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Vertical distribution of soil organic carbon and nitrogen under warm-season native grasses relative to croplands in west-central Indiana, USA

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Abstract

Establishment of grasslands can be an effective means of sequestering soil organic carbon (SOC) and reducing atmospheric CO_2 that is believed to contribute to global warming. This study evaluated the vertical distribution and overall sequestration of SOC and total nitrogen (N) under warm-season native grasses (WSNGs) planted 6–8 years earlier relative to a corn (*Zea mays* L.)–soybean (*Glycine max* L.) crop sequence, and switchgrass (*Panicum virgatum*) relative to tall mixed grasses of big bluestem (*Andropogon gerardi*), indiangrass (*Sorghastrum nutans*), and little bluestem (*Andropogon scoparius*). Paired soil samples from 0–15, 15–30, 30–60 and 60–100 cm depth increments were taken from WSNGs and adjoining croplands at 10 locations, and from switchgrass and adjoining tall mixed grasses at four locations in three major soil types of alfisols, mollisols, and entisols in Montgomery County, Indiana. Significant differences in SOC and N concentrations of WSNGs and croplands were limited to the surface 30 cm. On average, SOC concentrations in the surface 15 cm depth were higher in WSNGs than croplands (average: 22.4 and 19.8 g kg^{-1} C, respectively) but significant differences were observed in just 4 of 10 locations. Similarly, surface soil SOC concentrations were not different for switchgrass (22.1 g kg^{-1}) relative to tall mixed grasses (21.4 g kg^{-1}). Soil N concentrations never differed significantly among land use treatments. On average, SOC mass calculated to 1.0 m depth was 9.4% higher under WSNGs than cropland ($P < 0.058$), and 8.1% higher in switchgrass relative to tall mixed grass ($P < 0.054$), but soil N mass was the same for both WSNGs and cropland. Vertical distribution under WSNGs of SOC mass was 26, 21, 28, and 25%, and of total N mass was 31, 25, 28 and 16%, in the 0–15, 15–30, 30–60, and 60–100 cm depth intervals, respectively. Even though we acknowledge the potential influence of soil variability or prior landscape processes on our results at some locations, we estimated that WSNGs sequestered an average 2.1 Mg C ha^{-1} yr^{-1} more than the corn–soybean sequence.

Keywords: Carbon sequestration; Total nitrogen; Switchgrass; Tall mixed grasses; Corn; Soybean

1. Introduction

Recent concerns about global warming due to atmospheric CO_2 accumulation have encouraged the achievement of a better understanding of the role of agriculture in mitigating CO_2 emissions. Restoration of grasslands is believed to be a cheap, efficient, and environmentally friendly method to reduce the rate of increase of atmospheric CO_2 concentrations, virtually stop soil erosion, increase soil nutrient and water retention, and improve soil and environmental quality. Although reseeding tilled soils with perennial grasses have been shown to provide greater litter and root biomass for C storage than annual cereal crops (Mapfumo et al., 2002; Mensah et al., 2003), widely different effects and rates of C sequestration by grasses have been reported (Staben et al., 1997; Robbles and Burke, 1998). This is because the quantity and rate of SOC stored under grasses is affected by such factors as soil type (Gebhart et al., 1994; Ma et al., 2000a), soil nutrient status (Ma et al., 2000c), grass types, cultivars or grass combinations (Frank et al., 2004; Tufekcioglu et al., 2003; Ma et al., 2000c), and length of time after establishment (Ma et al.,

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2000a,c; Zan et al., 2001; Garten and Wullschleger, 2000; Gebhart et al., 1994).

The period of time following the establishment of grasses (age of grass) is important to the rate of SOC sequestration. Ma et al. (2000a) reported that although switchgrass influenced C mineralization, microbial biomass, turnover, and soil respiration in the short term, total SOC concentration measured at 0–15 and 15–30 cm depth intervals under switchgrass was not different 2–3 years after establishment. However, SOC was 45 and 28% higher in these depth intervals 10 years after establishment relative to adjacent fallow soil (Ma et al., 2000c). Staben et al. (1997) found that C mineralization potentials and SOC pools were significantly higher for wheatgrass (*Agropyron* spp.) but that total organic C and microbial biomass C were not significantly different for wheatgrass relative to wheat-fallow rotation, 4–7 years after grass establishment. Similarly, Garten and Wullschleger observed a significantly higher coarse root C for switchgrass relative to tall fescue, corn and pasture of mixed grasses, but SOC under switchgrass was not significantly different from these soil covers in the surface 40 cm soil depth, 5 years after establishment.

The effects of grass species on C accumulation also vary considerably. For example, Lal et al. (1998) showed that tall fescue (*Festuca arundinacea*) and smooth bromegrass (*Bromus inermis*) increased the soil C pool by 17.2% relative to a corn–soybean rotation. Garten and Wullschleger (2000) reported that 19–31% of soil C pool originated from switchgrass, 5 years after establishment. In contrast, Frank et al. (2004) reported that switchgrass accumulated more C than continuous wheat (*Triticum aestivum* L.) crop but less than native pasture. Varietal differences in SOC or N sequestration may also occur but, thus far, Sladden et al. (1991) showed that total N content of above-ground harvested biomass of eight switchgrass varieties were not significantly different. In the latter study soil N contents under these switchgrass varieties were not reported.

Fertilization practices and presence or absence of associated leguminous plants are other factors that affect the widely different rates of C sequestration reported for grasses. In a grass versus cropland study of conservation reserve programs (CRP), Gebhart et al. (1994) found that unfertilized perennial grasses added 1.1 Mg C ha^{-1} yr^{-1} to the upper 1 m of Midwestern soils over a 5-year period, but both rhizosphere deposition and fine root turnover in switchgrass may add up to 3 Mg ha^{-1} yr^{-1} (Bransby et al., 1998). In a more recent study in the Midwest, Al-Kaisi et al. (2005) in Iowa reported a 1.2 Mg C ha^{-1} yr^{-1} in the 0–15 cm soil depth for switchgrass, 10 years after establishment. Similarly, Mensah et al. (2003) reported that after 5–12 years of establishment a restoration grassland that consisted of mixed-species of wheat grass, blue gramagrass (*Tripsacum dactyloides*), and alfalfa (*Medicago sativa*) gained about 0.6–0.8 Mg C ha^{-1} yr^{-1} in the top 15 cm soil depth relative to wheat–wheat–canola–pea and wheat–wheat–fallow rotations in east central Saskatchewan, Canada. In Mandan, North Dakota, Frank et al. (2004) reported that SOC measured to 0.9 m depth increased at the rate of 10.1 Mg C ha^{-1} yr^{-1}, 3 years after establishment of switchgrass with fertilizer application.

