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Management alternatives for improving soil carbon stocks of exposed subsoil in Iowa

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Management alternatives for improving soil carbon stocks of exposed subsoil in Iowa

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Signatures have been redacted for privacy

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LIST OF ABBREVIATIONS

TC, total carbon

TN, total nitrogen

POMC, particulate organic matter carbon

MFC, associated mineral fraction carbon

SOC, soil organic carbon

DOY, day of year

MBC, microbial biomass carbon

CS, corn soybean rotation

SA, switchgrass burned annually

S5, switchgrass burned every five years

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ABSTRACT

Removal of topsoil from glacial till soils exposes unproductive subsoil that is low in soil organic carbon (SOC). The objective of this study was to determine if soil carbon stocks of exposed subsoil could be improved with topsoil addition and cropping systems. In experiment one, a corn (*Zea mays*)-soybean (*Glycine max* L. Merr.) rotation was established on exposed subsoil and topsoil that had been placed over exposed subsoil. In experiment two, corn-soybean rotation (CS), switchgrass (*Panicum virgatum* L.) burned annually (SA), and switchgrass burned every five years (S5) cropping systems were established on exposed subsoil. To examine soil carbon dynamics, we measured soil CO_2-C emissions, total carbon (TC) inputs from crop residues, microbial biomass carbon (MBC), and soil carbon fractions. Corn grown in topsoil produced 7.14 Mg ha^{-1} more aboveground biomass and 0.8 Mg ha^{-1} more root biomass and thus had greater potential C inputs than corn grown in subsoil. Topsoil had cumulative soil CO_2-C emissions 46% greater than subsoil and a 57% larger MBC pool. Topsoil had greater SOC contents than exposed subsoil, including the 30 to 45 cm soil depth, which was below any added topsoil. Switchgrass cropping systems were the most productive in the exposed subsoil, producing 3.47 and 2.33 Mg ha^{-1} more aboveground biomass than soybeans and corn, respectively. Switchgrass cropping systems also had a root biomass 15 Mg ha^{-1} greater than corn or soybeans. As a result potential carbon inputs from switchgrass residues were 6.08 and 6.71 Mg ha^{-1} greater than corn and soybeans, respectively. The switchgrass burned annually cropping system had the greatest cumulative soil CO_2-C emissions, followed by the S5 and CS cropping systems, respectively. The MBC pool of exposed subsoil was on average 200% greater in the switchgrass cropping systems than the corn-soybean rotation. There were no differences in SOC fractions between all

cropping system treatments in the exposed subsoil. These findings suggest that topsoil addition or switchgrass establishment on exposed subsoil will result in greater potential carbon inputs, greater soil CO_2 emissions and larger MBC pools. However, improving carbon stocks of exposed subsoil appears to be a slow and long-term process.

CHAPTER 1

General Introduction

Rising atmospheric CO_2 levels and concern over global warming have increased the importance of managing agricultural land as a potential sink for atmospheric CO_2. Soil organic carbon (SOC) is the largest terrestrial C pool (Post et al., 1990), and historically, the conversion from native vegetation to cultivated agriculture resulted in a 60 to 75% depletion of SOC, most of which was emitted to the atmosphere as CO_2 (Lal, 2004). Soil can function as a net sink for carbon and reduce atmospheric CO_2 levels if managed correctly (Lal et al., 1998).

The removal or loss of topsoil can result in a large loss of SOC (Lal et al., 1998). In Iowa, large areas of subsoil are exposed by erosion and road construction. Carbon sequestration is an effective management strategy for degraded soils, which can raise their productivity and offset CO_2 emissions from fossil fuel combustion (Lal, 2004). Therefore, reclamation techniques and cropping systems should be implemented to determine the best strategies for improving soil carbon stocks in exposed subsoil.

Topsoil addition is a common reclamation technique used on areas that have had topsoil removed for construction or mining. It was found that reclaiming mined-soils with perennial cropping systems can sequester carbon, and reclamation that included topsoil addition had greater carbon sequestration rates than reclamation without topsoil addition (Akala and Lal, 2001). Improvement in soil carbon stocks depends on sufficient biomass production, but subsoil is poorly suited for crop growth. Subsoil's productivity can be raised through intensive fertilization, but fertilizer alone cannot replace the benefits of topsoil

(Mielke and Schepers, 1986; Olson, 1977). Subsoil is also a poor environment for microbial activity because of poor aeration, and low substrate availability (Lomander et al., 1998).

Topsoil addition is not always possible over exposed subsoil, especially in areas of production fields that have become degraded due to water and wind erosion. Removing areas from row crop production and establishing perennial vegetation can improve soil carbon (Post and Kwon, 2000). Different cropping systems have different contributions to soil carbon. Generally, native grasses, such as switchgrass (*Panicum virgatum* L.), contribute greater amounts of carbon to the soil system than cultivated cropland, especially at deeper depths (Liebig et al., 2004). Much of the SOC accumulation under switchgrass can be attributed to its extensive root system (Liebig et al., 2004; Ma et al., 2000). It has also been found that microbial biomass carbon can increase as much as 168% after the conversion from row crop to switchgrass cropping (Ma et al., 2000).

The objectives of this study were to determine if topsoil addition or switchgrass establishment can improve soil carbon stocks in exposed subsoil, by evaluating soil CO_2 emissions and crop residue carbon inputs, in addition to examining certain soil carbon improvement indicators, such as, microbial biomass carbon, and SOC fractions.

Thesis Organization

I have organized this thesis into four chapters, each addressing a specific aspect of a research project conducted near Webster City, IA during the growing seasons of 2003 and 2004. Chapter one is a general introduction, which outlines the relevance of this study. Chapter two examines SOC dynamics of topsoil and exposed subsoil in a corn (*Zea mays*)-soybean (*Glycine max* L. Merr.) rotation. Chapter three examines SOC dynamics of exposed subsoil planted to switchgrass and a corn-soybean rotation. Chapter four summarizes the

overall findings of this project. This thesis has been prepared with the potential for chapters two and three to be submitted for publication in refereed journals at a later time.

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CHAPTER 2

Topsoil placement Effects on Soil Carbon Stock Improvement of Exposed Subsoil in a Corn-Soybean Rotation

Abstract

Exposed subsoil and highly eroded soils present a soil management challenge and an opportunity to examine potential techniques for improving soil carbon stocks. It is well documented that the construction of roadbeds leaves behind large areas of unproductive exposed subsoil, which is low in soil organic carbon (SOC) content. The objective of this study was to determine whether a topsoil addition coupled with a corn (*Zea mays*)-soybean (*Glycine max* L. Merr.) rotation could improve soil carbon in areas that have had topsoil removed. We measured soil CO_2 emissions, potential C inputs from crop residues, microbial biomass carbon (MBC) and SOC fractions from topsoil and exposed subsoil managed as a corn-soybean rotation during the growing seasons of 2003 and 2004. Soil temperature and soil moisture at the 5-cm depth also were measured concurrently with soil CO_2 emission readings. At no time during either year did subsoil have a greater rate of soil CO_2 emission than topsoil. Cumulative CO_2 emissions were 45% and 47% greater from topsoil in 2003 and 2004, respectively. Microbial biomass carbon contents were 247 and 157 $\mu g\ g^{-1}$ for topsoil and subsoil, respectively. Soil CO_2 emission rate was positively correlated with soil temperature, and a linear function best described the relationship (R^2=0.30). The relationship between soil CO_2 emissions and soil moisture was best described by a second order polynomial function with an R^2 of 0.11. Corn grown in topsoil produced 7.14 Mg ha^{-1} more aboveground biomass and 0.8 Mg ha^{-1} more root biomass than corn in the subsoil. This led to greater potential C inputs from corn grown in topsoil. Topsoil addition treatments had

greater SOC contents than exposed subsoil, including the 30 to 45 cm soil depth which is below any added topsoil. These findings suggest that topsoil addition to areas of exposed subsoil increases productivity, soil CO_2 emissions, MBC, and could potentially improve soil carbon.

Introduction

Large areas of subsoil become exposed as a result of roadbed construction and topsoil erosion. The removal of topsoil results in major depletion of the soil organic carbon (SOC) pool (Lal et al., 1998). Carbon sequestration in these highly disturbed low SOC areas could restore soil productivity and aid in the reduction of atmospheric CO_2 levels (Lal, 2004). Many investigators have documented carbon sequestration in topsoil, but relatively little work has focused on the potential of exposed subsoil as a potential a carbon sink.

Subsoil is a poor medium for plant growth because of high clay content and lack of nutrient availability (Gollany et al., 1992). However, the productivity of subsoil can be increased over time through proper management (Eck, 1987). Intensive fertility programs including micronutrients, can improve the productivity of subsoil, but fertilizer alone cannot replace the benefits of topsoil (Mielke and Schepers, 1986; Olson, 1977). Khalaf (1984) found that row crops grown in subsoil produced less biomass and grain yield than row crops grown on topsoil. In addition to poor fertility, the high bulk density of subsoil is not conducive to plants establishing an extensive root system. Extensive root biomass is a critical component of soil carbon input because of its role in the formation of stable macroaggregates and particulate organic matter carbon (POMC), which is a sensitive indicator of SOC change and soil quality (Cambardella and Elliot, 1992; Chan et al., 2002; Gale et al., 2000).

Differences in soil CO_2 emissions from topsoil and subsoil have been found to be significantly different. Lomander et al. (1998) found soil CO_2 emissions were as much as 4 to 5 fold greater from topsoil than subsoil in a controlled laboratory soil incubation study. However, Bajracharya et al. (2000a; 2000b) found greater soil CO_2 emission rates from topsoil compared to subsoil only during times of peak air and soil temperatures.

Factors that govern biological activities in the soil such as soil temperature and moisture availability influence CO_2 emission rates (Carlyle and Than, 1988). It is generally recognized that soil CO_2 emissions are positively correlated with soil temperature, but a relationship with soil moisture is not well understood. Kowalenko et al. (1978) found increasing soil moisture levels decreased soil CO_2 emissions; whereas Lomander (1998) found increasing CO_2 emission rates with increasing soil moisture content. In contrast, Bajracharya et al. (2000b) concluded that soil moisture had no effect on soil CO_2 emission, and Wilson and Griffin (1975) concluded that soil moisture only affected soil CO_2 emission during periods of extreme dry or extreme wet.

Microbial biomass carbon (MBC) is an important component of the SOC pool and may be an early indicator of SOC improvement or increase (Powlson and Brookes, 1987). However, the MBC pool is highly variable and difficult to quantify (Hargreaves et al., 2003). The size of the MBC pool can influence rates of soil CO_2 emission (Franzluebbers et al., 1996), but the amount of available substrate will ultimately determine the size of the microbial biomass pool (Wang et al., 2003). Limited substrate availability, poor aeration status, and high clay content result in low carbon mineralization rates in subsoil (Lomander et al., 1998; Wang et al., 2003).

Topsoil addition is a common reclamation practice used on areas where topsoil has been removed for road construction. The overall objective of this study was to determine whether a topsoil addition coupled with a corn (*Zea* mays)-soybean (*Glycine max* L. Merr.) rotation could improve soil carbon stocks of exposed subsoil by evaluating crop residue carbon inputs and soil CO_2-C output in addition to soil carbon pool improvement indicators such as, soil microbial biomass carbon and SOC fractions.

Materials and Methods

Site Description and Management

This study was conducted on a borrow site near Webster City, Iowa during the growing seasons of 2003 and 2004. Borrow sites are areas where topsoil has been removed and subsoil mined for construction purposes. The predominant soil on this site was a Nicollet (aquic hapludolls) with a Clarion (typic haplaquolls) on the hillsides. The topsoil was removed from this 2.43 ha site in 1977 for road construction purposes. The exposed subsoil was a calcareous, un-weathered, and un-oxidized glacial till of Cary age (Khalaf, 1984). In 1978, a portion of the area was converted to a research site, and three treatments applied by placing different depths of topsoil over the exposed subsoil. The treatments were: (1) exposed subsoil, (2) 15-cm topsoil, and (3) 30-cm topsoil. The experimental design was a generalized randomized complete block with 3 replications. Each plot was 9-m wide by 9-m long. Corn and soybeans are rotated annually on the site. Bulk densities and pH's of the three topsoil depth treatments are summarized in Table 2.1.

Each fall the site was tilled to a depth of 40-cm with a two shank deep ripper. The deep ripper shanks were spaced 45 cm apart. In the spring, the field was disked once at a

depth of 7 cm for seedbed preparation. In 2003, Pioneer[1] 35P17 corn was planted 20 May, day of year (DOY) 140, at 45,724 seeds ha^{-1} on 76-cm row spacing. Weed control consisted of one application of 2,4-D amine at a rate of 2.33 L ha^{-1}, followed by cultivation. In 2004, Pioneer 92B38 soybeans were planted on 1 July (DOY 182) at 74 kg ha^{-1} on 76-cm row spacing. Weed control consisted of one application of Glyphosate at a rate of 2.32 L ha^{-1}. No fertilizer was applied either year.

Field Soil CO_2 Emission Measurements

The exposed subsoil and 30-cm topsoil treatments were selected to measure soil CO_2 emissions from a corn-soybean rotation. Carbon dioxide emissions from the soil surface were measured by placing the soil chamber of a LI-6400 infrared gas analyzer (LI-COR Corporation, Lincoln, NE) over polyvinyl chloride (PVC) rings that were pressed 3 cm into the soil. The PVC rings had an inside diameter of 10 cm, and 2 cm of the rings remained above the soil surface. Four PVC rings were placed near the center of each plot. Two rings were placed in the crop row and two were placed between the rows. The mean of the four rings was considered to be the reading for the entire plot. The soil CO_2 measurements were taken approximately every 7 to 14 days from 5 June to 29 October in 2003 (DOY 156 to 302) and 6 July to 5 November in 2004 (DOY 187 to 309), between the hours of 10:00 am and 2:00 pm. No CO_2 measurements were taken for 48 hours following the row cultivation in 2003. Soil temperature and soil moisture at the 5-cm depth were measured concurrently with CO_2 measurements. Soil temperature was measured with a thermometer attached to the LI-6400, and volumetric soil moisture was measured with a TRIME-FM Time Domain

[1] All trade names and product lines are mentioned solely for the benefit of readers, and do not imply endorsement by Iowa State University.

