Contemporary Evidence of Soil Carbon Loss in the U.S. Corn Belt

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Temporal changes in soil C content vary as a result of complex interactions among different factors including climate, baseline soil C levels, soil texture, and agricultural management practices. The study objectives were: to estimate the changes in soil total C contents that occurred in the past 18 to 21 yr in soils under agricultural management and in never-tilled grassland in southwest Michigan; to explore the relationships between these changes and soil properties, such as baseline C levels and soil texture; and to simulate C changes using a system approach model (SALUS). The data were collected from two long-term experiments established in 1986 and 1988. Georeferenced samples were collected from both experiments before establishment and then were resampled in 2006 and 2007. The studied agricultural treatments included the conventional chisel-plow and no-till management systems with and without N fertilization and the organic chisel-plow management with cover crops. Total C was either lost in the conventional chisel-plowed systems or was only maintained at the 1980s levels by the conservation management systems. The largest loss in the agricultural treatments was 4.5 Mg ha^{-1} total C observed in the chisel-plow system without N fertilization. A loss of 17.3 Mg ha^{-1} occurred in the virgin grassland soil. Changes in C content tended to be negatively related to baseline C levels. Under no-till, changes in C were positively related to silt + clay contents. The SALUS predictions of soil C changes were in excellent agreement with the observed data for most of the agricultural treatments and for the virgin soil.

Abbreviations: CT, conventional tillage; CT-cover, conventional tillage with cover crops; CT-F, conventional tillage with fertilizers; CT-NF, conventional tillage without fertilizers; LTER, Long Term Ecological Research; NT, no-till; NT-F, no-till with fertilizers; NT-NF, no-till without fertilizers; POM, particulate organic matter; RTM, regression to the mean; SALUS, System Approach to Land Use Sustainability.

The soil is considered to be one of the major Earth reservoirs of C. It holds about 1550 Pg as organic C and 950 Pg as inorganic C (Lal, 2004). Rising global temperatures might reduce soil C stocks by enhancing the release of stored soil organic C as atmospheric CO_2, still further intensifying global warming (Jenkinson et al., 1991; Schimel et al., 1994; Bellamy et al., 2005; Jones et al., 2005).

Recently, soil C losses were observed in several regions across the world (Bellamy et al., 2005; Schipper et al., 2007; Stevens and van Wesemael, 2008). In a study of more than 2000 sites across England and Wales, Bellamy et al. (2005) reported C losses of about 0.12 kg C m^{-2} yr^{-1} with a net C loss of about 2.9 kg C m^{-2} during the last 25 yr. Similarly, Schipper et al. (2007) reported soil C losses of about 2.1 kg C m^{-2} during the last 20 yr in the pasturelands of New Zealand. Stevens and van Wesemael (2008) observed an approximately 1.0 kg C m^{-2} decrease from 1950–1960 levels in the soil C of temperate forest soils in the Belgian Ardennes. Smaller scale studies conducted at several locations in the United States and Canada during the last couple of decades also have reported soil C losses (VandenBygaart et al., 2002; Olson et al., 2005; Varvel, 2006; Khan et al., 2007). Even though some additional factors, such as reduction in the use of manure, an increased tillage depth, or measurement inaccuracies, have been proposed as alternative explanations for reported losses (Smith et al., 2007), on a global scale, soil C losses appear to have been observed for a wide range of soils, land uses, and management practices and seem to have accelerated during past couple of decades, pointing to the recent increases in global temperatures as a potential universal cause.

An increase in global temperature is likely to affect soil C by influencing soil organic matter decomposition and mineralization rates (Davidson et al., 2000; Knorr et al., 2005; Conant et al., 2008) as well as soil and root respiration (Kirschbaum, 2004; Jones et al., 2005). A review of data from several soil warming experiments showed that a 3°C increase in soil temperature increased the soil respiration rate by 20% (Rustad et al., 2001; Richter et al., 2007).