While several studies in the Great Plains region and elsewhere have shown that conversion of croplands to grasses can increase SOC, relatively few studies are available to better understand soil N cycling among grass types, or when croplands are converted to grasses, despite the acknowledged interdependency of SOC and N. The dynamics and accumulation of SOC and N may depend on vegetation composition. Legumes can increase SOC and N accumulation rate, C_3 grasses decrease these rates, while C_4 grasses may increase SOC but not N accumulation (Knops and Tilman, 2000). In the surface soil, Chen and Stark (1999) found total N to be significantly greater under big sagebrush (*Artemisia tridentata*) than wheatgrass. However, Svejcar and Sheley (2001) reported little or no consistent difference in total N when native perennial vegetation was replaced by annuals. In a recent study, Al-Kaisi et al. (2005) reported higher total N under switchgrass than corn–soybean–alfalfa rotation in the 0–5 and 15–30 cm depth intervals, 10 years after switchgrass establishment. McLaughlin and Kszos (2005) estimated the buildup of SOC under switchgrass could result in up to 100 kg N ha^{-1} yr^{-1} over a 10-year growing cycle. In contrast, Paustian et al. (1990) reported a net deficit of soil N in grass leys relative to barley due to a higher rate of mineralization under grass leys. Similarly, Kucharik et al. (2003) reported a relatively lower N under a 24-year restored prairie ecosystem relative to monoculture corn. Paustian et al. (1990) attributed higher N mineralization rates in grasses to the presence of a substantially larger root mass throughout the growing period, and a subsequently more significant rhizosphere influence of N mineralization leading to higher N demand of the grass.

Given that more than two-thirds of the annual grassland biomass production can be allocated to below-ground structures (Korner, 2002), accumulation of organic matter in deep soil layers can make an important contribution to C sequestration in most grassland ecosystems (Korner, 2002; Liebig et al., 2005). Rumpel et al. (2002) showed that 50% of SOC was stored within the deep horizons with a higher residence time than for SOC stored in upper layers where microbial activity is high. Ma et al. (2000b,c) suggested that rooting system of switchgrass extended up to 3 m down the soil profile; as much as about 10% of total root biomass of switchgrass have been reported in the 60–90 cm soil depth interval (Bransby et al., 1998; Liebig et al., 2005). However, little information is available on SOC and N sequestration in deep soil horizons because the majority of studies on SOC sequestration are limited to storage in the 0–30 cm soil layer (Lemaire et al., 2005). Lemaire et al. (2005) and Murphy et al. (2003) have argued that uncertainties surrounding SOC depth and the absence of an integrated view of the C and N dynamics posed a serious limitation to our knowledge of the carbon–nitrogen cycles in grassland ecosystems.

In the Midwest USA, farmers are encouraged to established WSNGs partly for wildlife habitat restoration, soil conservation, and the potential of harvesting certain WSNGs for fuel production (Bransby et al., 1998). However, in more recent times following the Kyoto Protocols on reduction of greenhouse gases, future possibilities of financial incentives resulting from carbon credit trading, whereby farmers trade SOC conserved in their fields for financial credits from greenhouse gas emitting entities are an additional incentive if the SOC sequestration potential of WSNGs can be established. Because other conservation practices such as reduced tillage or continuous no-till practices also help to conserve SOC, there is considerable uncertainty about which management practices conserve more SOC than the other and to what depth this can be expected. In Indiana and elsewhere in the Midwest, data to systematically quantify SOC sequestered by pure- and mixed-stands perennial grasses especially at deeper depths (>60 cm) relative to croplands that are managed under reduced or no-till are limited. The objectives of this study were to evaluate the vertical distribution and total SOC and N accumulation to a 1.0 m soil depth for (1) WSNGs relative to croplands, and (2) switchgrass relative to mixed grasses.

2. Materials and methods

2.1. Locations and site description

This study was conducted in 14 fields in ten locations in Montgomery County, west-central Indiana, latitude 40°6′30″–40°11′19″ and longitude 86°46′36″–86°54′12″, total annual precipitation of about 1043 mm and mean temperature of about 11 °C. The fields are located within the Wabash River watershed and are mostly on nearly level plains dissected by creeks (Sugar, Hazel, Bower, Lye, Little Potato, and Little Sugar Creeks), streams and drainage-ways with elevation ranging from 222–263 m above sea level. However, in some locations, fields are on a gentle rolling topography with slopes up to 4%. The soils were derived from glacial till or outwash and are overlain by loess in some locations. Detailed soil classifications and drainage classes for the locations are given in Table 1 (USDA-Soil Conservation Service, 1989). The fields have been managed in the past 50 years using different tillage systems that included no-till, chisel plow and cultivators (Table 2), and cropping system that consisted mainly of the standard corn (*Zea mays* L.) and soybean (*Glycine max* L.) rotations common to the Midwest.

The project was initiated by the Coal Creek Chapter of Pheasants Forever in 1997 to determine the suitability of WSNG species as wildlife habitats (especially for pheasants). In the spring of 1997 and 1998 about 10–50 ha portions of croplands were converted and seeded to either pure stands of switchgrass (var. Alamo) or tall mixed grasses that consisted of big bluestem, indiangrass and little bluestem or both (Table 2). In 10 fields either switchgrass or tall mixed grasses (hereafter collectively referred to as WSNGs) were planted adjacent to the croplands and, in another four fields, a pure stand of switchgrass was planted adjacent to a mixture of grasses (tall mixed). The fields were seeded using a Brillion grass seeder (Brillion Iron Works Inc., WI, USA) at the rate of 6 kg ha^{-1} for switchgrass and equal amounts (2 kg ha^{-1} for each of three species) for the tall mixed grasses. No fertilizers were applied during or after establishment and up to the time of soil sampling.

2.2. Soil sampling and laboratory analyses

In the fall of 2003 and spring of 2004, pairs of soil samples were taken from both the WSNGs and adjacent row-cropped fields in parallel transects. As much as it was possible, at each location field sampling positions were carefully chosen such that both the croplands and WSNGs were on fairly level topographic positions. Three pairs of sampling positions (WSNGs versus cropland; switch versus tall mixed) that were about 20 m apart were identified and sampled using a hydraulically driven probe mounted on a truck. At each sampling position three cores were taken to a depth of 1 m at 0–15, 15–30, 30–60 and 60–100 cm depth

Table 1
Field locations, soil types, drainage class, and the USDA and FAO soil classifications

