Long-Term Corn Residue Effects: Harvest Alternatives, Soil Carbon Turnover, and Root-Derived Carbon

A. R. Wilts,* D. C. Reicosky, R. R. Allmaras, and C. E. Clapp

ABSTRACT

A better understanding of C turnover, with estimates of root-derived C, is needed to manage soil C sequestration. The objective was to evaluate the long-term treatment and environmental effects on unharvestable soil C components. Two N fertilizer treatments and a control were imposed during 29 yr of continuous corn (*Zea mays* L.) with stover removal as silage vs. stover return during grain harvest with moldboard plow (MB) tillage. Soil organic carbon (SOC) declined and natural ^{13}C abundance ($\delta^{13}C$) increased during the 29-yr period. Field averages of SOC and $\delta^{13}C$ (0–30 cm) were 96.4 Mg ha^{-1} and −17.3‰ in 1965; respective values in 1995 were 78.9 Mg ha^{-1} and −16.6‰. Loss of SOC was greater with stover removed or no fertilization, but $\delta^{13}C$ increased for all treatments. Stover yield (SY), SOC, and $\delta^{13}C$ data were applied to a model to estimate unharvestable C and predict total source C (SC) input from corn. The SC for 29 yr totaled 172 to 189 Mg ha^{-1} when stover was harvested and 268 to 284 Mg ha^{-1} when stover was returned. The SC input from unharvestable sources was 1.8 times more than SC from aboveground stover when N was added and 1.7 when N was not added. The root-to-shoot ratio was 1.1 when N was added and 1.2 with no N. Only 5.3% of the SC was retained as SOC. Unharvestable C contributions to rhizodeposition are much larger than suggested from controlled studies including C-enriched CO_2 followed by soil respiration or CO_2 efflux measurements.

The management of crop residues and SOC is of primary importance for maintaining soil fertility and productivity as well as environmental quality. Management practices are needed to optimize net primary production (NPP) for improved soil C sequestration (Robinson et al., 1996; Paustian et al., 1997).

Reicosky et al. (1995) reviewed tillage and biomass production impacts on SOC in agricultural systems. They concluded that SOC was controlled by crop residue input that was largely determined by crop choice, fertilization, and climate. Crop residue return or removal, biological oxidation rates, and soil erosion controlled the SOC losses from agricultural systems.

Under continuous corn with MB tillage, the removal of stover plus grain decreased SOC of Mollisols in Iowa (Larson et al., 1972; Robinson et al., 1996), Indiana (Barber, 1979), Michigan (Vitosh et al., 1997), Wisconsin (Vanotti et al., 1997), and Minnesota (Bloom et al., 1982; Huggins et al., 1998a; Reicosky et al., 2002). Some studies have shown surprisingly little response of SOC to differences in C inputs. These results suggest an upper limit on C sequestration in mineral soils independent of the input rate, as demonstrated by Campbell et al. (1991a, 1991b) and Soon (1998), who showed no effect of varying C inputs on soil organic matter (SOM).

Huggins and Fuchs (1997) suggested that SOM changes were dependent on the unharvested corn biomass (aboveground and root) response to N. Balesdent and Balabane (1996) found that corn root-derived C contributed about 1.6 times more C to SOC than stover-derived C.

Natural ^{13}C abundance techniques have significantly improved knowledge about C sequestration. The $\delta^{13}C$ values of SOC represent the relative contribution of C_3 and C_4 plant species to NPP (Collins et al., 1997; Boutton et al., 1998). The $\delta^{13}C$ values from plants with C_3 photosynthesis typically range from −40 to −23‰, while those with C_4 photosynthesis range from −19 to −9‰ (Collins et al., 1997; Boutton et al., 1998). For corn and soybean [*Glycine max.* (L.) Merr.] in southern Minnesota, these values are −12 and −26‰, respectively (Huggins et al., 1998b). When vegetation becomes compositionally stable for a long period of time, the $\delta^{13}C$ values of SOC in the upper soil profile (0–20 cm) approach that of the plant community (Nadelhoffer and Fry, 1988) because only slight isotope fractionation may occur during early stages of SOM decomposition in well-drained, mineral soils (Boutton, 1996).

Since these unique $\delta^{13}C$ values persist during decomposition and SOM formation, the SOM turnover rate can be determined by the rate at which the $\delta^{13}C$ value of SOC changes to approach that of the new plant community (Balesdent et al., 1987; Boutton et al., 1998). Collins et al. (1999) found that $\delta^{13}C$ values in MB-tilled soil were higher than those from noncultivated soil under 8 to 35 yr of continuous corn. The proportion of C_4–derived corn C ranged from 22 to 40% of the total C and decreased with soil depth. Gregorich et al. (1996) reported that N fertilized soils accumulated more corn-derived soil organic carbon (cdSOC) than unfertilized soils. After MB tillage, Angers et al. (1995) found that C_4–derived SOC was distributed evenly in the upper 30 cm. Clapp et al. (2000) noted that N fertilization did not influence cdSOC, residue management did not influence cdSOC for MB tillage, and $\delta^{13}C$ was somewhat evenly depth-distributed in MB tillage.

A.R. Wilts and D.C. Reicosky, USDA-ARS, North Central Soil Conservation Research Lab, 803 Iowa Ave., Morris, MN 56267; R.R. Allmaras (retired), USDA-ARS, Soil and Water Management Research, St. Paul, MN 55108; C.E. Clapp, USDA-ARS, Soil and Water Management Research, St. Paul, MN 55108. All programs and services of the USDA are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, age, marital status, or handicap. Received 4 Feb. 2003. *Corresponding author (wilts@morris.ars.usda.gov).

Published in Soil Sci. Soc. Am. J. 68:1342–1351 (2004).

Abbreviations: $\delta^{13}C$, natural ^{13}C abundance; ρ_b, bulk density; A_t, relic carbon; ANPP, aboveground net primary production; BNPP, belowground net primary production; cdSOC, corn-derived soil organic carbon; GDU, growing degree units; HF, high fertility; HI, harvest index; *h*, stover harvested as silage; LF, low fertility; MB, moldboard plow; NPP, net primary production; *r*, stover returned after grain removal; SC, total source carbon; ^{S}, stover as a portion of SC, SOC or cdSOC; SOC, soil organic carbon; SY, stover yield; UC, unfertilized check; ^{U}, unharvestable material as a portion of SC or cdSOC.

The $\delta^{13}C$ technique can also determine the loss of relic SOC that was characteristic of the previous plant community (Gregorich et al., 1996; Clapp et al., 2000). Stover harvest shortened the relic half-life about 7% without N fertilization, but with N fertilization, stover harvest reduced the half-life by 56%. Clapp et al. (2000) found that N fertilization had no effect on relic SOC half-life in a MB treatment.

Although the $\delta^{13}C$ analysis has markedly improved our understanding of C sequestration, it has only recently (Balesdent and Balabane, 1996; Allmaras et al., 2004) produced a direct measure of the ^{U}SC in the corn root biomass, including the crown with brace roots, structural roots, sloughed root tissue, and exudates. There are suggestions in numerous studies to estimate root biomass from total shoot biomass from grain crops at the end of the growing season:

$$\text{Root biomass} = k(\text{shoot plus grain biomass}) = k(\text{grain biomass/HI}), \quad [1]$$

where HI = harvest index = grain yield/(total biomass in grain and vegetative shoot), and k is a constant (the root-to-shoot ratio at maturity) expressed as a proportion.

The HI in corn is a measure of production success (Sinclair, 1998). Crookston et al. (1991) determined an HI of 0.48 and Allmaras et al. (2004) observed an HI of 0.56 in their field environments. Estimations of root biomass from corn are more sensitive to k than HI; k has been suggested to range from 0.2 to 0.4 (Buyanovsky and Wagner, 1997). Laboratory measurements suggest that k must include a component from exudates in addition to biomass of intact roots (Buyanovsky and Wagner, 1997; Bolinder et al., 1999; Bottner et al., 1999).

