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Corn Yields and No-Tillage Affects Carbon Sequestration and Carbon Footprints

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ABSTRACT

The corn (*Zea mays* L.)–based ethanol carbon footprint is impacted by many factors including the soil's C sequestration potential. The study's objective was to determine the South Dakota corn-based ethanol surface SOC sequestration potential and associated partial C footprint. Calculated short-term C sequestration potentials were compared with long-term sequestration rates calculated from 95,214 producer soil samples collected between 1985 and 2010. National Agricultural Statistics Service (NASS) grain yields, measured root/shoot ratios and harvest indexes, soil organic C (SOC) and nonharvested C (NHC) first-order rate constants, measured SOC benchmarks [81,391 composite soil samples (0–15 cm) collected between 1985 and 1998], and 34,704 production surveys were used to calculate the short-term sequestration potentials. The SOC short-term, area weighted sequestration potential for the 2004 to 2007 time period was 181kg C (ha × yr)$^{-1}$. This relatively low rate was attributed to a drought that reduced the amount of NHC returned to soil. For the 2008 to 2010 time period, the area weighted short-term sequestration rate was 341 kg (ha × yr)$^{-1}$. This rate was similar to the long-term measured rate of 368 kg C (ha × yr)$^{-1}$. Findings from these independent SOC sequestration assessments supports the hypothesis that many of the regions surface soils are C sinks when seeded with corn. Based on short-term C sequestration rates, corn yields, and the corn conversion rate to ethanol, the area weighted surface SOC footprints for the 2004 to 2007 and 2008 to 2010 time periods was –10.4 and –15.4 g $CO_{2\ equ}$ MJ^{-1}, respectively.

Agricultural producers increasingly are being asked to document the impacts of their products on the environment. The life cycle analysis (LCA) methodology determines the C footprint (summation of all greenhouse gases) and converts soil, animal, and plant processes data into a cradle to grave environmental accounting (Wang et al., 2007; Wang 2008; Liska et al., 2009; Plevin, 2009). The C sequestration partial C footprint for corn grain–based ethanol is calculated by dividing the g CO_2 ha^{-1} sequestered in the soil during corn production by the energy contained in the ethanol. To be consistent with reported values, a positive value indicates that CO_2 was released, whereas a negative value indicates that CO_2 was sequestered. The power of LCA approach is that it provides a mechanism to compare products. For example, typical reported C footprints for coal, gasoline, and ethanol are 134, 96, and 65 g $CO_{2\ equ}$ MJ^{-1} (Liska et al., 2009).

For the calculated LCA to have meaning, the boundary conditions of the process must be clearly defined. In this article, the partial C footprint is restricted to corn used to produce ethanol. By defining the boundary conditions, the C sequestration partial footprint can be added to other C footprints that do not or incorrectly considers soil C storage (Wang, 2008; Liska et al., 2009; Plevin, 2009).

The soil C sequestration potential is influenced by many factors including the amount of C contained in the soil, the mineralization rate constants, tillage, and the amount of nonharvested C (NHC) returned to the soil (Clay et al., 2010). Calculating the C sequestration potential requires a starting point for comparisons (benchmarks). However, obtaining accurate benchmarks may be impossible due to lack of data. In addition, it may be prohibitory expensive to collect and analyze the number of samples required to determine current benchmarks. Many studies have estimated benchmarks from the USDA-NRCS STATSGO2 and USDA-NRCS SSURGO data sets (Davidson and Lefebvre, 1993; Hunt et al., 2005; Mednick et al., 2008; Reitsma et al., 2011; Zhong and Xu, 2011; Soil Survey Staff-NRCS). A problem with STATSGO2 and SSURGO is that the SOC benchmark errors and sampling protocols are not clearly defined.

An alternative source of benchmarks may be producer soil samples that were analyzed by public and private laboratories (Bauder et al., 2003; Corn Growers Association North Carolina, 2002; Janssen et al., 2008). These laboratories generally follow strict protocols where information is archived with time and location stamps. The protocols may: (i) include internal reference materials and standards; (ii) external quality control assessments; and (iii) provide protocols for collecting soil samples (Gelderman et al., 2006). If a change in the chemical analysis approach is implemented, calibration studies are conducted to compare the methods. These laboratory

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Abbreviations: LCA, life cycle analysis; NASS, National Agricultural Statistics Service; NHC, nonharvested carbon; SOC, soil organic carbon; SOM, soil organic matter.