Global climatic effects are likely to interact with influences operating at smaller scales, including locally varying land use and land management practices. Among land management practice characteristics that greatly affect soil C are tillage intensity and plant residue inputs. Conventional tillage systems disrupt soil structure and contribute to a rapid turnover of soil aggregates (Balesdent et al., 2000), while minimal soil disturbance under

Soil Sci. Soc. Am. J. 73:2078-2086
doi:10.2136/sssaj2009.0044
Received 29 Jan. 2009.
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no-till (NT) systems is known to provide an overall positive effect on soil C storage (Franzluebbers, 2004; Puget and Lal, 2005). Several long-term studies reported greater soil C in systems with greater C inputs (e.g., Paustian et al., 1997), while removal of crop residues has been often found to reduce soil organic matter content (Huggins et al., 1998). Organic management systems that rely on greater crop residue inputs have been reported to increase soil organic matter content as compared to conventional management systems (Pulleman et al., 2000; Robertson et al., 2000; Stockdale et al., 2001; Marriott and Wander, 2006; Teasdale et al., 2007).

Even though the overall effects of land management can be expected to be broad, their magnitudes are likely to differ in response to variations in inherent soil characteristics, including, among others, mineralogy (Rasmussen et al., 2006, 2008), baseline C contents (Bellamy et al., 2005), and soil texture (Hao and Kravchenko, 2007). A negative relationship between baseline C contents and the change in C due to conversion to NT management has been observed in a number of individual field experiments and experiment reviews (e.g., VandenBygaart et al., 2002; Tan et al., 2006). A relative loss in soil C in the topsoil has also been found to increase with an increase in baseline C values (Bellamy et al., 2005). Campbell et al. (1996) reported a stronger relationship between soil texture (clay content) and C content under NT than CT management at three sites in western Canada. Hao and Kravchenko (2007) observed a stronger relationship between total C and the silt + clay content under NT than under conventionally tilled management practices in southwest Michigan.

The historic difficulty in addressing the interactions between rising global temperatures, land use and management practice effects, and intrinsic soil properties originates from the small scale of most of the individual experiments and from difficulties in meta-analyses due to the immense variability among the individual studies in terms of management details, experiment durations, and other factors. The commonly encountered lack of baseline C measurements further contributes to difficulties in comparing individual experiment results. In most of the field studies, the differences in soil C between management systems have been examined at specific time points after initiation of the experiment. The changes in soil C are thus assessed on a relative scale via comparison with a certain control treatment. Reliance only on comparisons among the treatments can lead to erroneous conclusions about soil C changes (Khan et al., 2007). Not only relative but also absolute changes in soil C with time must be assessed to monitor trends in soil C dynamics related to temporal climate change.

Modeling is a necessary tool for spatially expanding the findings on C changes obtained from individual experiments to larger areas and regions, as well as temporally to assess future changes (e.g., Paustian et al.,1995). For realistic predictions, however, besides the soil characteristics, suitable models need to take into account a number of management-, climate-, and plant-related parameters. Moreover, before expanding the model predictions spatially or temporally, the model performance must be evaluated using existing data. The System Approach to Land Use Sustainability (SALUS) model was designed to simulate continuous crop, soil, water, and nutrient conditions under different management strategies for multiple years (Basso, 2000; Basso et al., 2006). It is equipped with functions allowing a comprehensive holistic treatment of key details in plant and soil processes under different land uses and management regimes in response to daily weather variations (Fig. 1).

The objectives of this study were to: (i) examine the changes that have taken place in soil C under different agricultural management practices and in virgin grassland during the past two decades in southwest Michigan; (ii) analyze the relationships between the changes in soil C with baseline soil C and soil texture under different tillage and management systems and in virgin grassland; and (iii) assess the performance of SALUS in modeling the observed 20-yr trends under different management practices and varying baseline C levels and textures.

MATERIALS AND METHODS

The study was conducted at two long-term experiments at the Kellogg Biological Station's Long-Term Ecological Research (LTER) site in southwest Michigan (85°24' W, 42°24' N), referred to as the Main Site and Interaction Site experiments. Soils at the LTER are Typic Hapludalfs of the Kalamazoo (fine-loamy, mixed, semiactive, mesic) and Oshtemo (coarse-loamy, mixed, active, mesic) series (Mokma and Doolittle, 1993). The climate is temperate with cool, moist winters and warm, humid summers, with approximately 90 cm of precipitation annually, about half of which is snow. The mean annual temperature is 9°C (Grandy and Robertson, 2007). The tilled portions of both studied sites have been conventionally managed in row crop agriculture from at least 1950; before that, the land was under native vegetation (oak–hickory [*Quercus–Carya* spp.] forest) (Robertson et al., 1993).