Carbon cycle components including above- and belowground NPP, soil surface CO_2 flux and grain C removal for several corn agroecosystems were estimated by Brye et al. (2002) to evaluate effects of land use. They indicated that C loss from the corn agroecosystems occurred mostly from soil surface CO_2 flux (4.6 to 13.0 Mg C ha^{-1} yr^{-1}) and C removed as grain harvest (1.9 to 4.5 Mg C ha^{-1} yr^{-1}).

Reicosky et al. (2002) reported stover harvest (silage) and fertility management effects on SOC after a 30-yr continuous corn study to evaluate the impact of continuous corn silage removal vs. stover return at low fertility (LF) and high fertility (HF). The crop was harvested either as grain or stover plus grain. The stover remaining after grain harvest was incorporated by MB tillage. The specific objective of this new research was to evaluate the long-term treatment effects of corn stover harvest or return on soil C components (SOC, $\delta^{13}C$, and root-derived C). Several levels of N and K fertilization were tested. Stover harvest for energy purposes now has concerns for crop yield sustainability and soil quality maintenance (Wilhelm et al., 2004).

MATERIALS AND METHODS

Thirty-Year Continuous Corn Field Experiment

The experimental site is located at the West Central Research and Outreach Center (WCROC) near Morris, MN (45°36′5″ N and 95°54′11″ W, elevation = 344 m). A 117-yr WCROC weather database indicates that mean annual rainfall is 610 mm, where 406 mm occurs during the growing season (between 1 April and 31 August) and mean annual temperature is 5.7°C (G.A. Nelson, 2003, personal communication). The growing season is characterized by warm, humid conditions during the summer months, and winters are cold enough to maintain frozen soil for an extended period. A weather station is located 300 m from the experimental area, where hourly temperature and precipitation were monitored. Growing degree units (GDU) were calculated by adding the daily high temperature (30°C maximum) to the daily low temperature (10°C minimum), dividing by two, and then subtracting 10. Cumulative GDU and cumulative precipitation were calculated for each of the 30 growing seasons included in this study.

The surrounding topography is a gently rolling, till plain. The experimental area extends over three soil series: Hamerly clay loam (fine-loamy, mixed, superactive, frigid Aeric Calciaquoll), McIntosh silt loam (fine-silty, mixed, superactive, frigid Aquic Calciudoll), and Winger silty clay loam (fine-silty, mixed, superactive, frigid Typic Calciaquoll). These soils have minor textural differences with similar surface water holding capacity, color, and C content (Reicosky et al., 2002).

The experimental land area was virgin prairie until 1875; since then, it has been farmed with conventional tillage methods (MB in the fall followed by disk harrow and field cultivation in the spring). The primary crops grown were corn, wheat (*Triticum aestivum* L.), alfalfa (*Medicago sativa* L.), and oat (*Avena sativa* L.) in various combinations or rotations until 1965. Then, during this subsequent 30-yr continuous corn experiment (Bloom et al., 1982; Reicosky et al., 2002), locally-adapted hybrids were planted on dates ranging from mid-April to mid-May at seeding rates of 55 000 plants ha^{-1} in early years and 75 000 plants ha^{-1} in later years. The experimental design was a Latin square with 15- by 15-m plots. The main treatments were arranged as a two-by-two factorial design with two levels of residue returned and two levels of fertilization.

Corn silage was typically harvested before 15 September during the late dough to early dent stage, but before the grain had completely dried. The silage was cut at 15 to 20 cm above the soil surface leaving the corn stalk with brace roots (crown). Silage yields were determined from three 3-m long rows collected from each plot. The plants were chopped by hand, weighed wet, dried for 48 h at 66°C, and reweighed. A forage harvester was used to harvest the bulk silage. Corn grain was harvested about 3 wk after the silage. Grain yields were calculated after harvesting two 14-m rows with a plot combine. A larger combine was then used to harvest bulk grain and all stover was returned to the same plot where harvested. Measurements were also obtained from an adjacent unfertilized check (UC) plot with only grain removed. Harvest index (the ratio of grain to total aboveground biomass) was calculated when both grain and SY were determined from the same plot.

Shortly after grain harvest, N, P, and K fertilizers were broadcast on all plots except the UC before MB tillage. This fertilization before tillage may have maximized contact between incorporated N and C (Allmaras et al., 1996). The annual LF treatment was 83, 23, and 45 kg ha^{-1} yr^{-1} of N, P, and K, respectively. The HF treatment, based on a typical fertilizer recommendation for 1965, was 166, 46, and 90 kg ha^{-1} yr^{-1} of N, P, and K, respectively. The experimental plots were generally MB-tilled in the fall as deep as 25 cm, followed by secondary cultivation with a disk or spring tooth cultivator in the spring. Further details of field experimental procedures, study objectives, and results were reported by Reicosky et al. (2002).

Detrended Harvest Index, Growing Degree Units, and Precipitation

Harvest indices and cumulative amounts of GDU and precipitation were each detrended to determine treatment-induced HI response to hydrothermal environment. A curvilinear fit of HI vs. time (yr) for each treatment was used to determine the detrended HI. A similar detrending procedure with only a linear fit was applied to cumulative GDU and cumulative precipitation observed in each of the 29 growing seasons. These detrended hydrothermal observations were then each correlated with detrended HI for each treatment.

Laboratory Analysis for Natural Carbon-13 Abundance

Two sets of soil samples were taken to measure total organic C and $\delta^{13}C$. Before the first year of the experiment (1966), soil samples were taken from the 0- to 20-cm depth within each of the 16 plots in the fall of 1965 and then stored air-dried in a heated building. In June 1995, six randomly selected soil cores were collected in nontracked interrows from each plot with a 35-mm-diam. probe. Samples were obtained from 0- to 15-, 15- to 30-, and 30- to 45-cm depths. All soil samples were air-dried, ground to pass a 5-mm sieve, and ball milled.

Measurements of total C and 10% HCl tests indicated the presence of inorganic C in all plots. To remove carbonates and sulfates before $\delta^{13}C$ analysis, the Follett et al. (1997) method was modified by increasing the concentration of the H_3PO_4 solution added to a 5- to 6-g soil sample from 0.03 *M* H_3PO_4 (100 mL) to either 0.1 *M* H_3PO_4 (100 mL for soils low in carbonate reaction and 150 mL for moderate carbonate presence) or 1.0 *M* H_3PO_4 (used when sulfates were also present). A combination spot-plate test with 10% HCl and 1:1 soil in water pH was used to determine use of either 0.1 *M* H_3PO_4 or 1.0 *M* H_3PO_4 for soils with pH 7.5 or higher. After several rinses to remove dissolved impurities, soil samples were oven-dried at 70°C [modified from the 55°C drying temperature described in the Follett et al. (1997) method] for 24 h and ball milled.

Duplicate subsamples of soil were run on an elemental analyzer and a stable isotope mass spectrometer (Carlo Erba, Model NA 1500 and Fisons, Optima Model; Fisons Ltd., Middlewich-Cheshire, UK) configured into a continuous-flow system. Soil samples of 1 to 5 mg, depending on C content, were used for analysis of total organic C and $\delta^{13}C$.

The isotope analyses were expressed as ‰ values:

$$\delta^{13}C = [(R_{sam}/R_{std}) - 1] \times 10^3, \qquad [2]$$

where $R_{sam} = {}^{13}C/{}^{12}C$ ratio for the sample, and $R_{std} = {}^{13}C/{}^{12}C$ ratio of the working standard. The ^{13}C values were calculated relative to Pee Dee Belemnite (PBD) as an original standard, and working standards were urea and soil with $\delta^{13}C$ of −18.2 and −17.6‰, respectively. The fraction of cdSOC from each treatment was determined by use of a proportional ratio procedure (Clapp et al., 2000):

$$\delta^{13}C_f = f\,\delta^{13}C_a + (1 - f)\,\delta^{13}C_i, \qquad [3]$$

where $\delta^{13}C_f$ = final $\delta^{13}C$ of SOC, $\delta^{13}C_a = \delta^{13}C$ from corn residue (−12.0‰), f = fraction of cdSOC, and $\delta^{13}C_i = \delta^{13}C$ from the initial SOC.