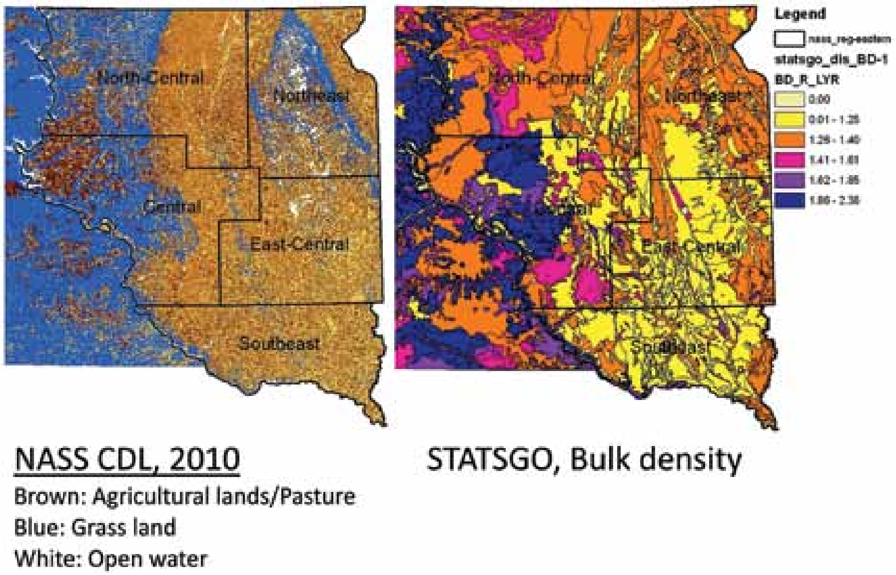

Fig. 1. Areal image showing crop and rangelands in glaciated regions of South Dakota and soil bulk density map derived from the STATSGO database. The Missouri River is the western edge of the regions.

databases can contain thousands of analyses and associated production surveys across many years. Once the SOC benchmark information is obtained, a first-order SOC model can be used to calculate turnover rates for short- and long-term sequestration potentials (Collins et al., 1999; Clay et al., 2006, 2010; Huggins et al., 1998; Paul et al., 2001; Mamani-Pati et al., 2010a). The study's objective was to determine the Northern Great Plains corn-based ethanol surface SOC sequestration potential and associated partial C footprint.

MATERIALS AND METHODS

Characteristics of the Glaciated Region of Eastern South Dakota

The glaciated region of Eastern South Dakota (east of the Missouri River) can be subdivided into the Northern and Northwestern glaciated plains ecoregions (USGS, 2011). These two ecoregions can be further subdivided into five National Agricultural Statistics Service (NASS) regions (Fig. 1; NASS, 2011). The Northern glaciated plain ecoregion contains most of the Northeast, East-Central, and Southeast NASS regions, while the Northwestern glaciated plain ecoregion contains the North-Central and Central NASS regions.

The tallgrass prairie was the dominant plant community in the Northern and Northwestern glaciated plain ecoregions before homesteading. Most of these regions' soils were mollisols derived from glacial drift or loess. The annual average rainfall is the greatest difference between these two zones and ranges from 46 to 61 cm the Northern ecoregion and from 38 to 46 cm in the Northwestern region. A large portion of the Northwestern ecoregion remains as rangelands (Fig. 1), which were specifically excluded from the analysis.

Producer Production Surveys

When soil samples were submitted to the South Dakota State Soil Testing Laboratory, producers were requested to submit a production survey. In the production survey, information about the cultural practices (current and prior crops, tillage practice, manure use, and expected yield goal) for the sampled field was obtained. Based on these surveys, samples from conservation reserve program (CRP) and grasslands were excluded from analysis. The numbers of completed production surveys for corn for the years 2004 to 2007 were 16,324 and for 2008 to 2010 were 18,380. Survey numbers by NASS region are presented in Table 1 (NASS, 2011). Based on these surveys, no-tillage adoption rates for the 2004 to 2007 and 2008 to 2010 time periods were determined (Table 1)

Calculated Carbon Sequestration and Footprints

Figure 2 is a flow chart showing the various calculations, sources of information for short-term C footprint calculations, and the linkages among the collected data, field experiments, the SOC model, and calculations. Each component is discussed below. Calculated short-term corn C sequestration potentials will be compared with measured long-term temporal changes in producer soil samples.

Table 1. The influence region on the number of surveys collected, no-tillage adoption, ksoc values, and Bulk density.

Region	Bulk density	2004–2007				2008–2010			
		Surveys	Planted corn	No-till adoption	k_{soc}	Surveys	Planted corn	No-tillage adoption	k_{soc}
	g cm^{-3}	no.	ha*1000	%	g soc/(g × yr)	no.	ha*1000	%	g soc/(g×year)
North-central	1.35	934	338	97	0.0117	796	346	69	0.0135
Central	1.31	2035	251	68	0.0135	941	229	57	0.0142
Northeast	1.29	3289	276	20	0.0165	2353	308	11	0.0171
East-central	1.24	6777	436	11	0.0171	12,479	447	5	0.0175
Southeast	1.25	3289	434	29	0.0160	1811	405	33	0.0157

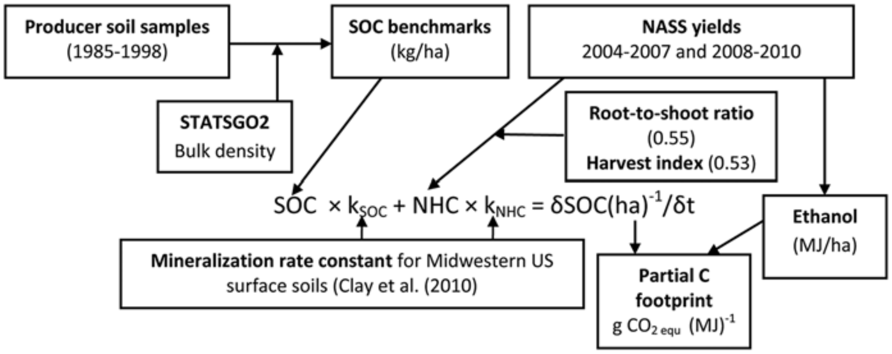

Fig. 2. A flow chart showing the different information layers used to calculate the C sequestration amounts (δSOC/δ*t*) and partial C footprints.

