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Soil organic carbon and ^{13}C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota

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Abstract

Long-term field experiments are among the best means to predict soil management impacts on soil carbon storage. Soil organic carbon (SOC) and natural abundance ^{13}C ($\delta^{13}C$) were sensitive to tillage, stover harvest, and nitrogen (N) management during 13 years of continuous corn (*Zea mays* L.), grown on a Haplic Chernozem soil in Minnesota. Contents of SOC in the 0–15 cm layer in the annually-tilled [moldboard (MB) and chisel (CH)] plots decreased slightly with years of corn after a low input mixture of alfalfa (*Medicago sativum* L.) and oat (*Avena sativa* L.) for pasture; stover harvest had no effect. Storage of SOC in no-till (NT) plots with stover harvested remained nearly unchanged at 55 Mg ha^{-1} with time, while that with stover returned increased about 14%. The measured $\delta^{13}C$ increased steadily with years of corn cropping in all treatments; the NT with stover return had the highest increase. The N fertilization effects on SOC and $\delta^{13}C$ were most evident when stover was returned to NT plots. In the 15–30 cm depth, SOC storage decreased and $\delta^{13}C$ values increased with years of corn cropping under NT, especially when stover was harvested. There was no consistent temporal trend in SOC storage and $\delta^{13}C$ values in the 15–30 cm depth when plots received annual MB or CH tillage. The amount of available corn residue that was retained in SOC storage was influenced by all three management factors. Corn-derived SOC in the 0–15 cm and the 15–30 cm layers of the NT system combined was largest with 200 kg N ha^{-1} and no stover harvest. The MB and CH tillage systems did not influence soil storage of corn-derived SOC in either the 0–15 or 15–30 cm layers. The corn-derived SOC as a fraction of SOC after 13 years fell into three ranges: 0.05 for the NT with stover harvested, 0.15 for the NT with no stover harvest, and 0.09–0.10 for treatments with annual tillage; N rate had no effect on this fraction. Corn-derived SOC expressed as a fraction of C returned was positively biased when C returned in the roots was estimated from recovery of root biomass. The half-life for decomposition of the original or relic SOC was longer when stover was returned, shortened when stover was harvested and N applied, and sharply lengthened when stover was not harvested and N was partially mixed with the stover. Separating SOC storage into relic and current crop sources has significantly improved our understanding of the main and interacting effects of tillage, crop residue, and N fertilization for managing SOC accumulation in soil. Published by Elsevier Science B.V.

Keywords: No-tillage; Moldboard-tillage; Chisel-tillage; Corn-derived carbon; Carbon storage

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1. Introduction

Soil organic carbon (SOC) storage is sensitive to tillage systems, crop residue return (or harvest of straw/silage), and nitrogen (N) management — each of these main effects and their interactions may have a significant impact on soil physical, chemical, and biological properties either directly or associated with changes in SOC. We report SOC storage in a Waukegan silt loam, a well drained Haplic Chernozem soil in the northern Corn Belt with no calcareous accumulation above 60 cm. The site had a high level of SOC characteristic of alfalfa (*Medicago sativum* L.) and oat (*Avena sativa* L.) in rotation pasture, with some manure applications, before continuous corn (*Zea mays* L.) provided the sole source of C additions and created a C_4-type input for tracing ^{13}C natural abundance. Accumulated SOC storage and the ^{13}C abundance in the soil derived from the corn stover allowed the separate accounting for the two C pools: (1) that in the soil before the corn (relic C) and (2) that derived from the corn (corn-derived C).

Tillage effects on SOC storage have been characterized either as a single factor or in combination with crop residue management, N fertilization, or both (Havlin et al., 1990; Franzluebbers et al., 1994; Ismail et al., 1994; Lal et al., 1994; Rasmussen and Parton, 1994; Paustian et al., 1997; Reeves et al., 1997; Salinas-Garcia et al., 1997; Dao, 1998). Storage of SOC in shallow soil depths <7.5 cm is usually greater with no-till than in annually-tilled systems when sweep, chisel, disk, or moldboard are the primary tillage tool. However, SOC storage below 7.5 cm can be greater in annually-tilled systems, as shown in two Ohio soils where SOC storage was greater in the no-till system near the surface, but below 7.5 cm the SOC storage was equal to or less than in the moldboard system (Dick and Durkalski, 1987). Wander et al. (1998) demonstrated that tillage system (no-till compared to moldboard) effects on SOC storage near the soil surface and deeper in the traditional Ap layer depended on which one of the three Illinois soils were tested. For comparing SOC storage the sampling depth for all treatments should be at least as deep as the maximum depth of tillage (Ellert and Bettany, 1995).

Perhaps more important than SOC storage in many studies with no-till was the impact of decomposing residue on infiltration, run-off, and soil erosion, because the residues were on or near the soil surface. Allmaras et al. (1988) demonstrated nearly identical depth distributions of coarse organic matter and SOC as controlled by tillage systems in a long-term field experiment in Oregon. Microbial biomass is commonly linked to decomposing organic matter (Martin and Haider, 1986), therefore suggesting more bioactive impact on water stable aggregation where there is a larger storage of SOC near the surface in non-moldboard systems.

The position and quantity of crop residue as well as N fertilization have variable influences on SOC storage (Paustian et al., 1997). When more crop residues are on or near the surface, the storage of SOC has been increased (Larson et al., 1972; Rasmussen et al., 1980; Havlin et al., 1990) but when incorporated by moldboard tillage the quantity of crop residue has had little or no influence on SOC storage (Huggins et al., 1998). Nitrogen fertilization can have variable effects ranging from significantly increased SOC (Blevins et al., 1977; Ismail et al., 1994; Salinas-Garcia et al., 1997) to only small increases of SOC storage (Havlin et al., 1990). Paustian et al. (1997) suggest numerous mechanisms for variable SOC storage response to crop residue return and N fertilization, but conclude that much unexplained variation exists among field experiments.

Recently, studies on SOC storage and turnover have employed ^{13}C natural abundance as an in situ marker of relic and recent SOC pools (Balesdent et al., 1987, 1988, 1990; Angers et al., 1995; Gregorich et al., 1996; Huggins et al., 1998; Liang et al., 1998). Mass concentrations of both SOC and ^{13}C are sufficient to calculate the amount of SOC coming from a C_4 (e.g., corn) crop or from a C_3 [e.g., soybean, *Glycine max* (L.) Merr.] crop. Angers et al. (1995) found that corn-derived SOC was evenly distributed with depth in a moldboard plow treatment and accumulated near the soil surface in shallow reduced-tillage treatments, but total SOC storage from corn residue in the 0–24 cm layer was reduced and not significantly affected by tillage when the stover was harvested. Storage of SOC in the study of Balesdent et al. (1990) was shallow tine tillage>no-till>moldboard tillage when stover was returned and N was not limiting. Gregorich et al. (1996) reported significant SOC turnover as influenced by long-term N fertilization of continuous corn. Total organic C and ^{13}C measurements indicated that fertilized soils had more SOC than unfertilized soils, the difference was accounted for by more C_4-derived C in fertilized soils. About 22–30% of the SOC in the Ap layer had turned over and was derived from corn in the fertilized soils; in unfertilized soils only 15–20% was derived from corn. Liang et al. (1998) showed a larger change in SOC storage in a coarse-textured than in a fine-textured soil as related to N fertilization and quantity of residue returned. They noted a fast SOC turnover early and a very small turnover after 12 years of continuous corn.