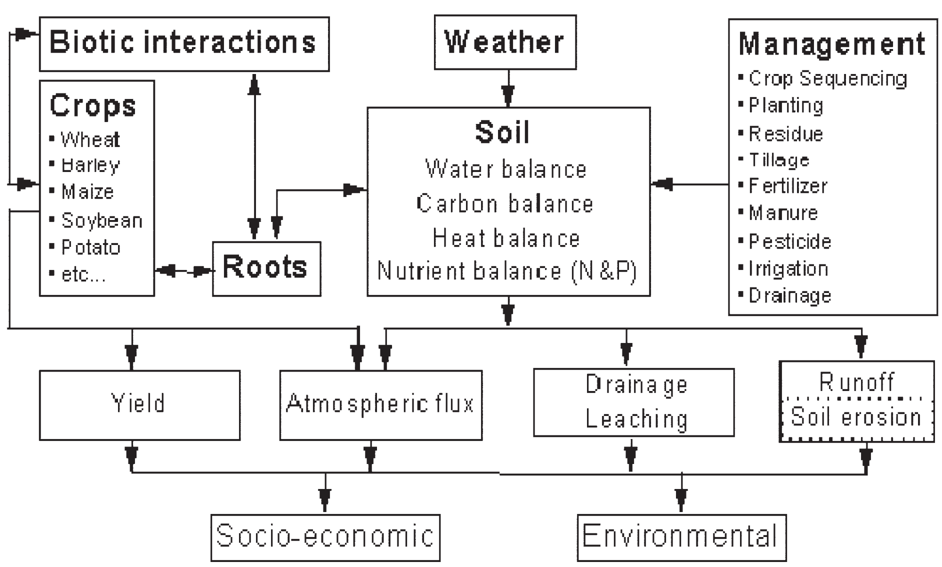

Fig. 1. Diagram of the components of the System Approach to Land Use Sustainability (SALUS) model.

Main Site Experiment

The first studied experiment is the LTER Main Site, which is a one-factor randomized complete block design, with seven treatments and six replications. The experimental plots are 80 by 100 m in size. The LTER management systems used in this study are conventional tillage (chisel plow) (CT-F) and no-till (NT-F) systems with conventional chemical inputs, and a certified organic, chisel-plowed system with a winter leguminous cover crop and zero chemical inputs (CT-cover). These agronomic treatments are in a corn (*Zea mays* L.)–soybean [*Glycine max* (L.) Merr.]–wheat (*Triticum aestivum* L.) rotation. A detailed description of the studied LTER treatments can be found at the Kellogg Biological Station LTER website (Kellogg Biological Station, 2007).

The experiment was started in 1988. Before the experiment initiation, in May of 1988, a set of 417 georeferenced soil samples was collected at the 0- to 15-cm depth from the area that then became Replicates 1 through 5 of the Main Site experiment (Robertson et al., 1997). During the year before the experiment initiation, the entire site was planted with corn, followed by fall-planted rye (*Lolium* sp.). The 1988 data are referred to here as the Main Site baseline samples.

In May of 2006, 50 of the locations sampled in 1988 were found using a global positioning system (Trimble Receiver Type Pro XRS Model 33302-51, Trimble Navigation Ltd., Sunnyvale, CA) and resampled. The sites chosen for resampling were those located within central portions of the plots of the present LTER experiment. Overall, 11, 22, and 17 locations suitable for resampling were found in the CT-F, NT-F, and CT-cover treatments, respectively, with approximately three to four locations per each plot.