Carbon Sequestration Model

The C sequestration potentials ($\delta SOC/\delta t_{(year\ 1)}$), when seeded with corn, for the 2004 to 2007 and 2008 to 2010 time periods were determined using the equation:

$$\delta SOC/\delta t_{(year\ 1)} = NHC \times k_{NHC} - SOC_{(benchmark)} \times k_{SOC} \qquad [1]$$

where NHC is the rapidly mineralized C pool, SOC is the slowly mineralized C pool, and k_{NHC} is a first order rate constant that represents the amount of remaining biomass after 1 yr and k_{SOC} is a first order rate constant that represents SOC mineralized in 1 yr. The methods to define the k_{NHC}, k_{SOC}, $SOC_{(benchmark)}$, and NHC values are defined below. This approach for estimating the short-term C sequestration potential and resulting SOC contained in the soil was validated using the data from Larson et al. (1972), Barber (1979), and Huggins et al. (1998) (Fig. 3). In this validation, the predicted and measured amounts of SOC at the end of each study were compared. The validation showed a strong relationship between predicted and observed responses ($r^2 = 0.98$) with a slope of 1.04.

Mineralization Rate Constants

In all calculations, k_{NHC} was 0.20 g NHC-C (g NHC × yr)$^{-1}$. This value was based on the findings of Larson et al. (1972) and Barber (1979). When considering the k_{NHC} value it is important to consider what is included in the NHC. In these calculations, NHC contains the roots, exudates, and crown components.

The k_{SOC} value is the amount of SOC mineralized in 1 yr. Clay et al. (2010) previously reported that for mollisols located in the central United States there is relationship between tillage intensity (tillage, cultivations, and disking) and k_{SOC} (Fig. 4). Data shown in Fig. 4 were obtained from long-term studies conducted in Iowa, Indiana, Minnesota, South Dakota, and Nebraska (Larson et al., 1972; Barber, 1979; Huggins et al., 1998; Allmaras et al., 2004; Wilts et al., 2004; Russell et al., 2005; Pikul et al., 2008). Based on this model and no-tillage adoption rates, k_{SOC} values for each NASS region were calculated using the equation:

$$k_{SOC} = (\%\text{no-tillage adoption}/100) \times [0.0115\,g(g \times yr)^{-1}] + [(1.00 - \%\text{no-tillage adoption})/100] \times 0.0178\,g(g \times yr)^{-1}$$

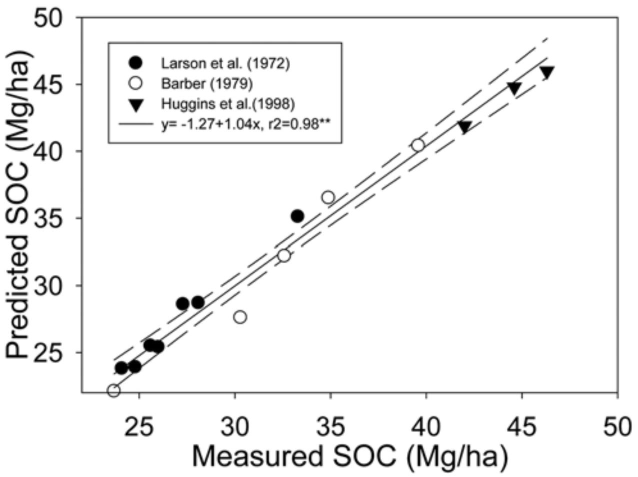

Fig. 3. SOC model validation using data reported by Larson et al. (1972), Barber (1979), and Huggins et al. (1998). Carbon amount in the surface (0–15 cm) soils after long-term studies are compared. The 95% confidence interval is the dashed lines on the chart.

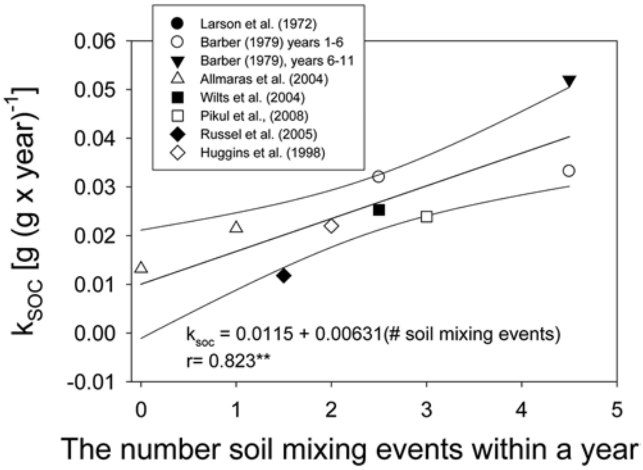

Fig. 4. The relationship between the number of annual soil mixing events (tillage, disking, and cultivations) vs. the first-order SOC mineralization rate constant (k_{SOC} [g (g × yr)$^{-1}$]. The 95% confidence interval is shown on the chart.