Reflectometry device (Mesa Corp, Medfield, MA). Cumulative CO_2 emissions for the growing season were calculated as follows:

$$\text{Cumulative } CO_2 \text{ (kg ha}^{-1}) = \sum_{i=\text{first}}^{n=\text{last}} X_i + X_{i+1} * N + X_{i+2} * N \ldots + X_{i+n} * N \quad (1)$$

where, X is CO_2 emission rate (kg ha^{-1} d^{-1}), (n) is last CO_2 measurement during the growing season, (i) is the first CO_2 rate measurement in the season, and N is the Number of days between two consecutive CO_2 rate measurements. Cumulative soil CO_2 emissions were then converted to Mg ha^{-1} of CO_2-C.

Soil Microbial Biomass Carbon

Samples for soil MBC determination were taken in 2004 when the soybean crop reached V_6 development stage. The same treatments being used for soil CO_2 measurements were used for this experiment. A composite soil sample of ten soil cores was taken from each plot at a depth of 15 cm. The soil samples were brought back to the laboratory, 4 mm sieved, and stored in a 4°C cold room overnight. Soil microbial biomass carbon was determined by performing the fumigation extraction method (Horwath and Paul, 1994). Fifty-gram moist soil samples were fumigated with ethanol-free $CHCl_3$ for 24 h in a vacuum desiccator. The soil samples were extracted for 30 minutes with 100 ml of 0.5 M K_2SO_4 and then filtered through Whatman No. 42 filter paper (Whatman International Ltd., Maidstone, UK). Non-fumigated samples were extracted the same way while the others were being set up for fumigation. Extractant alone was also filtered in order to determine the background level of C in the filter paper and extractant. Carbon recovered in the extract was determined with a Shimadzu TOC-5050 carbon analyzer (Rydalmere, New South Wales, Australia). Microbial biomass carbon was calculated on an oven-dry soil weight basis.

Laboratory Soil Incubation

The remainder of soil from the samples collected for microbial biomass analysis was used for laboratory soil incubation. A static incubation-titrimetric procedure (Zibliske, 1994) was used for this experiment. The soil samples were taken out of the cold room; 2 mm sieved, and allowed to air dry. Twenty-grams of each soil sample was weighed into 20 ml borosilicate vials. Approximately, seven grams of water was added to the vials to achieve 60% water filled pore space. Each vial with soil was placed into a 0.9 L wide mouth glass jar along with a 10 ml scintillation vial containing 1.0 ml of 2 N NaOH as a base trap. Approximately, 3-5 ml of water was added in the bottom of the glass jars in order to maintain proper humidity levels. The lids of the glass jars were twisted closed to completely seal the contents from the outside atmosphere. Three controls (blank) jars were also set up by placing a base trap in a jar that contained no soil. All of the glass jars were then placed in a dark incubation room at 30° C. The amount of CO_2-C evolved was determined by titration. Two ml of 1 M BaCl and 2-3 drops of phenolphthalein were added to the base traps. One N HCL was then added with a digital micro burette until the indicator showed neutral pH. After titration, a new base trap was added to each jar. Titrations were performed on days 1, 3, 5, 7, 14, 21, 28, 35, 42, 49, 56, 63, and 77. The amount of CO_2-C evolved during the soil incubation was calculated based on air-dry soil weight.

Soil inorganic N (NO_3-N and NH_4-N) concentration was determined prior to and after the incubation period using the KCl extraction method (Mulvaney, 1996). Ten-grams of soil was extracted with 50 ml of 2 M KCl for 30 min. The supernatant was then filtered through Whatman number 42 filter paper. Inorganic N concentration of the filtrate was measured with a Lachat QuickChem 8000 FIA+ (Lachat Instruments, Milwaukee, WI).

Soil Organic Carbon and Soil Total Nitrogen Determination

Prior to planting in 2003 and 2004, soil samples were collected from all of the topsoil depth treatments at depth increments of 0-15, 15-30, 30-45, and 45-60cm. A composite soil sample consisting of 10 cores was taken for each depth from each plot using a soil probe with an inner diameter of 1.9 cm. Soil samples were placed in a -4°C freezer until analysis was preformed. Soil samples for bulk density determination were taken at the same time and depth increments according to the procedure outlined in Doran and Mielke (1984). Prior to conducting soil C analysis, the soil samples were defrosted; 2 mm sieved, and allowed to air dry. Two 10-g soil sub-samples were weighed out from each soil sample. The first soil sub-sample was ground with a mortar and pestle and analyzed for SOC and soil total nitrogen (STN) content by dry combustion using a LECO CHN 2000 analyzer (LECO Corporation, St. Joseph, MI). The second soil sub-sample was used in the POMC fractionation procedure (Cambardella and Elliot, 1992; Kruse, 2005). The soil sub-sample was dispersed with sodium metaphosphate and then passed through a 53-μm sieve. The water was evaporated from the slurry that passed through the sieve by placing it in a forced air oven at 50°C for 72 hours. The dried soil slurry was ground and analyzed for associated mineral fraction carbon (MFC) organic carbon content with the LECO analyzer. Particulate organic matter carbon was calculated by subtracting MFC content from SOC content.

Soil pH was determined using a 1:1 (soil/water) dilution. If soil pH was greater than 7.1, inorganic carbon concentration was determined using a modified pressure calcimeter method (Sherrod et al., 2002) and subtracted from the total carbon content values determined initially by the LECO CHN analyzer.

The C content of each fraction was calculated on an equivalent soil mass by using the bulk density.

Potential Total Carbon and Nitrogen Inputs from Crop Aboveground Biomass

Crop residue was collected each fall from the subsoil and 30-cm topsoil treatments after mechanical harvest of the crop was completed. A one-m^2 frame was randomly placed in the center of each plot, and the entire residue within the frame was collected and placed in mesh bags. Residue was dried at 64°C for seven days, weighed, and then ground through a 2-mm screen using a Wiley Mill Model 2 grinder (Arthur H. Thomas Co., Philadelphia, PA). Crop residue total C and N concentrations were determined with the LECO CHN analyzer, and then multiplied by the biomass to determine potential C and N inputs.

Potential Total Carbon and Total Nitrogen Input from Crop Root Biomass

Root biomass samples were collected from the subsoil and 30-cm topsoil treatments in 2003 and 2004 when the crops reached R_1 growth stage. Root samples from corn in 2003 were obtained by excavating all roots from the top 30 cm of soil in a 1-m section of crop row near the center of each plot. Corn roots were taken back to the laboratory and soaked in water for 24 hours. After soaking, they were scrubbed and rinsed of any excess soil. Corn roots were dried in a 64°C forced air oven for seven days, weighed, ground with the Wiley Mill, and analyzed for TC and TN with the LECO CHN analyzer.

Corn root weight density in 2003 was calculated as follows:

$$RWD = RDM / (RL * RW * D) \quad (2)$$

where, RWD is root weight density (g cm^{-3}), RDM is root dry matter (g), RL is row length (cm), RW is row width (cm), and D is depth (cm).

Soil samples for soybean root biomass determination in 2004 were obtained by clipping the soybean plants at the soil surface and taking 6.3 cm diameter soil cores in the row, 30-cm deep from each plot. Soybean root samples were taken to the laboratory and stored in a -4°C freezer until they were washed using a hydropneumatic elutriation system (Smucker et al., 1982). Soybean roots were dried in a 64°C forced air oven for seven days, weighed, ground with the Wiley Mill, and analyzed for TC and TN with the LECO CHN analyzer. Soybean root weight density in 2004 was calculated as follows:

$$RWD = RDM / (\pi * CR^2 \times D) \quad (3)$$

where, CR is core radius (cm) and other terms are the same as in equation 2.

Corn and soybean root biomasses were calculated as follows:

$$RB = RWD * D * 100 \quad (4)$$

where, RB is root biomass (Mg ha^{-1}), 100 is a conversion factor for area and mass, and other terms are the same as in equation 2.

The total C and total N concentrations determined by the LECO were multiplied by the root biomasses to determine potential total C and total N inputs.

Statistical Analysis

All experiments were analyzed as generalized randomized complete blocks with three replications. Topsoil depths were treated as fixed factors and replications were treated as random. A mixed model procedure with repeated measures was used for the daily field soil CO_2 emission rate analysis of variance (SAS Inst., 2005). The repeated factor was day and the subject was the interaction of replication and soil depth. A compound symmetry covariance structure was used for the repeated measures. Regression analyses were used to test the effects of soil moisture and soil temperature on CO_2 emission rate. All other

experiments were analyzed with the general linear models (GLM) procedure of SAS. An alpha level of 0.05 was used for all comparisons.

Results and Discussion

Field soil CO_2 emissions, microbial biomass, laboratory incubation, and potential plant TC and TN input experiments involved only the 30-cm topsoil and exposed subsoil treatments. The two treatments will be referred to as topsoil and subsoil in presentation and discussion of results. The SOC and STN results will include the 15-cm topsoil, 30-cm topsoil, and exposed subsoil treatments.

Field Soil CO_2 Emissions

During the 2003 corn growing season, the daily rate of soil CO_2 emission was similar for topsoil and subsoil except for DOY 197 and 202 when topsoil CO_2 emissions were greater (Fig. 2.1c). During the 2004 soybean growing season, soil CO_2 emission rates were greater from topsoil than subsoil every day except DOY 187, 223, 280, and 309 (Fig 2.2c). Greater soil CO_2 emissions from topsoil generally occurred when soil temperatures were at their warmest for the year, and no differences were found once soil temperatures began to cool, approximately DOY 233 in 2003 and DOY 264 in 2004 (Figs. 2.1a&b and 2.2a&b). These findings are consistent with those of Bajracharya et al. (2000b), who found that slightly eroded soils had greater soil CO_2 emission rates than severely eroded soils only when soil temperatures were the warmest.

On no day of either year did subsoil have a greater CO_2 emission rate than topsoil (Figs 2.1a and 2.2a). As a result, cumulative CO_2-C emissions were 45 and 47% greater from topsoil in 2003 and 2004, respectively (Fig. 2.3). Even though the soybeans were planted extremely late in 2004, cumulative soil CO_2-C emissions were similar from both

treatments in both years (Fig. 2.3). Soil MBC contents were 247 and 157μg g^{-1} for topsoil and subsoil, respectively. These results agree with Franzluebbers et al., (1999), who found greater soil CO_2 emissions in soils with larger MBC pools. Low substrate availability and the harsh environment of subsoil are likely the reason for less MBC in the subsoil. Root respiration also contributes to soil CO_2 emissions. In 2003, the corn growing in topsoil had a larger root biomass than corn growing in subsoil (Table 2.2).

Results of the laboratory soil incubation support the field soil CO_2 emission findings, where topsoil had greater rates of CO_2-C evolution during every incubation period except for days 63, 70 and 77 (Fig. 2.4). Cumulative CO_2-C evolutions during incubation were also greater from topsoil than subsoil. Cumulative CO_2-C evolved was 1043 and 463 μg g^{-1} for topsoil and subsoil, respectively. Topsoil and subsoil had similar inorganic N concentration prior to incubation, but after incubation topsoil had twice the inorganic N concentration of subsoil (Fig 2.5). These results are similar to those of Lomander et al. (1998), who also found greater rates of CO_2-C evolution from topsoil than subsoil in a laboratory incubation study. The greater C and N mineralization in topsoil during the laboratory incubation can be attributed to larger amounts of substrate and greater MBC content.

Soil moisture and soil temperature were not affected by topsoil depth treatment in either year of this study (Figs. 2.1a&b and 2.2 a&b). However, regression analyses showed soil temperature and soil moisture affected soil CO_2 emission. Soil CO_2 emission rate was positively correlated with soil temperature, and a linear function best described the relationship (Fig. 2.6). Variability in soil CO_2 emission rate was greatest during the warmest soil temperatures. In a laboratory incubation study Kowalenko et al. (1978) also found a linear relationship explained the effects of soil temperature on soil CO_2 emissions. In field

studies it is commonly reported that second order polynomial (Bajracharya et al., 2000b) or exponential (Raich and Mora, 2005) functions best explain the effects of soil temperature on soil CO_2 emissions.

A second order polynomial function best described the relationship between soil moisture and soil CO2 emissions (Fig 2.7). The relationship only explains 11% of the variability in CO_2 emission due to soil moisture, but agrees with the theory that soil moisture only affects CO_2 emission rates at extremely low or extremely high soil moisture contents (Bajracharya et al., 2000a; Wilson and Griffin, 1975).

Potential Carbon and Nitrogen Inputs from Aboveground and Root Biomass

Corn grown in topsoil produced 7.14 Mg ha^{-1} more aboveground biomass and 0.8 Mg ha^{-1} more root biomass than corn grown in the subsoil (Table 2.2). Gollany et al. (1992) and Olson (1977) also found greater aboveground biomass production from corn grown in topsoil compared to corn grown in subsoil. The C:N ratio was greater in corn aboveground biomass from topsoil, but the C:N ratio of root biomass was greater from corn grown in subsoil (Table 2.2). The combined potential (aboveground + root) crop input of TC was 3.30 Mg ha^{-1} greater from corn grown in topsoil compared to corn grown in subsoil (Table 2.2). Potential TN inputs were negligible from either treatment because of the low N concentration of the biomasses caused by lack of N fertilization (Table 2.2).

The extremely late planting of soybeans in 2004 prevented the crop from reaching maturity, and statistical analysis showed no difference in aboveground biomass production between the two treatments. However, in research conducted on this site, Khalaf (1984) found soybeans produced less biomass in subsoil compared to topsoil.

Soil Organic Carbon Fractions and Total Nitrogen

Analysis of variance showed no difference in SOC fractions or STN between sample years; therefore, the main effect of soil depth treatment will be presented across years. Soil organic carbon content in the 15 and 30-cm topsoil treatments was greater than the SOC content of the exposed subsoil treatment in the 0-15 and 15-30-cm soil depths (Table 2.3). Additionally, the 15 and 30-cm topsoil treatments had greater SOC content than exposed subsoil in the 30-45-cm soil depth (Table 2.3). The 30-cm topsoil treatment had greater SOC content than the 15-cm topsoil treatment in the 15-30-cm soil depth. The associated MFC content was greater in the 15 and 30-cm topsoil treatments than the exposed subsoil treatment for the 0-15 and 15-30-cm soil depths (Table 2.3). The 15 and 30-cm topsoil treatments also had greater associated MFC content than exposed subsoil in the 30-45-cm soil depth (Table 2.3). The 30-cm topsoil treatment had greater associated MFC content than the 15-cm topsoil treatment for the 15-30 and 30-45-cm soil depths (Table 2.3). Topsoil inherently has more SOC than subsoil; however, it should be noted that both topsoil addition treatments had greater SOC and associated MFC contents than the exposed subsoil at the 30-45 cm soil depth (Table 2.3). This depth is below any added topsoil, and could indicate an accumulation of SOC in the subsoil below the topsoil additions. The greater potential C input (Table 2.2) of crops in the topsoil along with mixing effect of tillage have likely contributed to this increase of subsoil SOC.