Location	Soil type	Drainage class[a]	Classification	
			USDA	FAO
Branstetter	Fincastle-Miami silt loam	SWPD	Fine-silty, mixed, mesic Aeric Ochraqualfs	Alfisols
Cain #1	Martinsville-Ockley silt loam	WD	Fine-loamy, mixed, mesic Typic Hapludalfs	Alfisols
Cain #2	Martinsville-Ockley silt loam	WD	Fine-loamy, mixed, mesic Typic Hapludalfs	Alfisols
Dunbar	Mahalasville silty clay loam	PD	Fine-silty, mixed, mesic Typic Argiudolls	Phaeozems
Holts	Fincastle-Miami silt loam	SWPD	Fine-silty, mixed, mesic Aeric Ochraqualfs	Alfisols
Loop	Mahalasville silty clay loam	PD	Fine-silty, mixed, mesic Typic Argiudolls	Phaeozems
Loughs #1	Stonelick sandy loam	WD	Coarse-loamy, mixed (calcareous) mesic Typic Udifluvents	Fluvisols
Loughs #2	Stonelick variant fine sandy loam	WD	Sandy, mixed (calcareous) mesic Mollic Udifluvents	Fluvisols
Maxwell	Fincastle silt loam	SWPD	Fine-silty, mixed, mesic Aeric Ochraqualfs	Alfisols
Robertson	Fincastle-Miami silt loam	SWPD	Fine-silty, mixed, mesic Aeric Ochraqualfs	Alfisols
Stwalleys	Ockley loam	WD	Fine-loamy, mixed, mesic Typic Hapludalfs	Alfisols

[a] WD = well drained; PD = poorly drained; SWPD, somewhat poorly drained.

Table 2
Locations, grass types, age at sampling, field crop at sampling, cropland management history, management history of cropland prior to planting WSNGs of the selected fields used in this study

Location	Grass type	Grass age at sampling (years)	Crop at sampling	Management history of cropland	Management history of land prior to planting WSNGs
Branstetter	Switchgrass and tall mixed	6	Bean	Cornstalk, corn–bean rotation	10 years cool season CRP prior planting
Cain #1	Tall mixed	7	Bean	No-till since 1988, corn–soybean rotation	Chisel plow, corn–bean rotation prior to planting
Cain #2	Tall mixed	7	Corn	No-till since 1988, corn–soybean rotation	No-till prior to planting, corn–soybean rotation
Dunbar	Switchgrass	6	Bean	100% no-till since 1996, corn–bean rotation	No-till, corn–soybean rotation prior to planting
Holts	Switchgrass and tall mixed	6	Grass	Chisel plow in corn year, no-till soybean	Pasture till 1992, plowed 1 year and conventionally cropped
Loop	Switchgrass and tall mixed	8	Corn	100% no-till, corn–bean rotation	No-till prior to planting, corn–soybean rotation
Loughs	Switchgrass and tall mixed	6	Bean	100% no-till, corn–bean rotation	Cropped and 100% no-till prior to planting
Maxwell	Switchgrass	5	Bean	Reduced tillage (heavy chisel plow)	Same as cropland prior to planting
Robertson	Tall mixed	8	Corn	Chise0l plow bean stubble, corn–bean rotation	Same as cropland prior to planting
Stwalleys	Switchgrass and tall mixed	8	Corn	Chisel plowing, 100% no-till since 2000, corn–soybean-wheat rotation	Chisel plowing, corn–soybean rotation prior to planting

intervals and made into composites. The samples were carefully examined and plant roots, leaves, and other unwanted materials were removed by hand and then stored in bags and transported to the laboratory. Soil bulk density in each sampling depth interval was determined after drying at 105 °C for 48 h, as the mass of dry soil per volume of field-moist soil (Blake and Hartge, 1986). The samples were then processed first by grinding and sieving through a 2 mm mesh, second by grinding sub-samples to powder, and thirdly by subjecting these finely ground samples to laboratory analysis. Soil organic C and total N contents were determined by the dry combustion method using a LECO 2000 CHN Analyzer (Leco Corporation, St. Joseph, MI). Selected soil fertility parameters including pH (1:1 soil–water-mixture) and phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and cation exchange capacity (CEC) were determined in a commercial laboratory (A&L Great Lakes Laboratory, Forth Wayne, IN) after extraction with the Mehlich-3 extractant (Mehlich, 1984).

2.3. Calculations and statistical analyses

Soil organic C and total N contents were expressed both as concentration (g kg^{-1} soil) and mass (Mg ha^{-1}) to a fixed depth increment. We acknowledge that Ellert and Bettany (1995) and Ellert et al., 2002) have shown that equivalent mass procedure (nutrient mass calculated based on a reference soil mass) takes into consideration the influence of soil mass on nutrient storage, and can be more sensitive in detecting differences of SOC mass among treatments. However the equivalent mass procedure was not used to estimate SOC and total N mass in this study. This was because the locations used in this study varied widely in soil types, and prior management, and also because initial data analysis showed that significant differences among treatments in bulk density occurred only at 4 of 10 locations. Therefore, SOC and total N mass was estimated as product of the concentration, soil bulk density and soil layer thickness, and total or cumulative SOC and N mass was estimated by summing across depth intervals to 1 m depth.

Normality of the data was examined by their Skewness and Kurtosis that reflected the degree of non-normality by the amount of departure of their values from zero and the appropriate transformation methods were determined by the Box–Cox regression procedure. Most of the variables were normally distributed and all statistical analyses were carried out without transformation. Data published for similar experiments involving multiple locations clearly showed that significant effects (at $P < 0.1\%$ level of probability) of planted grasses on SOC sequestration occurred at some locations and not others (Gebhart et al., 1994; Potter et al., 1999; Zan et al., 2001; Liebig et al., 2005). This suggested that prevailing conditions in some locations can have significant effects on planted grasses and SOC sequestration. Unfortunately most of these experiments did not determine whether or not location could be a significant factor on SOC sequestration. For these reasons, statistical analyses were performed in different stages. First, the effect of location and the different land-use treatments effects (WSNGs versus croplands, and switchgrass versus tall mixed) on bulk density, SOC, total N concentration and mass were compared across locations and depths using the analyses of variance (ANOVA). In this analysis field locations and sample locations within fields were considered random and land use treatments were considered fixed sources of variation. Analysis of variance was then performed using the PROC MIXED procedure and significant differences were determined at $\alpha = 0.05$ level of probability. This analysis indicated that field location effect was highly significant ($P < 0.001$) at all depth intervals and for all the variables. However, land use, sample location within fields, and land use $\times$ location interaction effects were not significant. Thereafter, the effects of the land use systems were assessed on location or a field-scale basis using the pair-wise comparison to separate and compare treatment means within depth intervals in each location. Lastly, the treatment means for SOC and total N mass across locations were compared using the paired t-test procedure. Significant differences were determined at $\alpha = 0.05$ level of probability. All analyses were performed using SAS software (SAS, 2002).