The $0.0115\ \mathrm{g}\ (\mathrm{g} \times \mathrm{yr})^{-1}$ and $0.0178\ \mathrm{g}\ (\mathrm{g} \times \mathrm{yr})^{-1}$ were the rates for 0 and 1 tillage (Fig. 4). The no-till adoption rates ranged from 5 to 97%, with k_{SOC} values ranging from 0.0117 to $0.0175\ \mathrm{g\ SOC}\ (\mathrm{g} \times \mathrm{yr})^{-1}$ (Table 1).

Soil Organic Carbon Benchmarks

The SOC benchmarks were based on 81,391 surface composite soil samples (0- to 15-cm depth) that were collected between 1985 and 1998. Each composite sample typically consisted of 10 to 15 randomly collected cores from a 65-ha field, that was dried, ground, and analyzed for soil organic matter (SOM) by the South Dakota soil testing laboratory using the Walkley and Black (1934) method. The laboratory switched from Walkley and Black (1934) to weight loss-on-ignition (Combs and Nathan, 1998) in July 1999. However, based on extensive calibration studies, the weight loss-on-ignition values were adjusted first, to an equivalent Walkley and Black (1934) analysis value, and then to total C. For an additional validation, pre- and post-change SOC values are compared. This comparison showed that the SOC concentrations in 1998 (pre-change) and 2000 (post-change) were 23.1 and 22.7 g kg^{-1} in 1998 and 2000, respectively. This analysis suggests that higher SOC values after 2000 were not the result of a method change, but due to increased SOC accumulation. Summary reports on total number of samples submitted and chemical analysis for the South Dakota Soil Testing Laboratory are available (Gelderman et al., 1999; Gelderman and Gerwing, 2004; Gelderman and Ulvestad, 2010).

The SOC gravimetric values described above were converted to kg SOC ha^{-1} using area and depth weighted bulk density values. The area and depth weighted cropland regional bulk densities for the surface 15 cm were calculated from the STATSGO2 database. Bulk densities from rangelands were excluded from this calculation. The bulk densities for cropped areas in the five NASS regions are reported in Table 1 and Fig. 1. The accuracy of soil survey bulk densities was tested by Fortin and Moon (1999). They reported that within the Peace River region of British Columbia, soil survey bulk density values were within 5% of the measured values.

Nonharvested Carbon: Root/Shoot Ratios and Belowground Biomass

Belowground NHC was based on the root/shoot ratio, which was experimentally derived in experiments conducted in 2009 and 2010. Many different root/shoot ratios have been reported (Amos and Walters, 2006). For example, Allmaras et al. (2000) used a root/shoot ratio of 0.2, while Johnson et al. (2006) used a root/shoot ratio of 0.55, and Benjamin et al. (2010) used a root/shoot ratio of 0.6.

To determine which root/shoot ratio was appropriate, strategically located experiments were conducted in two widely different soil and climate regimes (Wessington [representing a Central region site] and Aurora [representing an East-Central region site]) in 2009 (Table 2). The experiment was repeated in 2010 at Wessington. The cultural practices used at the sites were consistent with producer practices in the East-Central (chisel plow and disk) and Central (no-tillage) regions. In both studies, the plot sizes were 10 by 3 m, each block contained 16 plots with a row spacing of 76 cm. The areas were fertilized based on soil test results with 180 kg N ha^{-1} applied before planting. Root distributions and root crowns were measured at silking (Crozier and King, 1993), and grain, cobs, and leaves and stalks yields were measured at physiological maturity (Mamani-Pati et al., 2010b).

Table 2. Selected characteristics of the two field experiments conducted in 2009 that were used to define harvest indexes, root/shoot ratios, and cob/dry ear ratios.

Characteristics	Aurora	Wessington-1
Location	96°40′ W, 44°18′ N	98°34′ W, 44°40′ N
Previous crop	corn	soybean
Planting date	15 May 2009	12 May 2009
Root sampling data (silking)	19 Aug. 2009	5 Aug. 2009
Planting population (seed/ha)	86, 500	74,000
Rainfall (cm)	18.52	39.83
GDD °C	1134	1315
Tillage system	tilled	no-tilled
Soil series	Brandt silty clay loam fine-silty, mixed, superactive, frigid Calcic Haplodolls	Houdek loam fine-loamy, mixed, mesic Typic Argiustolls

For corn roots, 4 cm wide soil cores from four locations in each plot were collected. Two samples were collected adjacent to a corn plant and two samples were collected half-way between the two rows. The four samples were analyzed separately. Samples were collected from the 0- to 15-, 15– to 30-, 30- to 60-, and 60- to 76-cm depths. Following root sampling, the root crowns from two plants per plot were collected from an area that was 4 cm wide, 4 cm long, and 15 cm deep.