The fraction (f) determined from $\delta^{13}C$ data in Eq. [3] was multiplied by the final SOC to estimate the cdSOC:

$$\text{cdSOC} = f\,(\text{SOC}). \qquad [4]$$

Soil bulk density (ρ_b) was not measured during these 1965 and 1995 samplings. However, in the spring of 1966, soil ρ_b was measured in one of the treatments in an adjacent experiment (Allmaras et al., 1977). The measured ρ_b of 1.23 Mg m^{-3} in the 0- to 30-cm depth was obtained from nonfragmented soil before spring tillage and should represent ρ_b during the 1965 growing season and extending into 1966. In 1965, fall field operations at the measurement site included light disking of soybean residue, uniform tractor-packing, and thinly seeding winter rye (Allmaras et al., 1977). In 1995, soil ρ_b measurements were made in several adjacent experiments tilled with a MB plow in the fall of 1994 and secondary tillage in 1995; these ρ_b measurements averaged 1.30 Mg m^{-3} for the 0- to 30-cm depth. The mass of SOC was calculated on a volume basis as follows: Mg C ha^{-1} = SOC (g kg^{-1} soil) × ρ_b (Mg m^{-3}) × L (cm) × 0.1, where L = layer thickness. Although the 1965 samples were taken from the 0- to 20-cm layer, it was assumed that the measured C (g kg^{-1}) represented that for the 0- to 30-cm layer. Uniformity of C content and ρ_b for the whole 30-cm layer was noted in the 1995 sampling of the 0- to 15-cm and 15- to 30-cm layers.

Estimating Relic Soil Organic Carbon

Relic carbon (A_t) was the portion of the original SOC (SOC_i) that remained at the end of the 29-yr of continuous corn. The A_t values were estimated from Table 1, where $A_t = SOC_i - |\Delta SOC| - \text{cdSOC}$.

Estimating Root-Derived Carbon

Molina et al. (2001) modeled the incorporation of C from corn roots and rhizodeposition into SOM using actual field data collected by Clapp et al. (2000) in Minnesota. Allmaras et al. (2004) then developed a model using paired plots (stover harvested or returned) to estimate SC in unharvestable material (crown, root, and root exudates). Some commonly used

Table 1. Mean soil carbon (mass basis) and $\delta^{13}C$ within the 0- to 30-cm layer as influenced by method of harvest (silage and corn stover return) and N rate.

Treatment†	N rate	Soil organic carbon (SOC) indicators‡						
		$\delta^{13}C_i$	$\delta^{13}C_f$	SOC_i	SOC_f	ΔSOC	cdSOC	cdSOC/SOC_f
	kg ha⁻¹ yr⁻¹	‰		Mg ha⁻¹				
HF, *r*	166	−17.39	−16.26	95.94	79.56	−16.38	16.71	0.210
HF, *h*		−17.41	−16.71	99.68	79.17	−20.51	10.21	0.129
LF, *r*	87	−17.32	−16.40	87.95	76.17	−11.78	13.18	0.173
LF, *h*		−17.43	−16.81	103.27	81.35	−21.92	9.27	0.114
UC, *r*	none	−17.01	−16.40	106.71	80.77	−25.94	9.85	0.122
SE§		0.11	0.16	2.54	2.04	2.15	1.21	0.026

† HF = high fertility, LF = low fertility, UC = unfertilized check, *r* = stover returned, and *h* = stover harvested.
‡ SOC_i and SOC_f = soil organic carbon observed in 1965 (initial) and 1995 (final), respectively; ΔSOC = change in soil organic carbon for 1965 to 1995; cdSOC = soil organic carbon derived from corn.
§ SE = standard error (with six df) determined from ANOVA of Latin square for the first four indicators and subsequent functional approximations (Allmaras and Kempthorne, 2002) for the last three indicators.

assumptions are summarized in this section and explained with more detail by Bolinder et al. (1999) and Allmaras et al. (2004). The required paired-plot data from this study meet model requirements. Residue treatment abbreviations are *r*, representing corn stover return after grain had been removed, and *h*, representing corn stover harvested as silage. Briefly, the model of Allmaras et al. (2004) consists of three steps: (i) cdSOC from unharvested C of the *h* treatment was estimated by the calculated cdSOC in the *h* treatment; (ii) cdSOC due to stover of the *r* treatment was obtained by subtracting out the cdSOC estimated in Step (i); and (iii) unharvested SC was obtained from the ratio of cdSOC (derived from stover) to total stover C, assuming a ratio of unharvested cdSOC to total unharvested SC.

The cumulative 29-yr SY, with an assumed average C content of 420 g kg^{-1} (Clapp et al., 2000), was an initial parameter used to estimate the total C available from stover (Allmaras et al., 2004). Stover returned was estimated by subtracting the harvested grain from the total aboveground biomass produced in the stover-return treatments. Since grain yields were not measured when silage was removed from the stover-harvest plots, corresponding grain yields from the stover-returned plots were subtracted from total aboveground biomass produced from the silage treatments. Cumulative stover, grain, and silage yields were calculated from 28 yr of measured yield data (29 yr total) reported by Reicosky et al. (2002). The 1993 yield data are missing because of an unharvestable crop and the 1995 (Year 30) yield data reported by Reicosky et al. (2002) were not included since SOC reported in this study were determined from samples collected in June 1995. Cumulative yields were plotted against time (years of continuous corn) to obtain a linear fit. The 29-yr SY estimates were used in the model.

After the cdSOC had been calculated from $\delta^{13}C$ and SOC (Eq. [4] to [7]) for the various treatments, they were then used to estimate SC (Eq. [8] to [11]). The *r* and *h* treatments differed in their SC, but were assumed to have similar cdSOC relationships. The high and low N fertility levels also differed in total SC, but were assumed to show the same relationship between cdSOC and SC. Data from the unfertilized *r* treatment plot was not applied to the model since it was not paired with a corresponding unfertilized *h* treatment that was necessary to predict ^{U}SC.

In *h* treatments, unharvestable material was assumed to solely influence cdSOC since both grain and stover were harvested. The following relationship was assumed [Step (i)]:

$$^{U}cdSOC_h = cdSOC_h, \qquad [5]$$

where the superscripted U indicates that cdSOC was derived from unharvestable materials and the subscripted *h* refers to the stover-harvested treatments.

An assumption was made that total cdSOC was derived from both stover SC (when returned) and ^{U}SC. The difference between total cdSOC and $^{U}cdSOC$ resulted in cdSOC from stover as follows [Step (ii)]:

$$^{S}cdSOC_r = cdSOC_r - {}^{U}cdSOC_h \qquad [6]$$

where the superscripted S indicates that cdSOC was derived from stover.

Another assumption made by Allmaras et al. (2004) was that the *r* and *h* treatments had an equivalent unharvested cdSOC that differed only in proportion to aboveground SY. Stover was an integral component of the corn plant until harvest. Thus, the estimated cdSOC from unharvested materials in the *r* treatment equaled cdSOC from unharvested materials in the *h* treatment multiplied by the ratio of SY represented as Step (iii):

$$^{U}cdSOC_r = (SY_r/SY_h)\,^{U}cdSOC_h, \qquad [7]$$

where SY_r represents cumulative SY from the *r* treatment and SY_h represents cumulative SY from the *h* treatment.

The ^{S}SC was determined by multiplying SY by the estimated stover C content of 420 g C kg^{-1}. For convenience, the ratio (F) equaled $^{S}cdSOC_r$ divided by the total C in stover:

$$F = {}^{S}cdSOC_r/(0.42 \times SY_r) = {}^{S}cdSOC_r/{}^{S}SC. \qquad [8]$$

Unharvested-source C (^{U}SC) was estimated by

$$^{U}SC = {}^{U}cdSOC/F. \qquad [9]$$

Allmaras et al. (2004) assumed that stover and unharvestable biomass contributed similarly as source C for cdSOC. To support this assumption, Allmaras et al. (2004) indicated that the C contribution to cdSOC from components of unharvestable material was somewhat balanced. They concluded that root biomass may contribute more C (Bolinder et al., 1999; Wilhelm et al., 2004), whereas, root exudates and other rhizodeposits may contribute less C to cdSOC (Bottner et al., 1999) than stover biomass.