3. Results

3.1. Soil fertility, organic C and total N concentration

Soil fertility characteristics of selected chemical properties are presented in Table 3. Soil fertility levels varied with location. Within the 0–15 cm (topsoil), soil pH ranged from slightly acidic to neutral except at Maxwell's where pH was slightly alkaline (pH 7.6). Soil P concentrations in WSNGS were lower than in croplands at 9 of 10 locations (except at Maxwell). Although available K was somewhat variable, on average K concentrations were also lower in WSNGs relative to croplands. When higher fertility levels occurred in croplands, especially of P and K, these were probably due to several years of fertilizer application in the croplands and a lack of application in the prairie grass areas. Fertility parameters evaluated for soils under switchgrass and mixed grasses were similar in all four

Table 3
Soil fertility characteristics in the 0–15 cm soil depth interval at 10 locations

Location		pH	P ($mg\ kg^{-1}$)	K ($mg\ kg^{-1}$)	Mg ($mg\ kg^{-1}$)	Ca ($mg\ kg^{-1}$)	CEC ($cmol\ kg^{-1}$)
WSNGs vs. cropland							
Branstetter	WSNGs	6.0	29	135	150	1000	7.8
	Cropland	6.3	33	71	200	1050	8.3
Cain #1	WSNGs	5.6	16	77	195	1000	10.4
	Cropland	5.9	52	214	85	1150	9.4
Cains #2	WSNGs	6.4	8	133	230	1500	11.0
	Cropland	6.5	20	125	100	1100	7.9
Dunbar[a]	WSNGs	6.6	64	200	586	3564	25
	Cropland	6.5	83	171	453	2949	21
Loop[a]	WSNGs	7.1	65	130	473	3235	22
	Cropland	6.0	103	203	458	2952	23
Loughs #1	WSNGs	7.1	75	143	362	3259	20
	Cropland	6.7	94	187	749	3846	28
Loughs #2	WSNGs	7.1	70	145	372	3244	20
	Cropland	6.8	89	190	750	3868	27.3
Maxwell[a]	WSNGs	7.6	78	143	555	3250	21.2
	Cropland	7.0	78	194	660	3150	21.7
Robertson	WSNGs	6.1	15	176	620	3450	27.7
	Cropland	6.2	30	105	370	2750	21
Stwalleys	WSNGs	6.4	36	161	180	2120	14
	Cropland	6.4	53	216	318	2413	18
Switchgrass vs. tall mixed							
Branstetter	Switchgrass	5.9	18	96	120	900	6.9
	Mixed grasses	6.3	10	78	140	950	7.3
Holt	Switchgrass	6.1	13	56	335	2300	18.0
	Mixed grasses	6.0	11	47	230	1600	12.4
Loop	Switchgrass	7.1	66	122	362	3128	16.6
	Mixed grasses	6.0	68	118	372	3100	16.1
Stwalleys	Switchgrass	6.4	36	161	180	2120	14
	Mixed grasses	6.4	40	166	177	2050	14

[a] Locations where the WSNG that was adjacent to cropland was switchgrass.

locations. In the soils of Indiana, little is known about critical soil P and K levels for long-term WSNGs; however in most field crops the recommended critical level for P is 15 ppm, and for K (at these CEC concentrations) is 110 ppm (Vitosh et al., 1995). Based on those assumptions, the biomass productivity of WSNGs may be limited by available P at the Cain #2, Branstetter, and Holt sites, and be limited by soil exchangeable K at Cain #1, Branstetter, and Holt sites.

Concentrations and vertical distribution of SOC and total N determined for WSNGs and croplands at different locations are shown in Table 4. Soil organic C and total N concentrations varied widely by location and decreased with increasing soil depth for both WSNGs and croplands except at Loughs #1 and Loughs #2. Across locations, SOC was higher under WSNGs (only in the top 30 cm soil depth) at 7 of 10 locations, but significant differences occurred at just 4 of 10 locations. On average, surface soil (0–15 cm) concentrations were 22.4 g kg^{-1} C and 1.6 g kg^{-1} N, respectively, for WSNGs and 19.8 g kg^{-1} C and 1.6 g kg^{-1} N, respectively, for croplands. In the 0–15 cm depth interval, WSNGs had significantly higher SOC at Branstetter ($P < 0.03$), Cain #1 (0.045), Loughs #2 ($P < 0.05$) and Robertson ($P < 0.01$), but with corresponding significant increases in total N only at Branstetter and Robertson. In the 15–30 cm depth interval, SOC was significantly higher for WSNGs than for cropland at Dunbar, Loop, Loughs #1 and Robertson locations, but with corresponding increase in total N only at Robertson. In contrast, SOC ($P < 0.058$) and total N ($P < 0.04$) concentrations were significantly higher under cropland than WSNGs at Stwalleys in both the 0–15 and 15–30 cm depth intervals.

A relatively lower SOC and total N concentration under WSNGs relative to adjacent cropland at Cain #2 was probably due to a relatively higher topographical position for the WSNG versus cropland plots, while the similar SOC and total N trend at Stwalleys was probably due to relatively poor establishment of the WSNGs. The Maxwell location is situated on low-lying plains next to a stream; sediment deposition from occasional flooding by adjoining streams may account for the absence of difference in C and N concentrations between WSNGs and croplands at these locations. The increase in SOC and total N concentrations with soil depth at Loughs #1 and #2 was probably due to annual flooding and sediment deposits over many years. The soils of these locations are classified as udifluvents and are frequently subjected to annual flooding and sediment deposition (USDA-Soil Conservation Service, 1989).

Concentrations and vertical distribution of SOC and total N under switchgrass and tall mixed grasses are presented in Fig. 1. Soil organic C and total N decreased with increased depth but differences of SOC and total N varied with depth and location. In the 0–15 cm depth interval, SOC and total N was higher for switchgrass relative to tall mixed grasses at Branstetter and Swalleys. Furthermore, SOC and total N concentrations were significantly higher for switchgrass in the 15–30 cm depth interval at all but the Branstetter location. Similarly, SOC and total N concentrations were significantly higher for switchgrass at Holts and Loop but not significantly different at Branstetter and Stwalleys in the 30–60 and 60–100 cm depth intervals. Across locations,

Table 4
Soil organic C and total N concentration at different depth intervals under WSNGs and adjacent croplands at different locations measured to 1 m soil depth