The soil root and crown samples were stored in a cold room (5°C) immediately after collection. Root crown samples were washed under a gentle running water spray to remove soil particles. The cleaned root crown samples were dried at 60°C and weighed. The soil and root mixture was washed with a hydropneumatic elutriator (Smucker et al., 1982) to separate roots from soil. Roots + organic materials were separated from soil particles by a submerged low kinetic energy primary sieve (925 μm). Using this approach, the main and lateral roots were separated from the soil particles. A secondary sieve (437 μm) was used to further separate roots from the mixture (Smucker et al., 1982). During final cleaning, root and nonroot materials were hand-separated in clean water, dried at 60°C, and weighed. Total root weights were calculated based on adjusting for soil volume based on sampling depth. Roots in the nonsampled area were calculated by assuming a linear model between the two sampling points. The measured root values did not account for exudates, and therefore based on Kuzyakov and Domanski (2000), the root + exudates values were calculated using the equation:

$$\text{Roots} + \text{Exudates} = \text{Measured roots} \times 2 \qquad [2]$$

This approach for determining roots plus net exudates was consistent with Balesdent and Balabane (1992), who reported that approximately 48% of the belowground biomass (roots + exudates) was rhizodeposition.

At physiological maturity, eight corn plants per plot were harvested. Leaves + stalks were dried at 60°C and weighed. Corn ears were dried and shelled. Cobs and grain were separated, dried, and weighed. Based on this information, the root to shoot ratios and harvest indexes were calculated with the equation:

$$\text{Root/shoot ratio} = (\text{Roots} + \text{Exudates} + \text{Crown}) / (\text{Cob} + \text{Grain} + \text{Leaves} + \text{Stalk}) \quad [3]$$

The measured root/shoot ratio for the two sites in 2009 was 0.55 g g^{-1}. This value was similar to results from 2010 (data not reported) and to the ratios used by Buyanovsky and Wagner (1986), Bradford et al. (2005), and Johnson et al. (2006), and Benjamin et al. (2010). Belowground NHC was calculated by assuming the root biomass contained 420 g C (kg $\text{biomass})^{-1}$. These calculations were based on roots and shoots having similar C contents (Gealy and Gealy, 2011). Based on root distributions with depth, 66% of the nonharvested belowground biomass-C (crown, roots, and exudates) were contained in the surface 15 cm of soil.

Nonharvested Carbon: Harvest Index and Aboveground Biomass

Based on the field measured values described above and previous studies (Mamani-Pati et al., 2010b) the harvest index [grain/(grain + stover)] was 0.53 g g^{-1}. This value was similar to values reported by Lorenz et al. (2010), Johnson et al. (2006), and Bradford et al. (2005). Findings from Lorenz et al. (2010) suggest that harvest indexes have been relatively stable for the past 50 yr. For the NHC calculations it was assumed that the harvest index was constant since 2004 and that the biomass contained 420 g C (kg $\text{biomass})^{-1}$. In addition, in the experiment described above, the cob to dry ear ratio [cob/(grain + cob)] was 0.128 g g^{-1}. Based on yields, obtained from NASS (2011) for the 2004 to 2007 and 2008 to 2010 time periods and the experimentally measured root/shoot ratios and harvest index values, NHC was calculated for the surface 15 cm.

Long-Term Soil Organic Carbon Sequestration Measurements

Producer Samples

Temporal changes in the SOC contents in 95,214 producer composite soil samples collected between 1985 and 2010 were used to calculate the long-term sequestration rates for the eastern (NE, SE, and EC) and western (NC and C) areas of the region. In these calculations, the gravimetric SOC values were converted to volumetric amounts using STATSGO2 derived bulk densities (Fig. 1). The depth-based sampling approach has been used numerous times for mollisols located in the central region of the United States (Davidson and Lefebvre, 1993; Allmaras et al., 2004; Hunt et al., 2005; Huggins et al., 2007; Mednick et al., 2008; Mamani-Pati et al., 2010a; Reitsma et al., 2011).

These calculations assumed that bulk densities were constant during the study period. In the northern Great Plains, reducing the tillage intensity by adopting no-tillage can either result in a slight increase in surface soil bulk density or have no-impact. For example, Logsdon and Karlen (2004) (Iowa), Eynard et al. (2004) (South Dakota), and Voorhees and Lindstrom (1984) (Minnesota) on soils similar to identical to those observed in this study showed no or only slight differences in the bulk densities of tilled and no-tilled systems. A sensitivity analysis of the regions mollisols showed that if no-tillage increases bulk density from 1.25 to 1.35 g cm^{-3} there is a risk for a 5% underestimation bias.