The objective of this study was to determine the main and interaction effects of tillage, stover harvest, and N fertilization on SOC storage, the $\delta^{13}C$ label, and corn-derived SOC in the soil within several depths of the tilled layer during a 13-year field experiment with continuous corn, a C_4 crop with a $-12‰$ $\delta^{13}C$ label. A separate characterization of the relic and corn-derived C afforded the opportunity to assess the impact of these three management treatments on SOC storage.

2. Materials and methods

2.1. Long-term field experiment

Soil samples for this study were taken from a field experiment, initiated in 1980, at the University of Minnesota Research and Outreach Center in Rosemount, Minnesota to investigate tillage, crop residue management, and N fertilization (Clay et al., 1989). The experiment consisted of eight tillage by residue (stover harvest or return) treatments, each on a randomly allocated, separate block 18×50 m. Each tillage by residue treatment, as a separate block, was subdivided into 12 plots, to give four plots for each of three N fertilization levels. The four N fertilization plots were randomly assigned to one of the three N treatments. Only those treatment combinations sampled for this study will be reported here. The primary tillage treatments in the fall were: no-till (NT), moldboard-plow (MB), and chisel-plow (CH). There was no secondary tillage. Residue treatments were: corn stover returned (r), and corn stover harvested (h). The N levels reported here were 0 and 200 kg N ha^{-1}, surface broadcast applied as ammonium sulfate before or within 10 days after planting. The current Minnesota soil test recommended N rate for a grain yield of 6 Mg ha^{-1} is 120 kg N ha^{-1} for this soil. The N fertilizer was not incorporated in either the annually-tilled (MB and CH) treatments or the NT treatment. Corn, cultivar Pioneer[1] 3780 with a maturity of 105 days, was grown for 13 years. Stover dry matter yields at the time of grain harvest were measured annually by hand sampling two 6 m lengths of row in the center of each plot.

The soil was a Waukegan silt loam (fine-silty over sandy or sandy skeletal, mixed, mesic Typic Hapludoll), formed from silt loam loess (about 50–80 cm) underlain by neutral to calcareous glacial outwash sand and gravel. The FAO classification is a Haplic Chernozem. The site had a uniform slope of less than 1%. Field history involved only 2 years of corn, 1 year of soybean, 5 years of oats interseeded with alfalfa and 20 years of pasture before the corn experiment was started in 1980. There is no historical information about fertilization and biomass production before 1980. At the start of the experiment, the 0–15 cm surface soil had an average pH of 6.4 (0.01 M $CaCl_2$); SOC of 55.5 Mg ha^{-1}; CEC of 2.37 cmol (NH_4^+) kg^{-1} of soil; and C/N ratio of 10.7 (Clay et al., 1989). Prairie grass levels of SOC in adjacent soil averaged 59.1 Mg ha^{-1}.

Average annual precipitation was 82 cm, 61% of which occurred during the growing season (1 May–30 September). The number of growing degree days annually averaged 2900 when a growing degree day had an air temperature above 10°C but less than 30°C. The average annual air temperature was 7°C with an average of −11 and 22°C in January and July, respectively. The climate is continental with a subhumid moisture regime.

2.2. Soil bulk density

A different system of bulk density (BD) measurement and soil sampling was used in 1993 than previously. Before 1993, BD was measured in selected 7.5 cm depth increments collected with a Giddings sampling tube (1980) or a Uhland core sampler. Both of these sampling methods removed a soil core with a diameter of 7.6 cm; the sampling position was always

[1] Mention of a trade or company name is for information only and does not imply an endorsement by the USDA-ARS or the University of Minnesota.

about 5 cm from the row center in a non-wheeltrack location. Except in 1980, before imposition of the tillage treatments, and in 1993 at the end of the experiment, soil samples for SOC and $\delta^{13}C$ were taken independently of the samples for BD, both as related to time and row–interrow position. For the 1993 sampling, soil cores were taken in the row using a procedure (Allmaras et al., 1988) that provided a continuous measure of BD in 5 cm increments to 60 cm. Within each subplot of each tillage×stover-return treatment at least 12 randomly selected cores (1.8 cm diameter) were composited for BD measurement; a subsample from the air-dried soil was then used in the SOC and $\delta^{13}C$ analyses.

Because the 1993 sampling provided paired BD and soil samples for SOC and $\delta^{13}C$ analysis and sufficient data to synthesize a continuous BD function over depth for all treatment combinations at the same time, all BDs between 1980 and 1993 were based upon the 1993 sampling. Comparisons were made, however, for BD measured annually to evaluate if there were any procedural, treatment, or time effects on BD. Whenever the sampling increment before 1993 was not 0–15 and 15–30 cm, the depth function of BD was used to estimate values of BD corresponding to their sampling increment.

2.3. Analyses for total organic carbon and ^{13}C abundance

Selected soil samples were collected spatially from the field site before planting in the spring of 1980. Core (5×15 cm^2) samples were collected on a grid arrangement in the soil profile overlying a gravel layer at a 90–100 cm depth (Clay et al., 1989). From 1980 to 1992 soil samples were taken within several days after planting (10×2.0 cm cores) from each plot corresponding to a tillage×stover management option; all plots were then sampled in mid-July 1993. During the 1980–1993-period soil cores were composited to the N treatment level. Samples were taken from CH treatments less frequently than from the other tillage treatments. Samples on annually-tilled plots were collected at 0–15 and 15–30 cm depths before 1993; on NT plots, samples were taken at 0–7.5, 7.5–15, and 15–30 cm depths. In 1993 all treatments were sampled for bulk density (BD) and analyzed for SOC in 5 cm increments. The data were normalized to match the 0–15 and 15–30 cm depths. An extra set of soil samples (fallow) was taken in 1980 and 1993 from four alleyways between the tillage×stover return plots. Alleyways had been clean-tilled without crops since 1980.

All soil samples were analyzed for SOC and ^{13}C natural abundance. Composite samples were passed through a 2 mm sieve, stones were removed, and roots and residues were returned. The composite was subsampled and ball milled for analysis. Duplicate subsamples of about 2 mg were then run on an elemental analyzer and a stable isotope ratio mass spectrometer (Carlo Erba[1], model NA 1500 and Fisons[1], Optima model; Fisons, Middlewich-Cheshire, UK) configured into a continuous flow system. The isotope analyses were expressed in terms of ‰ values

$$\delta^{13}C = \left[\left(\frac{R_{\mathrm{sam}}}{R_{\mathrm{std}}}\right) - 1\right] \times 10^3 \qquad (1)$$

where $R_{\mathrm{sam}}={}^{13}\mathrm{C}/{}^{12}\mathrm{C}$ ratio for the sample, and $R_{\mathrm{std}}={}^{13}\mathrm{C}/{}^{12}\mathrm{C}$ ratio of the working standard. The ^{13}C values were calculated relative to Pee Dee Belemnite as an original standard. Urea and soil with $\delta^{13}C$ values of −18.2 and −17.6‰, respectively, served as working standards.

The fraction of SOC derived from corn was calculated from the equation

$$\delta_{\mathrm{m}} = f\delta_{\mathrm{a}} + (1-f)\delta_{\mathrm{b}} \qquad (2)$$

where δ_{m} is the current $\delta^{13}C$ in the SOC, f the fraction of SOC from corn, δ_{a} the $\delta^{13}C$ from corn residue (−12‰), and δ_{b} the initial $\delta^{13}C$ in SOC. The corn-derived SOC in Mg ha^{-1} is the product of f and the measured SOC. The remaining SOC is relic SOC.

