatly among years due to differences in growing season moisture. This was especially apparent in the low yields of 2000, an abnormally dry year. Corn grain yields for the SBC system had a significant quadratic response function to N fertilization rate in all three years of the study (Fig. 3-1, 3-2, and 3-3). Maximum yields were achieved at the recommended N rate for the site (146 kg ha^{-1}), and yields did not increase when N was applied at 219 kg ha^{-1}. A similar quadratic response function was observed for the SY4C system in 2001, the third year of corn following sycamore harvest. However, a linear grain yield response function to N fertilization rate occurred in the SY4C system and in the SY5C system in the first two years of corn immediately following sycamore harvest (1999, 2000 and 2000, 2001, respectively). In these instances, maximum grain yields were reached only at the highest N fertilization rate (219 kg ha^{-1}).

Corn ear leaf N concentration was significantly correlated with grain yield in all cropping systems and all years (Table 3-4). In 1999, corn plants in the SY4C system had significantly lower ear leaf N concentrations than those of the SBC system at all N rates except 219 kg ha^{-1} (Table 3-5). In 2000, corn ear leaf N was significantly lower under the SY5C system compared to the SY4C and SBC systems only at 0 kg N ha^{-1}. Data from 2001 show a trend in which ear leaf N was lowest under the SBC system; however, the 2001 data were affected to an undetermined extent by the delayed sampling date.
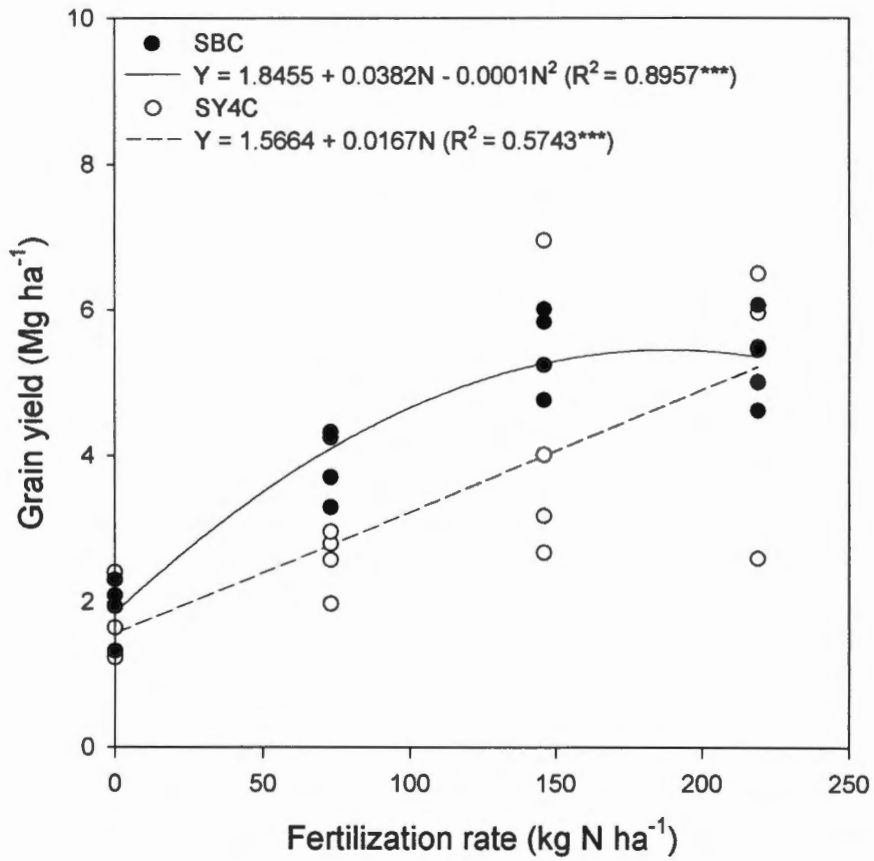
Figure 3-1. Yield response functions for corn after soybean (SBC) and corn after four-year-old sycamore (SY4C) in 1999 on a Memphis-Loring silt loam intergrade in southwestern TN.
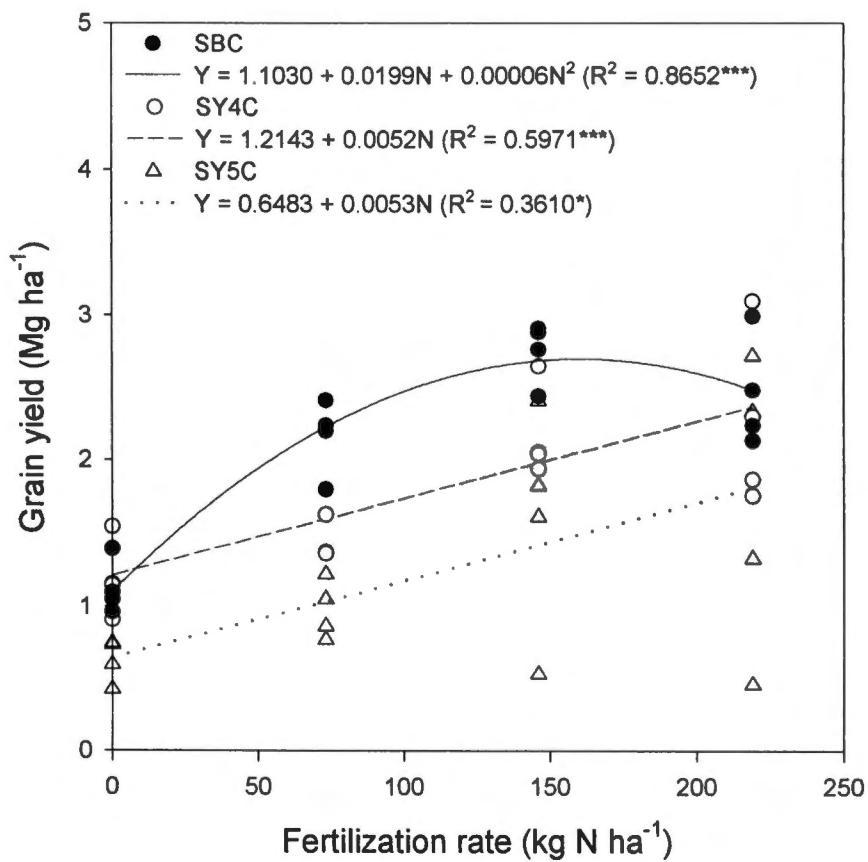
Figure 3-2. Yield response functions for corn after soybean (SBC), corn after four-year-old sycamore (SY4C), and corn after five-year-old sycamore (SY5C) in 2000 on a Memphis-Loring silt loam intergrade in southwestern TN.
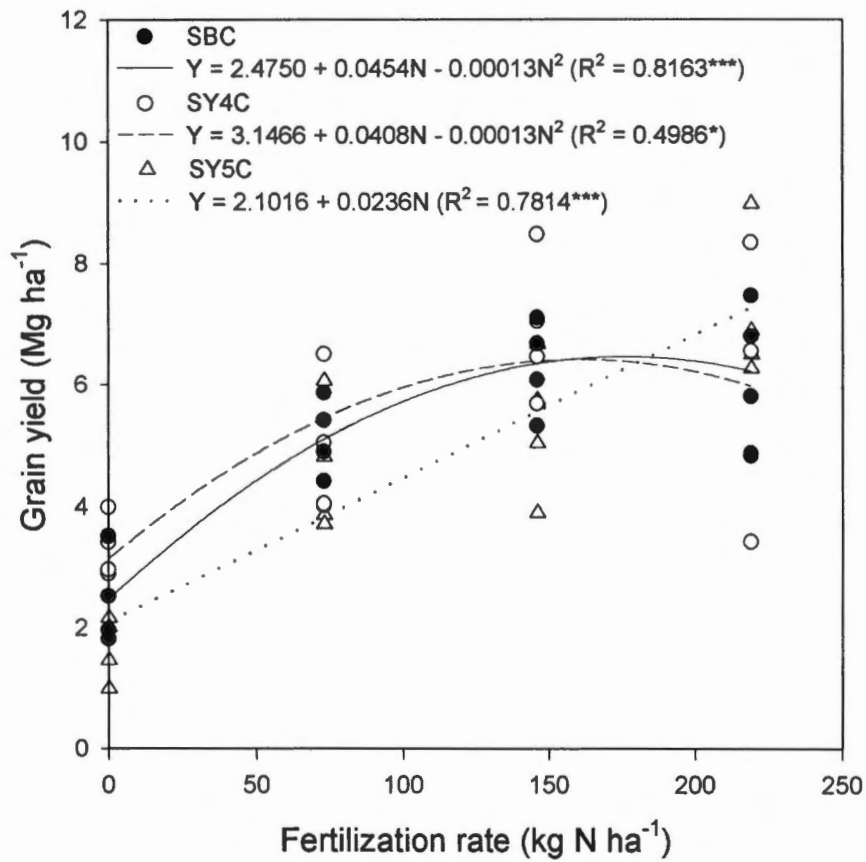
Figure 3-3. Yield response functions for corn after soybean (SBC), corn after four-year-old sycamore (SY4C), and corn after five-year-old sycamore (SY5C) in 2001 on a Memphis-Loring silt loam intergrade in southwestern TN.

Table 3-4. Correlation coefficients for the relationships between corn grain yield and ear leaf N concentration for corn after soybean (SBC), corn after four-year-old sycamore (SY4C), and corn after five-year-old sycamore (SY5C) on a Memphis-Loring silt loam intergrade in southwestern TN.

Cropping system	Year		
	1999	2000	2001
SBC	0.84***	0.91***	0.73**
SY4C	0.70**	0.71**	0.58*
SY5C	-	0.60*	0.80***

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

Table 3-5. Concentration of ear leaf N for corn on a Memphis Loring silt loam intergrade in southwestern TN. Samples were collected in late June of 1999 and 2000 and early August of 2001.

Cropping system	Fertilization rate (kg N ha^{-1})			
	0	73	146	219
	---------------------- g N kg^{-1} ----------------------			
1999				
SBC	19.0b†	23.5b	27.1b	24.2a
SY4C	13.5a	19.1a	24.0a	25.1a
2000				
SBC	19.5b	25.4a	31.0a	30.2a
SY4C	20.3b	25.1a	31.6a	32.5a
SY5C	14.6a	22.9a	32.0a	32.1a
2001				
SBC	7.0a	9.5a	12.8a	11.8a
SY4C	9.8b	11.0ab	15.8b	18.4b
SY5C	10.2b	13.7b	18.2b	21.3c

† Values within the same year and column followed by the same letter do not differ ($P > 0.05$).

Discussion

Sycamore biomass yields were equal to or greater than those of other short-rotation sycamore studies (Fribourg et al., 1989; Dickmann et al., 1985; Wittwer and Stringer, 1985; Francis, 1984; Wittwer et al., 1980; Blackmon, 1979; Wood et al., 1976), but were inferior to yields typical of hybrid poplars and willows (DeBell et al., 1997; Kopp et al., 1997).

The estimated N removal of 77 kg ha^{-1} in the 1999 sycamore harvest was comparable to that of other sycamore plantation studies that estimated N removals (excluding foliage) of 30 kg ha^{-1} for a five-yr-old plantation (Wittwer and Stringer, 1985), 27.5 and 127 kg ha^{-1} for fertilized and unfertilized five-year-old plantations, respectively (Wittwer et al., 1980), and 144 kg ha^{-1} for a four-year-old plantation (Blackmon, 1979). In a review of SRWC studies, Adegbidi et al. (2001) reported annual N removals ranging from 23 to 86 kg ha^{-1} for a variety of species. Blackmon (1979) estimated a N gain:loss ratio of 0.93 for a four-year coppiced, unfertilized sycamore rotation. For this estimate N influxes were mineralization and precipitation and efflux was harvest.

Estimated N removal in the harvest of the 5-year-old sycamore plantation was only slightly greater than the N removal estimated for the 1999 SBC corn grain harvest (68 kg N ha^{-1}) fertilized at the recommended rate of 146 kg N ha^{-1} and was less than that removed in the 2001 grain harvest for the SBC system (99 kg N ha^{-1}) fertilized at the same rate. Thus, as Heilman and Norby (1998) suggested, N removed in the harvest of woody biomass plantations is comparable to or less than the N harvest removed from an agricultural system, especially if the woody biomass crop is harvested after leaf

abscission. Removal of leaves in a SRWC harvest represents a significant N loss. The foliar N content of a four-year-old sycamore plantation was reported to be 90 kg N ha^{-1} (Wittwer et al., 1980).

Following harvest, the surface area of the sycamore stumps was 0.18% and 0.22% of the total site for the SY4C and SY5C plantations, respectively. Most corn rows did not coincide with rows of sycamore stumps, and when they did, coulters cut directly through the stumps. There appeared to be no reduction in germination or vegetative growth of corn plants due to the presence of the stumps. During the first season of corn after sycamore harvest, tree stumps showed little sign of decomposition other than occasional radial splits and separation of the bark. Stump decomposition was much advanced by the second season of post-sycamore corn, especially in stumps that had been damaged by the planter. Many stumps had broken into several pieces and most of the bark had separated from the wood. These physical breakdowns facilitate rapid invasion of the wood by microbial decomposers (Kaarik, 1974). Kuhnelt (1976) reported that when stumps of harvested trees decomposed, the flat-sawn surface of the stump often formed a hardened lid that was much more resistant to decay than the rest of the stump. In the present study this phenomenon was observed in some stumps two years after harvest, but these stump lids never impeded the planting process. By the third season of corn after sycamore harvest, many stumps were so decomposed that they were undetectable from the surface.

Significant ($P < 0.0001$) negative correlations observed between stump N concentration and absolute C content and between stump N concentration and wood density (data not shown) were expected because the microorganisms oxidizing the stump C resulted in a concentrating of N in the stumps. Stumps undergoing active

decomposition would have had a reduced density due to greater amounts of C oxidation. Thus, the C:N ratio of the stump was lowered by both the addition of microbial N and the loss of fixed C. The difference in absolute C content between 52- and 104-week-old stumps suggests that the rate of microbial C oxidation was maximized during this period. The relatively small differences in stump C concentration observed among different-aged stumps were comparable to results of other studies that found C losses proportionate to mass losses for decomposing woody debris (Keenan et al., 1993; Idol et al., 2001; Stewart and Burrows, 1994).