Long-Term Tillage and Nonharvested Carbon Impacts: Simulation Analysis

A simulation analysis was conducted to determine if gradual yield increases or no-till adoption could account for temporal changes in SOC. These calculations used a simple two pool first-order C model (Eq. [1]) to determine temporal changes in SOC changes from 1930 to 2010 (Clay et al., 2010). In this model, the time step was 1 yr and temporal changes in water and temperature were not considered. The simulations varied SOC, NHC, and k_{SOC} values. The starting conditions for simulations were: (i) a base-level SOC content of 60,000 kg ha^{-1} in 1930 (Puhr and Olsen, 1937); (ii) a base-level NHC of 750 kg $(ha \times yr)^{-1}$ that had an annual increase of 40 kg NHC $(ha \times yr)^{-1}$; (iii) an k_{NHC} value of 0.2 g $(g \times yr)^{-1}$; and (iv) a k_{SOC} value of 0.030 g $(g \times yr)^{-1}$ (tilled with moldboard plow) that was decreased to 0.018 (reduced tillage) and 0.0115 g $(g \times yr)^{-1}$ (no-tillage) in 1970 and 2002, respectively.

Partial Carbon Footprints

The partial C footprint due to SOC sequestration were based on: (i) the calculated amounts of sequestered C; (ii) a grain to ethanol conversion rate of 0.432 L ethanol (kg $\text{grain})^{-1}$ (2.89 gal bu^{-1}); and (iii) NASS reported corn yields. To determine the actual C footprints, the partial footprints should be added to LCA footprint that does not consider SOC sequestration (Liska et al., 2009; Liska and Cassman, 2009; Plevin, 2009).

RESULTS AND DISCUSSION

Calculated Short-Term Corn Carbon Sequestration Potentials

The short-term corn C sequestration potentials were a function of region, base-level SOC value, and year. The sequestration potentials were directly related to yield and negatively related to the SOC benchmark. Across all regions, the area weighted (based on seeded corn hectares) short-term sequestration potentials for the 2004–2007 and 2008–2010 time periods were 181 and 341 kg SOC $(ha \times yr)^{-1}$, respectively.

Table 3. The influence of NASS region and year on yield, no-tillage adoption rate, nonharvested C returned to soil (NHC), SOC mineralization rate, the SOC benchmark, and calculated sequestered SOC. The standard deviations are shown in parenthesis.

	Yield		NHC		SOC	Sequest.	SOC
Region	2004–2007	2008– 2010	2004–2007	2008–2010	benchmark	2004–2007	2008–2010
	Mg/ha					kg/(ha yr)	
NC	6.17	8.45	3.46	4.73	39.5(8.96)	229	412
C	5.45	8.95	3.06	4.36	40.2(9.76)	69	329
NE	8.27	7.76	4.64	5.02	45.2(9.51)	182	231
EC	7.98	9.33	4.46	5.24	44.8(9.60)	125	264
SE	7.2	9.51	4.04	5.34	39.1(8.50)	266	454

These findings suggest that the regions surface soils, when seeded with corn, were a C sink (Table 3). This interpretation is consistent with Allmaras et al. (2000) and producer soil samples from Wisconsin (http://uwlab.soils.wisc.edu/soilsummary/). Although no-till use was generally higher between 2004 and 2007 than 2008 and 2010, corn yields, NHC, and C sequestration potentials were generally lower (Table 3). These results were attributed to drought conditions that reduced yields, NHC, and subsequently, C sequestration.

Producer Long-Term Carbon Sequestration Potentials

The temporal SOC changes in producer soil samples indicates that during the past 25 yr, surface SOC amounts have increased at an average rate of 368 kg C (ha × yr)$^{-1}$ (Fig. 5). The long-term rate considers the entire system which includes manure and other crops such as wheat (*Triticum aestivum* L.) and soybean [*Glycine max* (L.) Merr.]. Each factor within the system can have positive or negative impacts on C sequestration. The long-term rate indicates that across the entire system, C is being sequestered.

The short-term area weighted SOC sequestration rate of 181 kg C (ha yr)$^{-1}$ between 2004 and 2007 was lower than the long-term rate of 368 kg C (ha × yr)$^{-1}$. Differences between these values were attributed to a wide scale drought that reduced yields and NHC. It should be noted that even with lower yields, it was predicted that C-sequestration was positive in all regions. For the time period between 2008 and 2010, the calculated area weighted sequestration potential [341 kg C (ha yr)$^{-1}$] and long-term value were similar (Table 3). The calculated C sequestration potentials and measured SOC rate changes were lower than the 570 kg C (ha × yr)$^{-1}$, for no-tillage adoption, reported by West and Post (2002). Others have used simulation analysis to produce similar results. For example, Allmaras et al. (2000) hypothesized that gradual yield increases and reduced tillage intensity could result in SOC increases. Since Allmaras et al. (2000), no-tillage adoption in the glaciated regions of South Dakota has increased from <10% in 1998 to a regional average of 44% between 2004 and 2007 (Table 2).