Total SC was the sum of ^{U}SC and ^{S}SC sources of C:

$$SC = {}^{U}SC + {}^{S}SC. \qquad [10]$$

A ratio of $R = {}^{U}SC/{}^{S}SC$ was determined for each treatment.

Estimating Net Primary Production and Carbon Loss

Aboveground net primary production (ANPP) was estimated by multiplying the mass of aboveground plant material by an assumed average C content of 420 g kg^{-1} (Clapp et al., 2000) for dried corn plant material. Belowground net primary production (BNPP) equaled the model estimates of annual ^{U}SC. Total NPP was calculated as the sum of ANPP and BNPP.

Rochette and Flanagan (1997) indicated that the proportion of rhizosphere respiration to total soil surface CO_2 flux averaged 0.45 during a corn growing season. Brye et al. (2002) used this proportion to estimate C losses from rhizosphere respiration that ranged from 2.1 to 5.8 Mg C ha^{-1} yr^{-1} for corn agroecosystems. This rhizosphere respiration range was generally applied for all treatments in our study as Brye et al. (2002) indicated that soil surface CO_2 fluxes in the corn agroecosystems were not significantly affected by tillage and fertilization.

All measurements of SOC and $\delta^{13}C$ were subjected to an ANOVA (SAS Institute, 1988) for the Latin square (four columns, rows, treatments) without a split plot for the 1965 data, but with a split plot for the 1995 samples, to accommodate the three soil depths sampled. Standard errors and means for yields of grain, stover, silage, HI, SOC, and $\delta^{13}C$ were all obtained from ANOVA. All other standard errors of functions of the original variables were estimated with the procedures of Allmaras and Kempthorne (2002). Tests ($P < 0.05$) were used for means comparisons. Regression equations and associated plots were obtained with Sigma Plot (SPSS, 1998).

RESULTS AND DISCUSSION

Soil Organic Carbon and Carbon-13 Natural Abundance

Separate ANOVAs for 1965 and 1995 data each showed no statistically significant treatment effects on SOC and $\delta^{13}C$, even though row and column combinations in the Latin square reduced field variability compared with a simple randomized block design. Yet, sequential measurements of SOC and $\delta^{13}C$ in the same plot did show significant treatment effects. A similar situation was observed by Clapp et al. (2000). Reicosky et al. (2002) used a Latin square ANOVA for SOC (g kg^{-1}) data from 1965 and 1995, and also did not find significant treatment effects.

Overall field averages of SOC and $\delta^{13}C$ in the 0- to 30-cm depth were 96.45 $\pm$ SE = 0.42 Mg ha^{-1} and $-17.346 \pm$ SE = 0.057‰ in 1965; respective values in 1995 for the 0- to 30-cm depth were 78.87 $\pm$ SE = 1.05 Mg ha^{-1} and $-16.575 \pm$ SE = 0.079‰. For the 30- to 45-cm depth in 1995, the respective field averages were 20.00 $\pm$ SE = 2.08 Mg ha^{-1} and $-15.372 \pm$ SE = 1.706‰. The mean annual SOC loss was 0.61 Mg ha^{-1} and the corn label ($\delta^{13}C = -12.0$‰) increased $\delta^{13}C$ by 0.026‰ yr^{-1} in the 0- to 30-cm layer associated with corn monoculture and MB tillage.

Our observations, and those of Reicosky et al. (2002), showed an overall SOC decrease during continuous corn production with MB tillage that agrees with that of Clapp et al. (2000) even though their experiment included an N application of 200 kg N ha^{-1}. Huggins et al. (1998b) have also shown no change of total SOC during 10 yr of continuous corn with MB tillage before and during the experiment. In contrast, Gregorich et al. (1996) showed a 13% increase in total SOC after 32 yr of continuous corn with MB tillage and N fertilization in eastern Canada. On the basis of the results of this study, changes in $\delta^{13}C$ from 1965 to 1995 are comparable with Liang et al. (1998), who indicated an almost 2‰ increase in $\delta^{13}C$, and only small (<8%) management-induced changes in SOC in the 0- to 20-cm soil depth within 12 yr of continuous corn with fall MB tillage followed by spring disk-harrow.

Treatment effects (N rate and disposition of corn stover) were examined for SOC loss and the $\delta^{13}C$ changes attributable to 29 yr of continuous corn (Table 1). Variations of $\delta^{13}C_i$ among treatments in 1965 resulted from field heterogeneity, but variations of $\delta^{13}C_f$ reflected both field variability and treatments imposed. Nevertheless, the $\delta^{13}C$ increased for all treatments. When stover was returned, $\delta^{13}C$ increased more than when harvested as silage. Applied fertilizer rates did not influence the $\delta^{13}C$ change. Variations in the final C content (SOC_f) are again influenced by field variability and treatments. A similarly large variation of initial SOC was also shown in Clapp et al. (2000). Stover harvest significantly ($P <$ 0.05) increased SOC loss (more negative ΔSOC), decreased cdSOC, and decreased cdSOC/SOC_f, but the two applied fertilizer treatments did not significantly differ in their influence on these three indicators (Table 1). There were no interactions resulting from fertilizer rate and stover management. Compared with the applied fertilizer treatments with corn stover returned, the nonfertilized control had a significantly ($P <$ 0.05) larger SOC loss (more negative ΔSOC), and less cdSOC (Table 1). There was also a smaller cdSOC/SOC_f. When stover was harvested from the applied fertilizer treatments, their means of ΔSOC, cdSOC, and cdSOC/SOC_f were within 20% of that in the nonfertilized control with stover return. Clapp et al. (2000) reported a smaller cdSOC/SOC_f of 0.10 for MB tillage. Moreover, their cdSOC/SOC_f did not change in response to stover management in contrast to that shown in Table 1. A notable difference between the two experiments was the absence of secondary tillage in the Clapp et al. (2000) study. Both experiments noted no cdSOC/SOC_f response to N fertilization even though the time and incorporation of N fertilizer differed in these two experiments. Gregorich et al. (1996) observed a larger overall cdSOC/SOC_f of 0.30 when N fertilized and 0.17 when nonfertilized.

Some analyses of $\delta^{13}C$ and total C made in the 1965 samples showed inorganic C as great as 40 Mg ha^{-1}. The $\delta^{13}C$ of the 30- to 45-cm layer increased about 1.20‰ and SOC decreased 12.4 Mg ha^{-1} relative to the 0- to 30-cm layer as measured in 1995. These changes with depth are consistent with Huggins et al. (1998b), who summarized several hypotheses that control $\delta^{13}C$ changes. Briefly, the hypotheses were listed as: (i) historic shifts of flora, (ii) decreases in atmospheric concentration of ^{13}C, (iii) translocations after humification, (iv) microbial-mediated discrimination against ^{13}C, and (v) biochemical variations in plant residues in soils undisturbed by tillage. Huggins et al. (1998b) suggested the influence of tillage (especially MB tillage) on depth distribution of crop residues may also change the depth distribution of $\delta^{13}C$. Staricka et al. (1991) has shown that the type of tillage tool controls the depth of crop residue incorporation. Clapp et al. (2000) found the most enriched and deepest label of $\delta^{13}C$ in MB compared with other tillage systems.