At each sampling location, a hydraulic soil core unit from Geoprobe Systems (Salina, KS) with 4.2-cm-diameter cylinder was used to collect an undisturbed soil core of 0- to 40-cm depth. The cores were segmented into 0- to 15-, 15- to 20-, 20- to 30-, and 30- to 40-cm depths. The measurements from the cores that were used in this study are total C, soil texture, and bulk density data for the 0- to 15-cm depth. The samples were air dried at room temperature and all plant residues and stones were removed. Smaller plant material was removed by gentle air blowing and the samples were ground on a shatterbox (Shatterbox Model 8530, SPEX CertiPrep, Metuchen, NJ) to pass through a 250-μm sieve. Total C was measured using an automatic Carlo-Erba CN analyzer (Carlo Erba Instruments, Milan, Italy). Soil texture analyses were performed using the hydrometer method (Gee and Bauder, 1986). The average bulk density values in 2006 were 1.45, 1.50, and 1.40 g cm^{-3} in CT-F, NT-F, and CT-cover, respectively. The difference in bulk densities between the treatments was not statistically significant ($P > 0.3$). Very high variability in bulk density measurements was observed among the individual sites, which could be in part an artifact of soil compaction during core sampling at some of the sites. Thus, to estimate changes in C stocks at the 0- to 15-cm depth, we used the average bulk density values. Bulk density in 1988 was assumed to be equal to that of the CT-F treatment in 2006.

The 2006 sampling was performed during the same period of time as the 1988 sampling (May), with corn being the previous year's crop (as in 1988). This reduced errors associated with seasonal soil C variations and differences in crop residues. To minimize the errors associated with differences in laboratory procedures, the 1988 archived samples from all 50 locations were reanalyzed for total C using the same procedure that was used for the analysis of the 2006 samples. The changes in soil C are reported based on the reanalyzed 1988 data.

Interaction Site Experiment

The LTER Interaction Site is a two-factor randomized complete block design experiment with four replicates. The two studied factors are fertilization with two levels, fertilized and unfertilized, and tillage with two levels, chisel plow tillage and NT. Each experimental plot is 27 by 40 m in size. The experiment is in a corn–soybean–wheat rotation. In the fertilized plots, urea is applied as a source of N (45 kg ha^{-1}) during the wheat years and liquid N fertilizer (28% active ingredient) is applied during the corn years according to Michigan corn recommendations. No fertilizer is applied when soybean is grown. During the last 5 yr, neither P nor K were applied even on the fertilized plots.

In addition to the agronomic treatments, we studied two virgin grassland sites adjacent to the Interaction Site experiment. The only management that has been done in the virgin grassland is mowing, conducted every year since 1960 in late fall. After the mowing, the plant residues are left on the surface.

The Interaction Site experiment was established in 1986. In May 1986 before starting the experiment, 256 samples were collected from the tilled portions and 65 samples from the virgin portions of the site at the 0- to 20-cm depth (Robertson et al., 1993). Sampling locations were georeferenced by taking the southwest corner of the Interaction Site as a reference point and defining the x and y coordinates of the sampled locations as distances from the reference point. In the year before soil sampling, the tilled portion of the site was planted to soybean followed by a winter cover of annual ryegrass (*Lolium multiflorum* Lam.). Unfortunately, there were no archived samples available for the Interaction Site experiment. In 1986, soil C measurements were conducted using the Walkley–Black wet combustion technique (Nelson and Sommers 1982). The 1986 data are referred to here as baseline samples for the Interaction Site.

In May of 2007, we collected a total of 57 samples from locations sampled in 1986. Locations for resampling were selected from central portions of the experimental plots. Approximately two to four samples were collected in each plot. At each location, the sample was taken between the plant rows and was composited from three 2.5-cm-diameter cores collected within a 0.2-m radius at the 0- to 20-cm depth. In addition, undisturbed samples of 4 cm in diameter and 7.6-cm height were collected from each site for bulk density measurements.

In 2007, main effects of tillage ($P > 0.13$), fertilizer ($P > 0.30$), or interaction effects ($P > 0.80$) on bulk density were not statistically significant. We used the average bulk density values of 1.37 and 1.42 g cm^{-3} observed for conventionally tilled and NT treatments, respectively, for estimating changes in C stocks on an areal basis at the 0- to 20-cm depth. Bulk density in 1986 was assumed to be equal to that of the conventionally tilled treatments. For the virgin sites, the average bulk density measured in 2007 was 1.12 g cm^{-3}; this value was assumed to be applicable to the 1986 data as well. The lack of bulk density measurements from the 1980s is a drawback in the C stock calculations of this study that reduces accuracy in the estimates of C stocks; however, it does not affect C concentration results.