There was not a large particulate organic matter carbon pool in any of the treatments. The 15 and 30-cm topsoil treatments had POMC contents 7.57 and 11.12 Mg ha^{-1} greater than the exposed subsoil treatment, respectively for the 0-15 cm soil depth (Table 2.3). Particulate organic matter carbon content of the 15 and 30-cm topsoil treatments was 6.25

Mg ha^{-1} greater than the exposed subsoil treatment in the 15-30-cm soil depth (Table 2.3). Particulate organic matter is an intermediate pool between residue and stable organic matter, and is closely related to stable soil macroaggregates (Cambardella and Elliot, 1993). The subsoil used in this study is very poorly aggregated, and inherently does not contain a significant POMC fraction. Additionally, low input of root residues and tillage operations, prevent the formation of stable macroaggregates (Cambardella and Elliot, 1992; Gale et al., 2000).

Soil total nitrogen contents did not differ between treatments, but the 15 and 30-cm topsoil treatments had greater C:N ratios than exposed subsoil in the 0-15 and 15-30- cm soil depths (Table 2.4).

Conclusions

Topsoil addition over exposed subsoil increased aboveground and root biomass production of corn. As a result, corn grown in topsoil can supply more carbon to the soil than corn grown in exposed subsoil. Cumulative field soil CO_2-C emissions were on average 46% greater from a corn-soybean rotation in topsoil, than a corn-soybean rotation in subsoil. Greater carbon mineralization occurs in topsoil than subsoil because of greater amounts of substrate and a larger MBC pool. Soil temperature and soil moisture affect soil CO_2 emissions, but temperature appears to be the dominant factor, unless extreme soil moisture conditions are present.

As expected, topsoil had greater SOC and MFC contents than exposed subsoil. However, the greater SOC content found in the zone between the topsoil addition and subsoil, (30-45 cm) could indicate carbon accumulation, but it needs to be examined closer to determine the extent of tillage mixing that has occurred. Topsoil addition also resulted in

greater POMC content in the 0-30-cm soil depth, and increased MBC in the 0-15cm soil depth.

The results of this study show that topsoil addition over exposed subsoil can be a viable technique for potentially improving SOC stocks of subsoil, because of the increase in soil productivity, which is a key component for soil carbon sequestration. Long-term improvement of SOC levels on this site is most likely to take place if proper crop and fertilization management practices are implemented.

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Table 2.1. Bulk density and pH of three topsoil depth treatments in the 0 to 60-cm soil profile.

	pH				Bulk Density (g cm^{-3})			
	Soil depth (cm)				Soil depth (cm)			
Treatment	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60
topsoil (cm)								
0	7.67	7.57	7.58	7.54	1.46	1.66	1.70	1.74
15	7.49	7.38	7.43	7.47	1.27	1.50	1.71	1.74
30	7.44	7.18	7.37	7.51	1.22	1.39	1.59	1.74

Table 2.2. Total carbon (TC) and total nitrogen (TN) inputs from aboveground and root biomasses of corn and soybeans grown in 30-cm topsoil and exposed subsoil. Root biomass was measured to 30-cm. Potential TC and TN inputs, and carbon to nitrogen ratios were calculated using the C and N concentrations of the respective biomass.

		Aboveground				Root				Total Inputs	
			Input				Input			Root + Aboveground	
Crop	Soil	Biomass	TC	TN	C:N	Biomass	TC	TN	C:N	TC	TN
		Mg ha^{-1}	------Mg ha^{-1}------			Mg ha^{-1}	------Mg ha^{-1}------			--------Mg ha^{-1}--------	
Corn	Subsoil	4.37a*	1.83a	0.17a	99.7a	1.33a	0.49a	0.05a	93.1a	2.32a	0.22a
	Topsoil	11.51b	4.93b	0.42b	116.7b	2.13b	0.59b	0.09a	62.1b	5.52b	0.51a
Soybean	Subsoil	3.23a	1.40a	0.62a	22.6a	0.76	0.29	0.13	21.8	1.69	0.75
	Topsoil	3.98a	1.74a	0.76a	23.1a	-	-	-	-	-	-

*Means with the same letter within each crop are not different at $P \leq 0.05$.

Table 2.3. Effects of topsoil depth on soil organic carbon (SOC), associated mineral fraction carbon (MFC), and particulate organic matter carbon (POMC) content of the 60-cm soil profile.

	SOC				MFC				POMC			
	Soil depth (cm)				Soil depth (cm)				Soil depth (cm)			
Treatment	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60
topsoil (cm)	---------- Mg ha^{-1} ----------											
0	20.56a*	18.76a	20.02a	20.34a	21.08a	19.17a	19.62a	18.87a	0.00a	0.00a	0.40a	1.47a
15	39.81b	36.73b	28.45b	20.55a	32.24b	30.49b	26.85b	19.68a	7.57b	6.25b	1.60a	0.87a
30	43.44b	46.10c	30.12b	18.56a	32.32b	39.85c	30.87c	19.97a	11.12b	6.25b	0.00a	0.00a

*Means with the same letter within each sample depth are not different at $P \leq 0.05$.

Table 2.4. Soil organic carbon (SOC) and soil total nitrogen (STN) contents, and C:N ratios of three topsoil depth treatments in the 0 to 60-cm soil profile.

	SOC				STN				C:N			
	Soil depth (cm)				Soil depth (cm)				Soil depth (cm)			
Treatment	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60
topsoil (cm)	----------Mg ha^{-1}----------											
0	20.56a*	18.76a	20.02a	20.34a	3.20a	2.33a	2.20a	2.36a	6.42a	8.05a	9.11a	8.61a
15	39.81b	36.73b	28.45b	20.55a	3.44a	2.74a	3.02a	2.28a	11.57b	13.41b	9.42a	9.01a
30	43.44b	46.10c	30.12b	18.56a	3.95a	4.19a	3.69a	2.59a	10.99b	11.01b	8.16a	7.16a

*Means with the same letter within each sample depth are not different at $P \leq 0.05$.

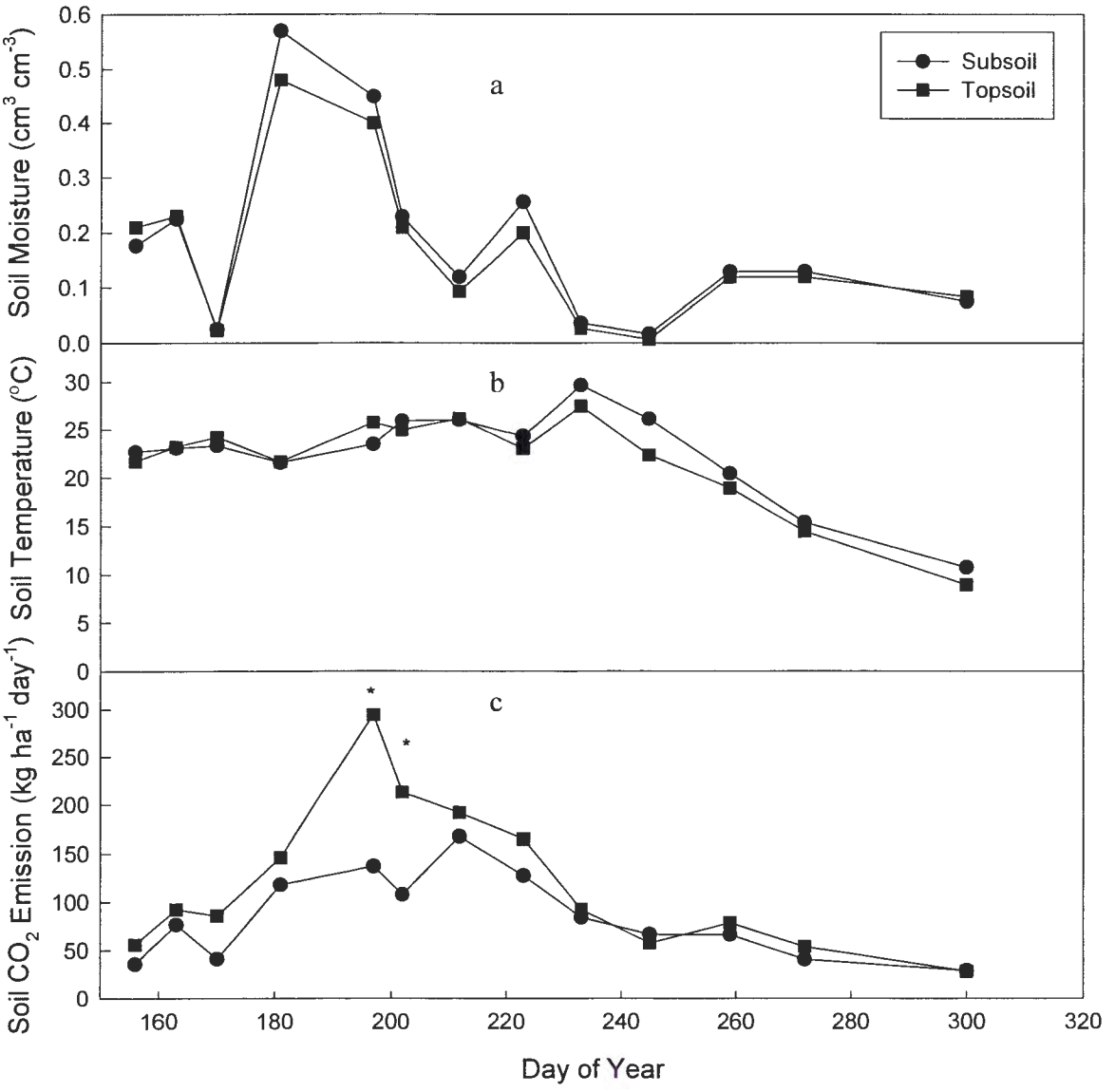

Figure 2.1. Soil moisture (a), soil temperature (b), and CO_2 emission rate (c) measured in topsoil and exposed subsoil planted to corn in 2003. Soil temperature and soil moisture were measured at the 5-cm depth. (*)Indicates dates where subsoil and topsoil CO_2 emission rates were different at $P \leq 0.05$.

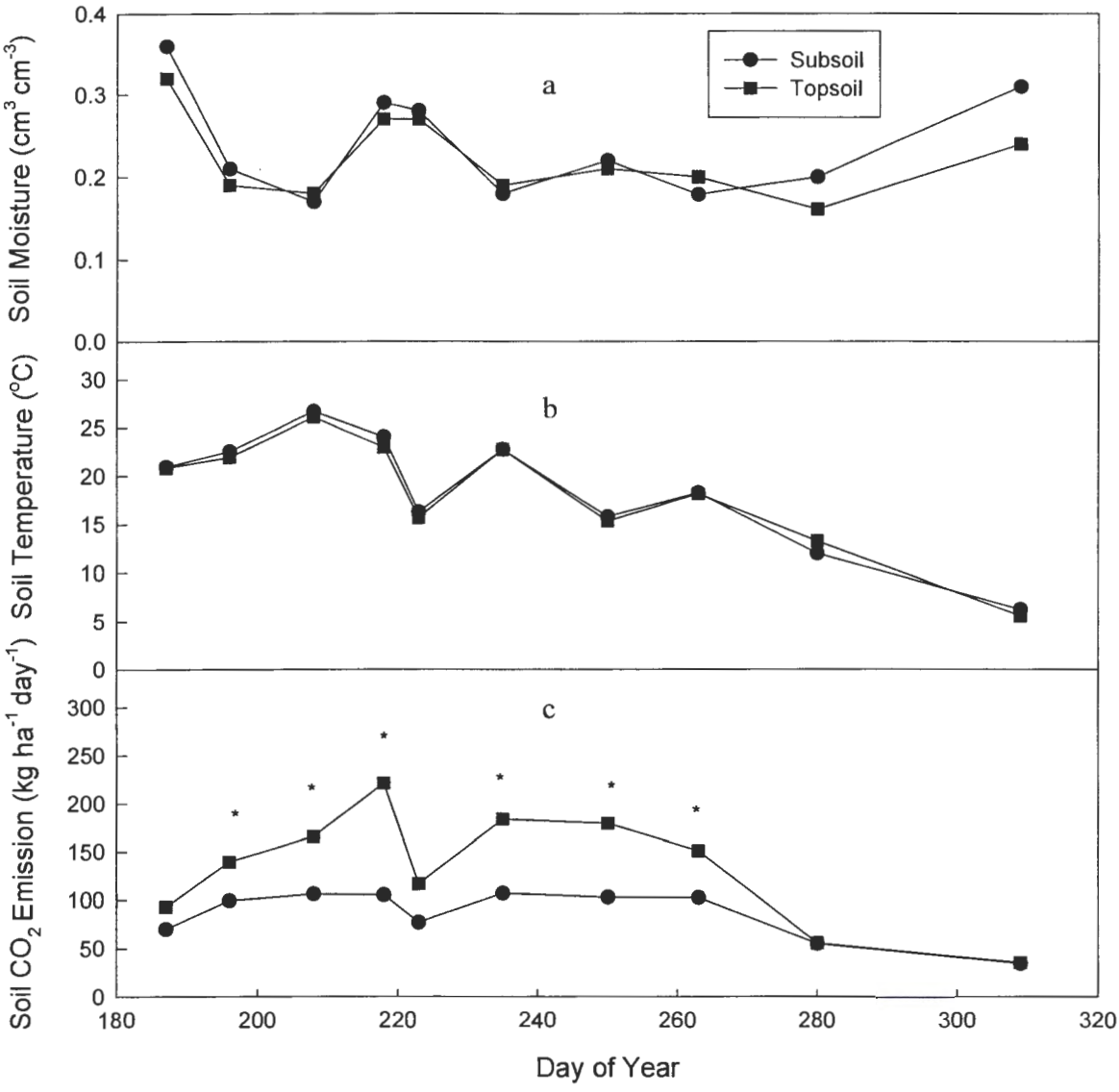

Figure 2.2. Soil moisture (a), soil temperature (b), and CO_2 emission rate (c) measured in topsoil and exposed subsoil planted to soybeans in 2004. Soil temperature and soil moisture were measured at the 5-cm depth. (*)Indicates dates where subsoil and topsoil CO_2 emission rates were different at $P \leq 0.05$.