Statistical procedures were based upon duplication of field-sampled BD, total SOC, and $\delta^{13}C$ values in the presence of random error. The tillage×stover-return treatments and the N rates within each tillage×stover-return treatment block were randomly assigned stagewise. The N treatments were quadruplicated within each tillage×stover-return treatment block.

3. Results

3.1. Soil bulk density

Profiles of soil BD (Fig. 1) indicate tillage depths consistent with those observed in an adjacent experi-

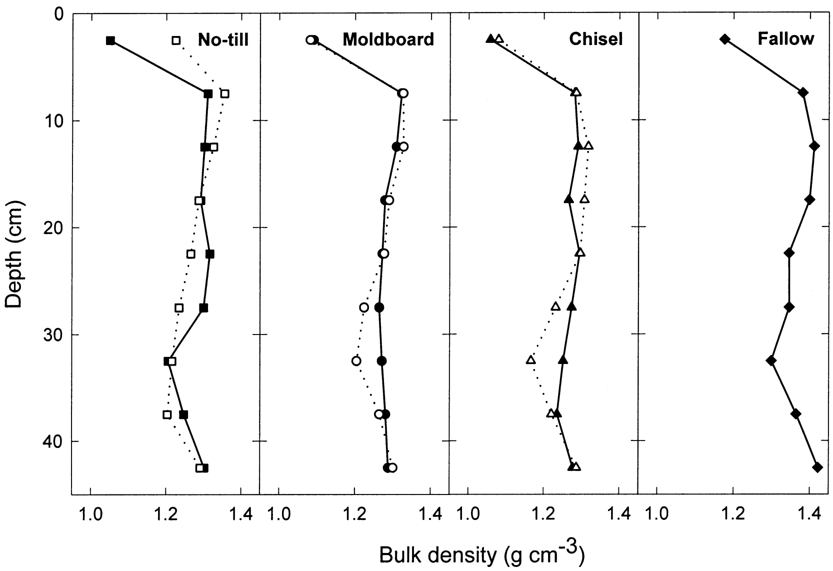

Fig. 1. Profiles of soil BD measured in 1993 for three tillage treatments with (—) and without (...) stover return, and for a fallow soil at the same field site (plotted points have a standard error of the mean=0.03 g cm^{-3}).

ment where the same machinery was used (Allmaras et al., 1996). The means in Fig. 1 averaged over the N treatments have a standard error of the mean <0.03 g cm^{-3}. Within the depth of annual tillage (17 cm in CH and 23 cm in MB), the BD of treatments with incorporated stover were somewhat less than when stover was removed. Earthworm burrowing, casting, and residue incorporation activity (observed visually) were higher in the NT treatment without stover harvest; it decreased BD in the upper 20 cm. Crop residue could have readily been carried down to 10 cm by earthworm activity, which produced a markedly greater brittle fracture of aggregates within the upper 10 cm of the treatment with stover return. Greater incorporation of crop residue into the 5–10 cm depth in the CH treatment may explain the lower BD (mean over both stover management options) compared to the MB and NT in this same depth interval. Buried crop residue in the MB system was concentrated close to the maximum tillage depth (Allmaras et al., 1996), which was about 23 cm in this study.

The BD was higher between 20 and 30 cm, in the NT treatment, and between 25 and 37 cm in the MB and CH treatments when stover was returned. These differences were below the residue return depth. This effect may be due to migration of C or some other constituent, and crop rooting depth (Dowdy et al., 1988), but cannot be completely explained. Over the depth range from 2 to 22 cm, the BD in the fallow treatment was higher than in any treatment with continuous corn. Comparative BD profiles (Fig. 1) show that corn rooting and corn stover return reduced BD in the soil layers above 20 cm.

The BD values measured annually with the Uhland sampler after planting and before significant rainfall were consistently 0.1 g cm^{-3} lower than those measured with the small diameter tube in 1993 (data not shown). The difference between methods was likely not large enough to be sensitive to the magnitude of the BD measured. Some of this difference may have been caused by soil consolidation within the tilled layer during the period between planting and the July 1993 sampling.

3.2. SOC and ^{13}C abundance

Amounts of SOC storage in the 0–15 cm layer over the 13-year period (Fig. 2A) generally remained constant or decreased with time for both the 0 and 200 kg N ha^{-1} rates. Each mean in Fig. 2A has a confidence interval (p<0.05) of 0.09 Mg ha^{-1} based

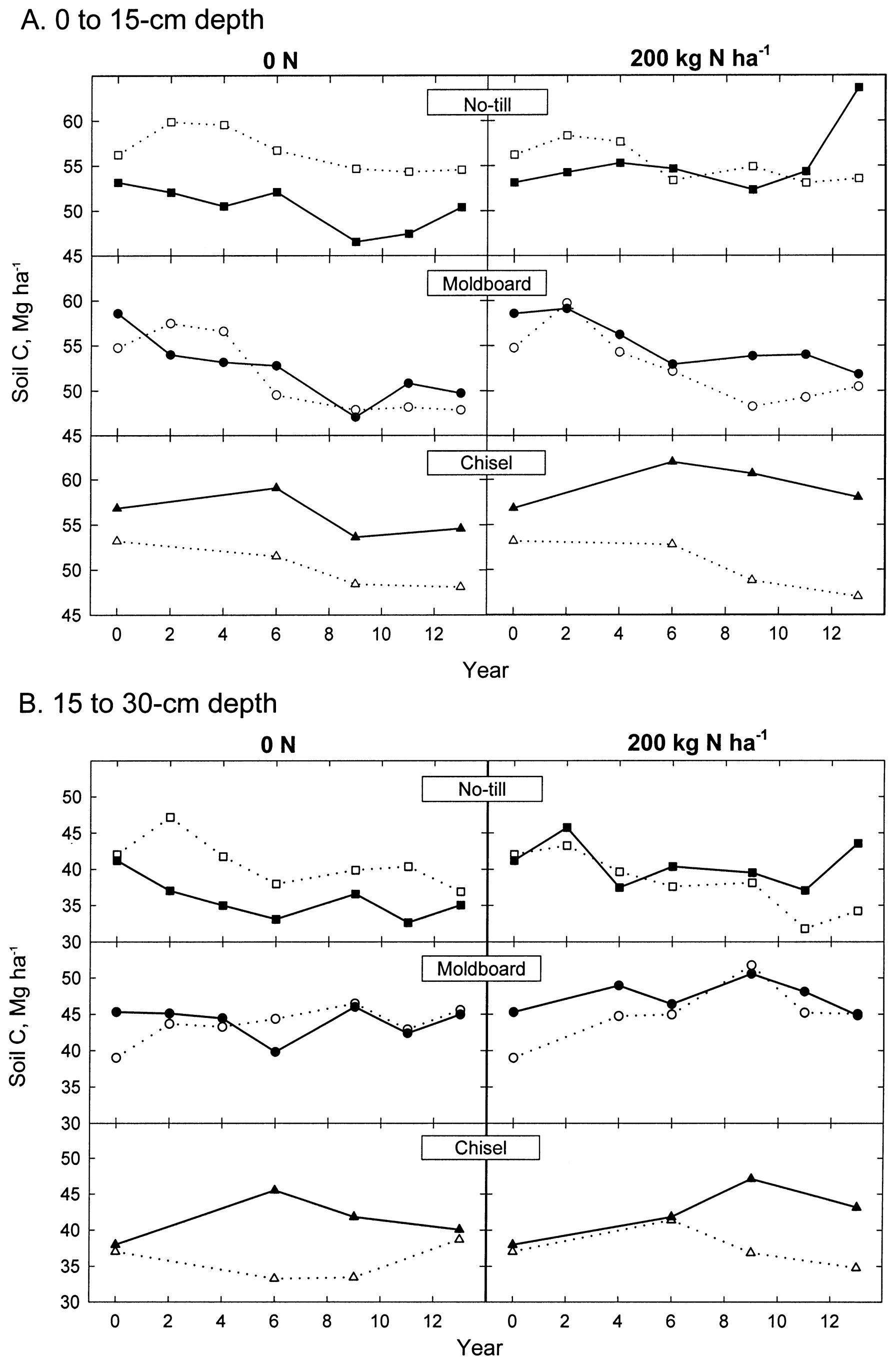

Fig. 2. SOC in: (A) 0–15 cm and (B) 15–30 cm depth over a 13-year period as influenced by tillage and N rate treatments with (—) and without (. . .) stover return (N applied annually). Each mean has a confidence interval ($p<0.05$) of 0.09 and 0.11 Mg ha^{-1} for (A) and (B) respectively.