As in the Main Site experiment, the sampling time (May) and the previous year's crop (soybean) were the same in both 1986 and in 2006. The procedures of sample cleaning, processing, and analyses for total C and soil texture were the same as those described for the Main Site above.

A summary of the studied treatments, numbers of samples, sampling depths and timing, and preceding crops for both experiments are shown in Table 1.

Table 1. Summary of data collection for individual treatments at the Kellogg Biological Station Long-Term Ecological Research Main Site (1988–2006) and Interaction Site (1986–2007) experiments.

Treatment†	*N*‡	Sampling depth		Sampling time		Previous crop		Analysis method	
Main Site		1988	2006	1988	2006	1988	2006	1988	2006
CT-F	11	0–15	0–15	May	May	corn	corn	Carlo-Erba CN analyzer	Carlo-Erba CN analyzer
NT-F	22	0–15	0–15	May	May	corn	corn		
CT-cover	17	0–15	0–15	May	May	corn	corn		
Interaction Site		1986	2007	1986	2007	1986	2007	1986	2007
CT-F	14	0–20	0–20	May	May	soybean	soybean	Walkley-Black method	Carlo-Erba CN analyzer
CT-NF	10	0–20	0–20	May	May	soybean	soybean		
NT-F	12	0–20	0–20	May	May	soybean	soybean		
NT-NF	11	0–20	0–20	May	May	soybean	soybean		
Virgin grassland	13	0–20	0–20	May	May	–	–	Walkley-Black method	Carlo-Erba CN analyzer

† The agronomic treatments are chisel-plow (CT) or no-till (NT) in a corn–soybean–wheat rotation either with (F) or without (NF) fertilization; CT-cover is a certified organic treatment with leguminous cover crops; the virgin grassland was mowed annually since 1960s.

‡ Number of samples co-located at each treatment.

SALUS Model

The SALUS models continuous crop, soil, water and nutrient conditions under different management strategies for multiple years (Basso, 2000; Basso et al., 2006). The model is composed of three main structural components: (i) a set of crop growth modules; (ii) a soil water balance and temperature module; and (iii) a soil organic matter and nutrient cycling module. The model executes all components daily for each management strategy being run. The crop growth and development component accounts for environmental conditions (particularly temperature and light) when calculating potential plant growth rates. This growth is then reduced based on water and N limitations. The water balance considers surface runoff, infiltration, surface evaporation, saturated and unsaturated soil water flow, drainage, root water uptake, soil evaporation, and transpiration.

The soil organic matter and nutrient module simulates organic matter decomposition, N mineralization, and the formation of NH_3 and NO_3, N immobilization, gaseous N losses, and three pools of P. The soil organic matter (SOM) and N module is derived from the Century model (Parton et al., 1988), with a number of modifications incorporated. The model simulates organic matter and N mineralization and immobilization from three SOM pools (active, slow, and passive), which vary in their turnover rates and characteristic C/N ratios. There are two crop residue and fresh organic matter pools (structural and metabolic), for representing recalcitrant and easily decomposable residues, based on residue lignin and N content. Decomposition and N mineralization rates for different pools are influenced by soil temperature and moisture, soil texture, and tillage intensity (as well as the pool C/N ratio for N mineralization). The main external inputs needed for the soil process module are soil texture, bulk density, horizon depths, total organic C and N, and initial mineral N content. Several modifications were made to adapt the model for use with daily-time-step crop growth routines. The original Century model operates on a monthly time step and, therefore, rate constants were recalibrated to correct for the difference in integration interval (from monthly to daily). A surface active SOM pool associated with the surface residue pools was added to better represent conservation tillage systems and perennial crops. Soil organic matter and litter pools were also added for up to 10 soil layers (vs. only a single topsoil layer in Century). The soil moisture control function for decomposition was replaced to make decomposition a function of water-filled pore space. Separate NH_3 and NO_3 pools were represented with nitrification rate calculations. An algorithm was developed that determines the initial fraction of total organic matter C and N in each of the three SOM pools (for model initialization) as a function of soil texture, the type of original native vegetation, and time under cultivation, based on a steady-state analytical solution of the decomposition equations (Paustian et al., 1992).