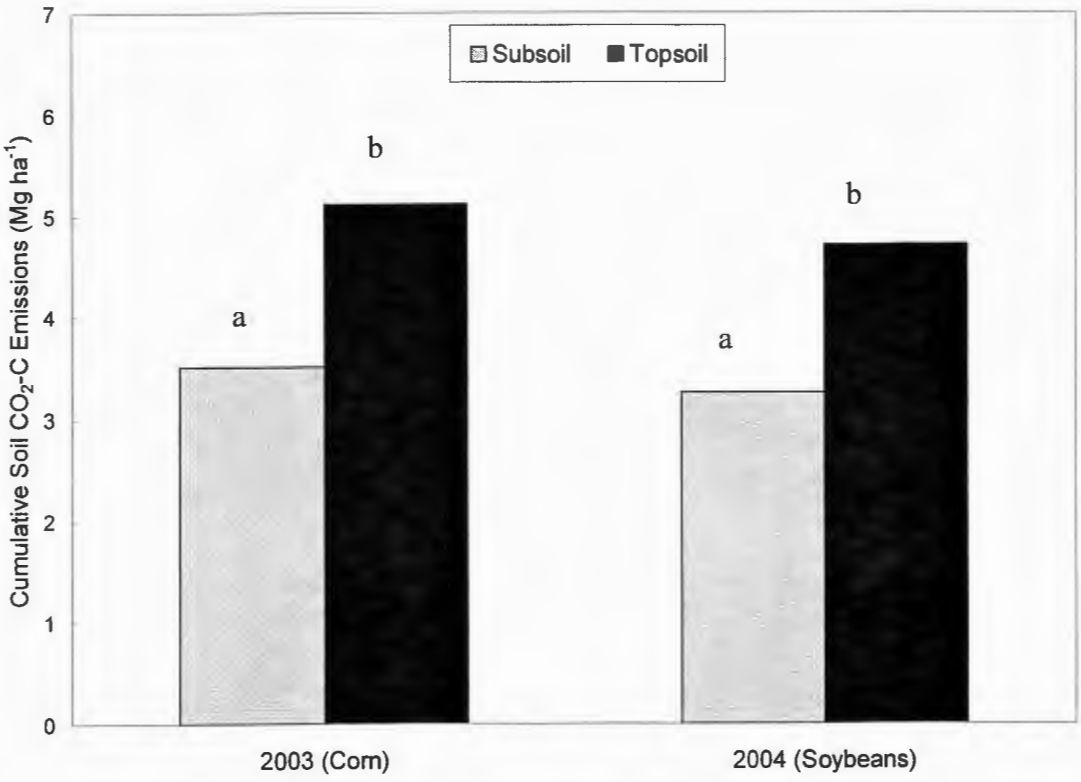

Figure 2.3. Cumulative soil CO_2–C emissions from topsoil and exposed subsoil planted to a corn-soybean rotation during the growing seasons of 2003 and 2004. Means with the same letter within each year are not different at $P \leq 0.05$.

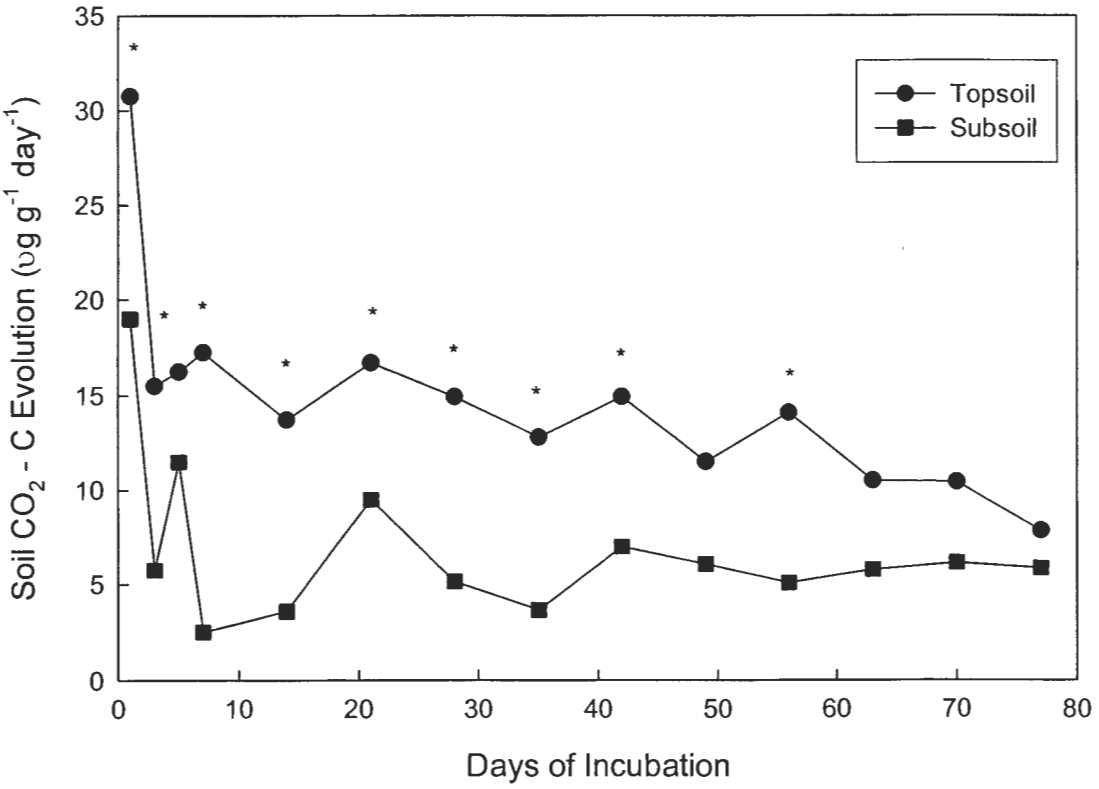

Figure 2.4. Soil CO_2 – C evolution rates from topsoil and subsoil during a 77-day laboratory incubation study. (*) Indicates days where CO_2-C evolution rates were different at $P \leq 0.05$.

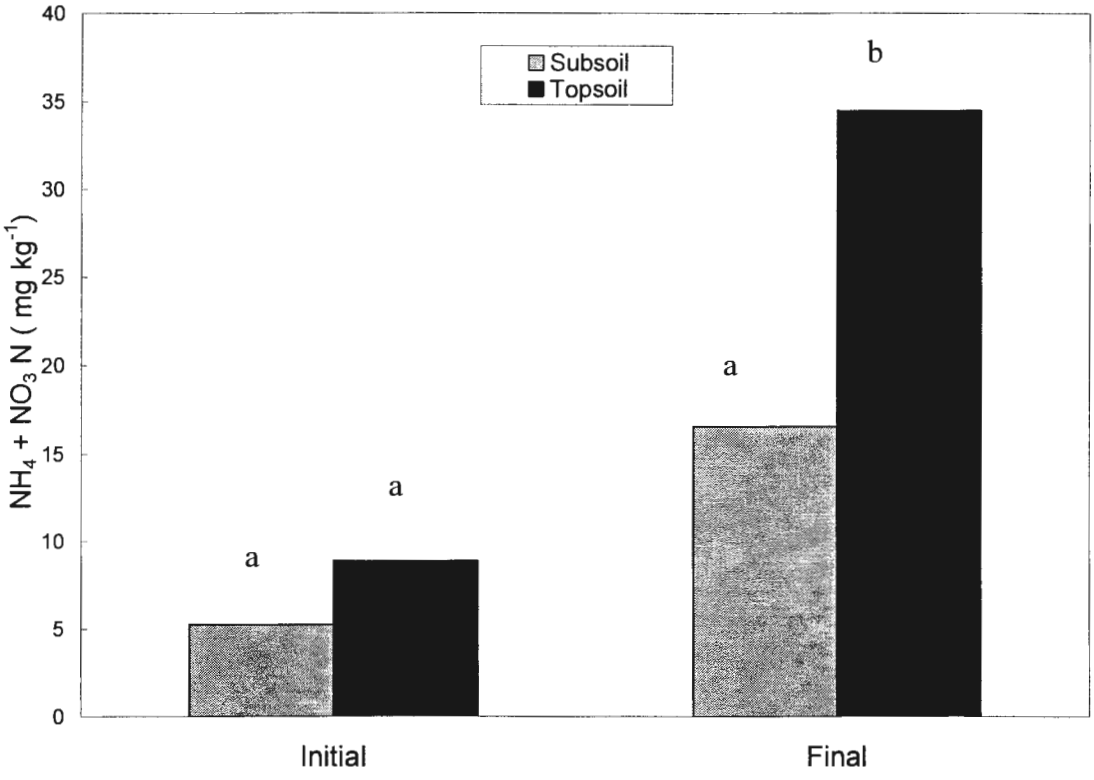

Figure 2.5. Inorganic nitrogen concentrations of topsoil and exposed subsoil planted to a corn-soybean rotation, before and after a 77-day laboratory incubation study. Means with the same letter within each sampling time are not different at $P \leq 0.05$.

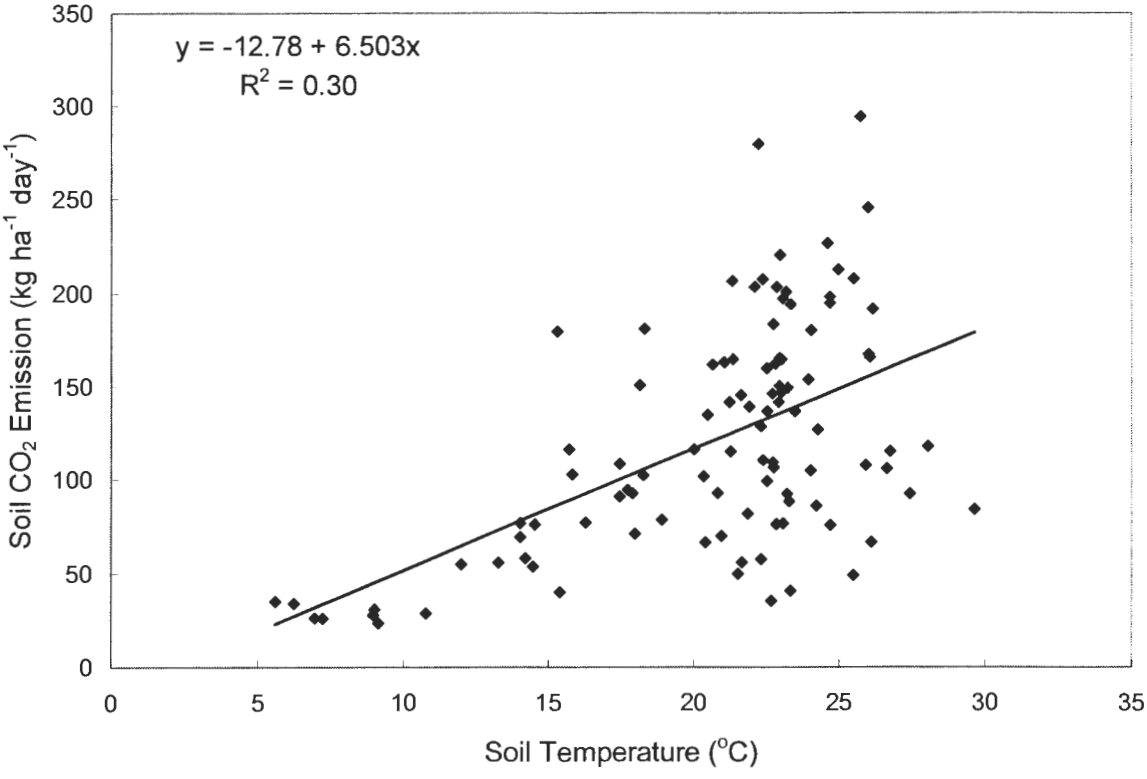

Figure 2.6. Soil CO_2 emission rate as a function of 5-cm soil temperature.