Although it was initially anticipated that N fertilization in this study would increase the rate of stump decomposition by providing available N to decomposers, there was no evidence that this occurred. The absence of significant correlations between N fertilization rate and stump decomposition rate as measured by wood density (r = 0.28 for SY4C; r = -0.16 for SY5C) may have been due to the fact that only a relatively small amount of fertilizer actually landed on or adjacent to the stumps. Furthermore, there was a relatively rapid uptake of this N fertilizer by corn plants, thus reducing the amount of fertilizer N available to microorganisms. Soil N losses such as leaching and denitrification also reduced the amount of N available to decomposers. It is also possible that inorganic fertilizer N is not a source of N that would stimulate decomposition by fungi. Boyle (1998) found that degradation of lignin by white-rot fungi was inhibited significantly more by amendments of simple N forms than by complex forms such as proteins. Fungal growth also was increased by complex N sources more than by simple N sources.

Studies of wood decomposition have consistently reported increases in N concentrations with increasing time of decomposition (Camiré et al., 1991; Keenan et al., 1993; Beauchemin et al., 1990; Idol et al., 2001; Stewart and Burrows, 1994). This trend is also well documented in forest leaf litter (Berg and Staaf, 1981) and herbaceous plants (Urquiaga et al., 1998). In Chapter 2 it was reported that, for this study, a litter layer did not begin to form on the sycamore plantation until the end of the third year. Before that point there was not sufficient litterfall accumulation or dropped limbs to keep the fallen leaves from blowing off site during winter. Thus, there was not a significant buildup of leaf matter on the soil surface at the time of sycamore harvest, and leaf litter probably did not affect N cycling significantly. Since the absolute N increase in stumps in this study appeared to occur primarily in the first 52 weeks after harvest, the majority of microbial colonization likely occurred during this period. Staaf and Berg (1977) reported that N accumulation in surface litter of a Scots pine forest ceased when the litter reached one and a half years of age. In the present study, the primary mechanism of N transfer from the soil to the aboveground stump wood was probably the extension of fungal hyphae. Frey et al. (2000) reported that fungi were responsible for the majority of N translocated from an agricultural soil to high-C:N surface residues. Berg and Söderström (1979) reported transfer of N by fungal hyphae into aboveground tree litter.

The consistent correlation between corn grain yield and ear leaf N concentration suggests that N was a factor that limited yield in this study. The significant reductions in ear leaf N concentration in the SY4C system (compared to the SBC system) in 1999 indicate a loss of plant-available N within the SY4C system for the first-year of post-sycamore corn. In 2000, abnormally low growing season moisture led to extremely low

yields on some plots of first-year corn (SY5C) and a corresponding weakening of the relationship between grain yield and ear leaf N. Corn ear leaf N concentration in 2001 was sampled during reproductive growth instead of at tasseling, and thus trends observed in 2001 cannot be compared to those of 1999 and 2000.

Corn grain yield response functions indicated that the N requirement for maximum grain yield was increased by the prior sycamore biomass crop for the first two years of post-sycamore corn. This may have been due to a loss of plant-available soil N to microbial immobilization during decomposition of woody residues. A significant decrease in soil inorganic N from a depth of 0 to 2.5 cm was observed in this study in the first growing season after sycamore were harvested (Chapter 2). If microbial N immobilization was occurring, the post-sycamore corn production would likely have benefited from a split application of N fertilizer rather than a single application. The single application of N in this study may have resulted in excessive immobilization of that fertilizer N not soon taken up by the corn plants.

Whereas most of the N immobilization [the absolute N increase in stumps and the N increase in large roots (Chapter 2)] in this study was observed in the first two years, it is likely that the N immobilized by decomposers had peaked by the third year after sycamore harvest. This would explain the return to a typical N fertilization response function for grain yield of SY4C corn in 2001. Devine et al. (2002) reported that the intact remnants of 1.5-year-old root systems in this study had a C:N ratio of 80:1 and were much less decomposed than 2.5-year-old root systems. Although 2.5-year-old intact roots had a C:N ratio of 46:1, much of these roots, especially the small ones, were very decomposed and may have become a source of mineralized N. Small live roots (< 2 mm

diameter) from a depth of 0 to 30 cm in a sycamore plantation adjacent to this study had a C:N ratio of 36:1 (unpublished data). Small roots, with their lower C:N and higher surface area:volume ratios, may have served as a source of mineralized N much sooner than larger roots. Ehrenfeld et al. (1997) and Fahey et al. (1988) reported that fine tree roots in mineral soil were a source of mineralized N for up to one year after root death. It is possible that, during root decomposition, the mineralization of N from small roots may occur at the same time as N immobilization in the larger roots. This may mask the effects of N immobilization and result in only a small net change in plant-available soil N.

Conclusions

Aboveground residues from a SRWC, including tree stumps, did not hinder the establishment of a no-tillage corn system six months after harvest of the trees. Microbial colonization of tree stumps appeared to take place in the first year after harvest, but substantial loss of stump mass did not occur until the second year. The quantity of N removed in the sycamore harvest was similar to that of one corn grain harvest. Corn grain yield response functions to N fertilizer rate and differences in ear leaf N concentration indicated that the prior sycamore crop affected N availability for up to two years after its harvest. Increased N fertilization or a split fertilizer application may be necessary for corn production during the two years immediately following harvest of a SRWC. Further research is needed to quantify N transformations in above- and belowground residues of SRWCs.

CHAPTER 4

Conversion from a Sycamore Biomass Crop to a No-Till Corn System: Quantification of Aboveground and Belowground Carbon and Nitrogen

Introduction

While Chapters Two and Three addressed the post-harvest effects of a sycamore plantation on an agricultural system, further quantification of the biomass and chemical content of the sycamore and corn crops was desirable. Although many of the C and N influxes and effluxes were beyond the scope of this study, the no-till corn systems and the belowground portions of the sycamore plantation warranted a more detailed examination. There has been little research conducted on the mass and turnover of tree roots in SRWC systems (Heilman and Norby, 1998; Friend et al., 1991). Sycamore roots in particular have rarely been studied (Steinbeck and Nwoboshi, 1980).

Due to the laborious nature of the field work, it is resource-intensive to obtain adequate sample sizes when researching the belowground portion of trees. However, C cycling in a forested ecosystem cannot be fully understood until estimates of root growth, root biomass, and fine root turnover rates are determined. With the relatively recent surge in C cycle and C sequestration research, the need for a better understanding of the C fluxes in the belowground portion of trees has been emphasized (Janssens et al., 2001; Cairns et al., 1997). While tree root C originates from photosynthesized CO_2, significant amounts are annually transferred from the tree to the soil C pool through the processes of root senescence, respiration, and exudation (Vogt et al., 1991). Thus, concerns about atmospheric CO_2 concentrations are addressed through tree root and forest soil research.

Annual fine root turnover constitutes a significant input of tree litter to the soil (McClaugherty et al., 1982). Nadelhoffer and Raich (1992) reviewed 59 studies of fine root production in forests and found that production estimates ranged from 52 to 1708 g m^{-2} $year^{-1}$. Joslin and Henderson (1985) review 15 forest ecosystem studies that reported fine root turnover of 218 to 1150 g m^{-2} $year^{-1}$. Fine root turnover may occur as trees adapt to changes in soil moisture and nutrient availability by adjusting their fine root mass through senescence and regrowth. It has been demonstrated in some studies that on sites with low concentrations of soil nutrients such as N and P, some tree species allocate more C to root production in search of these nutrients (Vogt et al., 1991). Roots of different diameters are known to differ in longevity. For example, in a Belgian Scots pine plantation, fine roots (<1 mm diameter) were estimated to have a longevity of 1.4 years, while 1-2 mm roots were estimated to live an average of 3.3 years (Janssens et al., 2001). However, root production research is presently limited by technologies for estimating root growth (Nadelhoffer and Raich, 1992).

The only definitively measured nutrient input in this study was N fertilizer. Measured nutrient removals included harvested sycamore N and corn grain N. Corn grain N removal increases with increased N fertilization and increased yield (Cerrato and Blackmer, 1990). Thus, N removed in harvested grain is a function of plant-available soil N. Yamoah et al. (1998) found that crop rotations increased both N removal and the amount of N in crop residues. The residue from the corn plants is an important factor in the present study because it represents the formation of a mulch layer in the newly-established, post-sycamore no-till system. Corn has been estimated to produce, on average, one kilogram of residue per kilogram of grain (Aldrich et al., 1986). Such a

relationship suggests that, if yields are reduced for corn following sycamore, crop residue production will also decline, perhaps with a negative effect on soils. The objective of this portion of the study was to quantify the above- and belowground biomass of sycamore and corn in a row crop-woody crop-row crop rotation system.

Materials and Methods

Experimental Design

The study was located on a Memphis-Loring silt loam intergrade on the Ames Plantation in southwestern TN (35° 08' N, 89° 13' W). Soils were composed of aeolian loess with a pH of 6.0 to 6.5. The study was analyzed as a completely-randomized design with a factorial treatment arrangement and four replications. The treatments were cropping system and N fertilization rate. Cropping systems were: *i*) soybean converted to sycamore in 1995 converted to corn in 1999 (SY4C), *ii*) soybean converted to sycamore in 1995 converted to corn in 2000 (SY5C), and *iii*) soybean converted to corn in 1999 (SBC) that served as a control treatment. All row crops were no-tillage systems.

In Feb. 1995, a 0.6-ha portion of a soybean field was planted with one-year-old American sycamore seedlings on a 1.5- x 3.0-m grid (2,222 trees ha^{-1}). Sycamore was fertilized at a rate of 134 kg N ha^{-1} in Apr. 1996 and 67 kg N ha^{-1} in Apr. 1997 and Apr. 1998. Lime was applied at 2.24 Mg ha^{-1} in Apr. 1995 and Apr. 1997 and P was applied at 56 kg ha^{-1} in Apr. 1997. Approximately 640 sycamore were harvested in Oct. 1998 (SY4C), and an equal number were harvested in Oct. 1999 (SY5C). At harvest, trees were cut as close to ground level as possible (approximately 2 to 5 cm from soil) with chainsaws, and stumps were treated with glyphosate to prevent sprouting.

After both the SY4C and SY5C sycamore harvests, the same process was applied to convert the site to corn production. Wheat (*Triticum aestivum* L.) was planted as a winter cover crop and killed the following April with an application of glyphosate (Roundup®) and atrazine (Bicep II® and AaTrex®). Sixteen plots, each 10.7 by 15.2 m and encompassing approximately 35 tree stumps, were established on the former sycamore plantation. In Apr. 1999, when the SY4C corn plots were established, another 16 plots (SBC) were established where the field had previously been in soybean. The SY5C plots were established in Apr. 2000. No-till corn was planted on 12 Apr. 1999, 21 Apr. 2000, and 30 Apr. 2001, at a row width of 76.2 cm. Each set of 16 plots contained four randomly assigned replications of four rates of NH_4NO_3 (0, 73, 146, and 219 kg N ha^{-1}) broadcast on 3 May 1999, 4 May 2000, and 30 May 2001. These N rates represented 0%, 50%, 100%, and 150% of the recommended rate for no-till corn production on the site. Corn grain was harvested 2 Sept. 1999, 15 Sept. 2000, and 25 Sept. 2001. The SY4C and SBC cropping systems remained in corn for three years (1999-2001), while the SY5C system was in corn for two years (2000-2001).

Harvested Sycamore

For each of the harvested trees (n=1,280), total aboveground green weight, total height, diameter breast height (DBH; 137 cm above ground level), and groundline diameter (GLD; 5 cm above ground level) were measured. Limbs were removed from 48 harvested trees in 1998, and stems and limbs were weighed separately. Thirty-one of these 48 trees, representing at least one tree per plot, were oven dried to constant weight at 65° C and then re-weighed. In 1999, one tree per plot (n=16) was separated into limb

and stem components, weighed, oven-dried to constant weight at 65° C, and then re-weighed.

Using the measured parameters from the trees selected for drying, equations were developed for estimation of individual tree dry biomass, stem dry biomass, and limb dry biomass of the remaining sycamore. The variables used in equations were selected from the variables that were measured for all plantation trees (height, DBH, GLD, and green mass). Separate equations were created for the 1998 and 1999 harvests. Estimation variables were chosen by stepwise variable selection using Proc Corr in SAS (SAS Institute, 1997). The variables available for selection were: height, height^2, DBH, DBH^2, GLD, GLD^2, green mass, green mass^2, DBH^2*height, and (DBH^2*height)^2. Harvestable dry sycamore biomass ha^{-1} was calculated using estimated dry biomass of individual trees, survival rate, and number of trees planted ha^{-1}. Sub-samples from the limbs and boles of the 16 trees that were dried after harvest in 1999 were ground and analyzed for C and N concentrations by combustion analysis (Matejovic, 1995) using a LECO CNS-2000 analyzer (LECO Corporation, St. Joseph, Michigan, USA). Foliage samples were not preserved, and thus foliage was not included C and N analyses.

Root Systems of Living Sycamore

The root systems of ten living sycamore were sampled on April 19-20, 2001 to estimate belowground biomass and nutrient content of the sycamore plantation. These sycamore were planted in February, 1995 as part of the same plantation as the SY4C and SY5C systems. At the time of sampling, the trees were in their seventh growing season after outplanting. These trees are subsequently referred to as "age 6.5". The ten trees

selected for sampling were chosen to represent a range of diameter sizes. Diameters at groundline and breast height were measured prior to root sampling. Root systems were sampled in a two-phase procedure similar to that used by Steinbeck and Nwoboshi (1980). In Phase I, soil cores were removed around each sample tree to estimate root mass at horizontal distances greater than 75 cm from the selected tree. In Phase II, intact root systems were excavated by backhoe.