upon random error between plots treated alike at one time of sampling. The SOC in the MB tillage (with both options of stover management and both N rates) decreased throughout the 13-year period, but SOC in the CH tillage (with both options of stover management) showed a distinct decline only after 6 years. Values of SOC in the NTh were considerably higher than in the NTr treatment in year 0 and remained offset throughout the 13-year period. Of the three tillage treatments, NT showed the least change from the original SOC contents.

The temporal patterns among tillage treatments in the 15–30 cm layer (Fig. 2B) differed from those in the 0–15 cm layer (Fig. 2A). Each mean in Fig. 2B has a confidence interval (p<0.05)=0.11 Mg ha^{-1}. The NT treatment showed a gradual reduction in SOC contents over time for both N rates, but the MB and CH treatments had no consistent trends over the 13-year period.

The different temporal patterns of SOC content in the 0–15 and 15–30 cm layers among tillage treatments (Fig. 2) are somewhat consistent with how crop residue is incorporated (Allmaras et al., 1996). Very little crop residue was mechanically buried below 15 cm in the NT treatment unless moved by earthworm activity. Nearly all crop residue in the CH treatment were buried above 15 cm. Crop residue on the surface at the end of summer in the MB treatment is buried below 15 cm, while the mostly decomposed crop residue from the prior year was inverted to be within the top 10 cm.

Soil $\delta^{13}C$ values generally increased in both the 0–15 and 15–30 cm layers (Fig. 3) throughout the 13-year period. Although Gregorich et al. (1996) suggest these increases should not be linear, the trend was linear over the 11-year period. The slope of these linear regressions, used as a trend indicator, shows differences of $\delta^{13}C$ change related to tillage system, stover return option, and N rate. All slopes except those in the NTh treatment in the 0–15 cm layer (Fig. 3A) were greater than 0 (p<0.05), irrespective of N rate. This lack of change in the NTh and not in the MBh and CHh treatments was probably caused by a characteristic slow decomposition pattern when corn crown and root tissue was not mechanically incorporated; lower dry matter yields may be partially causative. The mean standard error of a slope estimate in Fig. 3A was 0.02‰ per year.

The intercepts, or predicted $\delta^{13}C$ for the 0–15 cm layer at the beginning of the experiment in 1980, did not differ significantly as influenced by N rate and tillage treatment. There was a somewhat smaller predicted intercept when the stover was harvested in all tillage and N treatments, which suggests an immediate corn label of the $\delta^{13}C$ (Fig. 3A). The overall mean $\delta^{13}C$ (±standard deviation) for the 0–15 cm layer in 1980 was −19.79±0.13‰.

The slope and intercept estimates for the temporal $\delta^{13}C$ trends were much different in the 15–30 cm layer (Fig. 3B) than in the 0–15 cm layer (Fig. 3A). The only slope estimates greater than 0 (p<0.05) are those for both N rates in the NTr treatment; this response in the absence of mechanical incorporation is more evidence for biological incorporation of SOC below 15 cm. Although the SOC storage in the 15–30 cm depth of the MB treatment did not change significantly over the 13-year period, that in the NTh treatment declined (Fig. 2B). The $\delta^{13}C$ values increased in the NT tillage, but those in the MB tillage remained unchanged or declined over time. Because the soil samples were taken after incorporation and before significant decomposition during the summer, the measured $\delta^{13}C$ did not detect this reservoir of corn-C that left no residual label in the 15–30 cm layer of the MB treatment. Slope relations in the CH treatment were more like the NT probably because there was little or no mechanical incorporation into the 15–30 cm layer. The standard error for the slope parameter in the 15–30 cm layer was 0.03‰ per year, somewhat larger than in the 0–15 cm layer. Intercept estimates in the 15–30 cm layer were not sensitive to tillage, N rate, or stover treatment; the estimated mean $\delta^{13}C$±standard deviation for this layer in 1980 was −18.03±0.18‰. Thus, the initial mean $\delta^{13}C$ of this layer was substantially greater than in the 0–15 cm layer, indicating the longer term influence of C_4 plants into the SOC with depth. Observations made in the MB and NT treatments in 1993 (year 13) are not shown in Fig. 3 because there was an unusual C_3 label produced by weed infestation.

As mentioned above, some of the temporal responses of the $\delta^{13}C$ were true treatment effects related to amount of crop residue produced (Linden et al., 2000). Another indication that there were year effects on corn production is the comparative measures of error. The random error of the $\delta^{13}C$ derived