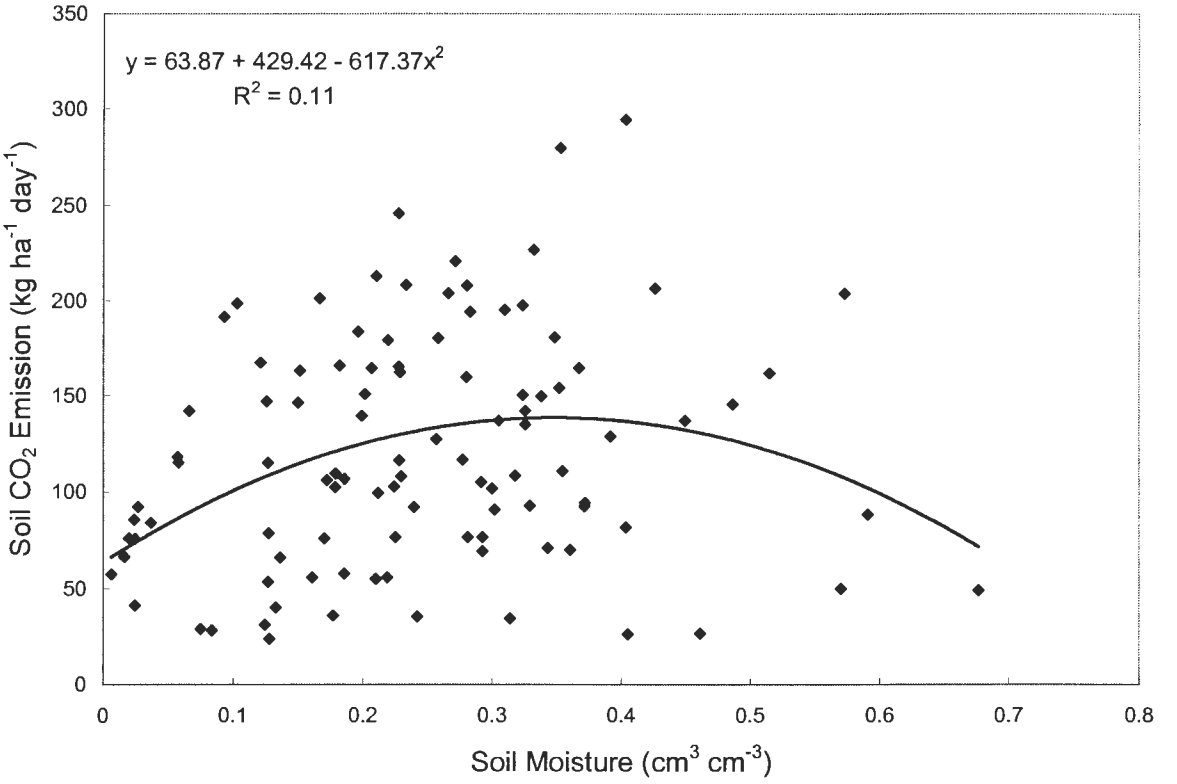

Figure 2.7. Soil CO_2 emission rate as a function of 5-cm soil moisture

CHAPTER 3

Cropping Systems Effects on Improving Soil Carbon Stocks of Exposed Subsoil

Abstract

Topsoil loss from glacial till soils exposes unproductive subsoil that is low in soil organic carbon (SOC). This study was conducted to determine whether switchgrass (*Panicum virgatum* L.) or corn (*Zea mays*)-soybean (*Glycine max* L. Merr.) cropping systems could improve the soil carbon stock and productivity of exposed subsoil. Soil CO_2 emissions, total carbon (TC) inputs from crop residue, microbial biomass carbon (MBC), and soil carbon fractions were measured during the growing seasons of 2003 and 2004 from switchgrass burned annually (SA), switchgrass burned every five years (S5), and corn soybean rotation (CS) cropping systems established on exposed subsoil near Webster City, Iowa. During both years of the study, the SA cropping system had the greatest cumulative soil CO_2-C emissions, followed by the S5 and CS cropping systems, respectively. Switchgrass cropping systems produced 3.47 and 2.33 Mg ha^{-1} more aboveground biomass than soybeans and corn, respectively. Switchgrass had a root biomass 15 Mg ha^{-1} greater than corn or soybeans. As a result potential carbon input from switchgrass residues was 6.08 and 6.71 Mg ha^{-1} greater than corn and soybeans, respectively. Microbial biomass carbon was on average 200% greater in the switchgrass cropping systems than in the corn-soybean rotation. There were no differences in SOC fractions between the three cropping systems. Switchgrass cropping systems in exposed subsoil appear to have an advantage over corn and soybeans in increasing MBC and providing greater C contribution to the soil, but not increasing SOC content.

Introduction

A removal or loss of topsoil from glacial till soils exposes infertile subsoil that is poorly suited for crop production (Olson, 1977). Subsoil is very low in soil organic carbon (SOC) content, which is a key component of soil fertility (Bauer and Black, 1994). Cropping systems that increase soil carbon could restore the productivity of degraded soils and reduce atmospheric CO_2 levels (Lal, 2004).

It is well established that perennial grasses contribute significantly to soil carbon stocks (Post and Kwon, 2000). It should also be noted that the large-scale conversion of grasslands to row crop agriculture resulted in tremendous losses of SOC (Lal et al., 1998). A significant portion of the SOC loss was associated with the particulate organic matter carbon (POMC) fraction associated with stable macroaggregates (Cambardella and Elliot, 1992). An increase in soil carbon stocks of degraded soils will depend on the productivity of the cropping system (Akala and Lal, 2001; Lal, 2004).

Liebig et al. (2004) reported that SOC contents are greater under switchgrass (*Panicum virgatum* L.) stands than cultivated croplands. The greater SOC content under switchgrass is most pronounced at deeper depths, which can be attributed to a large root biomass (Liebig et al., 2004; Ma et al., 2000a). The effectiveness of grass in improving soil C stock can partially be attributed to the slower decomposition of roots, which will increase carbon longevity in soil (Puget and Drinkwater, 2001). Therefore, even switchgrass harvested for bioenergy could potentially improve soil carbon stocks (Ma et al., 2000a; Zan et al., 2001). Additionally, root decomposition is important in aggregate formation and POMC dynamics (Gale et al., 2000; Puget and Drinkwater, 2001). The labile POMC fraction can be

a sensitive indicator of SOC change and soil quality (Cambardella and Elliot, 1992; Chan et al., 2002)

Prudent management of row crop fields can also improve soil carbon. Reduced tillage, nutrient management, and water conservation are management practices that can be implemented for carbon sequestration (Lal, 2004). Higher residue producing crops such as corn (*Zea mays*) can increase SOC better than crops that produce fewer residues, such as soybeans (*Glycine max* L. Merr.) (Paul et al., 1999).

Cropping systems can impact soil microbial biomass, which is an important component of the SOC pool and may be an early indicator of SOC changes (Powlson and Brookes, 1987). However, the microbial biomass is highly variable and difficult to quantify (Hargreaves et al., 2003). Ma et al. (2000a) found that microbial biomass carbon (MBC) content can increase as much 168% two years after switchgrass establishment on previously cropped soils It has also been found that the size of the microbial biomass pool can influence rates of soil CO_2 emission (Franzluebbers et al., 1996), but the amount of available substrate will ultimately determine the size of the MBC pool (Wang et al., 2003). Changes in residue management can alter MBC as well, and burning residues will result in a reduction of MBC (Powlson and Brookes, 1987).

The overall objective of this study was to determine whether corn-soybean or switchgrass cropping systems could improve soil carbon stocks of exposed subsoil by evaluating crop residue carbon input and soil CO_2-C output in addition to soil carbon pool improvement indicators such as, soil microbial biomass and SOC fractions.

Materials and Methods

Site Description and Management

This study was conducted on a borrow site near Webster City, Iowa during the growing seasons of 2003 and 2004. Borrow sites are areas where topsoil has been removed and subsoil mined for construction purposes. The predominant soil on this site was a Nicollet (aquic hapludolls) with a Clarion (typic haplaquoll) on the hillsides. The topsoil was removed from this 2.43 ha site in 1977 for road construction purposes. The exposed subsoil was a calcareous, un-weathered, and un-oxidized glacial till of Cary age (Khalaf, 1984). A portion of the area was converted to a research site, and three cropping system treatments were established on the exposed subsoil. The cropping systems were: (1) corn-soybean rotation (CS), (2) switchgrass burned annually (SA), and (3) switchgrass burned every five years (S5). The experimental design was a randomized complete block with 4 replications. Each plot was 9-m wide by 18-m long. Bulk densities and pH's for the three cropping system treatments are summarized in Table 3.1.

The corn-soybean rotation was established in 1978 and was managed during this study as follows: Each fall the corn-soybean plots were tilled to a depth of 40 cm with a two shank deep ripper. The deep ripper shanks were spaced 45-cm apart. In the spring, the plots were disked once at a depth of 7 cm for seedbed preparation. In 2003, Pioneer[2] 35P17 corn was planted 20 May, day of year (DOY) 140, at 45,724 seeds ha^{-1} on 76-cm row spacing. Weed control consisted of one application of 2,4-D amine at a rate of 2.33 L ha^{-1}, followed by cultivation. In 2004, Pioneer 92B38 soybeans were planted on 1 July (DOY 182) at 74 kg

[2] All trade names and product lines are mentioned solely for the benefit of readers, and do not imply endorsement by Iowa State University.

ha^{-1} on 76-cm row spacing. Weed control consisted of one application of Glyphosate at a rate of 2.32 L ha^{-1}. No Fertilizer was applied in either year.

The switchgrass cropping system treatments were Cave in Rock variety, and were established in 1980. Scheduled burnings take place in the spring, and the switchgrass burned every five years treatment was last burned in 2001. No fertilizer was applied to the switchgrass cropping systems during this study.

Field Soil CO_2 Emission Measurements

Carbon dioxide emissions from the soil surface were measured by placing the soil chamber of a LI-6400 infrared gas analyzer (LI-COR Corporation, Lincoln, NE) over polyvinyl chloride (PVC) rings that were pressed 3 cm into the soil. The PVC rings had an inside diameter of 10 cm, and 2 cm of the rings remained above the soil surface. Four PVC rings were placed near the center of each plot. For the corn-soybean rotation, two rings were placed in the crop row and two were placed between the rows. Switchgrass vegetation was clipped and removed from the inside of the rings to avoid measuring plant respiration. The mean of the four rings was considered to be the CO_2 emission rate for the entire plot. Carbon dioxide measurements were taken every 7 to 14 days from 5 June to 29 October (DOY 156 to 302) in 2003 from the corn-soybean rotation and switchgrass treatments. In 2004, soil CO_2 measurements were taken in the switchgrass treatments from 22 May to 5 November (DOY 142 to 309), and in the corn-soybean rotation from 6 July to 5 November (DOY 187 to 309) because of a delay in soybean planting. All CO_2 measurements were taken between the hours of 10:00 am and 2:00 pm. No measurements were taken for 48 hours following the row cultivation in 2003. Soil temperature and soil moisture at the 5-cm depth were measured concurrently with CO_2 measurements. Soil temperature was measured with a thermometer

attached to the LI-6400, and volumetric soil moisture was measured with a TRIME-FM Time Domain Reflectometry device (Mesa Corp, Medfield, MA).

Cumulative CO_2 emissions for the growing season were calculated as follows:

$$\text{Cumulative } CO_2 \text{ (kg ha}^{-1}) = \sum_{i=\text{first}}^{n=\text{last}} X_i + X_{i+1} * N + X_{i+2} * N \ldots + X_{i+n} * N \quad (1)$$

where, X is CO_2 emission rate (kg ha^{-1} d^{-1}), (n) is the last CO_2 measurement during the growing season, (i) is the first CO_2 measurement in the season, and N is Number of days between two consecutive CO_2 rate measurements. Cumulative soil CO_2 emissions were then converted to Mg ha^{-1} of CO_2-C.

Soil Microbial Biomass Carbon

Soil samples for soil MBC determination were taken from all of the cropping systems in 2004 when the row crop treatment reached the V_6 development stage. A composite soil sample of ten cores was taken from each plot at a depth of 15-cm. The soil samples were brought back to the laboratory, 4 mm sieved, and stored in a 4°C cold room overnight. Soil microbial biomass carbon was determined by performing the fumigation extraction method (Horwath and Paul, 1994). Fifty-gram moist soil samples of the three cropping systems treatments were fumigated with ethanol-free $CHCl_3$ for 24 h in a vacuum desiccator. The soil samples were extracted for 30 min with 100 ml of 0.5 M K_2SO_4 and then filtered through Whatman No. 42 filter paper (Whatman International Ltd., Maidstone, UK). Non-fumigated soil samples were extracted the same way while the others were being set up for fumigation. Extractant alone was also filtered to determine the background level of C in the filter paper and extractant. Carbon recovered in the extract was determined with a Shimadzu TOC-5050

carbon analyzer (Rydalmere, New South Wales, Australia). Microbial biomass carbon was calculated on an oven dry weight basis.

Laboratory Soil Incubation

The remainder of soil from the samples collected for microbial biomass analysis was used for laboratory soil incubation. A static incubation-titrimetric procedure (Zibliske, 1994) was used for this experiment. The soil samples were taken out of the cold room, 2 mm sieved, and allowed to air dry. Twenty-gram of each soil sample was weighed into 20 ml borosilicate vials. Approximately seven grams of water was added to the vials to achieve 60% water filled pore space. Each vial with soil was placed into a 0.9 L wide mouth glass jar along with a 10 ml scintillation vial containing 1.0 ml of 2 N NaOH as a base trap. Approximately, 3-5 ml of water was added to the glass jars in order to maintain proper humidity levels. The lids of the glass jars were twisted closed to completely seal the contents from the outside atmosphere. A base trap was also placed in a jar that contained no soil, to act as a control (blank). The glass jars were then placed in a dark incubation room at 30° C. The amount of CO_2-C evolved was determined by titration. Two-ml of 1 M BaCl, and 2-3 drops of phenolphthalein were added to the base traps. One N HCL was then added with a digital micro burette until the indicator showed neutral pH. After titration, a new base trap was added to each jar. Titrations were performed on days 1, 3, 5, 7, 14, 21, 28, 35, 42, 49, 56, 63, and 77.

Soil inorganic N (NO_3-N and NH_4-N) concentration was determined prior to and after the incubation period using the KCl extraction method (Mulvaney, 1996). Ten-grams of soil was extracted with 50 ml of 2M KCl for 30 min. The supernatant was then filtered through

Whatman number 42 filter paper. Inorganic N concentration of the filtrate was measured with a Lachat QuickChem 8000 FIA+ (Lachat Instruments, Milwaukee, WI).

Soil Organic Carbon and Soil Total Nitrogen Determination

In the spring of 2003 and 2004, soil samples were collected from all of the cropping system treatments at depth increments of 0-15, 15-30, 30-45, and 45-60-cm. A composite soil sample consisting of 10 cores was taken from each depth within each treatment using a soil probe with an inside diameter of 1.9 cm. Additionally, soil samples were taken from four fallow areas for baseline information. Soil samples were placed in a -4°C freezer until soil analysis was preformed. Soil samples for bulk density determination were taken at the same time and depth increments according to the procedure outlined by Doran and Mielke (1984).

Prior to conducting soil C analysis, the soil samples were defrosted, 2 mm sieved, and allowed to air dry. Two 10-g soil sub-samples were weighed out from each soil sample. The first soil sub-sample was ground with a mortar and pestle and analyzed for SOC and soil total nitrogen (STN) contents by dry combustion using a LECO CHN 2000 analyzer (LECO Corporation, St. Joseph, MI). The second soil sub-sample was used in the soil POMC fractionation procedure (Cambardella and Elliot, 1992; Kruse, 2005). The soil sub-sample was dispersed with sodium metaphosphate solution and passed through a 53-μm sieve. The water was evaporated from the slurry that passed through the sieve by placing it in a forced air oven at 50°C for 72 hours. The dried soil slurry was ground and analyzed for associated mineral fraction carbon (MFC) with the LECO analyzer. Particulate organic matter carbon was calculated by subtracting MFC content from SOC content.