Soil Organic Carbon Decomposition

The SOC_i ranged from 88 to 107 Mg ha^{-1} (Table 1), while A_t ranged from 62.8 to 72.1 Mg ha^{-1}. Assuming a first-order reaction, decomposition was expressed as $A_t = SOC_i\ e^{-\kappa t}$, where t was time (yr) and κ was an apparent decomposition constant. The κ ranged from 0.0115 to 0.0146 with a mean of 0.0136. On the basis of κ, the mean half-life was 77 yr, which was not influenced by any treatments. Clapp et al. (2000) measured a mean half-life of 68 yr with no effect of N when MB tillage was used, while residue return extended the half-life in all three tillage systems. Gregorich et al. (1995) also noted no influence of N on A_t decomposition (half-life near 20 yr), while Green et al. (1995) showed that A_t half-life was extended by applied N in contact with freshly incorporated corn residue.

Stover, Grain, and Silage Yields

Mean annual stover and grain yields were significantly increased ($P < 0.05$) by each N-fertilization increment, 0 to 87 to 166 kg ha^{-1} yr^{-1} (Table 2), which agreed with results from a similar long-term N management study (Huggins and Fuchs, 1997). Silage yield was also significantly increased ($P < 0.05$) by N application of 166 compared with 87 kg ha^{-1} yr^{-1}. Unlike the results of Allmaras et al. (2004), the stover return subtreatment within each N level was not significantly different in our study. Cumulative SYs were plotted vs. time (yr) to obtain linear regression r^2 values > 0.96, and Allmaras

Table 2. Mean annual corn grain, stover, silage, harvest index (HI), unharvestable material yield, root-to-shoot ratio (*k*), aboveground net primary production (ANPP), and belowground net primary production (BNPP) during the 29-yr period.

		Measured parameters‡				Estimated parameters			
Treatment†	N rate	Grain	Stover	Silage	HI	unharvestable biomass§	*k*	ANPP	BNPP
	$kg\ ha^{-1}\ yr^{-1}$	$Mg\ ha^{-1}\ yr^{-1}$				$Mg\ ha^{-1}\ yr^{-1}$		$Mg\ C\ ha^{-1}\ yr^{-1}$	
HF, *r*	166	5.04	8.22	–	0.38	15.07	1.14	5.57	6.33
HF, *h*		nm¶	8.46	13.51	–	15.52	1.15	5.67	6.52
LF, *r*	87	4.72	7.72	–	0.38	14.31	1.15	5.22	6.01
LF, *h*		nm	7.61	12.36	–	14.09	1.14	5.19	5.92
UC, *r*	none	2.66	5.48	–	0.33	9.52	1.17	3.42	4.10

† HF = high fertility, LF = low fertility, UC = unfertilized check, *r* = stover returned, and *h* = stover harvested.
‡ Grain, stover and silage yields were integrated from values reported by Reicosky et al. (2002) to account for missing data. All biomass yields have a SE = 0.15 $Mg\ ha^{-1}$; SE for HI = 0.01 for applied N and 0.02 for no N applied.
§ Unharvestable biomass includes crown, root, and root exudates; Unharvestable soil carbon (^{U}SC) values are listed in Table 3. Unharvestable biomass yield = (1/29)(^{U}SC/0.42).
¶ nm, not measured.

et al. (2004) suggested that linear regression with an $r^2 > 0.90$ facilitated an assumption of linear SOC and $\delta^{13}C$ across time.

Assuming quantities of ^{U}SC in both stover return and silage plots are different only as related to SY during the 29-yr study duration, more C was returned to the stover-returned plots than stover-removed plots, 94 Mg ha^{-1} for LF and 100 Mg ha^{-1} for HF. Huggins and Fuchs (1997) showed evidence from directly measured corn root biomass that N nutrition effects on root biomass were greatest in the upper soil profile. Since total shoot biomass affects root biomass, Buyanovsky and Wagner (1997) concluded that any variation in aboveground biomass should be reflected in the roots through a similar root-to-shoot ratio.

Corn-Derived Soil Organic Carbon

The cdSOC for the 0- to 30-cm depth after 29 yr ranged from 9.3 to 16.7 Mg ha^{-1} (Table 1). The cdSOC under the *h* treatments in this experiment ranged from 61 to 70% of the cdSOC under the *r* treatments, and the range increased with lower N fertilization. In similar experiments, comparing *h* to *r* treatments, values of 61 and 73% were reported by Balesdent and Balabane (1996) and Allmaras et al. (2004), respectively.

Total Source Carbon

Total SC for the *h* treatment ranged from 172 to 189 Mg ha^{-1}, while that for *r* treatments ranged from 268 to 284 Mg ha^{-1} (Table 3). The annual input of corn C ranged from 5.9 to 9.8 Mg ha^{-1} compared with 3.4 and 9.2 Mg ha^{-1} reported by Balesdent and Balabane (1996) and Buyanovsky and Wagner (1997), respectively.

The ^{U}cdSOC ranged from 9.3 to 10.2 Mg ha^{-1} with a SE of 1.2 Mg ha^{-1} (Table 3), while the ^{S}cdSOC ranged from 3.8 to 6.8 Mg ha^{-1} with a SE of 2.42 Mg ha^{-1}. The fraction of stover SC that entered the ^{S}cdSOC, the ratio *F*, was extremely low, 0.05 (SE = 0.03), while comparative values ranged from 0.12 to 0.17 in the Allmaras et al. (2004) study. Even though the overall ^{U}SC was greater from the higher compared with lower N rate, the computed *R* ratios of 1.83 and 1.85 were not significantly different because ^{S}SC also increased. With N fertilization, *R* ratios of 1.60 (Balesdent and Balabane, 1996) and 2.6 (Allmaras et al., 2004) have also been observed. Without N fertilization, the *R* ratio was 2.0 (Allmaras et al., 2004), suggesting that N fertilization may significantly increase SC contribution to unharvestable root components (plus exudates) relative to the contribution to stover.

The cdSOC (Table 3) as a function of SC input to

Table 3. Input and computed parameters used to estimate unharvestable and total source carbon (SC) in the 0- to 30-cm layer.

Treatment†	SY‡	Total SOC§ (final)	*f*¶	cdSOC#	^{U}cdSOC††	^{S}cdSOC‡‡	*F*§§	^{U}SC¶¶	*R*##	SC†††
	$Mg\ ha^{-1}$							$Mg\ ha^{-1}$		$Mg\ ha^{-1}$
HF, *r*	238.4	79.6	0.210	16.71	9.91	6.79	0.054	183.5	1.83	283.6
HF, *h*	245.5	79.2	0.129	10.21	10.21	0	–	189.1	–	189.1
LF, *r*	223.9	76.2	0.173	13.18	9.41	3.77	0.054	174.2	1.85	268.3
LF, *h*	220.5	81.3	0.114	9.27	9.27	0	–	171.7	–	171.7
UC, *r*	158.9	80.8	0.122	9.85	–	–	–	–	–	–
SE‡‡‡	0.1	2.0	0.025	1.21	1.0	1.10	0.030	6.0	0.35	10.0

† Stover management − grain harvested in all treatments; stover was harvested as silage. HF = high fertility, LF = low fertility, UC = unfertilized check, *r* = stover returned, *h* = stover harvested.
‡ SY = stover yield. The ^{S}SC = stover soil carbon was estimated to be 0.42 × SY.
§ SOC = soil organic carbon.
¶ *f* = fraction of soil organic carbon derived from corn.
# cdSOC = carbon in soil organic carbon derived from corn.
†† ^{U}cdSOC = carbon in soil organic carbon derived from unharvestables: ^{U} = unharvestable material as a portion of SC or cdSOC.
‡‡ ^{S}cdSOC = carbon in soil organic carbon derived from stover: ^{S} = stover as a portion of SC, SOC, or cdSOC.
§§ *F* = ratio of ^{S}cdSOC/^{S}SC. The *F* values for high and low fertility, 0.068 and 0.040, respectively, were not statistically different. The averaged value of 0.054 was used and the precision was increased by $\sqrt{2}$.
¶¶ ^{U}SC = unharvestable source carbon.
R = ratio of $^{U}SC/^{S}SC$.
††† SC = total source carbon (input to soil).
‡‡‡ SE = standard error with six df.