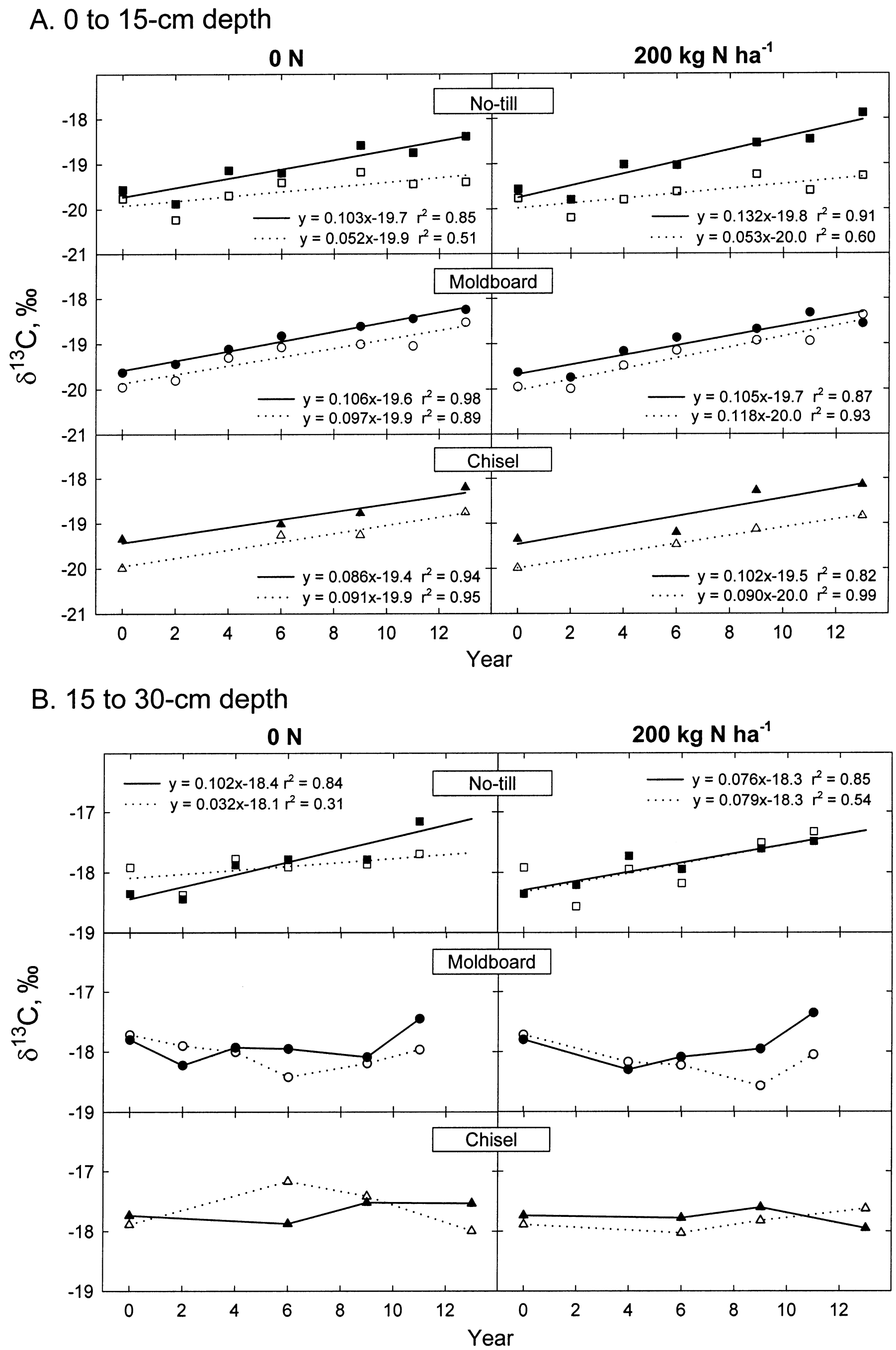

Fig. 3. Natural abundance ^{13}C label of SOC in: (A) 0–15 cm and (B) 15–30 cm depth over a 13-year period as influenced by tillage and N rate treatments with (—) and without (. . .) stover return (N applied annually; only statistically significant linear relations shown).

Table 1
SOC, C/N ratio and $\delta^{13}C$ in two soil depths as influenced by tillage, stover harvest, and N rate treatments at the beginning and after 13 years of continuous corn

Treatment[a]	SOC (Mg ha^{-1})			C/N			δ^{13}C (‰)		
	Year 0	Year 13		Year 0	Year 13		Year 0	Year 13[b]	
		0 N[c]	200 N[c]		0 N	200 N		0 N	200 N
0–15 cm[d]									
NTh	56.2	54.5	53.6	10.8	12.1	11.5	−19.8	−19.4	−19.3
NTr	53.1	50.4	63.6	10.6	11.5	11.7	−19.6	−18.4	−17.9
MBh	54.8	47.9	50.5	10.6	11.1	11.6	−20.0	−18.5	−18.4
MBr	58.6	49.7	51.8	10.8	12.0	12.1	−19.6	−18.2	−18.6
CHh	53.2	48.1	47.0	10.8	11.0	10.6	−20.0	−18.8	−18.8
CHr	56.9	54.6	58.0	10.9	11.8	11.3	−19.3	−18.2	−18.1
15–30 cm[d]									
NTh	42.0	36.9	34.2	11.5	11.0	12.1	−17.9	−17.8	−17.2
NTr	41.2	35.0	43.5	11.8	11.1	11.5	−18.4	−17.2	−17.2
MBh	39.0	45.6	45.0	11.2	11.4	11.1	−17.7	−17.9	−18.2
MBr	45.3	45.0	44.8	12.0	11.6	11.7	−17.8	−17.5	−17.8
CHh	37.0	38.7	34.7	11.4	11.0	11.2	−17.9	−18.0	−17.9
CHr	38.0	40.1	43.1	11.6	11.4	11.4	−17.7	−17.5	−17.7

[a] NT: no-till, MB: moldboard-plowed, CH: chisel-plowed; h: stover harvested, r: stover returned.
[b] Estimated values from regression for 15–30 cm depth.
[c] 0 N and 200 N are 0 and 200 kg N ha^{-1}.
[d] Soil layer depth.

from duplication among field plots treated alike was 0.005 and 0.012‰, respectively, for the 0–15 and 15–30 cm layers; the respective random error derived from the regressions (Fig. 3) were 0.051 and 0.105‰, about 10 times larger than the true random error.

The initial and final values of SOC storage and $\delta^{13}C$ label over the 13-year period are summarized in Table 1. Storage of SOC in the MB tillage decreased during the 13-year period in the 0–15 cm layer irrespective of stover harvest or N fertilization, but in the 15–30 cm layer there was no change. In the NT and CH tillages there was an SOC decrease in the 0–15 cm layer when stover was harvested. These changes of SOC in the 0–15 cm layer of NT carried on into the 15–30 cm layer. Corn residue increased the $\delta^{13}C$ label in the 0–15 and 15–30 cm soil layers for all treatment combinations, even when stover was harvested. When taken together these changes in SOC storage and $\delta^{13}C$ as related to common treatment inputs demonstrate the hazard of conclusions from observations in segments of the traditional plow layer.

The somewhat conservative C/N ratio (Table 1) not influenced by treatment and time suggests no N stress influences on microbial activity associated with C mineralization.

3.3. Soil storage of corn-derived carbon

The corn-derived SOC storage (Fig. 4) was influenced by all three management treatments: tillage system, stover harvest, and N rate. Corn-derived SOC storage varied significantly about the fitted relations. This variation was much larger than that indicated by laboratory duplication or field response of plots treated alike as determined in an ANOVA. These regression models had a 0 intercept even though the $\delta^{13}C$ signature indicated historical label from C_3 plants. This type of a regression model averages the slopes from 0, each slope determined by each observation. Observations in Fig. 4 are plotted in the year when sampled, but the regression lines were computed using the input: year x'=(year $x-1$) to focus on the year of incorporation.

Corn-derived SOC in the 0–15 cm layer of the NT system (Fig. 4A) had the largest slope with 200 N and stover return; the next largest was stover return without N addition. When the stover was harvested, the