Soil pH was determined using a 1:1 (soil/water) dilution. If soil pH was greater than 7.1, inorganic carbon content was determined using a modified pressure calcimeter method (Sherrod et al., 2002) and subtracted from the soil total carbon content values determined initially by the LECO CHN analyzer.

The C content of each fraction was calculated on an equivalent soil mass basis by using the bulk density.

Potential Total Carbon and Total Nitrogen Input from Aboveground Crop Biomass

Crop residue was collected each fall from all of the cropping systems after mechanical harvest of the row crop was completed. A one-m^2 frame was randomly placed in the center of each plot, and the entire residue within the frame was collected and placed in mesh bags. In order to collect residue from the switchgrass cropping systems, all of the biomass within the frame was clipped at the soil surface and then collected. Residue from all cropping systems was dried at 64°C for seven days, weighed, and then ground through a 2-mm screen using a Wiley Mill Model 2 grinder (Arthur H. Thomas Co., Philadelphia, PA). Crop residue total C and N concentrations were determined using the LECO CHN analyzer, and the values were multiplied by the biomass to determine potential total C and total N inputs.

Potential Total Carbon and Total Nitrogen Input from Crop Root Biomass

Root biomass samples were taken when the row crop treatment reached R_1 growth stage. Corn root samples in 2003 were obtained by excavating all roots from the top 30 cm of soil in a 1-m section of crop row near the center of each plot. Switchgrass root samples in 2003 were obtained by placing the one-m^2 frame on the ground, removing the vegetation, and then excavating all of the roots in the top 30-cm of soil. All roots were taken back to the

laboratory and soaked in water for 24 hours. After soaking, they were scrubbed and rinsed of any excess soil, then placed in a 64°C forced air dryer for seven days. After drying, the corn and switchgrass roots were weighed, ground with the Wiley Mill, and analyzed for total C and total N with the LECO CHN analyzer.

Corn root weight density in 2003 was calculated as follows:

$$RWD = RDM / (RL * RW * D) \quad (2)$$

where, RWD is root weight density (g cm^{-3}), RDM is root dry matter (g), RL is row length (cm), RW is row width (cm), and D is depth (cm).

Switchgrass root weight density in 2003 was calculated using equation 2 by substituting the dimensions (one meter by one meter) of the frame for RL and RW.

Soil cores for soybean and switchgrass root biomass determination in 2004 were obtained by clipping the respective vegetation at the soil surface, and then taking three 6.3 cm diameter soil cores 30-cm deep from each plot. The soybean cores were taken from the row. The switchgrass and soybean root samples were taken to the laboratory and stored in a -4°C freezer until they were washed with a hydropneumatic elutriation system (Smucker et al., 1982). Soybean and switchgrass roots were dried in a 64°C forced air oven for seven days, weighed, ground with the Wiley Mill, and analyzed for TC and TN with the LECO CHN analyzer.

Soybean and switchgrass root weight densities in 2004 were calculated as follows:

$$RWD = RDM / (\pi * CR^2 * D) \quad (3)$$

where, CR is core radius (cm), and other terms are the same as in equation 2.

Switchgrass, corn, and soybean root biomass was calculated as follows:

$$RB = RWD * D * 100 \quad (4)$$

where, RB is root biomass (Mg ha^{-1}), 100 is a conversion factor for area and mass, and other terms are the same as in equation 2.

The total C and total N concentrations determined by the LECO were multiplied by the root biomasses to determine potential total C and total N inputs.

Statistical Analysis

All experiments were analyzed as randomized complete blocks with three replications. Cropping systems were treated as fixed factors and replications were treated as random. A mixed model procedure with repeated measures was used for the daily field soil CO_2 emission rate analysis of variance (SAS Inst., 2005). The repeated factor was day and the subject was the interaction of replication and soil depth. A compound symmetry covariance structure was used for the repeated measures. All other experiments were analyzed with the general linear models (GLM) procedure of SAS. An alpha level of 0.05 was used for all comparisons. Two different methods of sample collection were used for root biomass each year, and the switchgrass cropping systems were the only treatments sampled both ways. Therefore, the two sampling methods were compared using the switchgrass data in paired t-tests and mean separation comparisons to asses any differences in root weight density estimation.

Results and Discussion

Field Soil CO_2 Emissions

During the 2003 growing season, the two switchgrass cropping systems had greater daily soil CO_2 emission rates than the CS cropping system, which was corn, 8 out of 13 sampling dates (Fig. 3.1c). Additionally, the switchgrass burned annually (SA) cropping system had greater soil CO_2 emission rates than the switchgrass burned every five years (S5) cropping system on DOY 156 and 163 (Fig 3.1c). During the 2004 growing season, soil CO_2 emissions were the greatest from the SA cropping system 40% of the sampling dates (Fig. 3.2c). The CS cropping system, which was soybeans, and the S5 cropping system had similar rates of soil CO_2 emission, except on DOY 196 and 208 (Fig 3.2c). Both years, soil CO_2 emissions were similar from all of the cropping system treatments once soil temperatures began to cool, with the exception being DOY 260 in 2003 (Figs. 3.1b&c and 3.2 b&c). These results are similar to Tufekcioglu et al. (1999), who found greater rates of soil respiration from switchgrass in riparian buffers than nearby row crop fields.

The differences between soil CO_2 emission rates of the CS cropping system and switchgrass cropping systems in 2003 were greatest early in the growing season (Fig. 3.1c). This could be due to the fact that annual crops have small root systems at the beginning of their life cycle. The brief period of extremely dry soil conditions in the CS cropping system also could have delayed development of the corn root system. The unexpected late planting of the soybeans in 2004 prevented early season measurements, but initial soil CO_2 emissions from the soybeans once they were established, were significantly less than the switchgrass cropping systems (Fig. 3.2c).

Both years, cumulative CO_2-C emissions were the greatest from the SA cropping system, followed by the S5 and CS cropping systems, respectively (Fig. 3.3). Even though the soybeans were planted late in 2004, cumulative soil CO_2-C emissions were similar to the corn in 2003 (Fig 3.3). The greater cumulative soil CO_2-C can be attributed to the larger root biomass (Table 3.2), and greater MBC content of the switchgrass cropping systems. Microbial biomass carbon content of the CS cropping system was approximately half that of the switchgrass cropping systems (Fig 3.4). Additionally, the S5 cropping system had 20% more MBC than the SA cropping system. Ma et al. (2000a) also found greater MBC in switchgrass cropping systems compared to row crops. The larger MBC content of the S5 cropping system could be due to the greater amount of detritus on the soil surface, because of less frequent burning. Powlson and Brookes (1987) also found less MBC in crops that annually had the aboveground biomass burned.

The results of the laboratory soil incubation support the field soil CO_2 findings. The SA and S5 cropping systems had greater rates of CO_2-C evolution than the CS cropping system from day 3 to 35 (Fig. 3.5). After day 35, CO_2-C evolution rates were similar for all cropping system treatments (Fig. 3.5). Rates of CO_2-C evolution were similar from the SA and S5 cropping systems during the entire incubation period (Fig. 3.6). Cumulative CO_2-C evolutions from the SA and S5 cropping systems were almost two times greater than CO_2-C evolutions from the CS cropping system (Fig. 3.6). Prior to soil incubation, the CS cropping system had a greater inorganic N content than the switchgrass cropping systems, but after incubation, inorganic N contents were similar for all of the cropping systems (Fig. 3.7).

Potential Total C and Total N Inputs from Aboveground and Root Biomass

Analysis of variance showed no difference between the two switchgrass cropping systems for aboveground and root biomasses across years; therefore, the mean of both switchgrass cropping system treatments was compared with the corn-soybean rotation. Statistical analysis also showed no difference between the two methods of root biomass sample collection. Additionally, aboveground biomass potential TC inputs from the SA cropping system cannot be calculated.

The unfavorable growing conditions of the subsoil resulted in poor aboveground biomass production of the switchgrass, corn, and soybeans. Switchgrass produced 3.47 and 2.33 Mg ha^{-1} more aboveground biomass than soybeans and corn, respectively (Table 3.2). Our aboveground biomass values (Table 3.2) are considerably lower than those reported for the same cropping systems in topsoil by Tufekcioglu et al. (2003). Even though switchgrass aboveground biomass production was impaired by the growing conditions, the root system did not appear to be. Root biomass of the switchgrass was 15.13 Mg ha^{-1}, which was over 8 Mg ha^{-1} greater than its aboveground biomass production. Switchgrass root biomass was also considerably greater than the root biomass of corn or soybeans (Table 3.2). Ma et al. (2000b) also found root the biomass of switchgrass to be quite large, up to 28 Mg ha^{-1} in some soils. Root biomass was only calculated to 30 cm in this study because root biomass past 30 cm was negligible in all of the cropping systems. Tufekcioglu et al. (2003) also found that up to 73% of root biomass could be found in the top 35 cm of soil. The high bulk density of the subsoil (Table 3.1) in our study likely contributed to almost the entire root system being in the top 30 cm.

Corn aboveground biomass had the greatest C:N ratio, followed by switchgrass and then soybeans (Table 3.2). Carbon to nitrogen ratios of the root biomasses followed the same trend as the aboveground biomasses (Table 3.2). Tufekcioglu et al. (2003) also found soybean aboveground and root biomasses to have the lowest C:N ratios but found greater C:N ratios in switchgrass biomasses than corn biomasses. The corn in their study received N fertilization, whereas ours did not.

The total (aboveground + root) potential TC input was greater from switchgrass than from corn or soybeans, due in large part to the massive root biomass of the switchgrass (Table 3.2). Several other investigators (e.g. Liebig et al., 2004; Ma et al., 2000a; Ma et al., 2000b) have also suggested that the large root system of switchgrass is a key component of carbon input and accumulation.

Soil Organic Carbon and Soil Total Nitrogen

Analysis of variance showed no change in SOC over the two years; therefore, the data were combined for the final analysis.

Soil organic carbon, associated MFC and POMC contents were similar for all cropping systems across all soil depths (Table 3.3). This is in contrast to the findings of Liebig (2004) who found greater SOC content in switchgrass stands compared to crop fields. One explanation is that this study was conducted on very poor soil, and aboveground biomass production was limited. Additionally, the scheduled burnings of the switchgrass cropping system treatments removed new and decaying detritus. Zan et al. (2001) also concluded that carbon accumulation under switchgrass stands is highly dependent on site conditions, and greater C accumulation can be expected on more fertile sites. Ma et al. (2000a) concluded that changes in SOC under switchgrass occur much slower than increases

in MBC and soil CO_2-C emossions. Additionally, they concluded that soil texture could control soil C fractions, as they found no increases in any of their parameters in soils with high clay content.

The S5 cropping system had greater STN content and lower C:N ratios than the SA and CS cropping systems in the 15-60 cm soil depths (Table 3.4). However, all of the cropping systems had similar STN content and the S5 cropping system had a greater C:N ratio in the 0-15 cm soil depth (Table 3.4). This could be due to the greater amount of decaying detritus on the soil surface in the S5 cropping system. Powlson and Brookes (1987) also found less STN in cropping systems where residue is annually burned.

Conclusions

Aboveground biomass production of switchgrass and corn-soybean cropping systems is impaired by the poor growing conditions of subsoil. Switchgrass can produce a large root biomass in subsoil, but it is limited in depth. Switchgrass cropping systems can contribute greater carbon input to the soil than a corn-soybean rotation, primarily due to its large root system. Switchgrass cropping systems improved subsoil MBC by approximately 200% over corn and soybeans.

Larger root systems and greater MBC cause greater cumulative soil CO_2 emissions from switchgrass cropping systems in subsoil, than corn-soybean rotations in subsoil. The larger MBC pool also leads to greater C mineralization from subsoil in switchgrass cropping systems compared to corn-soybean rotations in subsoil.

Twenty-five years after establishment of these cropping systems on exposed subsoil, there are no significant differences in soil C fractions between the cropping systems, regardless of the greater potential C inputs from switchgrass. This suggests that C

accumulates very slowly compared to increases in MBC, and the properties of subsoil may play a significant role in soil carbon dynamics. Additionally, the burning of the switchgrass likely disrupts the soil C dynamics.

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Table 3.1. Bulk density and pH of exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every five years (S5) and corn-soybean rotation (CS) cropping systems in the 60-cm soil profile.

	pH				Bulk Density (g cm^{-3})			
	Soil depth (cm)				Soil depth (cm)			
Cropping System	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60
SA	7.66	7.52	7.48	7.47	1.29	1.70	1.75	1.71
S5	7.65	7.47	7.42	7.40	1.30	1.64	1.68	1.70
CS	7.69	7.49	7.43	7.43	1.40	1.66	1.72	1.77

Table 3.2. Total carbon (TC) and total nitrogen (TN) inputs from aboveground and root biomass of switchgrass, corn, and soybeans grown in exposed subsoil. Root biomass was measured to 30-cm. Potential TC and TN inputs and carbon to nitrogen ratios were calculated using the C and N concentrations of the respective biomass.

	Aboveground				Root				Total Inputs	
		Input				Input			Root + Aboveground	
Treatment	Biomass	TC	TN	C:N	Biomass	TC	TN	C:N	TC	TN
	Mg ha^{-1}	------Mg ha^{-1}------			Mg ha^{-1}	------Mg ha^{-1}------			--------Mg ha^{-1}--------	
Corn	4.37a*	1.83a	0.02a	109.2a	1.33a	0.49a	0.01a	71.5a	2.32a	0.03a
Soybeans	3.23a	1.40a	0.06a	22.9b	0.76a	0.29a	0.01a	21.8b	1.69a	0.07a
Switchgrass	6.70b	2.84b	0.05a	72.3c	15.13b	5.56b	0.12a	47.5c	8.40b	0.17

*Means with the same letter within each column are not different at $P \leq 0.05$.

Table 3.3. Soil organic carbon (SOC), associated mineral fraction carbon (MFC), and particulate organic matter carbon (POMC) contents of exposed subsoil planted to corn-soybean rotation (CS), switchgrass burned annually (SA), and switchgrass burned every five years (S5) cropping systems, for the 0 to 60-cm soil profile.