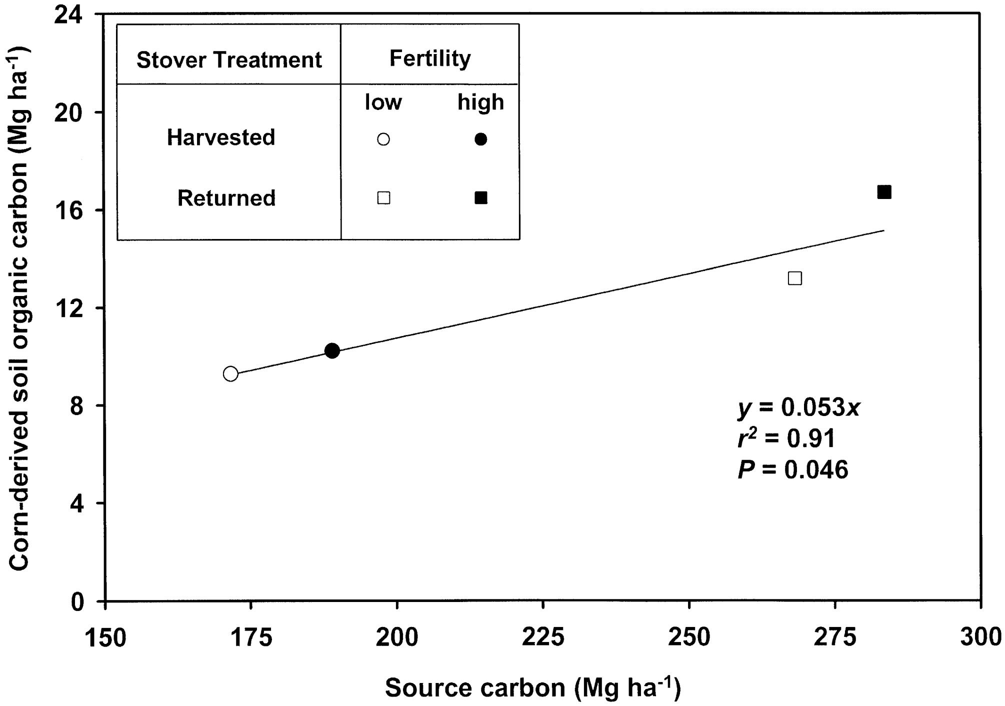

Fig. 1. Efficiency of moldboard tillage for incorporation of total source carbon into corn-derived soil organic carbon (cdSOC). The stover-returned treatment represents corn stover return after grain removal, and the stover-harvested treatment represents corn stover harvest as silage.

the soil produced an estimate of SC retained in the cdSOC (Fig. 1). The linear model ($y = 0.053x$), where y = cdSOC (Mg ha^{-1}) and x = total SC (Mg ha^{-1}), indicates that MB tillage in this study allowed total SC retention of 5.3%. Allmaras et al. (2004) measured total SC retention of 11% for MB tillage. When Clapp et al. (2000) used an empirical method to estimate the root-to-shoot ratio for the same experiment, they observed a retention coefficient of 0.21 to 0.26 for MB and chisel tillage when stover was returned.

Apparently, a large amount of the SC was lost from the system during the growing season and possibly as later tillage-induced CO_2 efflux (Reicosky and Lindstrom, 1993). The intimate proximity of fresh SC and N fertilizer, when fertilizer was surface broadcast before incorporation of residue in the fall, may have provided ideal conditions for denitrification and SOC mineralization (Aulakh and Rennie, 1987; Aulakh et al., 1991; Allmaras et al., 1996). Soil organic C losses due to soil erosion were not expected because slopes were <2%.

The UC with stover return was not paired with a stover harvest. Assuming the UC had 5.3% retention, similar to the other MB treatments, the equation in Fig. 1 suggests that the total SC was 186 Mg ha^{-1}, while Table 3 suggests stover C of 67 Mg ha^{-1}. The difference between the total SC and stover C indicates an ^{U}SC of 119 Mg ha^{-1} with an estimated R ratio in this case of 1.78.

Harvest Index and Biomass Estimation

Harvest index is an indicator of photosynthate partitioning related to genetic potential, plant species, and stress (Sinclair, 1998). Nitrogen deficiency, temperature, and water supply are three common stresses (Prihar and Stewart, 1990). Harvest index is also an important indicator when the root biomass is to be estimated and only grain or stover, but not both, are measured (Eq. [1]). Harvest index itself is a highly variable parameter. Without stress, the theoretical genetic HI maximum for corn has been suggested to be 0.65 (Prihar and Stewart, 1990). However, actual measurement of HI under field conditions indicates a maximum HI of 0.54 (Prihar and Stewart, 1990; Linden et al., 2000). Gregorich et al. (1996) estimated a HI of 0.45 when N fertilized and 0.30 when unfertilized. In this study, mean HI values were 0.38 and 0.33 (SE = 0.02) when N fertilized and unfertilized, respectively (Table 2). There was significant year-to-year variation in HI, cumulative GDU, and precipitation as shown in Fig. 2 and 3. The detrended HI variation across time did not differ among treatments with applied N, where the mean variance was 0.004. The variance for the UC (0.015) was 3.8 times larger, although not statistically different. The greater HI variation across time and a smaller mean HI in the UC both agree with the concept that greater N stress may have reduced HI (Table 2). Correlations between detrended HI and detrended cumulative GDU ranged from $r = 0.14$ for the highest N rate to $r = 0.49$ for the lowest N rate. Correlations between detrended HI and cumulative precipitation ranged from $r = 0.33$ for the highest N rate to $r = -0.14$ for the lowest N rate. Wilhelm and Varvel (1998) monitored vegetative development of corn and found that the growing degree days requirement to achieve a phyllochron increased when low N availability reduced the rate of development. Similarly, the relationships between HI and GDU reported in this study may be related to N rate.

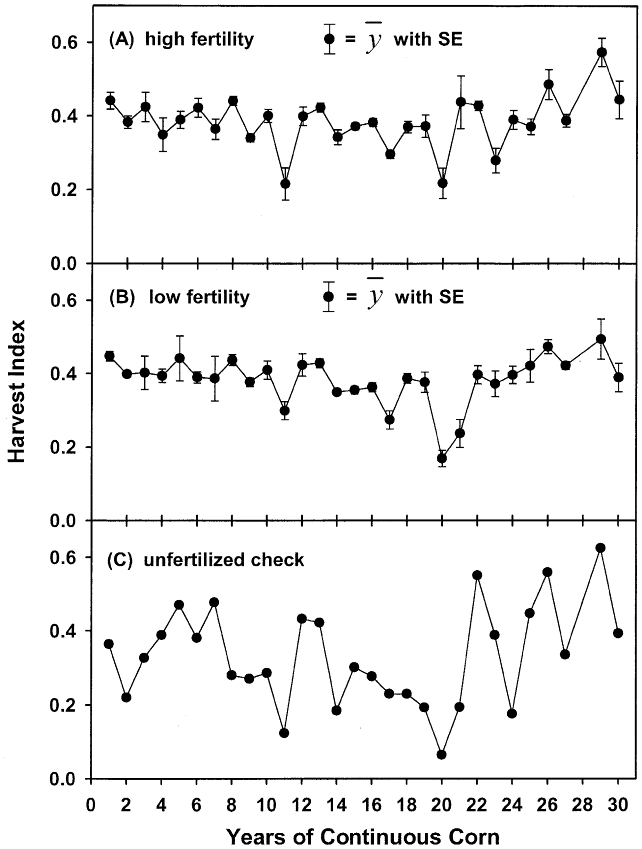

Fig. 2. Harvest indices from (A) high fertility, (B) low fertility, and (C) unfertilized check plots with stover returned for 30 yr of continuous corn except for crop failure in year 28. ($n = 4$ from high and low fertility treatments and $n = 1$ from unfertilized check.)