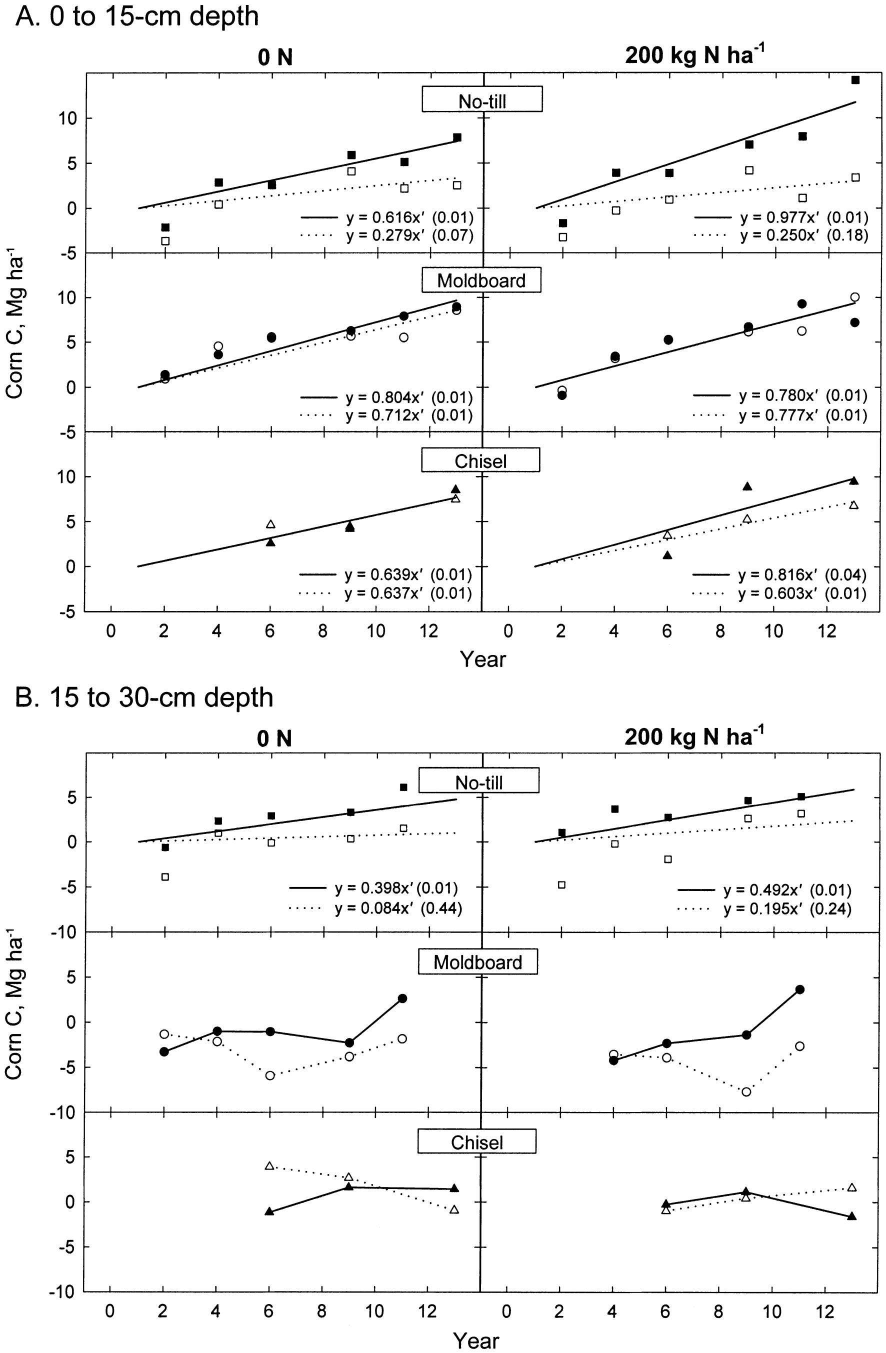

Fig. 4. Corn-derived SOC in: (A) 0–15 cm and (B) 15–30 cm depth over a 13-year period as influenced by tillage and N rate treatments with (—) and without (. . .) stover return (N applied annually; regressions with $p<0.05$ are statistically significant; x'=year $x-1$).

corn-derived SOC was small irrespective of N rate. The stover harvest option in the MB and CH tillage systems did not influence soil storage of corn-derived SOC over time, but when averaged over the stover harvest option, there was a small increase in corn-derived SOC in the CH and MB tillages when N was and was not applied, respectively.

Corn-derived SOC storage over time in the 15–30 cm layer (Fig. 4B) was less than in the 0–15 cm layer. In the NT tillage there was about the same maximum storage of 5.0 Mg ha^{-1} at both N rates when stover was returned, but when stover was harvested the storage was only about 2 Mg ha^{-1} irrespective of N rate. Corn-derived SOC generally increased in the MB system only when stover was incorporated. There was a zero gain of SOC (Fig. 2B) and only a slight C_4 label (Fig. 3B), even though there is mechanical placement of crop residues into the 15–30 cm layer. In the CH system there should be no significant gain of corn-derived SOC because CH tillage does not mechanically move crop residues into the 15–30 cm layer (Allmaras et al., 1996).

Table 2 contains estimates of corn residue returned in the two stover harvest options, the initial and final SOC storage in the 0–30 cm layer, and the final SOC derived from corn residue, all as related to N fertilization and tillage treatments. The amount of corn-C returned when stover was not harvested is based upon the sum of measured stover yields (42 g kg^{-1} C in the corn residue) and an estimate of C in the root plus crown biomass. When stover was harvested only about 10 cm of stalk and crown remained. Beauchamp and Voroney (1994) concluded that corn roots including the stalk and crown may contain about 40% as much C as the stover. A harvest index (HI) of 0.45, and a root : shoot biomass ratio of 0.22 were assumed. The HI is the ratio of harvested grain to above-ground biomass. According to Buyanovsky and Wagner (1986) this 40% estimate for root structured C is conservative unless there is water stress. The estimated corn-C returned in the residue was in the sequence MB>CH>NT for both the stover harvest options (Table 2). There was an overall increase of biomass-C production in response to N fertilization. Except for the NTr and CHr treatments, SOC storage decreased over the 11-year period. The overall SOC loss was 5.6 Mg ha^{-1} or 5.7% of the original average SOC of 98.9 Mg ha^{-1}.

Table 2
Corn-residue carbon returned, total SOC change, and corn-derived SOC over the 13-year period as influenced by tillage methods, stover management, and N rates

Treatment[a]	C returned in residue[b] (Mg ha^{-1})		SOC in 0–30 cm depth (Mg ha^{-1})				Corn-derived SOC in year 13[d] (Mg ha^{-1})		Efficiency of returned corn residue[e] (Mg ha^{-1})	
	0 N[f]	200 N[f]	Year 2[c]		Year 13		0 N	200 N	0 N	200 N
			0 N	200 N	0 N	200 N				
NTh	8.9	10.9	107.0	101.6	91.4	87.8	4.4 (0.05)	4.3 (0.05)	0.49	0.39
NTr	32.1	42.8	89.1	100.0	85.4	107.1	13.1 (0.15)	16.0 (0.15)	0.41	0.37
MBh	10.7	12.5	101.2	109.8	93.5	95.5	8.3 (0.09)	8.4 (0.09)	0.78	0.67
MBr	37.0	46.1	99.1	96.8	94.7	100.4	9.7 (0.10)	10.5 (0.10)	0.26	0.23
CHh	9.8	11.7	87.0	93.5	86.8	81.7	9.1 (0.10)	7.9 (0.10)	0.93	0.67
CHr	34.1	44.3	95.5	97.5	94.7	101.1	8.7 (0.09)	9.5 (0.09)	0.26	0.21
Standard error	0.30	0.30	0.10	0.10	0.10	0.10	1.98	2.34		

[a] NT: no-till, MB: moldboard-plowed, CH: chisel-plowed; h: stover harvested, r: stover returned.

[b] Estimated total corn-residue C returned; C return in the r treatment includes that from corn stover plus root biomass; C return in the h treatment is from root biomass; C in the root biomass, including the crown plus 10 cm of stalk not included in the stover biomass, estimated as 40% of that in the corn stover. Standard error for C returned estimated from standard error of stover yields, corrected for C content of residues (42%).

[c] SOC at year 2 is shown since this is the first observed data in the MB and NT treatments after a previous growing season of stover returned to the soil; in the CH treatment the year 2 data was estimated from the linear relation between years 1 and 6.

[d] Based upon change in $\delta^{13}C$ label of SOC since year 0. Parenthetical values are corn-derived C as a fraction of the SOC at year 13.

[e] Efficiency of returned corn residue calculated as the ratio of corn-derived SOC and the C returned.

[f] 0 N and 200 N are 0 and 200 kg N ha^{-1}.