Soil cores, seven cm in diameter, were augered from each of three locations 75 to 150 cm from each of ten sample trees (Figure 4-1). Cores were removed from depth intervals of 0-15, 15-30, 30-60, 60-90, and 90-120 cm below the surface for a total of 150 soil core samples. Core samples were stored at 4° C until analysis. In the laboratory, roots were separated from soil by washing. First, each soil core was placed in a bucket with approximately six liters of warm water. Sodium hexametaphosphate was added as a deflocculant. This mixture was stirred intermittently by hand for approximately 2 hours and then poured through a 1-mm sieve. For most samples, numerous soil aggregates were retained on the sieve. These aggregates were then disintegrated by a gentle shower of water that fell from a height of approximately 50 cm. After this treatment was applied for 30 minutes to 1 hour, the majority of the soil aggregates were reduced to a size of 5 mm or less in diameter. These aggregates, as well as the tree roots and any other pieces or organic matter that were retained on the sieve, were then poured onto a light-colored, absorbent paper. The tree roots were then separated from the soil and miscellaneous organic matter with forceps. These root samples were washed of residual soil and then dried to a constant weight at 65° C. The roots were separated into two classes according to diameter: greater than 2 mm, and equal to or less than 2 mm. Roots from each
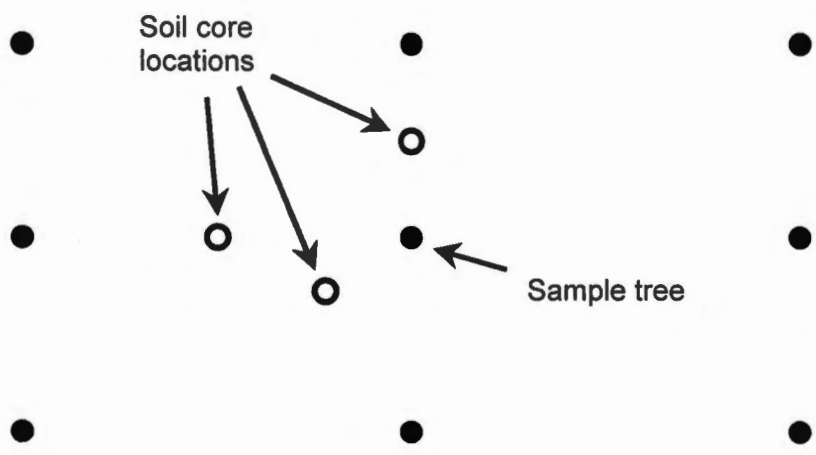
Figure 4-1. Locations of soil cores for root sampling.

diameter class and each sampling depth were then analyzed for total C and N concentration by combustion analysis (Matejovic, 1995) using a LECO CNS-2000 elemental analyzer (LECO Corp., St. Joseph, MI).

After soil cores were removed from each of the ten designated trees, the trees were felled and removed from the site. The root systems then were pulled slowly from the ground by backhoe, and all roots connected to the stumps subsequently washed in the field. The spread of the primary roots of each of these excavated root system was measured in two perpendicular directions on a plane equivalent to ground level. The first direction spanned the longest spread and the second was perpendicular to the first. The distance from the stump face to the tip of the deepest primary root was measured for each root system. The root systems were dried to constant weight at 65° C and each was weighed. Roots were sub-sampled, and sub-samples were analyzed for total C and N concentration by combustion analysis (Matejovic, 1995). Estimates of dry root biomass, C, and N per hectare for excavated root systems were calculated using initial planting density and an assumed survival rate of 97%.

Estimates of total sycamore root mass, C content, and N content per hectare to a depth of 120 cm were calculated by combining the root estimates from the core samples with the measurements of the excavated root systems. Based upon observations of the excavated root systems, it was determined that the soil volume containing the excavated portions of the roots could be approximated by the volume of an inverted pyramid (Figure 4-2). The volume of soil within this pyramid was calculated and this volume was subtracted from the theoretical volume of soil occupied by each tree (to a depth of 120 cm). The difference was the volume of soil from which the root mass was estimated by
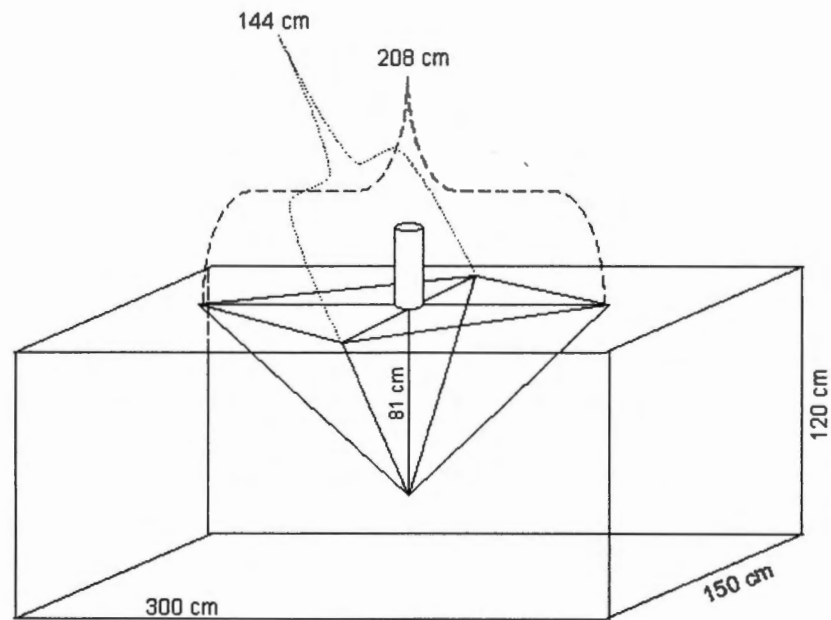
Figure 4-2. Diagram of the technique used to estimate root mass. The root mass within the inverted pyramid was estimated by excavation; the root mass in the remainder of the volume was estimated by core samples.

the soil core method. The two complimentary estimates (the inverted pyramid and the remainder of the volume) were added to create an estimate of the total root mass per tree to a depth of 120 cm.

Sycamore Stumps

Samples from sycamore stumps were collected from SY4C plots on 27 June 2000. The aboveground portion of one stump per plot was removed. Because this sampling methodology differed from the stump sampling in October 2000 (i.e. one instead of four samples per plot and manual instead of chainsaw sampling), June and October results were analyzed separately. Wood density of stump samples was calculated by water displacement. Samples were then dried at 65° C, ground, and total C and N concentrations were determined by combustion analysis (Matejovic, 1995) using a LECO CNS-2000 analyzer (LECO Corporation, St. Joseph, Michigan, USA).

Corn Plant and Grain Harvest Analyses

On June 6, 1999, September 15, 2000, and August 29, 2001, whole corn plant samples were collected. Aboveground portions of plants from 91.4 cm of row were removed from each plot (n=32 in 1999; n=48 in 2000 and 2001). These samples were dried, weighed, and then ground and analyzed for total C and N concentration by combustion analysis (Matejovic, 1995) using a LECO CNS-2000 analyzer (LECO Corporation, St. Joseph, Michigan, USA). Corn grain yields were measured by harvesting two center rows from each plot, for a total of 21.4 m of row per plot. This grain was sub-sampled for C and N analysis. The grain sub-samples were dried at 65° C,

ground, and total C and N concentration was determined by combustion analysis (Matejovic, 1995). Per-hectare estimates of whole plant mass and plant C and N contents were calculated using the total length of row per hectare.

Data Analyses

Correlation coefficients among measured parameters of the SY4C harvested trees, the SY5C harvested trees, and the ten living root systems were calculated with Proc Corr in SAS (SAS Institute, 1997). Equations for estimation of biomass were then created in Proc Reg in SAS. Stump C, N, and density data and corn whole plant and grain data were analyzed with analysis of variance (ANOVA) using Proc Mixed in SAS (SAS Institute, 1997). Protected post-ANOVA mean separations were performed with Fisher's least significant difference test (Steel and Torrie, 1980). A minimum confidence level of α=0.05 was used in all analyses.

Results

Harvested Sycamore

All measured parameters of the harvested SY4C system sycamore were significantly correlated (Table 4-1). All measured parameters of the SY5C system sycamore, with the exception of limb mass and height, also were significantly correlated (Table 4-2). Height and green mass of sycamore were variables most often chosen by stepwise variable selection to predict dry mass of individual trees (Table 4-3).

Table 4-1. Correlation coefficients and significance for measured parameters of sycamore harvested four years after out-planting (n=622 for DBH, GLD, height, and total green mass; n=48 for stem green mass and limb green mass; n=31 for total dry mass, stem dry mass, and limb dry mass).

	DBH	GLD	Height	Total green mass	Stem green mass	Limb green mass	Total dry mass	Stem dry mass	Limb dry mass
DBH	1.0000	-	-	-	-	-	-	-	-
GLD	0.8081 ***	1.0000	-	-	-	-	-	-	-
Height	0.7031 ***	0.5716 ***	1.0000	-	-	-	-	-	-
Total green mass	0.8823 ***	0.8387 ***	0.6803 ***	1.0000	-	-	-	-	-
Stem green mass	0.9505 ***	0.9222 ***	0.8242 ***	0.9847 ***	1.0000	-	-	-	-
Limb green mass	0.8426 ***	0.8118 ***	0.6207 ***	0.9326 ***	0.8686 ***	1.0000	-	-	-
Total dry mass	0.9655 ***	0.9362 ***	0.8135 ***	0.9889 ***	0.9919 ***	0.8959 ***	1.0000	-	-
Stem dry mass	0.9695 ***	0.9359 ***	0.8337 ***	0.9805 ***	0.9928 ***	0.8715 ***	0.9955 ***	1.0000	-
Limb dry mass	0.8996 ***	0.8848 ***	0.7073 ***	0.9588 ***	0.9340 ***	0.9193 ***	0.9579 ***	0.9262 ***	1.0000

*** Significant at the 0.001 probability level.

Table 4-2. Correlation coefficients for measured parameters of sycamore harvested five years after out-planting (n=630 for DBH, GLD, height, and total green mass; n=16 for stem green mass, limb green mass, total dry mass, stem dry mass, and limb dry mass).

	DBH	GLD	Height	Total green mass	Stem green mass	Limb green mass	Total dry mass	Stem dry mass	Limb dry mass
DBH	1.0000	-	-	-	-	-	-	-	-
GLD	0.8420 ***	1.0000	-	-	-	-	-	-	-
Height	0.6885 ***	0.5864 ***	1.0000	-	-	-	-	-	-
Total green mass	0.9211 ***	0.8596 ***	0.6961 ***	1.0000	-	-	-	-	-
Stem green mass	0.9708 ***	0.9204 ***	0.8307 ***	0.9811 ***	1.0000	-	-	-	-
Limb green mass	0.7561 ***	0.7044 **	0.3042 NS	0.7931 ***	0.6603 **	1.0000	-	-	-
Total dry mass	0.9800 ***	0.9284 ***	0.7055 **	0.9942 ***	0.9629 ***	0.8277 ***	1.0000	-	-
Stem dry mass	0.9797 ***	0.9325 ***	0.7987 ***	0.9875 ***	0.9935 ***	0.7052 **	0.9807 ***	1.0000	-
Limb dry mass	0.7701 ***	0.7170 **	0.2941 NS	0.7989 ***	0.6705 **	0.9909 ***	0.8386 ***	0.7158 **	1.0000

, * Significant at the 0.01 and 0.001 probability levels, respectively.

Table 4-3. Coefficients used to estimate dry mass of individual sycamore trees and components. Model was
$Y = b_0 + b_1*\text{Height} + b_2*\text{DBH} + b_3*\text{DBH}^2 + b_4*\text{GLD} + b_5*\text{Green mass} + b_6*\text{Green mass}^2 + b_7*\text{DBH}^2*\text{Height}$ (n=31 for SY4C treatment and n=16 for SY5C treatment).

Y	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	R^2
Total dry mass, SY4C	3.0132	-	-1.6238	0.1840	-	0.5917	-0.0052	-	0.9923
Total dry mass, SY5C	5.9847	-0.7608	-	-	-	0.5453	-	-	0.9925
Stem dry mass, SY4C	-0.4049	-	-	-	0.1953	0.1575	-	0.0076	0.9862
Stem dry mass, SY5C	-6.0213	0.7872	-	-	-	0.3549	-	-	0.9823
Limb dry mass, SY4C	1.5771	-0.3226	-	-	-	0.2163	-0.0018	-	0.9566
Limb dry mass, SY5C	12.0060	-1.5480	-	-	-	0.1904	-	-	0.8551

The C:N ratio of limbs was lower than that of stems for SY5C sycamore (Table 4-4). While sycamore stem mass was 9 Mg ha^{-1} greater for SY5C sycamore than for SY4C sycamore, limb mass was 1.6 Mg ha^{-1} less. The estimated C removed from the site (excluding foliage) in the SY5C sycamore harvest was 13.1 Mg ha^{-1}, and estimated N removal was 77 kg ha^{-1}.

Root Systems of Living Sycamore

Several of the variables measured for the ten excavated sycamore root systems were significantly correlated (Table 4-5). Root system dry mass was significantly correlated with diameter at breast height (DBH) and root area (i.e. maximum horizontal root spread*root spread in perpendicular direction) but not groundline diameter (GLD). Root area and root volume (inverted pyramid estimate) were significantly correlated with DBH but not GLD. Core sample root mass was not correlated with any other variable. Because ANOVA showed no difference in soil core root mass among the three sampling locations (Table 4-6), these data were combined by sampling depth for all subsequent analyses and estimates. Table 4-7 shows C and N concentrations and volumetric estimates of root mass by depth and root diameter based on soil core root samples. Because the data were highly unbalanced due to minimum sample size requirement for combustion analysis, ANOVA was not performed on these data. There were apparent differences in root N concentration and C:N ratio between the two root size classes and among the five sampling depths. Nitrogen concentrations in roots ≤2 mm diameter decreased with depth, but at all depths concentrations were greater than those of roots >2 mm in diameter.

Table 4-4. Sycamore C and N concentrations and estimated mass, C content, and N content. Carbon and nitrogen data were not available for SY4C sycamore.