	SOC				MFC				POMC			
	Soil depth (cm)				Soil depth (cm)				Soil depth (cm)			
Treatment	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60
	Mg ha^{-1}											
CS	19.38a*	19.35a	22.09a	24.61a	12.15a	13.81a	13.42a	13.21a	7.23a	5.54a	8.67a	11.40a
SA	20.36a	21.27a	23.03a	21.51a	13.51a	12.56a	12.56a	12.75a	6.85a	8.71a	10.47a	8.76a
S5	25.87a	22.99a	22.38a	24.28a	13.65a	12.30a	14.34a	13.86a	12.22a	10.69a	8.04a	10.42a
Control†	2.85	0.66	1.40	0.70	1.80	2.02	2.90	2.51	1.05	0.00	0.00	0.00

*Means with the same letter within each sample depth are not different at $P \leq 0.05$.

†The soil carbon fractions of the control were determined in order to estimate soil carbon content prior to treatment initiation.

Table 3.4. Soil organic carbon (SOC), soil total nitrogen (STN) contents, and C:N ratios of exposed subsoil planted to three cropping system treatments for the 0 to 60-cm soil profile.

	SOC				STN				C:N			
	Soil depth (cm)				Soil depth (cm)				Soil depth (cm)			
Treatment	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60	0-15	15-30	30-45	45-60
	---------- Mg ha^{-1} ----------											
CS	19.38a	19.35a	22.09a	24.61a	3.39a	4.38a	3.32a	3.58a	5.71a	4.41a	6.65a	6.87a
SA	20.36a	21.27a	23.03a	21.51a	3.59a	4.07a	2.79a	2.79a	5.67a	5.22a	8.25a	7.71a
S5	25.87a	22.99a	22.38a	24.28a	3.01a	6.23b	6.21b	6.19b	8.59b	3.69b	3.61b	3.92b
Control[†]	2.85	*0.66*	1.40	0.70	0.27	0.24	0.15	0.21	10.55	2.72	9.33	3.33

[*]Means with the same letter within each sample depth are not different at $P \leq 0.05$.

[†]The soil organic carbon and soil total nitrogen contents of the control were determined in order to estimate soil carbon and nitrogen content prior to treatment initiation.

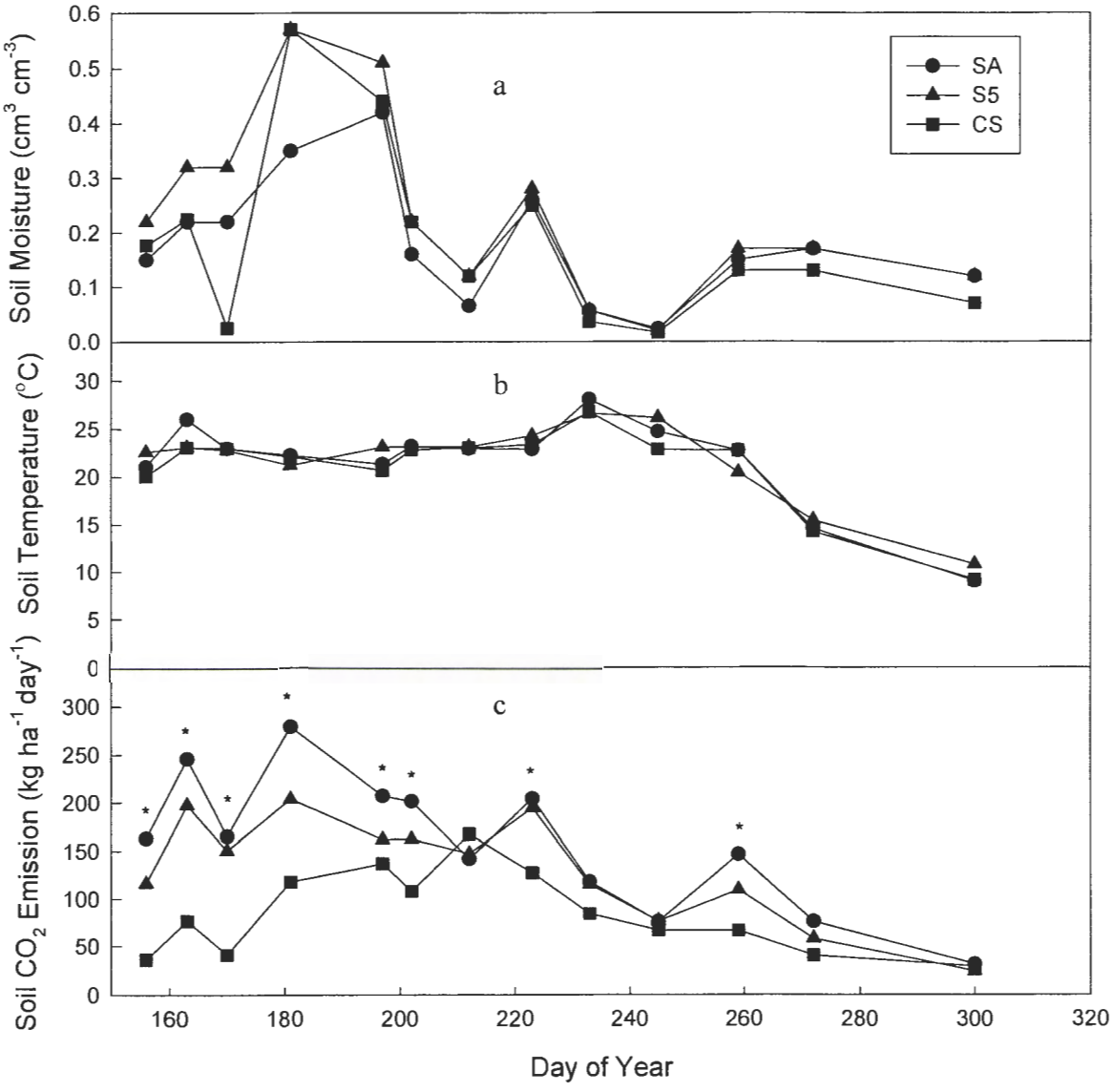

Figure 3.1. Soil moisture (a), soil temperature (b), and CO_2 emission rate (c) measured in exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every 5 years (S5), and corn in corn-soybean rotation (CS) in 2003. Soil temperature and soil moisture were measured at the 5-cm depth. (*)Indicates dates where CO_2 emissions were different at $P \leq 0.05$.

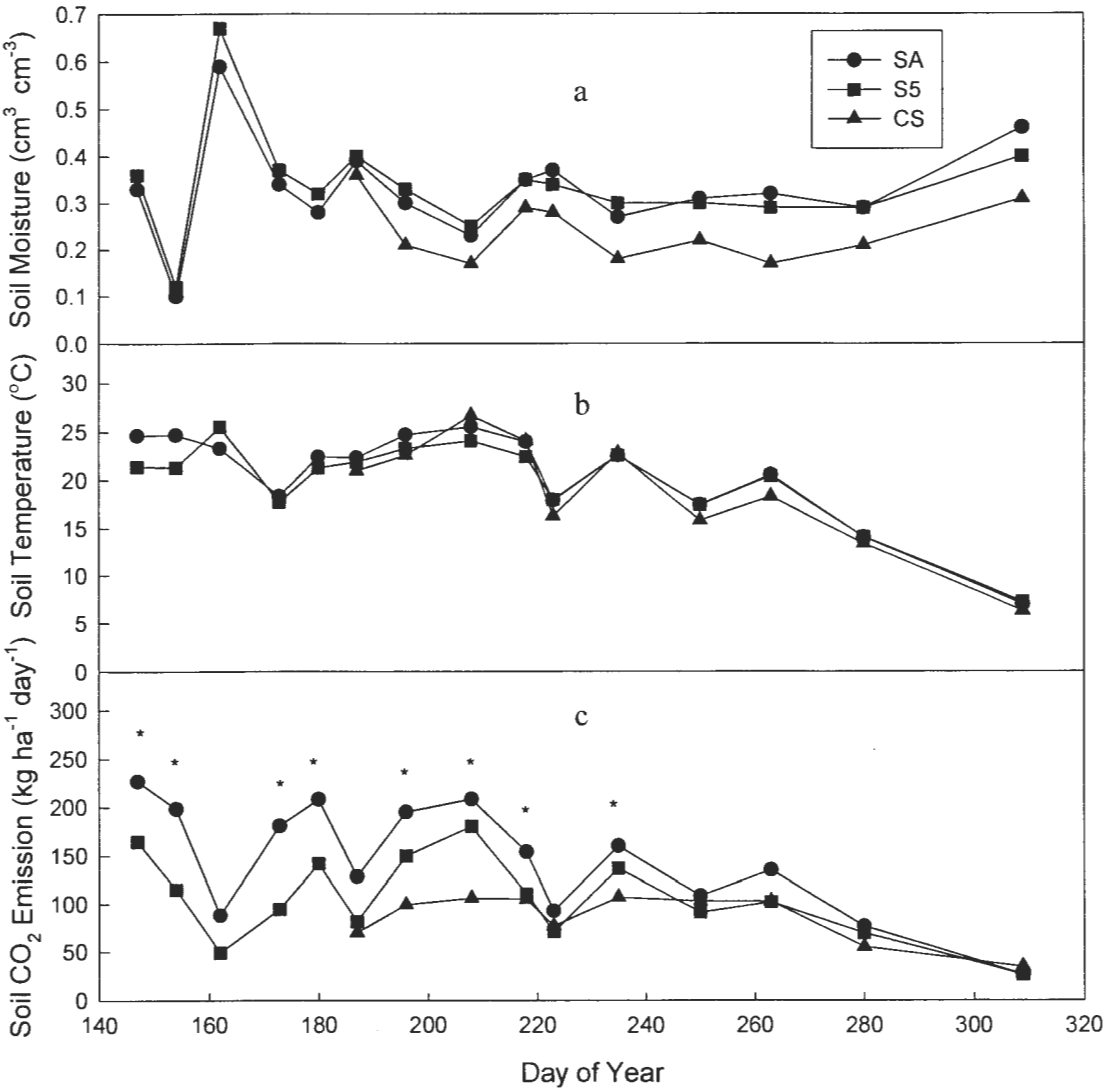

Figure 3.2. Soil moisture (a), soil temperature (b), and CO_2 emission rate (c) measured in exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every 5 years (S5), and soybean in corn-soybean rotation (CS) in 2004. Soil temperature and soil moisture were measured at the 5-cm depth. (*)Indicates dates where CO_2 emissions were different at $P \leq 0.05$.

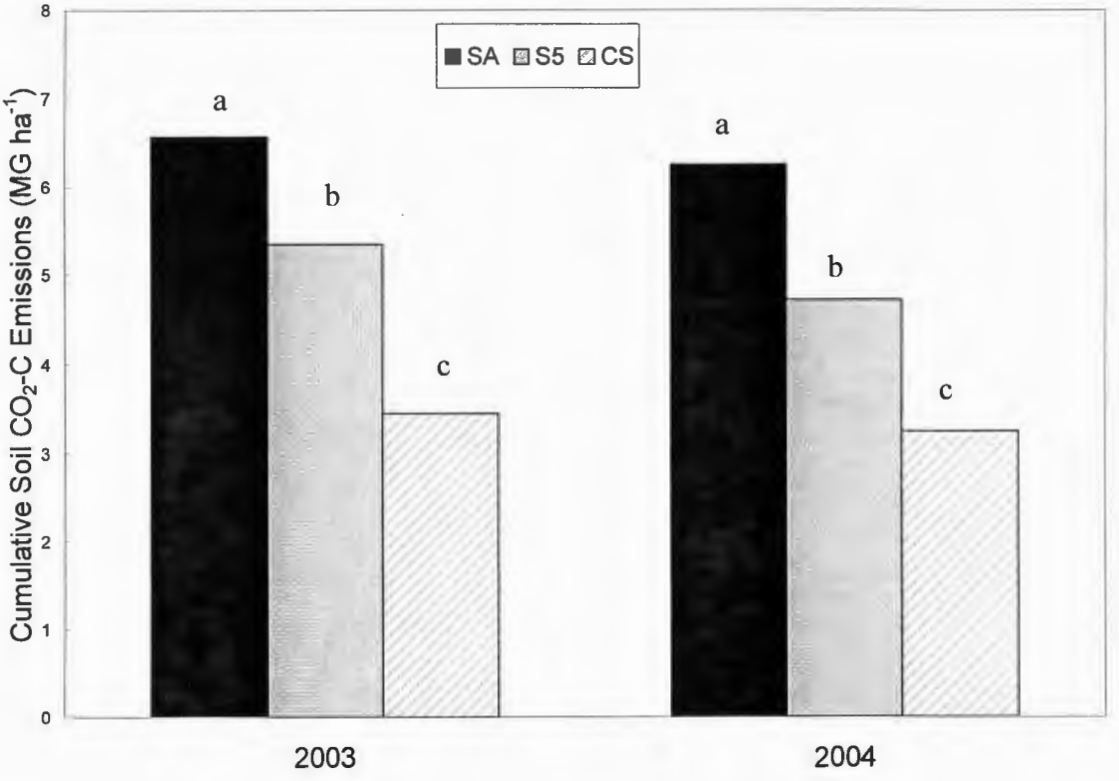

Figure 3.3. Cumulative soil CO_2–C emissions from exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every five years (S-5), and corn-soybean rotation (CS) cropping systems during the growing seasons of 2003 and 2004. The Corn-soybean rotation was corn in 2003 and soybeans in 2004. Means with the same letter within each year are not different at $P \leq 0.05$.