Corn-derived SOC storage at the end of the 13-year period (see Eq. (2)) ranged from 4.3 to 16.0 Mg ha^{-1} — it was mostly affected by tillage and stover management treatments. Nitrogen fertilization had a much smaller effect, even though it consistently increased corn residue production. The corn-derived SOC as a fraction of the SOC after 13 years was remarkably insensitive to N fertilizer treatment; these corn-derived SOC fractions fell into three ranges, 0.05 for the NTh treatment, 0.15 for the NTr treatment, and 0.09–0.10 for all treatments with annual tillage.

The corn-derived SOC storages were estimated independently for each sampling (Figs. 2 and 3) using Eq. (2), but their estimated standard errors (Table 2) were derived from the slope estimates in Fig. 4. When the slopes were negative as in the 15–30 cm layer of the MB or CH treatments and r^2 was small (Fig. 4B) a standard error could not be estimated. The standard error associated with the SOC storage in the 0–30 cm layer was derived from random error associated with field plots treated alike, so that original SOC associated with tillage and stover harvest treatments (Fig. 2) reflected true field variations.

Another fraction of merit for interpreting the C sink dynamic is the fraction that expresses corn-derived SOC relative to the amount of corn-C returned (Table 2). These fractions used published estimates of root-to-shoot C and ranged from 0.21 to 0.93. When N fertilizer was applied, the fractions are always smaller irrespective of stover harvest, i.e., a mean of 0.52 vs. 0.43 for 0 N and 200 N, respectively. When stover was harvested, the fraction of applied C in the corn-derived SOC was always larger than when the stover was not harvested; these fractions were 0.45, 0.73 and 0.81 when corn stover was harvested in the NT, MB and CH tillage systems, respectively, compared to 0.39, 0.24, and 0.23 when stover was not harvested. This array of measured corn-C retention relative to the input of corn-C shows a more accelerated decomposition of shoot than root C, as noted by Balesdent and Balabane (1996). It also shows that tillage systems and N rate impacted the relative recalcitrance of corn shoot and root tissue.

3.4. Dynamics of the relic SOC

Soil samples obtained from the same four alleyways between plots in 1980 and 1993 and analyzed for SOC had: 27.3, 26.5, and 37.0 Mg ha^{-1} in the layers 0–7.5, 7.5–15, and 15–30 cm in 1980, respectively. Corresponding SOC mass was 22.0, 25.5, and 30.4 Mg ha^{-1} in 1993. Losses of SOC during this period of summerfallow were 5.3, 1.0, and 6.6 Mg ha^{-1} in the above, respective, layers, and 12.9 Mg ha^{-1} from the 0–30 cm layer. This was a larger loss than observed for any treatment in Table 1. The mean loss during corn cropping was 5.6 Mg ha^{-1}. During this period the $\delta^{13}C$ shifted from −19.7 to −19.3‰ in the 0–7.5 cm layer, −19.7 to −19.2‰ in the 7.5–15 cm layer, and −17.9 to −17.0‰ in the 15–30 cm layer. An equation for conservation of labeled units was used to estimate that the C lost had a $\delta^{13}C$ equal to −22.7‰, i.e., dominated by a C_3 label.

Loss of the original SOC with a C_3 label (Table 3) was less whenever the stover was returned, except for the nearly equal loss in the CH treatment with no N applied. When there was annual tillage and stover was harvested (CHh and MBh) and N was applied, significantly more C_3-labeled SOC was lost, but the addition of 200 kg N ha^{-1} in the NTr treatment reduced the loss of the C_3-labeled SOC.

The half-life for decomposition of the C_3-labeled SOC provides some interesting treatment effects (Table 3). An exponential decay of the C_3-derived SOC was assumed: $A_t=A_0\,e^{-kt}$; where A_t and A_0 are the SOC in the 0–30 cm layer in years 13 and 2, respectively, t the time in years, and k the decay constant. The mean k was 0.0147 indicating a half-life of 68 years; in the fallow treatment the half-life was 86 years. For the 12 treatment combinations (Table 3) the half-life ranged from 44 to 176 years.

The half-life of C_3 carbon was extended by N fertilization in the NT and CH treatments when the stover was not harvested, but N fertilization in the MB treatment had no effect. This tillage differential effect on soil organic matter decomposition can be explained by laboratory observations of Green et al. (1995) in which N fertilization stimulated C mineralization from corn stover and reduced mineralization of soil organic matter. The MB treatment separated the recent stover addition from the surface applied N, while in the CH and NT treatments there was less separation. When stover was not returned, the N fertilizer had no effect on the half-life in the NT treatment, where the crown was often not disturbed and remained on the surface. In the MBh and CHh treatments N reduced

Table 3
Relic SOC decomposition as determined from shifts in natural abundance of $\delta^{13}C$ in soil as related to N rates, tillage methods, and stover harvest options during the 13-year continuous corn experiment

Treatment[a]	Estimated C_3-SOC lost[b] ($Mg\ ha^{-1}$)		Half-life of C_3-SOC[c] (year)	
	0 N	200 N	0 N	200 N
NTh	20.0	18.1	53	56
NTr	16.8	8.9	54	118
MBh	16.0	22.7	64	47
MBr	14.1	13.6	72	73
CHh	9.3	20.7	97	44
CHr	9.5	5.9	105	176
Standard error	1.98	2.34	2.1	2.1

[a] NT: no-till, MB: moldboard-plowed, CH: chisel-plowed; h: stover harvested, r: stover returned.
[b] C_3-SOC lost=SOC_0-SOC_t-corn-derived SOC, where SOC_0 and SOC_t were measured in year 2 and year 13, respectively (see Table 2).
[c] Based upon the first-order kinetic assumption for organic matter decomposition.

the half-life, where contact between N fertilizer and crown was assured during every annual tillage. The mean half-life in the CH treatment was 83 years, whereas that in the other two tillage treatments was 62 years.

4. Discussion

4.1. SOC dynamics mediated by the ^{13}C:^{12}C label

Five characteristics of SOC dynamics were measured in each of the 12 treatment inputs (N variable, stover harvest option, and three tillage systems) as derived from $\delta^{13}C$ and total C in continuous corn. The original $\delta^{13}C$ label in the soil reflected a strong C_3 input of −19.8 and −18.0‰ in the 0–15 and 15–30 cm layers, respectively. The mean SOC mass in the 0–30 cm depth was relatively high in 1980 because of past management history.

The mass of SOC increased in all three tillage treatments only with N fertilization and when stover was not harvested, but these increases were less than 7% after 13 years of continuous corn; the initial SOC mass was 98 $Mg\ ha^{-1}$. Other continuous corn field trials with a $\delta^{13}C$ measurement (Balesdent et al., 1988, 1990; Angers et al., 1995; Gregorich et al., 1995, 1996; Balesdent and Balabane, 1996) estimated continuous corn label in soils ranging from 36 to 122 $Mg\ ha^{-1}$ SOC. Gregorich et al. (1996) measured a 32% loss of SOC with an N rate of 128 $kg\ ha^{-1}$ compared to a 38% loss without N fertilization; stover was not harvested in their 32-year field trial starting with 118 $Mg\ ha^{-1}$ SOC. Angers et al. (1995) measured a 20% loss of the original 83 $Mg\ ha^{-1}$ of SOC when stover was harvested and 180 $kg\ N\ ha^{-1}$ was applied over a 11-year period; moldboard-, tine-, and ridge-tillage treatments all had similar losses. Balesdent et al. (1990) showed about an 8% gain over the 36 $Mg\ ha^{-1}$ initial SOC; tine- and no-tillage provided larger gains than moldboard tillage. They did not harvest stover and had a moderate N fertilization rate.