Parameter	C concentration	N concentration	C:N ratio	Estimated dry mass	Estimated C content	Estimated N content
	----------- g kg^{-1} -----------			Mg ha^{-1}	------------ kg ha^{-1} ------------	
Total dry mass, SY4C	-	-	-	19.9†	-	-
Total dry mass, SY5C	485.9	2.9	167.6:1	26.9	13,071	77
Stem dry mass, SY4C	-	-	-	14.4	-	-
Stem dry mass, SY5C	488.4	2.8	174.4:1	23.4	11,429	66
Limb dry mass, SY4C	-	-	-	5.0	-	-
Limb dry mass, SY5C	471.2	3.2	147.3:1	3.6	1,696	12

† Estimates of stem plus limb mass may not equal estimates of total dry mass due to discrepancies in models.

Table 4-5. Correlation coefficients and significance for measured parameters of sycamore root systems sampled in April of their seventh growing season after outplanting (n=10).

Parameter	Core root mass	Root green mass	Root dry mass	DBH	DBH^2	GLD	GLD^2	Maximum root depth	Root area	Root volume
Core root mass	1.0000	-	-	-	-	-	-	-	-	-
Root green mass	0.1701 NS	1.0000	-	-	-	-	-	-	-	-
Root dry mass	0.2112 NS	0.9414 ***	1.0000	-	-	-	-	-	-	-
DBH	0.2591 NS	0.9031 ***	0.8746 ***	1.0000	-	-	-	-	-	-
DBH^2	0.2473 NS	0.9110 ***	0.8908 ***	0.9989 ***	1.0000	-	-	-	-	-
GLD	-0.1642 NS	0.5444 NS	0.6083 NS	0.5599 NS	0.5617 NS	1.0000	-	-	-	-
GLD^2	-0.1708 NS	0.5416 NS	0.6108 NS	0.5593 NS	0.5620 NS	0.9993 ***	1.0000	-	-	-
Maximum root depth	-0.4282 NS	-0.1205 NS	-0.0941 NS	0.0274 NS	0.0123 NS	0.2144 NS	0.1994 NS	1.0000	-	-
Root area	0.1057 NS	0.6134 NS	0.7440 *	0.6352 *	0.6631 *	0.3665 NS	0.3843 NS	-0.3088 NS	1.0000	-
Root volume	-0.1937 NS	0.4950 NS	0.6213 NS	0.6358 *	0.6510 *	0.4721 NS	0.4786 NS	0.3822 NS	0.7554 *	1.0000

*, *** Significant at the 0.05 and 0.001 probability levels, respectively.

Table 4-6. Analysis of variance for dry mass of roots determined by soil core sampling.

Effect	Degrees of freedom	Pr > F
Depth	4	0.0392
Location	2	0.1600
Depth*Location	8	0.7372

Table 4-7. Properties of sycamore root systems sampled by soil coring. Samples were collected in April of the seventh year after out-planting.

Soil depth	Root diameter	Root C concentration	Root N concentration	Root C:N ratio	Estimated root dry mass	Estimated root C concentration	Estimated root N concentration
cm	mm	------------ g kg^{-1} ------------			----------------------- g m^{-3} soil -----------------------		
0-15	≤ 2	479.0	14.4	33.4	248	119	4
	> 2	481.4	8.6	56.1	159	77	1
15-30	≤ 2	505.4	13.4	37.8	103	52	1
	> 2	481.9	8.8	55.1	79	39	1
30-60	≤ 2	477.7	11.1	43.2	155	74	2
	> 2	454.4	7.5	60.5	256	116	2
60-90	≤ 2	466.8	10.5	44.4	118	55	1
	> 2	475.8	6.8	69.6	262	125	2
90-120	≤ 2	478.2	11.2	42.9	94	45	1
	> 2	487.5	7.4	65.9	20	10	<1
0-120	≤ 2	475.6	11.1	45.7	136	65	2
	> 2	474.8	8.9	54.9	164	77	1
0-120	All	475.2	10.0	50.5	300	142	3

Diameter of roots appeared to vary by depth. At depth intervals from 0 to 30 cm and 90 to 120 cm, the majority of root mass was composed of roots ≤ 2 mm in diameter. At depth intervals from 30 to 90 cm, the majority of root mass was composed of roots >2 mm in diameter. Concentration of root C expressed on a soil volumetric basis (g C m^{-3} soil) followed a similar trend: greater C was in roots ≤ 2 mm in diameter at 0 to 30 cm and 90 to 120 cm depth intervals and greater C was in roots >2 mm in diameter at depth intervals from 30 to 90 cm. Concentration of root N in soil was greatest at a depth of 0 to 15 cm due primarily to the N in roots ≤ 2 mm in diameter. To a depth of 120 cm, the average concentration of root N in soil, as estimated by the soil core samples, was 3 g m^{-3}.

Excavated root systems averaged 5.35 kg dry mass per tree (Table 4-8). The majority of this mass was in roots >30 mm in diameter. The roots had a lower N concentration and a higher C:N ratio with increasing diameter. It was estimated that the excavated portions of the root systems in the 6.5-year-old sycamore plantation represented over 11.5 Mg ha^{-1}.

When the root estimates from the excavated root systems were combined with the soil core root estimates, it was determined that the total dry mass of roots in the 6.5-year-old sycamore plantation was 13.38 Mg ha^{-1} (Table 4-9). The total root C content was 6.36 Mg ha^{-1} and the N content was 112 kg ha^{-1}. Assuming a linear rate of growth, the total dry root mass was estimated to have been 8.23 Mg ha^{-1} at age 4 and 10.29 Mg ha^{-1} at age 5. Estimated root C content was 3.91 Mg ha^{-1} for the age 4 plantation and 4.89

Table 4-8. Properties of sycamore root systems sampled by excavation. Samples were collected in April of the seventh year after out-planting.

Root diameter	Individual root systems					Estimated dry mass†	Estimated C content†	Estimated N content†
	Mean dry mass	Fraction of total	C concentration	N concentration	C:N ratio			
mm	kg	%	------------ g kg⁻¹ ------------			------------------ kg ha⁻¹ ------------------		
< 10	0.57	10.7	483.0	13.0	37.2	1228	593	16
10-30	1.58	29.8	478.7	8.9	53.8	3405	1630	30
> 30	3.20	59.5	471.6	6.9	68.3	6896	3252	48
All	5.35		474.9	8.2	60.8	11529	5475	94

† Estimates assume 97% survival rate.

Table 4-9. Mean values and estimates for sycamore root systems derived from samples collected in April of the seventh year after out-planting.

Parameter	Value
Total soil volume per tree to a depth of 120 cm, m^3	5.40
Estimated mean soil volume per tree sampled by root excavation, m^3	0.43
Soil volume per tree not sampled by root excavation, m^3	4.97
Mean dry mass of roots per tree in excavated fraction, kg	5.35
Estimated mean dry mass of roots per tree in non-excavated soil fraction (from core samples), kg	0.86
Estimated total dry root mass per tree (excavated + core), kg	6.21
Estimated total dry root mass (excavated + core), Mg ha^{-1}†	13.38
Estimated total root C (excavated + core), Mg ha^{-1}†	6.36
Estimated total root N (excavated + core), kg ha^{-1}†	112
Estimated total root C:N ratio (excavated + core)	56.8:1
Estimated total dry root mass at age 4, Mg ha^{-1}†‡	8.23
Estimated total dry root mass at age 5, Mg ha^{-1}†‡	10.29
Estimated total root C at age 4, Mg ha^{-1}†‡	3.91
Estimated total root C at age 5, Mg ha^{-1}†‡	4.89
Estimated total root N at age 4, kg ha^{-1}†‡	69
Estimated total root N at age 5, kg ha^{-1}†‡	86

† Assumes 97% survival rate.

‡ Assumes a linear growth rate.

Mg ha^{-1} for the age 5 plantation. Root N content was estimated to have been 69 kg ha^{-1} in the age 4 plantation and 86 kg ha^{-1} in the age 5 plantation.

Sycamore Stumps

Wood density, N concentration, C:N ratio, and absolute N content of the 88-week-old stumps were not significantly affected by N fertilization rate (Table 4-10).

Corn Plant and Grain Harvest Analyses

Estimates of total dry mass of corn plants did not differ by cropping system at each N rate, but large differences in dry mass among years were apparent (Table 4-11). Nitrogen concentration of whole corn plants was higher for SBC plants than for SY4C plants at all N fertilization rates except 219 kg N ha^{-1} in 1999 (Table 4-12). In 2000 and 2001 there were no significant differences in whole plant N concentration among cropping systems.

The estimated C in corn plants was significantly lower in the SY5C system in 2000 at 146 kg N ha^{-1} and in 2001 at 73 kg N ha^{-1} (Table 4-13). Estimated corn plant N was significantly lower in the SY5C system in 2000 at 146 kg N ha^{-1} and in 2001 at 73 and 219 kg N ha^{-1}. The estimated amount of C removed in grain harvest in 2000 was significantly less in the SY5C system than in the SBC system at 73 and 219 kg N ha^{-1} and in 2001 at 0 and 146 kg N ha^{-1} (Table 4-14). Estimated corn grain N removal was significantly lower in the SY5C system in 2000 at 73 kg N ha^{-1} and 219 kg N ha^{-1} and in 2001 at 146 kg N ha^{-1}.

Table 4-10. Properties of 88-week-old sycamore stumps in the SY4C cropping system. Absolute C and N content is content of each element expressed on a volumetric basis.

Property	Fertilization rate (kg N ha^{-1})				Average
	0	73	146	219	
Wood density, g cm^{-3}	0.33a†	0.30a	0.33a	0.34a	0.32
C concentration, g kg^{-1}	452.9a	463.5a	462.5a	450.0a	457.2
N concentration, g kg^{-1}	6.6a	7.3a	7.6a	7.6a	7.3
C:N ratio	70.6:1a	64.8:1a	61.5:1a	60.5:1a	64.3:1
Absolute C content, g m^{-3}	$1.5 * 10^5$a	$1.4 * 10^5$a	$1.5 * 10^5$a	$1.5 * 10^5$a	$1.5 * 10^5$
Absolute N content, g m^{-3}	$2.2 * 10^3$a	$2.2 * 10^3$a	$2.5 * 10^3$a	$2.6 * 10^3$a	$2.4 * 10^3$

† Within each row values followed by the same letter are not significantly different ($P > 0.05$).

Table 4-11. Estimated dry biomass of whole corn plants. Samples were collected on June 6, 1999, September 15, 2000, and August 29, 2001.

Cropping system	Fertilization rate (kg N ha-1)			
	0	73	146	219
	---------------------- Mg ha^{-1} ----------------------			
1999				
SBC	3.30a†	3.67a	4.51a	4.56a
SY4C	3.97a	4.06a	4.84a	4.77a
2000				
SBC	5.05a	11.27a	12.34a	11.44a
SY4C	4.67a	10.84a	8.92a	8.66a
SY5C	4.10a	7.78a	7.16a	9.14a
2001				
SBC	9.96a	15.29a	17.44a	17.78a
SY4C	9.36a	18.89a	18.05a	19.44a
SY5C	6.03a	12.64a	17.17a	17.01a

† Values within the same year and column followed by the same letter do not differ ($P > 0.05$).

**Table 4-12. Nitrogen concentration of whole corn plants.
Samples were collected on June 6, 1999, September 15, 2000,
and August 29, 2001.**

Cropping system	Fertilization rate (kg N ha^{-1})			
	0	73	146	219
	----------------------- g N kg^{-1} -----------------------			
_1999_				
SBC	1.5b†	2.3b	2.4b	2.5a
SY4C	1.1a	1.5a	2.1a	2.3a
_2000_				
SBC	0.8a	0.9a	1.1a	1.1a
SY4C	1.0a	0.9a	1.3a	1.2a
SY5C	0.9a	1.0a	1.2a	1.3a
_2001_				
SBC	0.5a	0.8a	0.9a	1.0a
SY4C	0.5a	0.7a	0.8a	1.1a
SY5C	0.5a	0.8a	0.9a	0.9a

† Values within the same year and column followed by the same
letter do not differ ($P > 0.05$).

Table 4-13. Estimated C and N contents of whole corn plants. Samples were collected on June 6, 1999, September 15, 2000, and August 29, 2001.

Cropping system	Fertilization rate (kg N ha^{-1})				Fertilization rate (kg N ha^{-1})			
	0	73	146	219	0	73	146	219
	----------------------- Mg C ha^{-1} ------------------------				----------------------- kg N ha^{-1} -----------------------			
1999								
SBC	1.45a†	1.64a	2.00a	2.02a	49a	84a	108a	114a
SY4C	1.71a	1.81a	2.17a	2.08a	43a	60a	101a	107a
2000								
SBC	2.37a	5.35a	5.63b	5.39a	41a	106a	136b	129a
SY4C	2.15a	5.00a	4.20ab	4.05a	44a	102a	110ab	99a
SY5C	1.89a	3.65a	3.39a	4.26a	37a	78a	80a	124a
2001								
SBC	4.34a	6.79ab	7.74a	8.34a	54a	121ab	159a	191b
SY4C	4.11a	8.38b	8.02a	8.61a	49a	139b	147a	210b
SY5C	2.64a	5.59a	7.66a	7.54a	32a	93a	147a	149a

† Values within the same year and column followed by the same letter do not differ ($P > 0.05$).

Table 4-14. Estimated C and N removed in grain harvests of 1999, 2000, and 2001.

Cropping system	Fertilization rate (kg N ha⁻¹)				Fertilization rate (kg N ha⁻¹)			
	0	73	146	219	0	73	146	219
	------------------------ Mg C ha⁻¹ ------------------------				------------------------ kg N ha⁻¹ ------------------------			
1999								
SBC	0.84a†	1.72a	2.42a	2.34a	25a	49a	68a	68a
SY4C	0.72a	1.14a	1.86a	2.27a	21a	32a	56a	69a
2000								
SBC	0.50a	0.96b	1.22b	1.09b	15a	28b	39b	35b
SY4C	0.53a	0.68ab	0.89a	1.00ab	16a	20ab	29a	34b
SY5C	0.28a	0.43a	0.70a	0.76a	9a	13a	23a	24a
2001								
SBC	1.12ab	2.34a	2.87ab	2.84a	32a	73a	99ab	95ab
SY4C	1.52b	2.23a	3.18b	2.65a	42a	63a	102b	90a
SY5C	0.75a	2.12a	2.43a	3.34a	23a	62a	78a	113b

† Values within the same year and column followed by the same letter do not differ ($P > 0.05$).