Our estimates of HI and especially the root-to-shoot ratio show the hazard of estimating root biomass with only grain and stover biomass. The root-to-shoot ratio (k) was estimated by the mean annual grain plus stover biomass to match the mean annual value of the calculated cumulative unharvested material (root) biomass (Table 2). In the two-by-two factorial arrangement of applied N and stover harvest, the mean k for stover return and stover harvest was 1.1, with no significant difference between the two N rates. The estimated k for UC was 1.2. Harvest index in corn under field conditions can vary from 0.30 to 0.54, as reported by Gregorich et al. (1996) and Linden et al. (2000), while our reported k estimates near 1.0 are much larger than empirically derived estimates, most of which are <0.4.

Net Primary Production and Carbon Loss Estimation

Aboveground NPP were greater for the fertilized treatments than the UC (Table 2), which agrees with Brye et al. (2002) results from corn agroecosystems. Total NPP estimates ranged from 7.5 to 12.2 Mg C ha^{-1} yr^{-1} and BNPP estimates were 53% of total NPP. Brye et al. (2002) reported total NPP estimates ranging from 5.3 to 12.2 Mg C ha^{-1} yr^{-1} with BNPP estimates that were 13% of total NPP. The lower BNPP estimated by Brye et al. (2002) were calculated from measured root biomass, root N concentration, and an assumed belowground biomass C/N ratio.

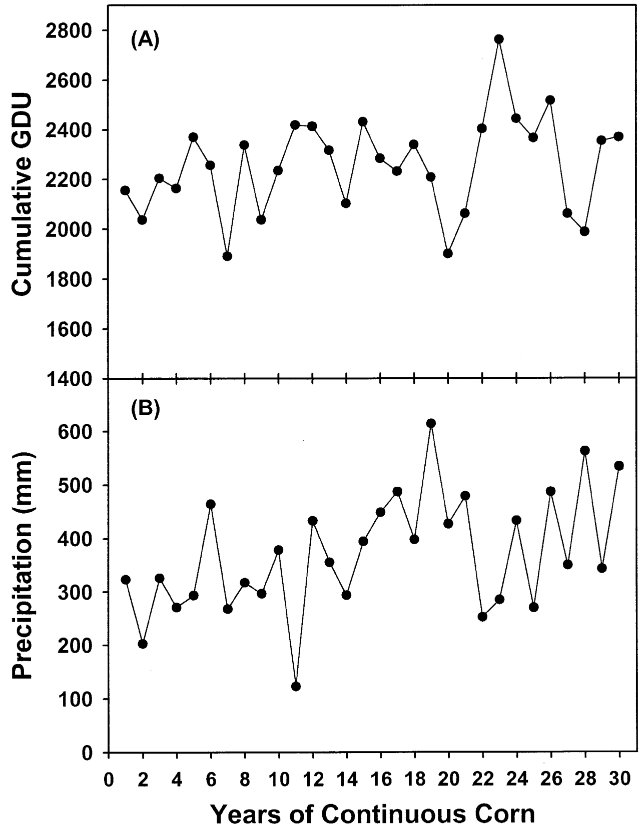

Fig. 3. (A) Cumulative growing degree units and (B) cumulative precipitation from the time of planting until grain was harvested.

The C removed in grain averaged 2.0 Mg C ha^{-1} yr^{-1} for fertilized treatments and 1.1 Mg C ha^{-1} yr^{-1} for the unfertilized treatment. Grain C was 33 to 38% of ANPP estimated from the r treatments and within the range of 28 to 61% of ANPP that Brye et al. (2002) reported for corn agroecosystems. The estimated total C loss due to biomass removal and rhizosphere respiration for the h treatments averaged 9.4 Mg ha^{-1} yr^{-1} (80% of NPP), while that for fertilized r treatments averaged 6.0 Mg ha^{-1} yr^{-1} (52% of NPP). The estimated total C loss due to biomass removal and rhizosphere respiration for the unfertilized r treatment averaged 5.0 Mg ha^{-1} yr^{-1} (67% of NPP).

CONCLUSIONS

Soil organic C and δ^{13}C, when measured in this long-term field experiment of continuous corn under MB tillage, were influenced by stover and N management. Soil organic C in the top 30 cm declined during the 29-yr period and losses differed significantly between the treatments in a two-by-two factorial arrangement of stover management and N, P, and K rates. The overall δ^{13}C increase of 0.77‰ in the top 30 cm and increases of 25% or more when stover was returned instead of harvested or a higher fertilizer rate was applied were sufficiently precise to estimate the cdSOC independent of total SOC change. Source C input from unharvestable sources (crowns, roots, and root exudates) was 1.8 times more than SC from aboveground stover residues when N was added and 1.7 when N was not added. The amount of cdSOC and its ratio to final SOC were both greater with stover return than with stover harvest or no N added. Corn-derived SOC as a function of total SC indicated only a 5.3% retention coefficient because of MB tillage.

The harvest indices were about 20% lower, and the root-to-shoot ratios almost 200% higher than most values shown in the literature. Nitrogen fertilizer addition effects on HI and year-to-year HI variations indicated physiological stress. The root-to-shoot ratios for stover-returned and stover-harvested treatments when N was applied were no more than 10% lower than ratios determined from treatments without N application.

Model estimates of SC from unharvestable roots were as much as two times greater than most SC estimated from HI and empirical root-to-shoot ratios. Much of the greater SC may account for rhizodeposition susceptible to mineralization during the growing season. These research findings showed that corn harvest alternatives and residue management practices had important implications for SC incorporation into cdSOC and may now offer guidance when determining rates of stover harvest for energy purposes.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the West Central Research and Outreach Center staff for the use of their resources; particularly, Sam Evans, Al Koehler, George Anderson, Carlos Bright, and George Nelson, who provided the historical soil samples, as well as soil data and management information. Authors also acknowledge Steve Copeland and Meg Layese for soil preparation and $\delta^{13}C$ analyses.

REFERENCES

Allmaras, R.R., S.M. Copeland, P.J. Copeland, and M. Oussible. 1996. Spatial relations between oat residue and ceramic spheres when incorporated sequentially by tillage. Soil Sci. Soc. Am. J. 60:1209–1216.

Allmaras, R.R., E.A. Hallauer, W.W. Nelson, and S.D. Evans. 1977. Surface energy balance and soil thermal property modifications by tillage-induced soil structure. Tech. Bull. 306. Minnesota Agric. Exp. Stn., St. Paul, MN.

Allmaras, R.R., and O. Kempthorne. 2002. Errors, variability, and precision. p. 15–44. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4—Physical methods. SSSA Book Ser. No. 5. SSSA, Madison, WI.

Allmaras, R.R., D.R. Linden, and C.E. Clapp. 2004. Corn-residue transformations into root and soil carbon as related to nitrogen, tillage, and stover management. Soil Sci. Soc. Am. J. 68:1366–1375 (this issue).

Angers, D.A., R.P. Voroney, and D. Côté. 1995. Dynamics of soil organic matter in corn residues affected by tillage practices. Soil Sci. Soc. Am. J. 59:1311–1315.

Aulakh, M.S., J.W. Doran, D.T. Walters, A.R. Mosier, and D.D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. Soil Sci. Soc. Am. J. 55:1020–1025.

Aulakh, M.S., and D.A. Rennie. 1987. Effect of wheat straw incorporation on denitrification of N under anaerobic and aerobic conditions. Can. J. Soil Sci. 67:825–834.

Balesdent, J., and M. Balabane. 1996. Major contribution of roots to soil carbon storage inferred from maize cultivated soils. Soil Biol. Biochem. 28:1261–1263.

Balesdent, J., A. Mariotti, and B. Guillet. 1987. Natural ^{13}C abundance as a tracer for studies of soil organic matter dynamics. Soil Biol. Biochem. 19:25–30.

Barber, S.A. 1979. Corn residue management and soil organic matter. Agron. J. 71:625–627.

Bloom, P.R., W.M. Schuh, G.L. Malzer, W.W. Nelson, and S.D. Evans. 1982. Effect of nitrogen fertilizer and corn residue management on organic matter in Minnesota Mollisols. Agron. J. 74:161–163.