	Depth (cm)	Organic C (g kg^{-1})		Total N (g kg^{-1})	
		WSNGs	Cropland	WSNGs	Cropland
Branstetter	0–15	26.3	20.8**	2.3	2.0**
	15–30	12.8	9.6	1.1	0.9
	30–60	4.8	3.6	0.4	0.3
	60–100	2.7	2.5	0.2	0.2
Cains #1	0–15	16.7	12.0**	1.1	1.0
	15–30	7.6	7.1	0.5	0.5
	30–60	3.9	4.1	0.2	0.2
	60–100	3.1	3.3	0.2	0.2
Cain #2	0–15	11.9	12.5	0.8	1.0
	15–30	6.6	7.9	0.4	0.6
	30–60	5.2	5.2	0.3	0.4
	60-100	4.0	2.7	0.1	0.1
Dunbar[a]	0–5	31.1	27.8	2.5	2.4
	15–30	27.9	26.3**	2.2	2.3
	30–60	21.8	22.8	1.6	1.9
	60–100	8.2	6.9	0.4	0.4
Loop[a]	0–15	29.1	31.0	2.2	2.5
	15–30	31.0	19.3**	2.4	1.4
	30–60	16.2	7.8	0.7	0.4
	60–100	11.1	8.4	0.1	0.2
Loughs #1[a]	0–15	13.1	11.6	0.7	0.7
	15–30	13.4	9.2**	0.7	0.5
	30–60	15.2	13.2	1.3	1.0
	60–100	13.5	12.2	1.1	0.9
Loughs #2	0–15	14.6	6.6**	0.9	0.6
	15–30	6.8	5.4	0.3	0.2**
	30–60	7.4	5.4	0.3	0.1**
	60–100	4.0	4.2	0.2	0.2
Maxwell[a]	0–15	32.4	32.8	2.6	2.7
	15–30	25.9	28.8	2.0	1.8
	30–60	21.9	18.7	1.5	1.2
	60–100	15.6	15.2	0.5	0.9
Robertson	0–15	34.7	24.3***	2.5	1.7**
	15–30	24.6	19.8**	1.7	1.4
	30–60	7.9	7.4	0.1	0.2
	60–100	6.9	3.0	0.1	0.1
Stwalleys[b]	0–15	14.0	18.7	0.8	1.4**
	15–30	5.5	12.7**	0.2	0.8*
	30–60	2.9	5.7	0.2	0.3
	60–100	1.6	2.7	0.1	0.1

[a] Locations where the WSNG that was adjacent to cropland was switchgrass.
[b] Locations where organic C or N was significantly higher in cropland than in WSNGs.
** $P(T \leq t)$ was significant at 0.05 level of probability.
*** $P(T \leq t)$ was significant at 0.01 level of probability.

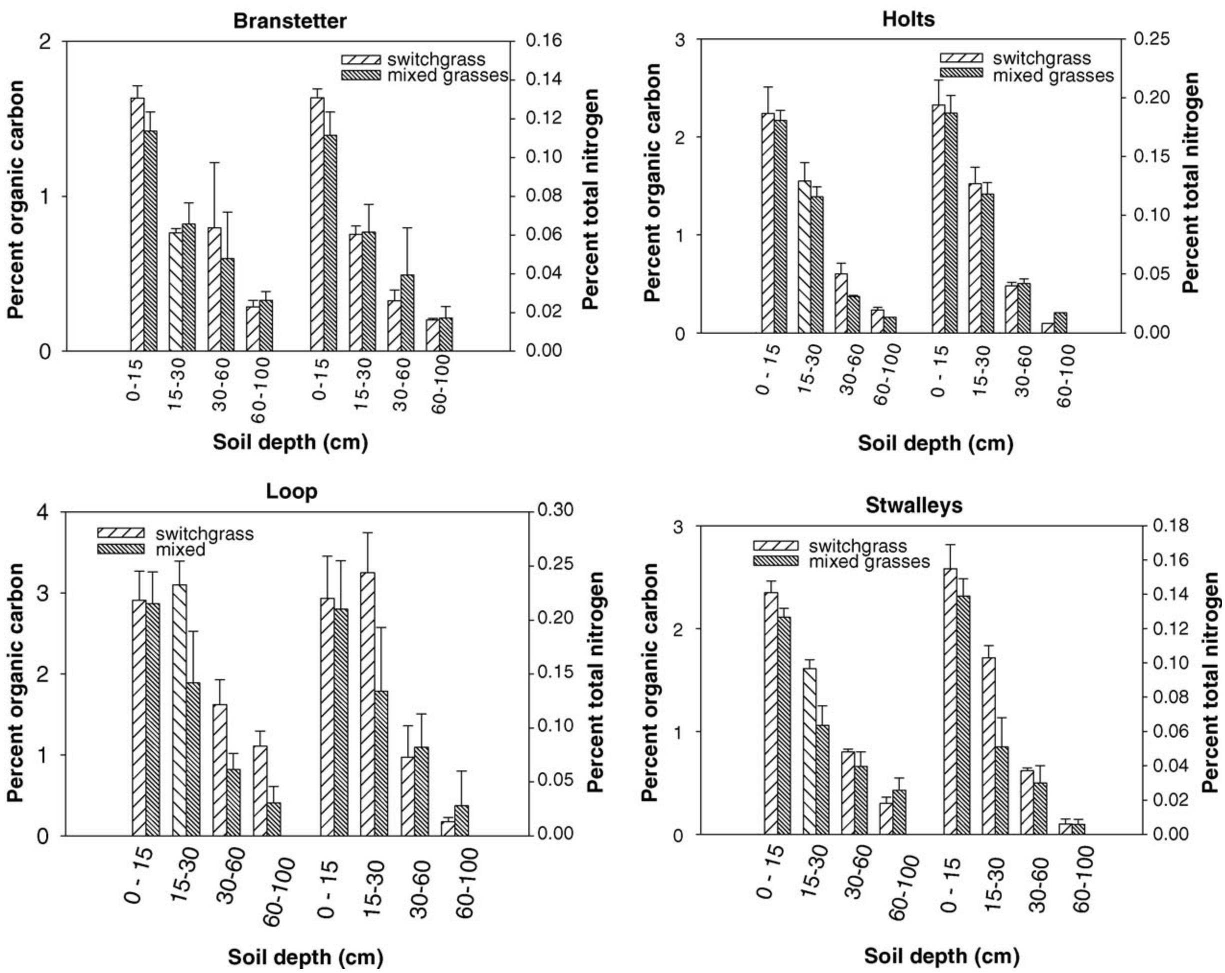

Fig. 1. Organic C and total N concentrations under switchgrass tall mixed grasses at Branstetter, Holts, Loop, and Stwalleys. Error bars represent S.E. ($n = 3$).

SOC and total N concentrations appeared to be numerically higher under swichgrass but differences of SOC and total N were not statistically significant.

3.2. Bulk density, carbon and nitrogen mass

In SOC sequestration studies, soil bulk density values are an important factor for the conversion of concentrations to mass values for the purpose of comparing treatment effects on below ground SOC storage, and assessing soil quality in general. Soil bulk density values determined for the WSNGs and croplands fields are presented in Table 5. As expected, bulk density generally increased with increase in soil depth. In the 0–15 cm depth interval, bulk density values ranged from 1.14 to 1.56 Mg m^{-3} in the WSNGs and from 1.33 to 1.57 Mg m^{-3} in the cropped fields, and bulk density values were significantly lower for WSNGs at Cains #1, Dunbar, and Robertson. In the 15–30 cm depth increment, bulk density was significantly lower in the WSNGs only at Robertson ($P < 0.005$).