Discussion

<u>Harvested Sycamore</u>

Using the measured variables it was possible to accurately model ($R^2 > 0.99$) total dry mass of individual trees for subsequent estimation of dry biomass production per hectare. While most of the measured variables of the harvested sycamore were correlated, the variables with the greatest practical importance, total dry mass and DBH, were highly correlated in both the SY4C and SY5C systems. Total dry mass has practical importance because it is the standard measure of biomass production. Diameter at breast height is important because it can be measured rapidly in the field. Based on the observed correlations between these two variables, future measurements and growth estimations for sycamore biomass plantations may be expedited by intensive measurement of a sample of trees as small as 2.5% of the total population (e.g. 16 of 640 trees). The relationship between DBH and total dry mass then may be used develop an equation for prediction of individual tree dry mass based upon DBH measurements.

The higher correlation coefficients among some variables in the SY4C system than in the SY5C system (e.g. limb mass and height) may have been due in part to larger sample sizes for the SY4C system. The weaker correlations at plantation age five also may have been due to an increase in heterogeneity of tree form with increased age. The best-fitted model for dry limb mass estimation for SY5C trees had a lower R^2 value (0.8551) than the SY4C dry limb mass model (0.9566). This may be an indication of increased variability among trees as different crown classes began to develop as a result of competition among trees for direct sunlight.

Witter et al. (1980) reported a decrease in the amount of biomass allocated to sycamore limbs relative to that of stems between plantation ages four and five. This was observed in the present study as estimated dry limb mass decreased from 5.0 Mg ha^{-1} to 3.6 Mg ha^{-1} in the SY4C and SY5C systems, respectively. Physiological changes in the trees were likely responsible for this phenomenon. Canopy closure in the sycamore plantation resulted in less sunlight reaching the lower limbs of the trees. These limbs were dropped as the trees relied on leaves in the upper portions of their crowns for photosynthesis.

Witter et al. (1980) found that the aboveground N content (excluding foliage) of five-year-old sycamore plantations ranged from 27.5 to 130.4 kg N ha^{-1} depending on site and fertilization. Fertilized sycamore plantations on a terrace site contained an average of 127 kg N ha^{-1}. Blackmon (1979) estimated an average N removal of 145 kg ha^{-1} during the dormant season (without foliage) for a four-year-old unfertilized sycamore plantation that yielded 28.8 Mg ha^{-1} dry biomass. Van Miegroet (1994) reported N removals (excluding foliage) of 112-197 kg N ha^{-1} for a four-year old sycamore plantation, but Wood et al. (1977) found that the woody portion of a three-year-old fertilized bottomland sycamore plantation contained only 25.5 to 60.8 kg N ha^{-1} depending on tree spacing. In the present study, estimated N removal was 77 kg N ha^{-1} for a five-year-old plantation. While the variability in N removal estimates among the aforementioned studies can often be explained by differences in dry biomass yield, estimates are heavily dependent upon the accuracy of N tissue analyses. Because stem bark of young sycamore has a much higher N concentration than stem wood (Wood et al., 1977), it must be proportionally

analyzed and estimated. Branches also have a higher N concentration than stems (Wood et al., 1977), and thus must be weighed and analyzed separately.

Generalized estimates of C storage, or sequestration, can be made from the sycamore measurements. Assuming a constant rate of growth through plantation age five, the 13.1 Mg C ha^{-1} in the SY5C sycamore plantation represents a mean storage of approximately 2.6 Mg C ha^{-1} yr^{-1} in the aboveground woody portion of the sycamore during the rotation. If the sycamore trees were subsequently burned for power production, the period of time after harvest and before combustion constitutes an additional period of C sequestration. The harvested portion of the sycamore is only one component of the total C storage resulting from the plantation. Inclusion of estimates of aboveground litter C and soil C increases due to the sycamore raises the total estimated C storage resulting from the plantation.

Trees grown as energy feedstock, such as the ones in this study, are most often combusted within a year of harvest. Thus the amount of time that the aboveground C is fixed, from photosynthesis to mineralization, is relatively brief for SRWCs. Their potential as a C sink lies in their rapid growth rates, their potential for large-scale production, and the residual C in plantation soils and tree litter. Thus, SRWCs can sequester C by two mechanisms: *i*) storing large quantities of "short-lived" C in plantations, and *ii*) increasing the amount of "long-lived" C in plantation soils. Although most of the short-lived C in SRWCs (e.g. wood and leaf litter) is mineralized in less than 10 years, the plantation ecosystems maintain an increased level of C, relative to many alternative land uses, constituting sequestration of C.

Of the various C forms in a SRWC plantation, the only long-lived form of C is in soil recalcitrant C. Although only a small fraction of the C fixed by a SRWC reaches the recalcitrant C pool, this C may remain fixed in soils for centuries to millennia. Soil recalcitrant C is bound in humus which is a variety of complex organic molecules that are resistant to microbial decomposition. Humus may be the end product of microbially-decomposed plant residues or resistant tissues synthesized by the decomposers themselves (Brady, 1974).

Root Systems of Living Sycamore

The strong correlation (r = 0.8908) between DBH^2 and excavated dry root mass indicates that accurate belowground biomass estimations may be made for young sycamore based on DBH. Heilman et al. (1994) created equations to predict the mass of stumps and attached coarse roots of four-year-old poplar hybrids. Diameter at breast height predicted root mass of various poplar clones with R^2 values ranging from 0.887 to 0.988. Thies and Cunningham (1996) developed equations for prediction of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] root biomass from diameter at stump height and DBH measurements. Their intensive study involved extraction of 84 trees with belowground woody biomass of up to 614.4 kg per tree. The resultant equations predicted root biomass from DBH with an average R^2 value of 0.86.

Although estimates of root system mass exist for short-rotation sycamore (Steinbeck and Nwoboshi, 1980), little is know about the rate of root growth. In this study, estimates of root biomass at plantation ages 4 and 5 assumed a linear rate of growth between plantation age 0 and plantation age 6.5. Heilman et al. (1994) found the

root:shoot ratios for four-year-old *Populus* clones ranged from 0.22:1 to 0.33:1. The root:shoot ratio of the sycamore plantation in the present study was estimated to have been 0.41:1 at plantation age 4 and 0.38:1 at plantation age 5. These estimates suggest that young sycamore trees allocate a greater portion of biomass to roots than do poplars. If this is the case, it may partially explain why poplars produce greater aboveground biomass than sycamore in their first years of growth.

Heilman and Norby (1998) speculated that although the root systems and stumps of a harvested SRWC appear to represent a substantial amount of organic matter, this amount is likely no greater than that produced by a grassland during the same period. While this may be accurate in some instances, the composition and microbial accessibility of the organic matter in a SRWC root system is significantly different from that found in a grassland root system.

Friend et al. (1991) reported that roots of 2-year-old poplars extended more than 400 cm from the stem and reached depths of 150 cm. Roots of plantation-grown eastern cottonwood (*Populus deltoides* Bartr.) have been reported to extend over 360 cm from the stem (Tolbert et al., 2000). The relatively small root spread observed in the present study may be primarily due to root breakage, especially of small roots, as the root systems were pulled from the ground. At the time of sampling, the objective was to extract the majority of the root mass, not the majority of the root length. Differences in root spread between the sycamore of this study and the *Populus* studies may also be genetic.

The finding of significant correlations between DBH and root area and volume may be used in the future to better understand competition among plantation trees for

belowground resources. Such competition may be especially important for sites where moisture or nutrients are particularly limited (Brisson and Reynolds, 1994). Mou et al. (1995) found that while the larger roots in plantation sweetgum seldom overlapped, small roots often did. Friend et al. (1991) found significant overlap for trees planted at a close (1m x 1m) spacing.

The lack of correlation between aboveground parameters (i.e. DBH and GLD) and fine root mass (as measured from soil cores) was not surprising. Much variation has been reported in the ratio of aboveground mass to fine root mass for poplars (Heilman et al., 1994). Mou et al. (1995) reported that the distribution of fine roots in monospecific plantations was unrelated to aboveground biomass; abundance and distribution of fine roots was instead related primarily to soil nutrient availability. The vertical trends in fine root distribution observed in this study do not differ from those of other studies (Gale and Grigal, 1987; Janssens et al., 2001; Heilman et al., 1994). The greater mass of fine roots closer to the surface likely corresponded to greater nutrient availability in this zone (Mou et al., 1995). The C in woody roots at lower depths (e.g. 60-120 cm) is important due to the typical decrease in soil biological activity with greater soil depth (Blume et al., 2002). If there are fewer heterotrophs at lower soil depths, C mineralization rates may be much less and the potential for soil sequestration of C may be greater.

Average estimated root biomass (6.21 kg tree^{-1}) was less than that of loblolly pine (*Pinus taeda* L.) (8.2 kg tree^{-1}) in a six-year-old plantation (Kormanik et al., 1998). Root biomass per hectare in the present study (13.4 Mg ha^{-1}) was approximately twice that of a two-year-old poplar plantation (6.3 Mg ha^{-1}) at a 1- x 1-m spacing (Friend et al., 1991), but was much less than that of a 7-year-old sycamore plantation (25.2 Mg) (Steinbeck

and Nwoboshi, 1980). Heilman et al. (1994) reported belowground biomass estimates of 19.2 to 37.8 Mg ha^{-1} for four-year-old poplar clones. From the studies to date, site quality and sampling methodology appear to be important factors in production and estimation of root mass, respectively.

Sycamore Stumps

Nitrogen fertilization rate did not significantly affect the decomposition of sycamore root systems (Chapter 2) or the aboveground portion of stumps (Chapters 3 and 4). While the lack of effect may have been due to insufficient N fertilizer in close proximity to the woody materials, a significant fraction of the fertilizer N was taken up by the corn plants during the growing season. This resulted in less inorganic soil N available to decomposers. Furthermore, fungi have shown a preference for complex forms of N, such as those in proteins, over mineral N (Boyle, 1998). The C:N ratio of the 88-week-old stumps (64.3:1) was lower than that of 84-week-old woody root systems (85.3:1; Chapter 2). This may be a result of the exposed surface area of the stump that facilitated entry of moisture and microorganisms. Much of the root system mass was in large-diameter woody roots that were likely less accessible to decomposers.

Corn Plant and Grain Harvest Analyses

The large differences in corn plant dry mass among years were probably due to an early sampling date in 1999 and an abnormally dry growing season in 2000. Of the three years in which plants were sampled, the mass of plants in 2001 was the most typical for the site. Corn plant N concentration was substantially higher in 1999 than in 2000 and

2001 because samples were collected when the corn was still in its vegetative growth stage. Much of this N would be later translocated to the grain during reproductive growth (Hanaway, 1963). Although whole corn plant N concentration is not used to gauge N sufficiency, the significant differences between cropping systems in June 1999 may represent less plant-available N in the SY4C system. Similar differences were observed in ear leaf N concentration in samples collected three weeks later (Chapter 3).

The estimated C and N contents ha^{-1} of corn plants are important because they represent the C and N that is returned to the soil annually as crop residue. Since corn plant C concentration is virtually constant regardless of management practice, any factor that increases plant growth leads to an increase in crop residues and a potential increase in soil C over time. Greater residue also represents an increased mulch layer in the no-till system. The lower estimated plant C in the SY5C system in 2000 and 2001 was accompanied by a lower grain yield (Chapter 2). Thus, the same fertility factors that increase yields (in this case probably N availability) simultaneously increase residue C.

The organic N contained in residues is eventually mineralized and made available for plant uptake after it is consumed and released by the soil biota. The decreases in residue N content under the SY5C cropping system in 2000 and 2001 represent a lower soil organic N input. However, the high C:N ratio of corn plant residues means that mineralization of this organic N will likely be slow and will follow a period of N immobilization. Because there were no differences in crop residue N content between third-year corn after sycamore (SY4C) and the continuously row-cropped system (SBC) in 2001, the reduction in corn residue N content due to the sycamore crop lasted no longer than two years after sycamore harvest.

The corn grain C and N harvest removals represent losses of these elements from the system. While the grain C is short-lived and thus of little importance, the grain N removal must be considered in conjunction with annual N inputs to the system. In this study fertilization was the only documented N input, but mineralization of organic N, N fixation by non-symbiotic N-fixing bacteria, and atmospheric deposition certainly occurred to some degree. The differences in grain N removal among cropping systems are a result of differences in plant-available N, and thus grain yield, in the systems. The observed differences in N removal were small enough, relative to N inputs such as fertilizer, that they will likely be of little importance in long-term site fertility.

Conclusions

Due to uniformity among the plantation sycamore, it was possible to create equations for prediction of individual tree dry mass based on a small sample of trees. Tree form changed between plantation ages four and five as lower, shaded limbs were dropped following canopy closure. The amount of N removed in the harvest of five-year-old sycamore was probably not enough to significantly affect soil fertility.

Belowground biomass of the short-rotation sycamore plantation was substantial. Mass of woody root systems of individual trees could be estimated by DBH, but fine root mass was not related to DBH or proximity to tree. Decomposition rate of sycamore stumps was not affected by the rate of N fertilizer applied to them.

When corn was grown after sycamore, amounts of C and N in crop resides were slightly reduced, likely due to less plant-available N in the post-sycamore soils. This reduction in crop residue was detected only during the first two years immediately

following sycamore harvest. Increases in N fertilization rate during these two years,

intended to counteract reductions in N uptake and grain yield of corn plants, would likely

eliminate this decrease in residue production.