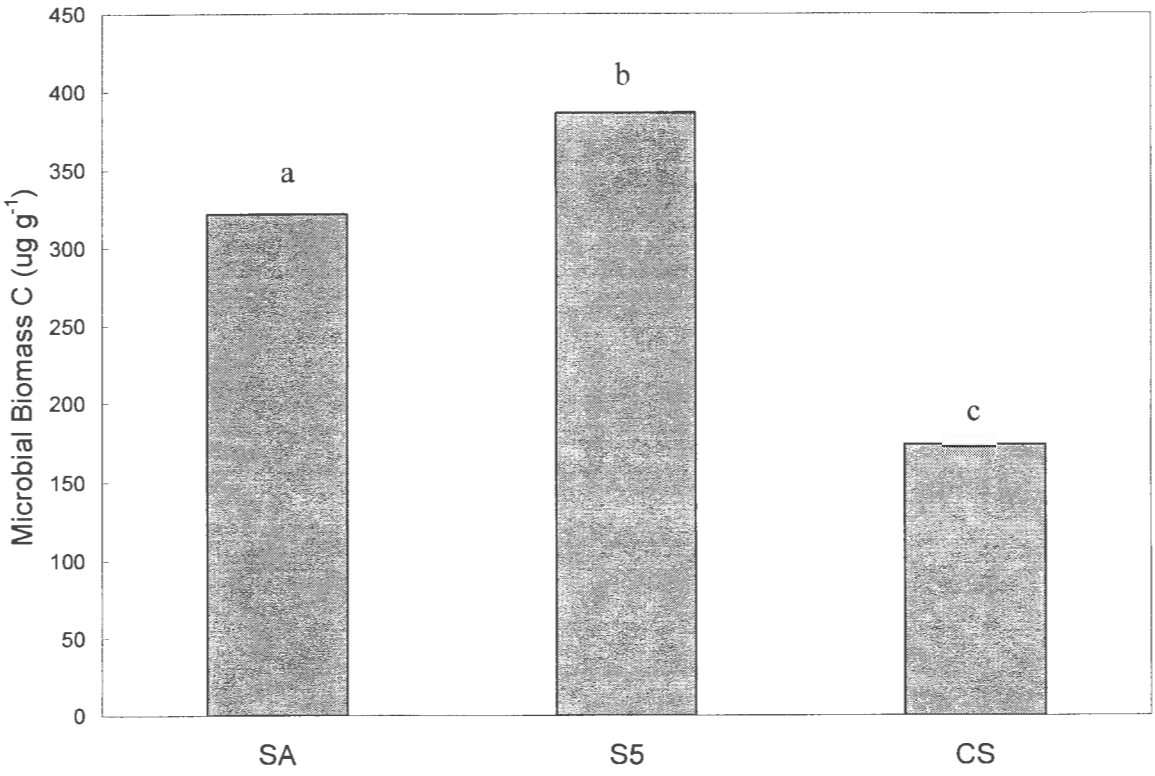

Figure 3.4. Microbial biomass carbon content in the 0-15 cm soil depth of exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every five years (S-5), and corn-soybean rotation (CS) cropping systems. The corn-soybean rotation was soybeans when the field was sampled. Means with the same letter are not different at $P \leq 0.05$.

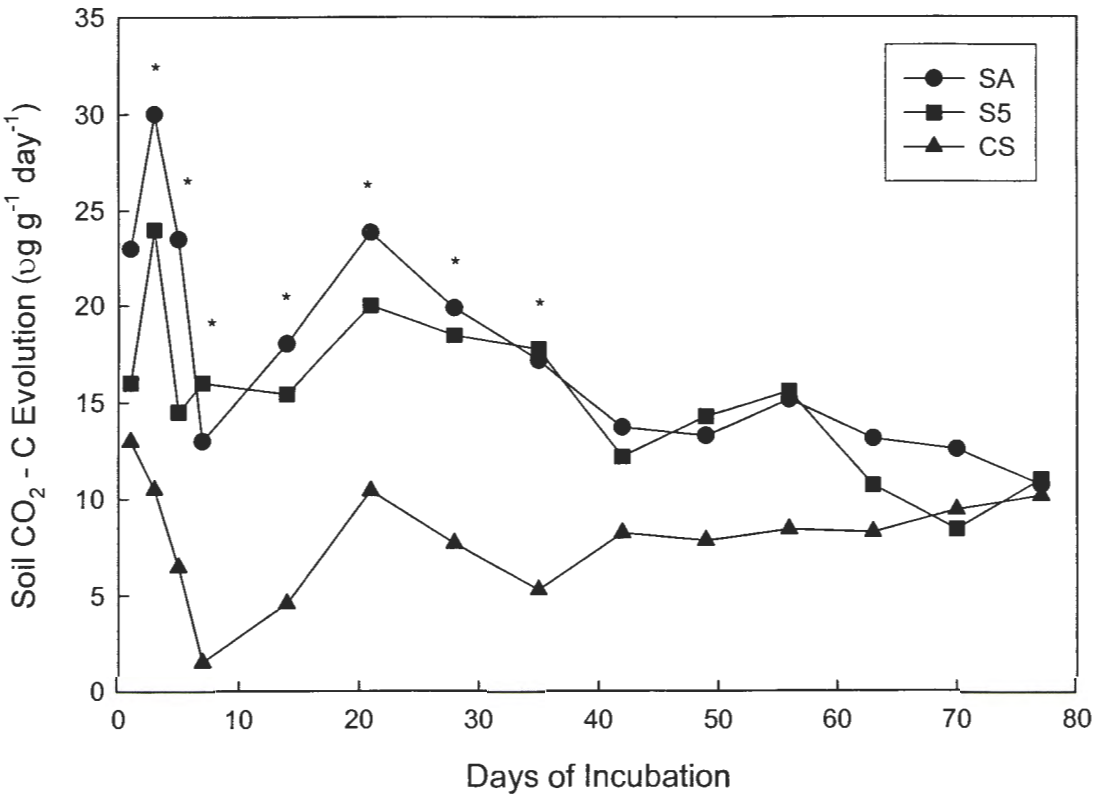

Figure 3.5. Soil CO_2 - C evolution rates of subsoil planted to switchgrass burned annually (SA), switchgrass burned every five years (S-5), and corn-soybean rotation (CS) cropping systems during a 77 day laboratory incubation study. (*)Indicates days where CO_2 emissions were different at $P \leq 0.05$.

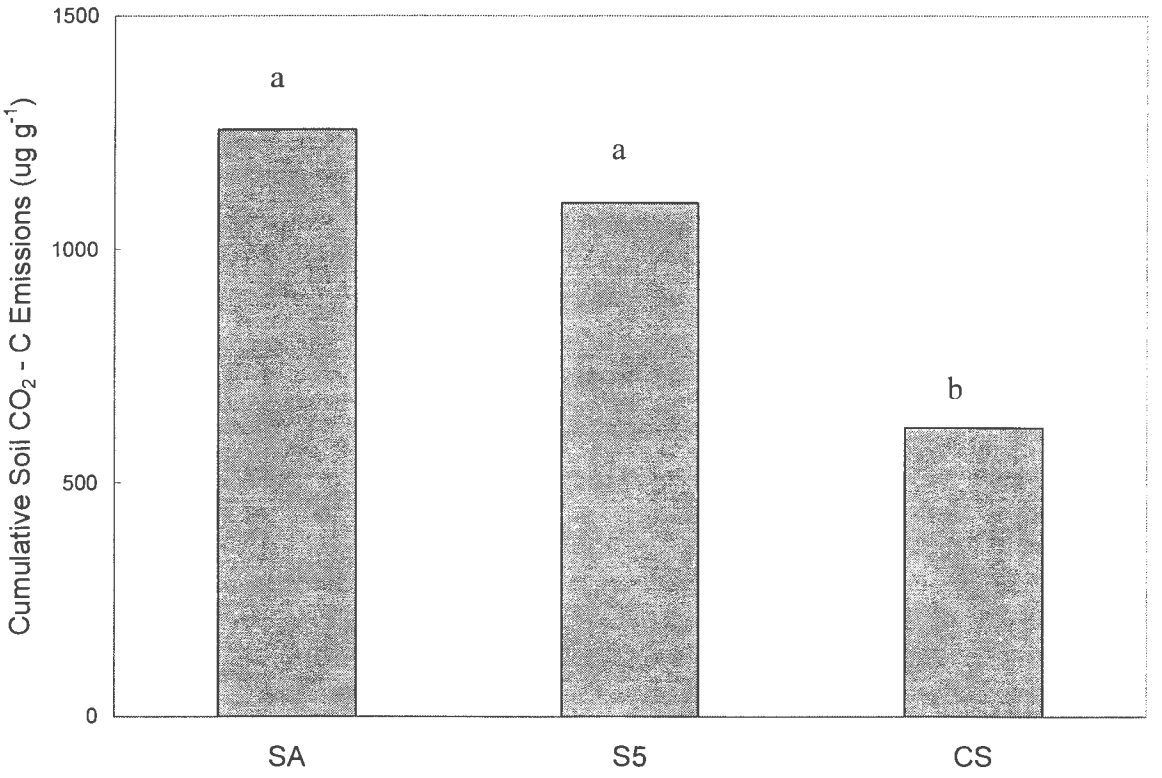

Figure 3.6. Cumulative soil CO_2-C emissions from exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every five years (S-5), and corn-soybean rotation (CS) cropping systems after a 77 day laboratory incubation study. The corn-soybean rotation was soybeans when the field was sampled. Means with the same letter are not different at $P \leq 0.05$.

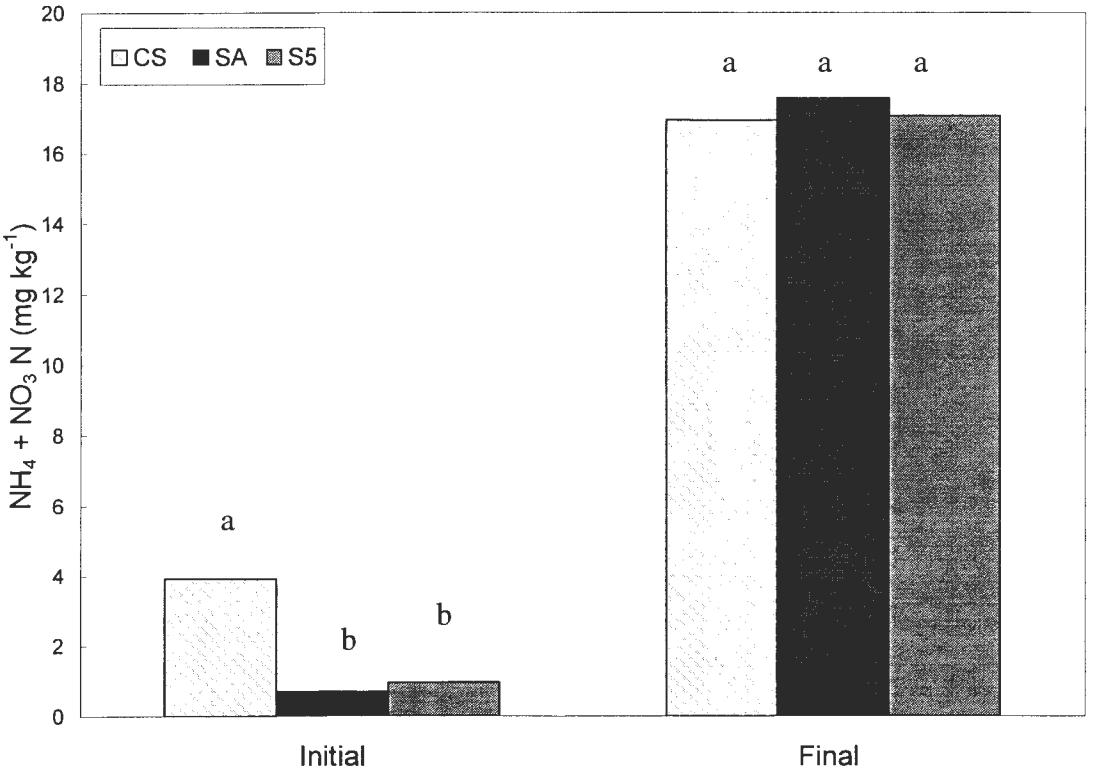

Figure 3.7. Nitrogen concentrations of exposed subsoil planted to switchgrass burned annually (SA), switchgrass burned every five years (S-5) and corn-soybean (CS) cropping systems before and after a 77 day laboratory soil incubation. Means with the same letter are not different at $P \leq 0.05$.

CHAPTER 4

General Conclusions

Topsoil addition over areas of exposed subsoil creates a better soil environment for crops to supply carbon input to the soil because of increased aboveground and root biomass production. Topsoil placement over exposed subsoil results in a larger pool of microbial biomass carbon. Similarly, switchgrass cropping systems on exposed subsoil showed a greater potential for carbon input to the soil than corn or soybeans, primarily because of the large root biomass and microbial biomass carbon pool.

Soil CO_2 emission and carbon mineralization were closely related to cropping system productivity in this study. Both years of this study, the subsoil never had a soil CO_2 emission rate greater than topsoil, and as a result cumulative soil CO_2-C emissions were 45 and 47% greater from topsoil in 2003 and 2004, respectively. Cumulative soil CO_2 emissions from the switchgrass cropping systems also exceeded the corn-soybean rotation in both years of the study.

Soil temperature and soil moisture affect soil CO_2 emissions, but soil moisture only appears to have an effect during times of extreme moisture conditions.

These results show that carbon accumulation in subsoil is difficult and complex. We found that switchgrass supplies much greater amounts of carbon to the soil than a corn-soybean rotation, but did not result in significantly greater SOC content. This could be related to the physical and chemical properties of the subsoil, or could be a result of the scheduled burnings of the switchgrass cropping systems. Even with burning, the large root system of the switchgrass can supply considerable carbon to the soil. Soil organic carbon was greater in the topsoil addition, as expected, but it was also greater at depths below any

added topsoil. This could be an accumulation of carbon, or mixing of topsoil with subsoil from tillage. Unfortunately no baseline data exists that would have enabled us to track carbon changes in the topsoil addition or the subsoil below it. There was not a significant particulate organic matter carbon content change in any of the treatments. Particulate organic matter is closely related to aggregation, and the subsoil of this site is poorly aggregated with poor physical properties.

There are several trends in these results that warrant further investigation and the continuation of this study. While changes in SOC and POMC contents are not found significant, they show a trend of increase in the S5 cropping system treatment. Additional long-term monitoring may provide insight into the carbon dynamics of switchgrass cropping systems on subsoil. Carbon evolution from the SA cropping system trended greater than that of S5 cropping system in the laboratory incubation, and was significantly greater on some dates in the field. Additionally, further long-term monitoring of SOC under the topsoil additions could provide insight into any potential carbon accumulation. The results of this study provide a good set of baseline data for future work on this site.

Future research on this site should also focus on different management practices, such as, a reduced tillage system, different cropping systems, and a nutrient management plan.