Bolinder, M.A., D.A. Angers, M. Giroux, and M.R. Laverdiere. 1999. Estimating C inputs retained as soil organic matter from corn (*Zea mays* L.). Plant Soil 215:85–91.

Bottner, P., M. Pansu, and Z. Sallih. 1999. Modelling the effect of active roots on soil organic matter turnover. Plant Soil 216:15–25.

Boutton, T.W. 1996. Stable carbon isotope ratios of soil organic matter and their use as indicators of vegetation and climate change. p. 47–82. *In* T.W. Boutton and S. Yamasaki (ed.) Mass spectrometry of soils. Marcel Dekker, New York.

Boutton, T.W., S.R. Archer, A.J. Midwood, S.F. Zitzer, and R. Bol. 1998. $\delta^{13}C$ values of soil organic carbon and their use in documenting vegetation change in a subtropical savanna ecosystem. Geoderma 82:5–41.

Brye, K.R., S.T. Gower, J.M. Norman, and L.G. Bundy. 2002. Carbon budgets for a prairie and agroecosystems: Effects of land use and interannual variability. Ecol. Appl. 12:962–979.

Buyanovsky, G.A., and G.H. Wagner. 1997. Crop residue input to soil organic matter in the Sanborn field. p. 73–83. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Campbell, C.A., K.E. Bowren, M. Schnitzer, R.P. Zentner, and L. Townley-Smith. 1991a. Effect of crop rotations and fertilization on soil organic matter and some biochemical properties of a thick Black Chernozem. Can. J. Soil Sci. 71:377–387.

Campbell, C.A., G.P. LaFond, R.P. Zentner, and V.O. Biederbeck. 1991b. Influence of fertilizer and straw baling on soil organic matter in a thin, Black Chernozem in western Canada. Soil Biol. Biochem. 23:443–446.

Clapp, C.E., R.R. Allmaras, M.F. Layese, D.R. Linden, and R.H. Dowdy. 2000. Soil organic carbon and C-13 abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. Soil Tillage Res. 55:127–142.

Collins, H.P., R.L. Blevins, L.G. Bundy, D.R. Christenson, W.A. Dick, D.R. Huggins, and E.A. Paul. 1999. Soil carbon dynamics in corn-based agroecosystems: Results from carbon-13 natural abundance. Soil Sci. Soc. Am. J. 63:584–591.

Collins, H.P., E.A. Paul, K. Paustian, and E.T. Elliott. 1997. Characterization of soil organic carbon relative to its stability and turnover. p. 51–72. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113.

Follett, R.F., E.A. Paul, S.W. Leavitt, A.D. Halvorson, D. Lyon, and G.W. Peterson. 1997. Carbon isotope ratios of Great Plains soils and in wheat-fallow systems. Soil Sci. Soc. Am. J. 61:1068–1077.

Green, C.J., A.M. Blackmer, and R. Horton. 1995. Nitrogen effects on conservation of carbon during corn residue decomposition in soil. Soil Sci. Soc. Am. J. 59:453–459.

Gregorich, E.G., B.H. Ellert, C.F. Drury, and B.C. Liang. 1996. Fertilization effects on soil organic matter turnover and corn residue placement. Soil Sci. Soc. Am. J. 60:472–476.

Gregorich, E.G., B.H. Ellert, and C.M. Monreal. 1995. Turnover of soil organic matter and storage of corn residue carbon estimated from ^{13}C natural abundance. Can. J. Soil Sci. 75:161–167.

Huggins, D.R., G.A. Buyanovsky, G.H. Wagner, J.R. Brown, R.G. Darmondy, T.R. Peck, G.W. Loesing, M.B. Vanotti, and L.G. Bundy. 1998a. Soil organic C in the tallgrass prairie-derived region of the Corn Belt: Effects of long-term crop management. Soil Tillage Res. 47:219–234.

Huggins, D.R., C.E. Clapp, R.R. Allmaras, J.A. Lamb, and M.F. Layese. 1998b. Carbon dynamics in corn-soybean sequences as estimated from natural carbon-13 abundance. Soil Sci. Soc. Am. J. 62:195–203.

Huggins, D.R., and D.J. Fuchs. 1997. Long-term N management effects on corn yield and soil C of an Aquic Haplustoll in Minnesota.

p. 121–128. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Larson, W.E., C.E. Clapp, W.H. Pierre, and Y.B. Morachan. 1972. Effects of increasing amounts of organic residues on continuous corn. II. Organic carbon, nitrogen, phosphorous and sulfur. Agron. J. 64:204–208.

Liang, B.C., E.G. Gregorich, A.F. MacKenzie, M. Schnitzer, R.P. Voroney, C.M. Monreal, and R.P. Beyaert. 1998. Retention and turnover of corn residue carbon in some eastern Canadian soils. Soil Sci. Soc. Am. J. 62:1361–1366.

Linden, D.R., C.E. Clapp, and R.H. Dowdy. 2000. Long-term corn grain and stover yields as a function of tillage and residue removal in east central Minnesota. Soil Tillage Res. 56:167–174.

Molina, J.A.E., C.E. Clapp, D.R. Linden, R.R. Allmaras, M.F. Layese, R.H. Dowdy, and H.H. Cheng. 2001. Modeling the incorporation of corn (*Zea mays* L.) carbon from roots and rhizodeposition into soil organic matter. Soil Biol. Biochem. 33:83–92.

Nadelhoffer, K.J., and B. Fry. 1988. Controls on natural nitrogen-15 and carbon-13 abundances in forest soil organic matter. Soil Sci. Soc. Am. J. 52:1633–1640.

Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls on soil carbon. p. 15–49. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Prihar, S.S., and B.A. Stewart. 1990. Using upper-bound slope through origin to estimate genetic harvest index. Agron. J. 82:1160–1165.

Reicosky, D.C., S.D. Evans, C.A. Cambardella, R.R. Allmaras, A.R. Wilts, and D.R. Huggins. 2002. Continuous corn with moldboard tillage: Residue and fertility effects on soil carbon. J. Soil Water Conserv. 57:277–284.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas, Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage and biomass production. J. Soil Water Conserv. 50: 253–261.

Reicosky, D.C., and M.J. Lindstrom. 1993. The effect of fall tillage method on short-term carbon dioxide flux from soil. Agron. J. 85:1237–1243.

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

Rochette, P., and L.B. Flanagan. 1997. Quantifying rhizosphere respiration in a corn crop under field conditions. Soil Sci. Soc. Am. J. 61:466–474.

SAS Institute. 1988. SAS/STAT users guide. Release 6.03 ed. SAS Inst., Cary, NC.

SPSS. 1998. SigmaPlot 5.0 Programming Guide, SPSS, Chicago, IL.

Sinclair, T.R. 1998. Historical changes in harvest index and crop nitrogen accumulation. Crop Sci. 38:638–643.

Soon, Y.K. 1998. Crop residue and fertilizer management effects on some biological and chemical properties of a dark, Gray Solod. Can. J. Soil Sci. 78:707–713.

Staricka, J.A., R.R. Allmaras, and W.W. Nelson. 1991. Spatial variation of crop residue incorporated by tillage. Soil Sci. Soc. Am. J. 55:1668–1674.

Vanotti, M.B., L.G. Bundy, and A.E. Peterson. 1997. Nitrogen fertilizer and legume cereal rotation effects on soil productivity and organic matter dynamics in Wisconsin. p. 105–119. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Vitosh, M.L., R.E. Lucas, and G.H. Silva. 1997. Long-term effects of fertilizer and manure on corn yield, soil carbon and other soil chemical properties in Michigan. p. 129–139. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Wilhelm, W.W., J.M.F. Johnson, J.L. Hatfield, W.B. Voorhees, and D.R. Linden. 2004. Crop and soil productivity response to corn residue removal: A literature review. Agron. J. 96:1–17.

Wilhelm, W.W., and G.E. Varvel. 1998. Vegetative development of corn under various N management strategies. p. 94. *In* 1998 Agronomy abstracts. ASA, Madison, WI.