The distribution of SOC and total N mass with depth for WSNGs and cropland are shown in Table 6. As with concentrations, significant difference in C and N of WSNGs and croplands in the different depth intervals was inconsistent and was limited mostly to the surface 30 cm (Table 6). Soil organic C mass was significantly greater ($P < 0.05$) in WSNGs than cropland at Branstetter, Cain #1, Loughs #2 and Robertson in the surface 15 cm depth, and at Dunbar and Loop in the 15–30 cm depth interval. In contrast, SOC and total N mass was greater in the surface 30 cm for cropland than WSNGs at Stwalleys.

Soil organic C and total N mass calculated to 1 m soil depth for WSNGs and croplands for the locations are presented in Table 7. Soil organic C mass ranged from 68.9 to 310.9 Mg C ha^{-1} under WSNGs and from 82.4 to 305.4 Mg C ha^{-1} under croplands. Soil organic C mass was significantly greater in the WSNGs relative to croplands at Loop ($P < 0.012$), Loughs #1 ($P < 0.043$), and Robertson ($P < 0.052$). Averaged over depth intervals and locations (Fig. 2), SOC mass in WSNGs was numerically greater but was statistically non-significant ($P < 0.058$) for WSNGS (171.4 Mg C ha^{-1}) than for cropland (155.1 Mg C ha^{-1}). Similarly, although total N mass was greater for WSNGs (13.5 Mg N ha^{-1}) than for croplands (10.4 Mg N ha^{-1}), the difference was not statistically significant ($P < 0.15$).

Table 5
Bulk density values of WSNGs and croplands at different soil depth intervals

	Soil depth (cm)	Bulk density ($Mg\ m^{-3}$)		$P > \lvert t \rvert$
		Grass	Row crop	
Branstetter	0–15	1.20	1.33	NS
	15–30	1.49	1.49	NS
	30–60	1.60	1.59	NS
	60–100	1.68	1.65	NS
Cains #1	0–15	1.40	1.48	**
	15–30	1.67	1.58	NS
	30–60	1.70	1.58	**
	60–100	1.79	1.73	NS
Cain #2	0–15	1.56	1.51	NS
	15–30	1.69	1.62	NS
	30–60	1.61	1.64	NS
	60–100	1.76	1.73	NS
Dunbar[a]	0–15	1.20	1.37	**
	15–30	1.42	1.41	NS
	30–60	1.43	1.40	NS
	60–100	1.47	1.51	NS
Loop[a]	0–15	1.39	1.47	NS
	15–30	1.46	1.54	NS
	30–60	1.57	1.59	NS
	60–100	1.58	1.59	NS
Loughs #1	0–15	1.48	1.57	NS
	15–30	1.78	1.68	NS
	30–60	1.46	1.56	NS
	60–100	1.43	1.30	NS
Loughs #2[a]	0–15	1.38	1.50	NS
	15–30	1.70	1.74	NS
	30–60	1.74	1.66	NS
	60–100	1.71	1.59	NS
Maxwell[a]	0–15	1.40	1.39	NS
	15–30	1.50	1.56	NS
	30–60	1.45	1.45	NS
	60–100	1.55	1.50	NS
Robertson	0–15	1.14	1.46	***
	15–30	1.31	1.48	***
	30–60	1.44	1.58	NS
	60–100	1.23	1.49	NS
Stwalleys	0–15	1.46	1.41	NS
	15–30	1.59	1.56	NS
	30–60	1.60	1.63	NS
	60–100	1.69	1.70	NS

[a] Locations where the WSNG that was adjacent to cropland was switchgrass.
** $P(T \le t)$ was significant at 0.05 level of probability.
*** $P(T \le t)$ was significant at 0.01 level of probability.

Table 6
Profile distribution of organic carbon and total nitrogen mass at various depth intervals in warm-season native grasses and croplands measured to 1 m soil depth

	Depth (cm)	Organic C ($Mg\ ha^{-1}$)		Total N ($Mg\ ha^{-1}$)	
		WSNGs	Cropland	WSNGs	Cropland
Branstetter	0–15	46.44	40.97**	4.12	3.90**
	15–30	28.05	21.58	2.50	2.05
	30–60	23.16	17.17	1.91	1.63
	60–100	18.07	16.62**	1.16	1.42
Cains #1	0–15	35.17	26.63**	2.21	2.24
	15–30	18.53	16.82	1.32	1.13
	30–60	20.09	19.56	0.87	1.16
	60–100	22.42	22.94	1.33	1.06
Cain #2	0–15	27.86	28.27	1.77	2.23
	15–30	16.59	19.17	0.93	1.55
	30–60	24.95	25.65	1.32	2.15
	60–100	27.87	18.76	0.39	0.31
Dunbar[a]	0–15	55.81	56.91	4.52	4.93
	15–30	59.36	49.86**	4.67	4.81
	30–60	91.73	95.54	6.83	8.01
	60–100	48.06	41.83	2.60	2.45
Loop[a]	0–15	59.67	67.87	4.54	5.43
	15–30	67.62	44.43**	5.30	3.24
	30–60	76.08	37.20**	3.43	2.05
	60–100	70.25	53.45	0.85	1.39
Loughs #1	0–15	29.02	27.20	1.48	1.76**
	15–30	35.84	23.15	1.94	1.29
	30–60	66.24	61.40	5.57	4.62
	60–100	77.09	63.23	6.21	4.47**
Loughs #2 [a]	0–15	29.88	14.99**	1.85	1.22
	15–30	17.39	14.18	0.83	0.57**
	30–60	38.18	26.61	1.91	0.64***
	60–100	27.22	26.62	1.12	1.41***
Maxwell[a]	0–15	67.78	68.12	5.43	5.47
	15–30	57.95	67.29	4.55	4.27
	30–60	91.87	79.63	6.40	5.19
	60–100	93.30	90.37	2.29	5.22
Robertson	0–15	59.06	53.00**	4.19	3.66
	15–30	48.08	43.62	3.32	3.05
	30–60	34.35	35.08	0.59	0.75
	60–100	33.56	18.26	0.70	0.67
Stwalleys [b]	0–15	30.74	39.78	1.64	2.89**
	15–30	13.01	29.73**	0.45	1.77
	30–60	14.07	28.29	0.76	1.25
	60–100	11.12	18.57	0.49	0.56

[a] Locations where the WSNG that was adjacent to cropland was switchgrass.
[b] Locations where organic C and total N was higher in cropland than WSNGs.
** $P(T \le t)$ was significant at 0.05 level of probability.
*** $P(T \le t)$ was significant at 0.01 level of probability.