Tillage and Nonharvested Carbon Impact on Long-Term Changes in Soil Organic Carbon

Since the 1930s, yields have gradually increased and tillage intensity has gradually decreased (Fig. 6). The higher yields have been associated with: (i) the release of new corn hybrids that have gradually increased their yield potential, (ii) extensive fertilizer use, and (iii) improved pest management strategies. Since the 1930s, corn yields have increased at a rate of 81.5 kg grain (ha × yr)$^{-1}$. Associated with higher yields are increased amounts of NHC returned to soil (Lorenz et al., 2010). For example, Allmaras et al. (2000) reported that in 1940 and 1990 the amount of C returned to the soil increased from 1940 to 4090 kg C ha^{-1}. Similar NHC increases are predicted across the Great Plains. In addition, the amount of land seeded to corn in many areas has increased, which has increased the amount of NHC returned to soil (Allmaras et al., 2000; Johnson et al., 2006). For example, between 1985 and 1989 corn was planted on 1.33 million ha annually in South Dakota, whereas between 2004 and 2007 corn was seeded on 1.88 million ha annually in South Dakota. This increase is not attributed to reductions in land dedicated to hay production (which remained constant at 1.51 million ha) but to reductions in the land dedicated to minor crops such as flax (*Linum usitatissimum* L.), sunflower (*Helianthus annuus* L.), canola (*Brassica napus* L.), and oat (*Avena sativa* L.).

From 1998 to 2004 no-tillage was adopted by many farms in the five NASS regions, which resulted in no-tillage being adopted on approximately 2.3 million ha between 2004 and 2007. These increases are attributed to improved planting equipment, wide-scale adoption of genetically modified soybean and crop genotypes, which improved weed and insect management, improved techniques for managing fertilizers and weeds, and reduced evaporation, which increases yields in drought-stressed environments. Between 2004 and 2007 no-tillage was not uniformly adopted across the state and was higher in the central (68–97% adoption) than eastern (11–29%) regions. Others have reported high no-tillage adoption rates across the United States (Horowitz et al., 2010). For example, Horowitz et al. (2010) reported that in

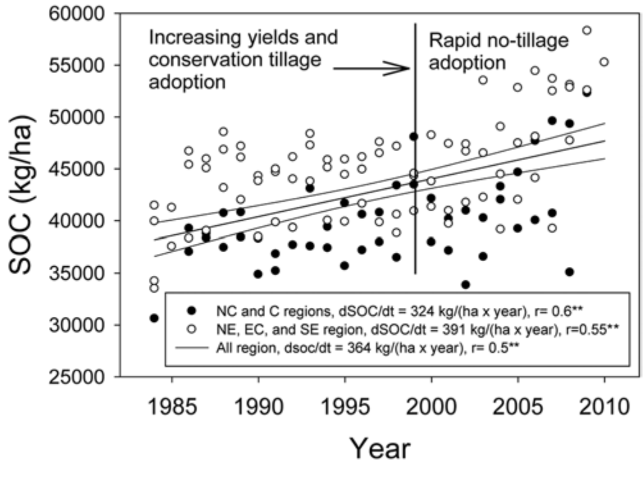

Fig. 5. The influence of year and five sampling regions on the average amount of SOC contained in the surface 15 cm. The number of samples in the NC, C, NE. EC, and SE regions was 20,217, 10,278, 23,891, 34,832, and 14,218, respectively. The 95% confidence interval is shown on the graph.

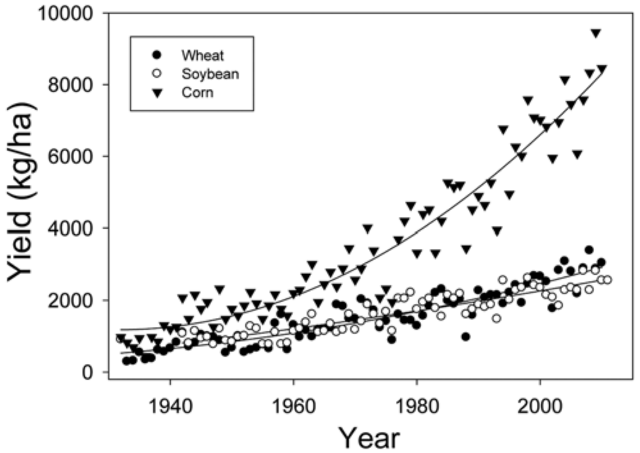

Fig. 6. Temporal changes in the South Dakota state-wide wheat (*Triticum aestivum* L.), soybean [*Glycine max* (L.) Merr.] and corn (*Zea mays* L.) yield per hectare (NASS, 2011).