CHAPTER 5

Summary and Conclusions

Prior research has shown improvements in soil chemical and physical properties after establishment of SRWCs on formerly agricultural sites. However, it was not known whether these soil improvements would endure after a site was converted from SRWC production back to row crop production. Also, the effect of a woody crop rotation on subsequent row crop yields was unknown. This study was conducted to determine the residual effects of one woody crop rotation on soils and subsequent row crop production on a historically agricultural site.

Results showed that four- and five-year sycamore rotations significantly affected chemical and physical properties of a loessal soil in southwestern TN. From 0.5 to 2.5 years after the site was converted from SRWC to row crop production, significant increases in soil C, due to the SRWC, were detected. The majority of these increases were at soil depth intervals from 2.5 to 30 cm and appeared to be from tree roots rather than from surface litter. A leaf litter layer did not begin to accumulate in the sycamore plantation until the end of the third year after planting. After harvest, there was no residual litter layer. Sycamore leaves appeared to be more resistant to decomposition than leaves of other SRWCs such as hybrid poplars. The observed soil C increases in this study were similar in magnitude to those of other studies conducted in the southern USA. There were no detectable trends in the spatial distribution of soil C or N 1.5 or 2.5 years after sycamore were harvested. This spatial uniformity indicates that the effects of the woody crop rotation on the top 30 cm of soil were evenly distributed on the site.

Mean weight diameter of water-stable soil aggregates at depth intervals from 2.5 to 15 cm was greater six months after the harvest of a sycamore plantation than under a continuously row-cropped system. Other studies have indicated that additions of high-C woody residues to soil cause increases in fungal populations and soil aggregate stability. Prior to the present study, research on the Ames Plantation indicated that, while sycamore plantations did not improve soil structure after three years of growth, twelve-year-old sycamore plantations had significantly reduced soil bulk density and improved hydrologic properties. The present study showed that soil aggregation improvements were present after four years of sycamore plantation growth.

Soil plant-available, inorganic N concentrations were higher in the SBC system than in the SY4C system at a depth of 0 to 2.5 cm at 2 of 4 sampling dates. However, there were few overall differences in soil inorganic N among the three cropping systems. This may have been due to rapid uptake of soil inorganic N by corn plants after fertilization. Additionally, sampling intensity and precision during the growing season may not have been sufficient to detect differences in soil inorganic N among cropping systems.

The sycamore biomass crop yielded 19.9 and 26.9 Mg ha^{-1} dry aboveground biomass for four- and five-year rotations, respectively. Yields were similar to or greater than those of other short-rotation sycamore studies but were inferior to those reported in studies of poplar and willow. Changes in tree form were observed between plantation ages four and five as lower, shaded limbs were dropped following canopy closure. As these dead limbs accumulated on the ground they began to trap leaf litter and hold it on the site. Previously, wind had carried leaves away during winter, a phenomenon

attributed to the relatively small size of the sycamore plantation in this study. The aboveground woody biomass of a five-year sycamore rotation contained an estimated 77 kg N ha^{-1}, less than that of a typical corn grain harvest. Belowground sycamore dry biomass was estimated to be 8.2 and 10.3 Mg ha^{-1} for the four- and five-year-old plantations, respectively. Mass of individual root systems was significantly related to tree DBH, facilitating future estimates of belowground tree biomass.

Significant changes occurred in sycamore stumps during the two years following tree harvest. Stump wood density decreased significantly between 52 and 104 weeks after harvest. Stump N content per unit volume increased significantly during the first 52 weeks after harvest, suggesting that substantial microbial colonization occurred during this period. Stump C content per unit volume declined significantly between 52 and 104 weeks after harvest, indicating that this was a period of rapid C mineralization by microbes. Sycamore stump decomposition was not affected by rate of N fertilization. This may have been due to the relatively small amount of fertilizer in close proximity to the stumps and the short period of time before this fertilizer was taken up by corn plants. Root system decomposition was considerably more advanced 136 weeks post-harvest than 84 weeks post-harvest. This was evidenced by a higher N concentration and lower C:N ratio in the 136-week-old roots, suggesting N immobilization and C mineralization.

This study revealed no obstacles that would prevent production of corn on a site that had been a short-rotation sycamore plantation the previous year. Although corn grain yields differed greatly among years due to differences in growing season rainfall, statistically significant yield response functions to N fertilization rate existed for all cropping systems in all years. First- and second-year corn following sycamore had a

linear yield response function to N fertilizer rate, with grain yield maximized at 219 kg N ha^{-1}. Corn grown for three consecutive years after soybean and third-year corn after sycamore both reached maximum yields at 146 kg N ha^{-1}; yields did not increase at 219 kg N ha^{-1}. These trends indicated that there was less plant-available soil N present for the two years immediately following sycamore harvest. This may have been due to a loss of soil inorganic N to microbial immobilization during decomposition of woody residues. Most of the N immobilization in stumps and large roots was observed in the first two years after sycamore harvest, and it is likely that immobilization had peaked by the third year after harvest. This would explain the return to a typical N fertilization grain yield response function in the third year of corn after sycamore harvest.

In 1999, the first year of corn after sycamore, corn plants in the SY4C system had significantly lower ear leaf N concentrations than those of the SBC system at all N fertilization rates except 219 kg ha^{-1}. Differences among cropping systems in grain yields and ear leaf N concentrations indicate that N fertilizer requirement during the first two years of corn following sycamore was increased.

Based on corn grain yield data, increasing the rate of N fertilization to 150% of the standard rate for the system may be necessary to maximize yields for the first two years of corn grown immediately following sycamore harvest. Alternatively, a management practice that could potentially reduce fertilizer N immobilization is a split application of N fertilizer. A split N application may increase the total amount of fertilizer N recovered by corn plants. In addition to increasing grain yields, improved N availability for crops maintains high residue inputs important to the success of the no-till system.

The observed increases in soil C suggest improvements in nutrient- and water-holding capacities after the sycamore rotation. Evidence of these improvements in corn grain production was not observed in this study. However, immobilization of soil inorganic N in decomposing woody residues may have masked the beneficial effect of increased soil C. After the mineralization rate of N surpasses that of immobilization, perhaps in the fourth or fifth year after sycamore harvest, there may be a detectable benefit of the sycamore rotation in terms of corn grain yield.

Field observations and the results of other research indicate that a longer (>5 years) woody crop rotation than the one in this study would likely increase the contribution of aboveground litter to soils. The formation of an organic soil horizon by decomposing surface litter would likely improve soil physical, chemical, and biological properties. Coppicing multiple woody crop rotations, using inter-row cover crops, or planting faster-growing tree species are known to increase the organic inputs to soils during SRWC growth. But greater inputs of high-C:N residues could lead to increased immobilization of plant-available N.

This "agro-woody crop" system may be well-suited to sites that are in particular need of soil organic matter. Eroded or otherwise degraded agricultural land may benefit from the soil organic C and aggregation improvements that follow a woody crop rotation. However, rotations lengths longer than the ones used in this study, or multiple rotations, may often be necessary to achieve such improvements. But by following the woody crop with a no-till system, the soil improvements will not be lost through the destruction of soil aggregates and the oxidation of organic matter that result from tillage.

Due to current energy policy in the USA, the agro-woody crop system examined in this study will probably not soon be adopted for biofuel production. However, this system is equally applicable to SRWC production for fiber. In regions with sufficient demand for wood fiber, this system provides the flexibility to produce either woody crops or row crops on the same site. Although a woody crop rotation can have a short-term negative effect on yields of subsequent row crops, increases in soil C may lead to long-term improvements in soil quality.

List of References

120

Adegbidi, H.G., T.A. Volk, E.H. White, L.P. Abrahamson, R.D. Briggs, and D.H. Bickelhaupt. 2001. Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State. Biomass Bioenergy. 20:399-411.

Aldrich, S.R., W.O. Scott, and R.G. Hoeft. 1986. Modern corn production. A & L Publishers, Champaign, IL.

Anderson, I.C., D.R. Buxton, D.L. Karlen, and C. Cambardella. 1997. Cropping system effects on nitrogen removal, soil nitrogen, aggregate stability, and subsequent corn grain yield. Agron. J. 89:881-886.

Arunachalam, A., H.N. Pandey, R.S. Tripathi, and K. Maithani. 1996. Fine root decomposition and nutrient mineralization patterns in a subtropical humid forest following tree cutting. For. Ecol. Management. 86:141-150.

Bandaranayake, W.M., D.D. Tyler, A.E. Houston, M. Shiers, B.C. Bock, J.D. Joslin, F.C. Thornton, and M.D. Mullen. 1996. Vegetative cover effects on infiltration and other soil physical parameters in a no-till loess soil. p. 785-792. in Bioenergy '96: Proc. National Bioenergy Conference, 7th. 15-20 Sept. 1996. Nashville, TN.

Batjes, N.H. 1998. Mitigation of atmospheric CO_2 concentrations by increased carbon sequestration in the soil. Biol. Fertil. Soils. 27:230-235.

Beare, M.H., S. Hu, D.C. Coleman, and P.F. Hendrix. 1997. Influences of mycelial fungi on soil aggregation and organic matter storage in conventional and no-tillage soils. Appl. Soil Ecol. 5:211-219.

Beauchemin, S., A. N'dayegamiye, and M.R. Laverdiere. 1990. Effects of fresh and humified wood residues on potato yields and N availability in a sandy soil. Can. J. Soil Sci. 70:555-564.

Berg, B., and B. Söderström. 1979. Fungal biomass and nitrogen in decomposing Scots pine needle litter. Soil Biol. Biochem. 11:339-341.

Berg, B., and H. Staaf. 1981. Leaching, accumulation and release of nitrogen in decomposing forest litter. p. 163-178. *In* F.E. Clark and T. Rosswall (ed.) Terrestrial nitrogen cycles: processes, ecosystem strategies, and management impacts. Ecological bulletins, 33. Stockholm.

Bioenergy Feedstock Development Program. 2001. Bioenergy: frequently asked questions [online]. Available at http://bioenergy.ornl.gov/faqs/index.html (verified 10 June 2002).

Blackmon, B.G. 1979. Estimates of nutrient drain by dormant-season harvests of coppice American sycamore. USDA For. Serv Res. Note SO-245. USDA For. Serv., New Orleans.

Blume, E., M. Bischoff, J.M. Reichert, T. Moorman, A. Konopka, and R.F. Turco. 2002. Surface and subsurface microbial biomass, community structure and metabolic activity as a function of soil depth and season. Appl. Soil Ecol. 20: 171-181.

Bossuyt, H., K. Denef, J. Six, S.D. Frey, R. Merckx, and K. Paustian. 2001. Influence of microbial populations and residue quality on aggregate stability. Appl. Soil Ecol. 16:195-208.

Boyle, D. 1998. Nutritional factors limiting the growth of *Lentinula edodes* and other white-rot fungi in wood. Soil Biol. Biochem. 30:817-823.

Brisson, J., and J.F. Reynolds. 1994. The effect of neighbors on root distribution in a creosotebush (*Larra tridentate*) population. Ecol. 75:1693-1702.

Brown, S., J. Mo, J.K. McPherson, and D.T. Bell. 1996. Decomposition of woody debris in Western Australian forests. Canadian J. For. Res. 26(6):954-966.

Cairns, M.A., S. Brown, E.H. Helmer, and G.A. Baumgardner. 1997. Root biomass allocation in the world's upland forests. Oecologia. 111:1-11.

Camiré, C., B. Côté, and S. Brulotte. 1991. Decomposition of roots of black alder and hybrid poplar in short-rotation plantings: nitrogen and lignin control. Plant and Soil. 138:123-132.

Cerrato, M.E., and A.M. Blackmer. 1990. Relationships between grain nitrogen concentrations and the nitrogen status of corn. Agron. J. 82:744-749.

Coleman, S. 1996. Southern perspectives: Boise Cascade's short-rotation woody crop operations. Conf. Short Rotation Woody Crops Operations Working Group, 1st. 23-25 Sept. 1996. Paducah, KY.

Cox, J. 1996. Short rotation woody crops operations in the industrial South. Conf. Short Rotation Woody Crops Operations Working Group, 1st. 23-25 Sept. 1996. Paducah, KY.

Czereyski, K., I. Galinska, and H. Robel. 1965. Rationalization of stump extraction. United Nations Publications, Geneva.

DeBell, D.S., C.A. Harrington, G.W. Clendenen, M.A. Radwan, and J.C. Zasada. 1997. Increasing the productivity of short-rotation *Populus* plantations. Final report. ORNL/M-5943. Oak Ridge National Laboratory, Oak Ridge, TN.

Devine, W.D., D.D. Tyler, M.D. Mullen, A.E. Houston, J.D. Joslin, D.G. Hodges, V.R. Tolbert, and M.E. Walsh. 2002a. Integrating woody biomass crops and row crops in rotation. I: Management implications. *In* Proc. World Congress of Soil Sci., 17th, Bangkok, Thailand. 14-21 Aug. 2002.

Devine, W.D., M.D. Mullen, D.D. Tyler, A.E. Houston, J.D. Joslin, D.G. Hodges, V.R. Tolbert, and M.E. Walsh. 2002b. Integrating woody biomass crops and row crops in rotation. II: Effects on soils. *In* Proc. World Congress of Soil Sci., 17th, Bangkok, Thailand. 14-21 Aug. 2002.

Dickmann, D.I., K. Steinbeck, and T. Skinner. 1985. Leaf area and biomass in mixed and pure plantations of sycamore and black locust in the Georgia Piedmont. Forest Sci. 31:509-517.

Dickson, E.L., V. Rasiah, and P.H. Groenevelt. 1991. Comparison of four prewetting techniques in wet aggregate stability determination. Can. J. Soil Sci. 71:67-72.

Dickson, R.R., and D.K. Springer. 1964. Climate. p. 65-68. *In* Soil survey – Fayette County Tennessee. USDA Ser. 1960, no. 13. Gov. Print. Office, Washington, D.C.

Dyer, B. 1902. Results of investigations on the Rothamsted soils. USDA Bull. 106. Gov. Print. Office, Washington, D.C.

Edwards, N.T., and W.F. Harris. 1977. Carbon cycling in a mixed deciduous forest floor. Ecol. 58:431-437.