An underlying hypothesis tested in this study was that SOC would be greater at depths >60 cm under switchgrass than the mixed grass because roots of switchgrass can extend up to 3 m deep into soil (Ma et al., 2000b,c; Bransby et al., 1998). Unfortunately, no significant difference in either SOC or N mass was observed between switchgrass and the mixed grasses at different depth intervals. However, SOC mass estimated to 1 m depth across locations showed that SOC under switchgrass ($129.5\ Mg\ C\ ha^{-1}$) was significantly higher ($P < 0.054$) than under tall mixed ($119.0\ Mg\ C\ ha^{-1}$); even though these two grass species were similar in total N accumulation (Fig. 2). Recent

Table 7
Mass of organic carbon and total nitrogen calculated to 1 m depth for WSPGs and adjacent croplands, and for switchgrass and tall mixed

Location	Organic C (Mg ha^{-1})		Total N (Mg ha^{-1})	
	WSNGs	Cropland	WSNG	Cropland
WSNGs vs. cropland				
Branstetter	115.7	96.3	9.7	9.0
Cain #1	96.2	86.0	5.7	5.6
Cain #2[a]	97.3	91.9	4.4	6.2**
Dunbar	255.0	244.1	18.6	20.2
Loop	273.6	203.0***	14.1	12.1
Loughs #1	208.2	175.0**	15.2	12.1**
Loughs #2	112.7	82.4	5.7	3.9**
Maxwell	310.9	305.4	19.4	20.1
Robertson	175.1	150.0**	8.8	8.1
Stwalleys[b]	68.9	116.4	3.3	6.5
	Switchgrass	Tall mixed	Switchgrass	Tall mixed
Switchgrass vs. tall mixed				
Branstetter	93.7	78.7	6.3	6.4
Holt	132.0	114.1	10.3	10.5
Loop	152.4	155.3	8.8	13.7
Stwalleys	139.8	127.8	7.3	6.0

[a] Locations where N in cropland was higher than WSPGs.
[b] Locations where C in cropland was higher than WSPGs.
** $P(T \leq t)$ significant at 0.05 probability.
*** $P(T \leq t)$ at 0.01 level of probability.

statistical assessments of relative accumulation of SOC to a 40 cm depth under different land-use systems (switch, mixed grasses, corn, and forest) have indicated that about 16 composite soil samples are needed to detect a significant statistical difference if the SOC difference among treatments was 10–15%, and about 100 samples for a SOC difference of 2–3% (Garten and Wullschleger, 1999). Similarly, in paired-site (grass versus croplands) assessments to verify SOC and N sequestration such as in this study, Kucharik et al. (2003) indicated that statistically significant differences within soil depth intervals from 0–25 cm were more likely when >40 locations were sampled, if composite samples were taken at 5 cm depth increments, and if the change in SOC and N was more than 23 and 29%, respectively. Thus, although there were

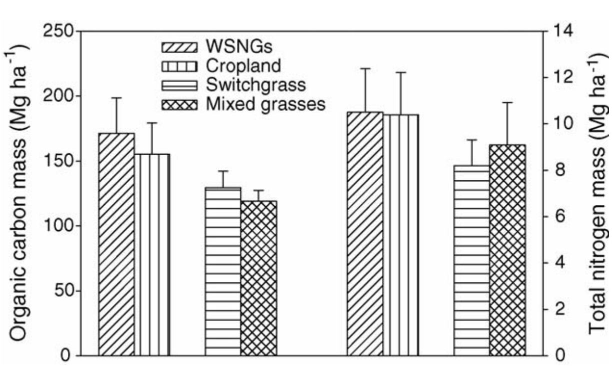

Fig. 2. Cumulative organic C and total N mass of WSNGs and croplands, and of switchgrass and tall mixed averaged over all locations. Error bars represent S.E. ($n = 3$).

numerical differences between WSNGs vs. cropland, and switchgrass vs. tall mixed, the low frequency of statistically significant differences occurring within and across locations in our study was probably due in part to the relatively limited number of locations and soil samples per location, soil variability, and differences in soil management systems.

4. Discussion

WSNGs are generally associated with more extensive rooting systems, greater root and litter biomass, and reduced soil erosion relative to annual crop production systems, even though the latter may be produced with a conservation tillage system (Ma et al., 2000b; Gebhart et al., 1994). One of the hypotheses in this study was that WSNGs would accumulate more SOC than croplands because of greater biomass and more extensive rooting systems of grasses. Although the latter hypothesis appeared to be true at four locations, our overall results for the 10 locations did not support this hypothesis; the overall absence of significant differences of SOC between WSNGs and croplands was contrary to expectations. However, in some ways our results were similar to Gebhart et al. (1994) who, in a 3 m depth sampling study in the Great Plains of the United States, reported significantly higher SOC in grasses only in the surface 40 cm soil depth after 5 years of grass establishment. Similarly, Potter et al. (1999) sampled to a depth of 1.2 m and found differences in restored grassland and cropped fields to be restricted to the surface 60 cm for SOC (40 cm for N) but only after more than 26 years of establishment. In more recent research, Kucharik et al. (2003) found SOC for CRP was only significantly higher than croplands in the surface 5 cm in fields sampled to 25 cm depths.

The numerically higher values of SOC of WSNGs over croplands in most of the locations suggested that more plant-based carbon from either shoot or root sources was retained by WNSGs than corn–soybean production systems, and under switchgrass than the mixed grasses. Although we have no accompanying shoot or root dry matter data to draw any firm conclusions, Bransby et al. (1998) reported that carbon pools (from above- and below-ground C) in sandy loam soils in Alabama was in the order: 18.8, 10.8, 7.3, 4.9 Mg C ha^{-1} for Bahiagrass, switchgrass, corn, and cotton, respectively. In this study, little or no above-ground biomass was added to the soil by WSNGs from the time of establishment to soil sampling. Therefore, higher SOC accumulation for WSNGs at certain locations was probably due to greater root biomass, rhizodeposition (root residues, exudates, exfoliates) in WSNGs (Gebhart et al., 1994) relative to annual crops. Native grasses are known to undergo complete root turnover only once in 4 years (Zan et al., 2001; Dahlman and Kucera, 1965) therefore, the contribution to SOC of roots may not be fully evident compared to an annual turnover for croplands. Although WSNGs were planted in 1997, the roots of WSNGs may not have been well established until years later, or may not have been at their maximum potential at the time of soil sampling due to lack of fertilizer application, and harvesting or grazing which are preferred conditions for greater SOC turnover (Ma et al., 2000c) in grasses. In contrast, croplands received regular fertilizer inputs and have been mostly under no-till soil management systems for a relatively longer period of time.

Higher storage of SOC by WSNGs over croplands (9%) and by switchgrass over tall mixed (8%) in our study were consistent with results in the literature (Gebhart et al., 1994; Tufekcioglu et al., 2003; Mensah et al., 2003; Lal et al., 1998; Frank et al., 2004; Al-Kaisi et al., 2005). However, our results contrasted with those of Garten and Wullschleger (2000) who found no difference in SOC inventory between switchgrass, tall fescue, corn or native pastures. Similarly, Robbles and Burke (1998), Frank and Dugas (2001) and Baer et al. (2000) found no significant differences between warm-season grasses approximately 5–10 years after establishment relative to matching cropped fields.