Corn-derived SOC in our experiment ranged from 0.05 to 0.15 of the final SOC mass (Table 2) and was sensitive to tillage system; without stover harvest the corn-derived fraction of final SOC increased only in the NT treatment. When adjusted linearly for length of continuous corn history to 12 years as in Table 2, the literature suggests that the corn-derived SOC fraction ranged from 0.07 when stover was harvested and 180 $kg\ N\ ha^{-1}$ was applied (Angers et al., 1995) to about 0.12 when moldboard tilled and a high rate of N was used (Gregorich et al., 1995, 1996). With similar experimental inputs to Gregorich et al. (1995), but a smaller initial SOC mass, Balesdent et al. (1990) noted a fraction closer to 0.20.

The $\delta^{13}C$ analysis was used to separate any SOC mass change into the corn-derived gain and the relic C_3 (previous label) loss components (Table 3). Stover harvest shortened the half-life about 7% without N fertilization, but with N fertilization, stover harvest reduced the half-life by 56%. When stover was not harvested, N application markedly extended the half-life of the C_3-derived SOC in the NT and CH, but there was no effect in the MB treatment. This is an intimate fertilizer–corn residue contact effect. Gregorich et al. (1996) also observed no N effect where MB was the only tillage tested. The 30% longer half-life for the C_3-derived SOC in CH compared to the NT and MB treatments agrees with Balesdent et al. (1990) showing a half-life of 88 years for a tine (chisel-like) tillage and a mean of 42 years for NT and MB. Nearly all the decomposition half-lives estimated from the shift in the natural abundance $\delta^{13}C$ (Gregorich et al., 1995) are smaller than the average of 68 years estimated from Table 2. These effects of N on soil organic matter decomposition provide guidelines about N amount when considering stover management options, and also about the impact of intimate N fertilizer contact with corn stover.

4.2. Efficiency of corn biomass return

The ratio of corn-derived SOC and the corn biomass introduced into the soil (including the below ground import) has great merit to evaluate soil management of the C sink, but the ratio is tenuous because root import of C is being estimated in the field. Although there were differences of estimating root import of C, the ratio varied from 0.09 to 0.29 (Balesdent et al., 1990; Angers et al., 1995; Gregorich et al., 1995, 1996; Balesdent and Balabane, 1996). When stover was harvested, ratios of 0.38 (Balesdent and Balabane, 1996) and 0.29 (Angers et al., 1995) were observed, but without stover harvest, a ratio of 0.11 was observed (Balesdent and Balabane, 1996). Balesdent et al. (1990) observed a smaller ratio with no-tillage than with tine and moldboard tillage; Gregorich et al. (1996) observed a somewhat minor ratio decrease when N was applied in a moldboard-tillage system.

A recalcitrance index for the accumulation of corn-derived SOC in root compared to shoot tissue was estimated from the difference in corn-derived SOC in the two stover harvest options. This ratio was sensitive to tillage treatment, but not N rate (Table 2). In the NT treatment the ratio was 0.4; in the MB and CH treatments the ratio was 4.8. Undoubtedly the reduced exposure of the shoot tissue in the NT caused a recalcitrance different from that in the annual tillage treatments where shoot and root are exposed to nearly the same decomposition environment. Balesdent and Balabane (1996) estimated the root tissue to be 1.56 times more resistant than shoot tissue in a continuous corn field trial with a moderate N fertilization and MB tillage. The disparity of recalcitrance index in the MB treatment between experiments appears excessively large.

The efficiency of returned corn residue was estimated using directly measured stover biomass without including the crown (Table 2). An HI of 0.45 and a root : shoot ratio of 0.22 were used for all 12 treatments based upon field observed root biomass recovered. Root and shoot biomass measurements in corn as related to long-term N fertilization (Huggins and Fuchs, 1997) indicated that N stress reduces the HI and the root : shoot ratio, such that the efficiency ratio would be increased somewhat more in the 200 N compared to the 0 N rate. Corn root and shoot measurements (unpublished data) in four different cultivars in a Normania clay loam indicated a root : shoot ratio of 0.35, assuming that C input to the soil consists of two equal components: recoverable root biomass and rhizodeposition. If a larger HI were used, all of the efficiency ratios would be reduced.

In these experiments, Dowdy et al. (1988) noted differences in corn rooting as related to tillage and corn stover harvest option. Some of these differences occurred below 30 cm, deep enough to evade any influence on measurements in Tables 2 and 3. However, the uniformly low soil BD (Fig. 1) does not suggest significant rooting differences due to tillage. Any tillage system effects on the C return via the root : shoot ratio are unlikely to change conclusions about the efficiency of corn residue on the amount of corn-derived SOC. The large differences among the ratios suggest that more evaluation is required of recalcitrance of root tissue and how it is influenced by tillage. An independent estimate of root exudation and rhizodeposition is needed to obtain rational measures of 'efficiency of returned corn residue' in Table 3.

5. Summary and conclusions

SOC and natural abundance ^{13}C, as measured in long-term field experiments, are sensitive to tillage, stover and N management. The 13-year field experiment on a Waukegan silt loam soil involved three tillage systems (NT, MB, and CH), two stover options (returned or harvested), and two N rates (0 and 200 kg N ha^{-1}).

1. All three tillage treatments showed a distinctly lower BD at lower depths when the stover was returned, with no effect of N rate; nearer to the surface, BD were somewhat higher where stover was harvested.
2. Storage of SOC in the 0–15 cm layer over the 13-year period changed little for both the 0 and 200 kg N ha^{-1} rates. Of the three tillage treatments, NT showed the least change from the original SOC storage. Different temporal patterns of SOC content in the 0–15 and 15–30 cm layers among tillage treatments are consistent with crop-residue incorporation.
3. With stover harvest and N fertilizer addition, SOC storage in the MB treatment decreased during the 13-year period in the 0–15 cm layer, but with stover return, N addition was required to increase residue production and thus increase SOC storage in the NT and CH treatments. Storage of SOC in the 15–30 cm layer remained steady or increased whenever the stover was returned and there was mechanical or faunal activity to place the residue into this layer. Soil $\delta^{13}C$ values generally increased as a linear function in both the 0–15 and 15–30 cm layers throughout the 13-year period. The slope of these linear regressions showed differences of $\delta^{13}C$ temporal response related to tillage system, stover management, and N rate, as well as soil depth.
4. The amount of corn residue in SOC storage was influenced by all three management factors of tillage system, stover management, and N rate. Corn-derived SOC in the 0–15 cm depth of the NT system was largest with 200 N and no stover harvest; the next largest was stover return without N addition. The residue option in MB and CH tillage systems did not influence corn-derived SOC storage, but there was a small increase for these two tillage treatments when N was applied. Corn-derived SOC in the 15–30 cm depth was less and more variable, especially for the annually-tilled treatments.
5. The half-life for the original or relic SOC with a C_3-label was longer when stover was returned, shortened when N was applied and stover was harvested in the annual tillage systems, and sharply lengthened by N rate when stover was returned and the N fertilizer was at least partially mixed with the corn stover as in NT and CH. The half-life for decomposition of the C_3-labeled SOC showed a range from 44 to 176 years for the 12 treatment combinations with an average of 68 years.
6. The ratio of corn-derived SOC and corn biomass introduced into the soil has great merit to evaluate soil management of the C sink, but the ratio is tenuous unless root contribution of C can be better estimated. Large differences in the root : shoot ratios suggest that further evidence is required to evaluate decomposition of root, shoot, and crown tissues and the influence by tillage.

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