Ehrenfeld, J.G., W.F.J. Parsons, X. Han, R.W. Parmelee, and W. Zhu. 1997. Live and dead tree roots in forest soil horizons: contrasting effects on nitrogen dynamics. Ecology. 78:348-362.

Ellsworth, T.R., C.E. Clapp, and G.R. Blake. 1991. Temporal variations in soil structural properties under corn and soybean cropping. Soil Sci. 151:405-416.

Ezell, A.W., W.J. Lowe, W.K. Murphey, and J.A. Wright. 1983. Plantation culture for energy production- the importance of within-species selection. Wood Fiber Sci. 15(1):69-73.

Fahey, T.J., and M.A. Arthur. 1994. Further studies of root decomposition following harvest of a northern hardwoods forest. For. Sci. 40(4):618-629.

Fahey, T.J., J.W. Hughes, M. Pu, and M.A. Arthur. 1988. Root decomposition and nutrient flux following whole-tree harvest of northern hardwood forest. For. Sci. 34:744-768.

Falloon, P.D., and P. Smith. 2000. Modeling refractory soil organic matter. Biol. Fertil. Soils. 30:388-398.

Francis, J.K. 1984. Biomass accumulation by single- and multiple-stemmed young sycamore. For. Sci. 30:372-374.

Frey, S.D., E.T. Elliot, K. Paustian, and G.A. Peterson. 2000. Fungal translocation as a mechanism for soil nitrogen inputs to surface residue decomposition in a no-tillage agroecosystem. Soil Biol. Biochem. 32:689-698.

Fribourg, H.A., G.R. Wells, H. Calonne, E. Dujardin, D.D. Tyler, J.T. Ammons, R.M. Evans, A. Houston, M.C. Smith, M.E. Timpson, and G.G. Percell. 1989. Forage and tree production on marginal soils in Tennessee. J. Prod. Agric. 2:262-268.

Friend, A.L., G. Scarascia-Mugnozza, J.G. Isebrands, and P.E. Heilman. 1991. Quantification of two-year-old hybrid poplar root systems: morphology, biomass, and 14C distribution. Tree Physio. 8:109-119.

Gale, W.J, C.A. Cambardella, and T.B. Bailey. 2000a. Surface residue- and root-derived carbon in stable and unstable aggregates. Soil Sci. Soc. Am. J. 64:196-201.

Gale, W.J, C.A. Cambardella, and T.B. Bailey. 2000b. Root-derived carbon and the formation and stabilization of aggregates. Soil Sci. Soc. Am. J. 64:201-207.

Gale, M.R., and D.F. Grigal. 1987. Vertical root distributions of northern tree species in relation to successional status. Can. J. For. Res. 17:829-834.

Garten, C.T. 2002. Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass Bioenergy. [*In press*].

Grigal, D.F., and W.E. Berguson. 1998. Soil carbon changes associated with short-rotation systems. Biomass Bioenergy. 14:361-370.

Grigg, D.B. 1974. The agricultural systems of the world: an evolutionary approach. Cambridge University Press, London.

Hairston, J.E. 1990. The nitrogen story (from acclamation to condemnation). Environmental Education Series WQ-10-90. Auburn Univ., Auburn, AL.

Halvorson, A.D., C.A. Reule, and R.F. Follett. 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63:912-917.

Hanaway, J.J. 1963. Growth stages of corn (*Zea mays* L.). Agron. J. 55:487-492.

Hansen, E.A. 1993. Soil carbon sequestration beneath hybrid poplar plantations in the north central United States. Biomass Bioenergy. 5:431-436.

Harris, R.F., G. Chesters, and O.N. Allen. 1966. Dynamics of soil aggregation. Adv. Agron. 18:107-169.

Havlin, J.L., D.E. Kissel, L.D. Maddux, M.M. Claassen, and J.H. Long. 1990. Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil. Sci. Soc. Am. J. 54:448-452.

Haynes, R.J. 2000. Interactions between soil organic matter status, cropping history, method of quantification and sample pretreatment and their effects on measured aggregate stability. Biol. Fertil. Soils. 30:270-275.

Heilman, P.E., G. Ekuan, and D. Fogle. 1994. Above- and below-ground biomass and fine roots of 4-year-old hybrids of *Populus trichocarpa* x *Populus deltoides* and parental species in short-rotation culture. Can. J. For. Res. 24:1186-1192.

Heilman, P., and R.J. Norby. 1998. Nutrient cycling and fertility management in temperate short rotation forest systems. Biomass Bioenergy. 14:361-370.

Herrick, A.M., and C.L. Brown. 1967. A new concept in cellulose production: silage sycamore. Agric. Sci. Rev. 5(4):8-13.

Houston, A.E., D.D. Tyler, W. Bandaranayake, F.C. Thornton, B.R. Bock, M.D. Mullen, and J.D. Joslin. 1997. Short rotation woody crop environmental impact study, Ames Plantation. Annual progress report, submitted to Tennessee Valley Authority and Oak Ridge National Laboratory. Ames Plantation, Grand Junction, TN.

Idol, T.W., R.A. Figler, P.E. Pope, and F. Ponder, Jr. 2001. Characterization of coarse woody debris across a 100 year chronosequence of upland oak-hickory forests. For. Ecol. Manag. 149:153-161.

Ince, P.J. 1979. How to estimate recoverable heat energy in wood or bark fuels. USDA For. Serv. For. Prod. Lab. GTR-29. USDA Forest Service, Madison, WI.

Inman, D.J. 2000. Relative efficacies of GPR and EM-31 compared to traditional soil investigation techniques on loess/tertiary deposits in Southwest Tennessee. M.S. Thesis. Univ. of Tennessee, Knoxville.

Intergovernmental Panel on Climate Change. 2001. Summary for policymakers: a report of working group I of the Intergovernmental Panel on Climate Change. Cambridge Univ. Press, Cambridge.

Janssens, I.A., D.A. Sampson, J. Curiel-Yuste, A. Carrara, R. Ceulemans. 2001. The carbon cost of fine root turnover in a Scots pine forest. For. Ecol. Manag. [*In Press*]

Johnson, M.G. 1995. The role of soil management in sequestering soil carbon. p. 351-363. *In* R. Lal et al. (ed.) Soil Management and Greenhouse Effect. Lewis Publishers, Boca Raton.

Joslin, J.D. and G.S. Henderson. 1985. Organic matter and nutrients associated with fine root turnover in a white oak stand. For. Sci. 33: 330-346.

Kaarik, A.A. 1974. Decomposition of wood. p. 129-174. *In* C.H. Dickinson and G.J.F. Pugh (ed.) Biology of plant litter decomposition. Academic Press, London.

Kaur, B., S.R. Gupta, and G. Singh. 2000. Soil carbon, microbial activity and nitrogen availability in agroforestry systems on moderately alkaline soils in northern India. Appl. Soil Ecol. 15:283-294.

Keenan, R.J., C.E. Prescott, and J.P. Kimmins. 1993. Mass and nutrient content of woody debris and forest floor in western red cedar and western hemlock forests on northern Vancouver Island. Can. J. For. Res. 23:1052-1059.

Kemper, W.D., and W.S. Chepil. 1965. Size distribution of aggregates. p. 499-510. *In* C.A. Black (ed.) Methods of Soil Analysis. Part 1. Agron. Monogr. ASA, Madison, WI.

Kemper, W.D., and R.C. Rosenau. 1986. Aggregate stability and size distribution. p. 425-442. *In* A. Klute (ed.) Methods of Soil Analysis, Part 1. 2nd ed. Agron. Monogr. no. 9. ASA, Madison, WI.

Kimmins, J.P. 1987. Forest ecology. Macmillan Publishing Company, New York.

Kirchner, M.J. 1999. The effect of conversion from annual row crops to short-rotation woody crops on soil microbial community structure. Ph.D. diss. Univ. of Tennessee, Knoxville.

Kopp, R.F., L.P. Abrahamson, E.H. White, K.F. Burns, and C.A. Nowak. 1997. Cutting cycle and spacing effects on biomass production by a willow clone in New York. Biomass Bioenergy. 12(5): 313-19.

Kormanik, P.P., and S.S. Sung. 1998. Immature loblolly pine growth and biomass accumulation: correlations with seedlings initial first-order lateral roots. South. J. Appl. For. 22:117-123.

126

Kort, J., M. Collins, and D. Ditsch. 1998. A review of soil erosion potential associated with biomass crops. Biomass Bioenergy. 14:351-359.

Krinitzsky, E.L., and W.J. Turnbull. 1967. Loess deposits of Mississippi. Geol. Soc. Am. Special Paper no. 94.

Kroth, E.M., and J.B. Page. 1946. Aggregate formation in soils with special reference to cementing substances. Soil Sci. Soc. Proc. 11:27-36.

Kuhnelt, W. 1976. Soil biology, with special reference to the animal kingdom. 2nd ed. Faber and Faber, London.

Lal, R., J. Kimble, E. Levine, and C. Whitman. 1995. World soils and greenhouse effect: an overview. p. 1-8. *In* R. Lal et al. (ed.) Soils and global change. Lewis Publishers, Boca Raton.

Lalande, R., V. Furlan, D.A. Angers, and G. Lemieux. 1998. Soil improvement following addition of chipped wood from twigs. Am. J. Alternative Agric. 13:132-137.

Mann, L. and V.R. Tolbert. 2000. Soil sustainability in renewable biomass plantings. Ambio. 29(8):492-498.

Matejovic, I. 1997. Determination of carbon and nitrogen in samples of various soils by the dry combustion. Commun. Soil Sci. Plant Anal. 28:1499-1511.

Matejovic, I. 1995. Total nitrogen in plant material determinated by means of dry combustion: a possible alternative to determination by Kjeldahl digestion. Commun. Soil Sci. Plant Anal. 26:2217-2229.

McAlpine, R.G., C.L. Brown, A.M. Herrick, and H.E. Ruark. 1966. "Silage" sycamore. For. Farmer. 26:6-7.

McClaugherty, C.A., J.D. Aber, and J.M. Melillo. 1982. The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems. 63(5):1481-1490.

Mehdi, B., C. Zan, P. Girouard, and R. Samson. 1999. Soil organic carbon sequestration under two dedicated perennial bioenergy crops. p. 17-23. *In* R.P. Overend and E. Chornet (ed.) Biomass, a growth opportunity in green energy and value added products. Proc Biomass Conf. Am., 4th, Oakland, CA. 29 Aug. - 2 Sept. 1999. Elsevier Science, Oxford.

Metting, F.B., J.L. Smith, and J.S. Amthor. 1999. Science needs and new technology for soil carbon sequestration. p. 1-39. *In* N.J. Rosenberg et al. (ed.) Carbon

sequestration in soils: science, monitoring, and beyond. Battelle Press, Columbus, OH.

Miller, F.P., W.D. Rasmussen, and L.D. Meyer. 1985. Historical perspective of soil erosion in the United States. p. 23-48. In R.F. Follett and B.A. Stewart (ed.) Soil erosion and crop productivity. ASA, CSSA, and SSSA, Madison, WI.

Miller, R.A. 1974. The geologic history of Tennessee. TN Dept. of Conservation, Div. of Geology. Bulletin 74. Nashville, TN.

Mitchell, B.L. 1997. Hydrologic impacts of converting cotton to short-rotation cottonwood in the Mississippi Delta. M.S. thesis. Mississippi State Univ., Mississippi State, MS.

Monroe, C.D., and E.J. Kladivko. 1987. Aggregate stability of a silt loam soil as affected by roots of corn, soybeans and wheat. Commun. Soil Sci. Plant Anal. 18:1077-1087.

Mou, P., R.H. Jones, R.J. Mitchell, and B. Zutter. 1995. Spatial distribution of roots in sweetgum and loblolly pine monocultures and relations with above-ground biomass and soil nutrients. Functional Ecol. 9:689-699.

Myrold, D.D. 1998. Transformations of nitrogen. p. 259-294. In D.M. Sylvia et al. (ed.) Principles and Applications of Soil Microbiology. Prentice Hall, Upper Saddle River, NJ.

N'dayegamiye, A., and D.A. Angers. 1993. Organic matter characteristics and water-stable aggregation of a sandy loam soil after 9 years of wood-residue applications. Can. J. Soil Sci. 73:115-122.

N'dayegamiye, A., and A. Dube. 1986. Effects of bark application on yields and on soil chemical characteristics. Can. J. Soil Sci. 66:623-631.

Nadelhoffer, K.J., and J.W. Raich. 1992. Fine root production estimates and belowground carbon allocation in forest ecosystems. Ecol. 73(4)1139-1147.

Nyborg, M., E.D. Solberg, S.S. Malhi, and R.C. Izaurralde. 1995. Fertilizer N, crop residue, and tillage alter soil C and N content in a decade. p. 93-99. In R. Lal et al. (ed.) Soil Management and Greenhouse Effect. CRC Press, Boca Raton.

Perfect, E., B.D. Kay, W.K.P. van Loon, R.W. Sheard, and T. Pojasok. 1990. Factors influencing soil structural stability within a growing season. Soil Sci. Soc. Am. J. 54:173-179.

128

Potter, K.N., O.R. Jones, H.A. Torbert, and P.W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern great plains. Soil Sci. 162(2):140-147.

Raimbault, B.A., and T.J. Vyn. 1991. Crop rotation and tillage effects on corn growth and soil structural stability. Agron. J. 83:979-985.

Read, J.W. 1921. Practical significance of the organic carbon nitrogen ratio in soils. Soil Sci. 12:491-495.

Risasi, E.L., B.T. Kang, and E.E. Opuwaribo. 1998. Assessment of N availability of roots of selected woody species and maize. Biol. Agric. Hort. 16:87-96.

Robinson, C.A., R.M. Cruse, and M. Ghaffarzadeh. 1996. Cropping systems and nitrogen effects on Mollisol organic carbon. Soil Sci. Soc. Am. J. 60:264-269.

Rodbell, D.T., S.L. Forman, J. Pierson, W.C. Lynn. 1997. The stratigraphy and chronology of Mississippi Valley loess in western Tennessee. Geological Soc. Am. Bulletin. 109:1134-1148.