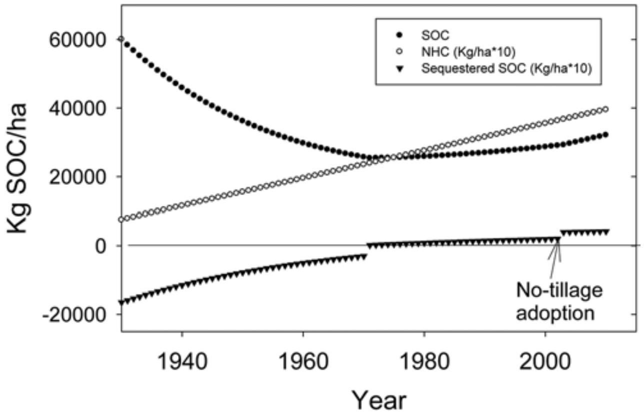

Fig. 7. Simulated temporal changes in SOC resulting from conservation and no-tillage adoption and increasing amount of NHC returned to soil. In this chart, the NHC value is multiplied by 10, whereas the sequestered C value is multiplied by 20. The initial conditions for this simulation were k_{SOC} = [0.030 g (g × yr)$^{-1}$], SOC = 60,000 kg C ha^{-1}; and k_{NHC} = 0.20 g [(g × yr)$^{-1}$].

2009 approximately 35.5% of the land seeded with the major crops (35.6 million ha) had no-tillage operations. After 2007, no-tillage use declined. This decrease is attributed higher rainfall which delayed spring seeding.

A simulation analysis showed that gradual yield increases and reduced tillage intensity from 1930 to 2010 could result in higher SOC concentrations (Fig. 7). These results were attributed to rapid decrease in SOC values following homesteading, gradual yield increases with time, and the adoption of conservation and then no-tillage by area farmers. Following homesteading, the SOC decrease was the result of intensive tillage, low yields, and little NHC returned to the soil. During this time period, surface residues were routinely harvested for livestock feed. The decrease in SOC values following cultivation is consistent with historical records. Based on values reported by Puhr and Olsen (1937) and those in this report it is estimated that 42 and 60% of the SOC contain in the soil in the 1880s was lost by 1937 and 1985, respectively. This loss of C could be explained by the first-order rate equation, $SOC_t = (138 \text{ Mg ha}^{-1}) \times e^{(-0.01 \times t)}$, where t is cultivation years (Six and Jastrow, 2002).

In the future, a third land-use change, crop residue harvesting for livestock feed or ethanol production, will need to be addressed. Producer surveys show that crop residue harvesting has increased from 16% in 2007 (Janssen et al., 2008) to near 50% in 2010 (Mamani-Pati et al., 2010b). Increased crop residue harvesting is attributed to the residues being mixed with distillers grains to produce high quality feed rations (Carlson et al., 2010). Industry investments on the cellulosic conversion of corn stalks and cobs to ethanol will likely accelerate crop residue harvesting that may reduce the C sequestration potential. However, if these materials can be harvested sustainably, the energy gains can be increased 44% (Mamani-Pati et al., 2010b).

Partial Carbon Footprints

Corn's partial C footprint decreased with increasing sequestered C (Table 4). The greenhouse gas (GHG) reduction associated with C storage in surface soil ranged from −5.1 to −14.9 g CO_{2eq} MJ^{-1} for the time period between 2004 and 2007. Slightly higher C sequestration potentials (more negative footprint) were observed between 2008 and 2010. The more negative footprint between 2008 and 2010 were attributed to higher yields and amounts of NHC returned to the soil.

Currently, SOC sequestration is not considered or treated as a source in many C footprint calculations (Mueller and Unnasch, 2007; Wang, 2008; Liska et al., 2009). For example, Wang (2008) considered corn production as a C source (+0.9 g CO_2eq MJ^{-1}), whereas switchgrass was treated as a C sink (−6.73 g CO_2eq MJ^{-1}). This research suggests that annually cropped Northern Great Plains surface soils when seeded with corn should be treated as a C sink. Additional research for subsurface soils is needed to expand this conclusion. Considering C sequestration can have a large impact on C footprints. For example, if a surface soil has a C sequestration potential of −12.5 g CO_2eq MJ^{-1}, then the SOC adjusted C footprint for an ethanol plant with footprint of 58 g CO_2eq MJ^{-1} would be 45.5 g CO_2eq MJ^{-1}. This value would meet the proposed California advanced fuel standard (Arons et al., 2007).

In summary, analysis suggests that C is being sequestered in many Northern Great Plains surface soils. These results are attributed to: (i) SOC mining that occurred following homesteading, (ii) gradual crop yield increases which increased NHC returned to soil, and (iii) wide-scale adoption of reduced tillage and then no-tillage. Increasing SOC content, over the past 25 yr in producer surface soil samples, supports this hypothesis. Calculations and producer soil samples suggest that surface soils of this region are a C sink. These results are different than a general perception that annually cropped soils in the Northern Great Plains are a losing C. These findings may have ramifications relative to water quality and soil resilience.

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Table 4. The influence of sampling region and the short-term sequestered C rates on partial C footprints for the 2004 to 2007 and 2008 and 2010 time periods.

	2004–2007		2008–2010	
Region	Sequestered C	Partial C footprint	Sequestered C	Partial C footprint
	kg SOC/(ha × yr)	g CO_2eq/MJ	kg SOC/(ha × yr)	g CO_2eq/MJ
North-central	229	−14.9	412	−19.6
Central	69	−5.10	329	−14.8
Northeast	182	−8.86	231	−12.0
East-central	125	−6.31	264	−11.4
Southeast	266	−14.9	454	−19.2

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