The amounts of SOC sequestered by WSNGs in the 0–15, 15–30, 30–60, and 60–100 cm depth increments were on average 26, 21, 28, and 25%, respectively. From data presented by Gebhart et al. (1994) we calculated SOC sequestered by WSNGs in these depth intervals to be 29, 19, 28 and 24%, respectively. Both results showed that considerable amounts of C were stored at deeper depths. Although previous data to ascertain the amounts of C sequestered at deeper depths by grasses are lacking, the amounts of SOC sequestered in the 60–100 layer was less than the 50% reported for forest soils by Rumpel et al. (2002). However, our results support the theory by Lemaire et al. (2005) that significant amounts of SOC can be stored at greater depths by grassland soils.

Very little information exists in the literature on the assessment of the relative N recovery of annuals and perennials (Bransby et al., 1998; Al-Kaisi et al., 2005) or the profile N distribution and storage beyond 30 cm soil depth (Lemaire et al., 2005); therefore, our comparison and discussion of soil N status at deeper depths was limited by available information. Our results showed that, although differences of total N mass for WSNGs versus cropland, and switchgrass versus tall mixed were not significant, average total N mass for WSNGs and tall mixed were about 10% higher than for cropland and switchgrass, respectively. The greater total N mass for WSNGs reported here was consistent with those reported for shallow soil depths (Al-Kaisi et al., 2005; Kucharik et al., 2003; Whalen et al., 2003; Staben et al., 1997) if we considered N sequestration in the surface 30 cm. Information on N sequestration is limited, but data on N storage at deeper depths is even less available. However, in similar research sampled to 1.2 m, Potter et al. (1999) found no significant difference in total N sequestered despite total N mass being numerically higher for grasslands than croplands.

Vertical distribution showed that N was higher for cropland at the surface 15 cm and depths >60 cm (WSNGs: 31, 25, 28 and 16%; cropland = 33, 23, 26, and 18% in the 0–15, 15–30, 30–60 and 60–100 cm depth intervals, respectively). Relatively greater N sequestration for croplands in the 0–15 and 60–100 cm depth intervals was probably due to N input from fertilizer application, higher mineralization rate in the surface and subsequent downward leaching, and less root nutrient uptake associated with annual crops at deeper depths. Although the croplands used in this study were mostly managed under no-till system, farmers occasionally tilled the croplands for the corn year following soybean in sequence. Conversely, no nitrogen fertilizers were applied to WNSGs; therefore, lesser N accumulation at the 60–100 cm depth interval suggested superiority in N recovery by WSNGs at deeper depths relative to croplands.

If it is correct to assume that soil chemical composition in WSNG areas were not different from adjacent soils retained for crop production at the time of WSNG establishment, the annual rate of C and N sequestration for WSNGs was estimated at 2.1 Mg C ha^{-1} yr^{-1} and 14 kg N ha^{-1} yr^{-1}, respectively. The relatively high rate for SOC was consistent with the 3.0 Mg C ha^{-1} yr^{-1} reported by Lal et al. (1998) and Tufekcioglu et al. (2003) over 6–7 years under perennial tall fescue relative to annual corn, and the 1.2 Mg C ha^{-1} yr^{-1} reported by Al-Kaisi et al. (2005) for switchgrass in the 0–15 cm soil depth interval. However, this rate was higher than 0.8 Mg C ha^{-1} yr^{-1} to 15 cm depth and 1.1 Mg C ha^{-1} yr^{-1} to 0.9 m depth reported by Mensah et al. (2003) and McLaughlin et al. (1994), respectively. Nevertheless, our estimate is substantially lower than the 10.1 Mg C ha^{-1} yr^{-1} accumulation rate reported by Frank et al. (2004). A comprehensive comparison of the rate of total N sequestration found in this study was limited by relatively lack of published data. However, recent data presented by Kucharik et al. (2001) in CPR fields versus croplands in Wisconsin estimated total N stored in the surface 5 cm to range from negative to 88 kg N ha^{-1} yr^{-1} (average of 17 kg N ha^{-1} yr^{-1}).

5. Conclusions

This study was conducted to evaluate SOC and total N accumulation due to planting of WSNGs relative to corn–soybean, and pure stands of switchgrass compared to tall mixed grasses in the Eastern regions of the US Corn Belt. We presumed initially that WSNGs had the inherent ability to sequester SOC beyond the rooting depth of many annual row crops. Pair-wise comparison showed that significant differences of SOC and total N for WSNGs versus cropland occurred at just 4 of 10 locations (for a $P = 0.05$, but for 6 of 10 locations for a $P = 0.1$) and was restricted to the surface 30 cm soil depth. Soil organic C and total N mass estimated to 1 m soil depth across all locations were numerically higher for WSNGs, but were not statistically different relative to corn–soybean rotation. It is possible that significant differences in SOC and N in WSNGs versus corn–soybean would have been more apparent if we had doubled our paired sampling positions at each location. However, even with the limitations of our sampling intensity, SOC and N mass calculated to 1 m depth was significantly higher for switchgrass relative to mixed grasses. The tall mixed selection of grasses used in this study was an attempt at achieving the biodiversity of grass species typically associated with the native prairies of the Midwest. Further studies would be needed to evaluate the desired stand ratio of tall mixed grasses in their C sequestration abilities as only relatively few studies have examined the impact of vegetation biodiversity on C sequestration rates (Knops and Tilman, 2000; Tilman et al., 2001).

The rate of sequestration calculated for SOC (2.1 Mg C ha^{-1} yr^{-1}) and for total N (14 kg N ha^{-1} yr^{-1}) relative to cropland was high relative to other rates reported for CRPs in the Midwest, but was still impressive despite the inferior soil fertility (e.g. lower available P or exchangeable K) with the WSNG areas at a number of locations. Analysis of variance indicated a highly significant location effect on SOC; therefore, this rate may have been affected by factors that were location-specific such as soil variability, previous management history, and sediment deposition. Similarly, differences between our sequestration estimate and those in prior studies of grasses may have been a consequence of our sampling depth; most previous estimates were based on soil layers close to the surface and these may have underestimated SOC and N storage rates. We observed a substantial presence of SOC and N (more than 20% of SOC and more than 16% of soil N) stored between 60 and 100 cm. We suggest that future research to evaluate SOC sequestration by native grasses relative to cropland involve more than three paired sampling positions per location from fields that are as uniform as possible (i.e. in soil types and management history). In addition, subsoil SOC and N evaluation should routinely be included in such studies for more accurate assessments of overall SOC and N sequestration.

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