Salinas-Garcia, J.R., F.M. Hons, and J.E. Matocha. 1997. Long-term effects of tillage and fertilization on soil organic matter dynamics. Soil Sci. Soc. Am. J. 61:152-159.

Salter, F.J. 1931. The carbon-nitrogen ratio in relation to the accumulation of organic matter in soils. Soil Sci. 31:413-430.

SAS Institute, Inc. 1997. SAS/STAT Software: changes and enhancements through release 6:12. SAS Institute, Inc., Cary, NC.

Schlesinger, W.H. 1999. Carbon sequestration in soils. Sci. 284:2095.

Schlesinger, W.H. 1995. An overview of the carbon cycle. p. 9-25. *In* R. Lal et al. (ed.) Soils and global change. Lewis Publishers, Boca Raton.

Schomberg, H.H., P.B. Ford, and W.L. Hargrove. 1994. Influence of crop residues on nutrient cycling and soil chemical properties. p. 99-121 *In* P.W. Unger (ed.) Managing agricultural residues. Lewis, Boca Raton, FL.

Sims, G.K., T.R. Ellsworth, and R.L. Mulvaney. 1995. Microscale determination of inorganic nitrogen in water and soil extracts. Commun. Soil Sci. Plant Anal. 26:303-316.

Six J., E.T. Elliott, and K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32:2099-2103.

Smith, D.M. 1986. The practice of silviculture. John Wiley & Sons, New York.

Staaf, H., and B. Berg. 1977. Mobilization of plant nutrients in a Scots pine forest mor in central Sweden. Silva Fennica. 11:210-217.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics: a biometrical approach. 2nd ed. McGraw-Hill, New York.

Steinbeck, K. and L.C. Nwoboshi. 1980. Rootstock mass of coppiced *Platanus occidentalis* as affected by spacing and rotation length. For. Sci. 26:545-547.

Stevenson, F.J., and M.A. Cole. 1999. Cycles of soil: carbon, nitrogen, phosphorus, sulfur, micronutrients, 2nd ed. John Wiley & Sons, Inc., New York.

Stewart, G.H., and L.E. Burrows. 1994. Coarse woody debris in old-growth temperate beech (*Northofagus*) forests of New Zealand. Can. J. For. Res. 24:1989-1996.

Strickling, E. 1950. The effect of soybeans on volume weight and water stability of soil aggregates, soil organic matter content, and crop yield. Soil Sci. Soc. Am. Proc. 15:30-34.

Sundquist, E.T. 1993. The global carbon dioxide budget. Sci. 259:934-941.

Thies, W.G., and P.G. Cunningham. 1996. Estimating large-root biomass from stump and breast-height diameters for Douglas-fir in western Oregon. Can. J. For. Res. 26:237-243.

Thornton, F.C., J.D. Joslin, B.R. Bock, A.E. Houston, T.H. Green, S. Schoenholtz, D. Pettry, and D.D. Tyler. 1998. Environmental effects of growing woody crops on agricultural land: First year effects on erosion and water quality. Biomass Bioenergy. 15: 57-69.

Tillman, D.A. 1978. Wood as an energy resource. Academic Press, New York.

Tisdale, S.L., W.L. Nelson, J.D. Beaton, and J.L. Havlin. 1993. Soil fertility and fertilizers, 5th ed. Macmillan Pub. Co., New York.

Tisdall, J.M., and J.M. Oades. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33:141-163.

Tolbert, V.R., F.C. Thornton, J.D. Joslin, B.R. Bock, W. Bandaranayake, A.E. Houston, D.D. Tyler, D.A. Mays, T.H. Green, and D.E. Pettry. 2000. Increasing below-ground carbon sequestration with conversion of agricultural lands to production of bio-energy crops. New Zealand J. For. Sci. 30(1/2):138-149.

Tolbert, V.R., J.D. Joslin, F.C. Thornton, B.R. Bock, D.E. Pettry, W. Bandaranayake, D. Tyler, A. Houston, and S. Schoenholtz. 1999. Biomass crop production: Benefits for soil quality and carbon sequestration. p. 127-132 *In* R.P. Overend and E. Chornet (ed.) Biomass: A Growth Opportunity in Green Energy and Value-Added Products, Biomass Conf. Am., 4th. 30 Aug.-2 Sept. 1999. Oakland, CA.

Urquiaga, S., G. Cadisch, B.J.R. Alves, R.M. Boddey, and K.E. Giller. 1998. Influence of decomposition of roots of tropical forage species on the availability of soil nitrogen. Soil Biol. Biochem. 30(14):2099-2106.

Vogt, K.A., D.J. Vogt, and J. Bloomfield. 1991. Input of organic matter to the soil by tree roots. p. 171-190. *In* B.L. McMichael and H. Persson (ed.) Plant roots and their environment. Proc. of an ISRR-symposium, Uppsala, Sweden. 21-26 Aug. 1988. Elsevier, Amsterdam.

Van Miegroet, H., R.J. Norby, and T.J. Tschaplinski. 1994. Nitrogen fertilization strategies in a short-rotation sycamore plantation. For. Ecol. Manage. 64:13-24.

Van Veen, J.A., and P.J. Kuikman. 1990. Soil structural aspects of decomposition of organic matter by micro-organisms. Biogeochem. 11:213-233.

Varvel, G.E. 1994. Rotation and nitrogen fertilization effects on changes in soil carbon and nitrogen. Agron. J. 86:319-325.

Vogt, K.A., D.J. Vogt, and J. Bloomfield. 1991. Input of organic matter to the soil by tree roots. p. 171-190. *In* B.L. McMichael and H. Persson (ed.) Plant roots and their environment. Proc. of an ISRR-symposium, Uppsala, Sweden. 21-26 Aug. 1988. Elsevier, Amsterdam.

Wagner, G.H., and D.C. Wolf. 1999. Carbon transformations and soil organic matter formation. p. 218-258 *In* D.M. Sylvia et al. (ed.) Principles and Applications of Soil Microbiology. Prentice Hall, Upper Saddle River, NJ.

Waird, J.S. 1974. Decomposition of roots. p. 175-211 *In* C.H. Dickinson and G.J.F. Pugh (ed.) Biology of plant litter decomposition. Academic Press, London.

Waksman, S.A., and R.L. Starkey. 1924. Influence of organic matter upon the development of fungi, actinomycetes, and bacteria in the soil. Soil Sci. 17:373-378.

Walsh, M.E., D.G. de la Torre Ugarte, H. Shapouri, and S.P. Slinsky. 2000. The economic impacts of bioenergy crop production on U.S. agriculture. *In* E. van Ireland et al. (ed) Proc. of sustainable energy: New challenges for agriculture and implications for land use. 18-20 May 2000. Waginengen, Netherlands.

Wittwer, R.F., M.J. Immel, and F.R. Ellingsworth. 1980. Nutrient uptake in fertilized plantations of American sycamore. Soil Sci. Soc. Am. J. 44:606-610.

Wittwer, R.F., and J.W. Stringer. 1985. Biomass production and nutrient accumulation in seedling and coppice hardwood plantations. For. Ecol. Manag. 13:223-233.

Wood, B.W., S.B. Carpenter, and R.F. Wittwer. 1976. Intensive culture of American sycamore in the Ohio River Valley. For. Sci. 22(3):338-343.

Wood, B.W., R.F. Wittwer, and S.B. Carpenter. 1977. Nutrient element accumulation and distribution in an intensively cultured American sycamore plantation. Plant and Soil. 48:417-433.

Yamoah, C.F., G.E. Varvel, W.J. Waltman, and C.A. Francis. 1998. Long-term nitrogen use and nitrogen-removal index in continuous crops and rotations. Field Crops Res. 57:15-27.

Yoder, R.E. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. J. Am. Soc. Agron. 28:337-351.

Young, A. 1997. Agroforestry and soil management, 2nd ed. CAB International. Wallingford, UK.

Appendix

Appendix. Diameter at breast height (DBH), groundline diameter (GLD), total height, green mass, and dry mass of American sycamore grown on a Memphis-Loring silt loam intergrade in southwestern TN.

Plot	Tree no.	DBH	GLD	Total height	Total green mass	Stem green mass	Limb green mass	Total dry mass	Stem dry mass	Limb dry mass
		cm	cm	m	kg	kg	kg	kg	kg	kg
1	29	4.6	8.1	7.60	11.804	8.626	2.27	5.448	4.086	1.362
2	14	4.8	8.1	6.96	12.258	8.626	2.27	5.448	4.086	1.362
2	25	5.8	10.9	8.21	28.602	19.976	5.902	13.166	9.534	3.632
2	28	6.4	11.2	8.30	24.516	17.252	4.994	11.35	8.172	3.178
3	14	5.3	7.6	7.48	14.074	10.896	2.27	6.356	4.994	1.362
3	26	7.9	13.0	9.00	34.05	24.97	6.356	15.436	11.35	4.086
4	9	2.5	4.1	5.11	3.632	2.724	0.454	1.816	1.362	0.454
4	19	7.6	11.7	7.96	29.51	20.884	6.81	14.074	10.442	3.632
5	22	4.8	8.6	7.81	10.896	8.626	1.816	5.448	4.086	1.362
5	23	8.9	15.0	9.15	46.762	29.964	14.074	19.068	14.528	4.54
6	11	4.6	6.6	7.69	8.626	6.356	1.362	4.54	3.632	0.908
6	12	8.9	12.7	9.70	37.228	28.148	6.81	18.614	14.528	4.086
7	7	7.9	12.4	9.06	35.866	24.97	8.172	15.436	10.896	4.54
7	38	2.8	4.8	5.32	4.994	4.086	0.908	2.27	1.362	0.908
8	22	7.4	12.4	9.03	26.786	22.246	2.724	12.258	9.988	2.27
8	23	6.4	9.4	8.33	19.976	15.436	2.724	9.534	7.264	2.27
9	33	6.1	10.2	8.18	19.522	13.62	4.086	9.08	6.356	2.724
10	19	7.6	12.2	9.24	28.148	21.338	5.448	14.074	10.896	3.178
10	29	6.1	10.7	8.03	19.068	14.074	3.178	9.08	6.81	2.27
11	6	7.6	15.5	8.72	31.326	24.062	5.902	15.436	11.804	3.632
11	14	5.1	8.6	7.87	11.35	9.08	1.816	5.448	4.086	1.362
12	6	7.6	15.5	8.72	31.326	24.062	5.902	15.436	11.804	3.632
12	14	5.1	8.6	7.87	11.35	9.08	1.816	5.448	4.086	1.362
13	13	6.1	11.2	8.21	26.332	16.798	6.356	11.804	8.172	3.632
14	34	6.4	8.9	7.81	16.344	12.712	2.724	8.626	6.356	2.27
14	37	3.8	7.6	7.02	8.626	6.356	1.362	4.54	3.178	1.362
15	2	4.3	6.6	7.75	8.172	7.264	0.454	4.54	3.632	0.908
15	12	9.1	14.5	9.03	34.504	25.878	6.81	17.706	13.62	4.086
16	26	6.9	10.7	6.69	25.424	16.798	6.81	12.258	8.172	4.086
16	27	4.6	9.9	7.08	12.258	9.08	2.27	6.356	4.54	1.816
16	28	3.6	5.3	5.93	6.356	4.54	0.908	3.632	2.724	0.908
17	8	9.9	14.2	9.48	47.67	33.142	14.528	25.424	17.252	8.172

Appendix. Continued.

Plot	Tree no.	DBH	GLD	Total height	Total green mass	Stem green mass	Limb green mass	Total dry mass	Stem dry mass	Limb dry mass
		cm	cm	m	kg	kg	kg	kg	kg	kg
18	18	6.4	8.4	9.09	18.614	17.252	1.362	9.08	8.172	0.908
19	24	6.9	12.2	8.72	20.43	18.614	1.816	10.442	9.08	1.362
20	36	6.1	7.9	9.30	19.522	18.16	1.362	9.988	9.08	0.908
21	35	7.1	10.7	10.00	27.24	24.062	3.178	12.258	10.896	1.362
22	17	6.4	10.7	10.18	20.884	19.522	1.362	10.896	9.988	0.908
23	22	8.6	11.9	10.46	35.866	31.78	4.086	18.16	15.89	2.27
24	38	5.1	7.1	8.85	17.706	15.436	2.27	7.718	6.356	1.362
25	18	4.1	5.8	8.60	9.08	8.626	0.454	4.994	4.54	0.454
26	32	5.3	7.1	9.55	13.166	11.804	1.362	5.902	5.448	0.454
27	13	7.6	9.9	11.10	30.418	28.602	1.816	14.074	12.712	1.362
28	39	7.6	12.7	10.73	33.142	28.602	4.54	15.89	13.62	2.27
29	37	10.2	15.2	11.43	50.848	45.854	4.994	24.516	21.792	2.724
30	40	4.6	6.9	9.03	11.35	9.534	1.816	4.994	4.54	0.454
31	28	8.1	12.2	10.18	30.418	27.694	2.724	14.528	12.712	1.816
32	16	11.4	15.8	11.07	54.48	45.4	9.08	27.24	22.246	4.994

Vita

Warren Downe "Casey" Devine, III was born in Corvallis, Oregon on January 27, 1975 to Warren Downe Devine, Jr. and Carol Sue Duckwald Devine. In 1976 he moved to Oak Ridge, Tennessee and attended St. Mary's Catholic School through grade eight. He graduated from Oak Ridge High School in 1993. Warren entered Clemson University in Clemson, South Carolina in 1993 and graduated with a Bachelor of Science degree in Forest Resource Management in 1997. In August of 1997 he entered the Master's program at The University of Tennessee, Knoxville and graduated with a Master of Science degree in Forestry in 1999. He began the Doctoral program in Plant and Soil Sciences at The University of Tennessee, Knoxville in August 1999. On March 10, 2001 Warren married Kathryn Michelle McDonald in Oak Ridge, Tennessee. Warren received his Ph.D. in Plant and Soil Sciences in August, 2002.