Data Analyses

General Statistical Analyses

Data analysis was conducted using SAS (SAS Institute, 2001). The effects of the studied factors and continuous covariates, including baseline C and texture, were assessed using analysis of covariance (ANCOVA) in PROC MIXED (Milliken and Johnson, 2002). For the Main Site experiment, the statistical model included treatments as a fixed factor, and blocks and plots nested within treatments as random factors, with plots used as an error term for testing the treatment effects. For the Interaction Site, the statistical model included fixed effects of tillage, fertilization, and their interaction, and random effects of blocks and plots.

Mean baseline C data were varied among the treatments (Table 1). To account for these initial variations when evaluating the changes in soil C and making comparisons among the treatments, the baseline C values were first standardized by subtracting the respective treatment means and then used as a covariate in C change data analyses. Standardization is the customary practice in ANCOVA for dealing with covariates that are different among the studied treatments (Milliken and Johnson, 2002).

In both experiments, the assumptions of normality of the residuals and homogeneity of variances were checked and analysis with heterogeneous variances was conducted, if found necessary, using the REPEATED/GROUP statement in PROC MIXED. When the fixed effects were found to be statistically significant, either at $P < 0.05$ or at $P < 0.10$, the comparisons between the treatments were conducted using *t*-tests.

Regression to the Mean Correction

Regression analysis of the relationships between the changes in soil C and baseline C values was conducted with accounting for the regression-to-the-mean (RTM) phenomenon. The RTM occurs when unusually large or small measurements obtained by chance during baseline sampling are followed by measurements that are less extreme and closer to the mean in the subsequent sampling. Thus, even in the absence of the real relationship between the changes and the baseline levels, larger change values are often associated with more extreme baseline values, leading to negative sample correlation (Barnett et al., 2005; Lark

Table 2. Means and standard errors (in parentheses) for baseline (1980s) and contemporary (2000s) soil C contents and for changes in soil C content adjusted for standardized baseline C in the Main Site and Interaction Site experiments; *P* values are from an ANCOVA for testing the significance of the factor effects.

Treatments†	Soil C		Change in soil C
	g kg^{-1} of soil		
Main site experiment	1988	2006	From 1988 to 2006
CT-F	9.3 (0.7) a	8.2 (0.3) a**	−1.15 (0.27) a*
NT-F	10.6 (0.5) a	9.9 (0.5) b	−0.71 (0.48) ab NS‡
CT-cover	10.0 (0.5) a	9.8 (0.3) b	−0.16 (0.29) b NS
P value	0.13	0.002	0.06
Interaction site experiment	1986	2007	From 1986 to 2007
CT-F	9.8 (1.4) a	9.5 (0.5) a	−0.22 (0.46) ab NS
CT-NF	9.8 (1.4) a	8.2 (0.5) b	−1.54 (0.51) a
NT-F	7.4 (1.4) a	8.3 (0.5) ab	0.31 (0.48) b NS
NT-NF	8.7 (1.4) a	8.9 (0.5) ab	0.19 (0.51) b NS
P value	0.11	0.07	0.07
Virgin grassland	23.0 (0.9)	15.3 (0.6)	−7.7 (1.0)

* Means within the same column within the experiment followed by the same letter are not significantly different at $\alpha = 0.1$.

** Means within the same column within the experiment followed by the same letter are not significantly different at $\alpha = 0.05$.

† The agronomic treatments are chisel-plow (CT) or no-till (NT) in a corn–soybean–wheat rotation either with (F) or without (NF) fertilization; CT-cover is a certified organic treatment with leguminous cover crops; the virgin grassland was mowed annually since 1960s.

‡ NS, the mean value is not significantly different from zero ($P < 0.05$).

et al., 2006). To overcome the RTM effect and to get unbiased estimates of regression slopes and confidence intervals for regressions between changes in soil C and baseline C values, we used a method proposed by Blomqvist (1977) (Lark et al., 2006). The sample regression slope obtained from the ordinary simple linear regression between the change and the baseline, $\hat{\beta}$, is adjusted as follows:

$$\hat{\beta}_{\text{adjusted}} = \frac{\hat{\beta} + (1 - V)}{V} \qquad [1]$$

where $\hat{\beta}_{\text{adjusted}}$ is the adjusted regression slope obtained after accounting for the RTM effect. The V component is calculated as

$$V = 1 - \frac{S_{\text{u}}^2}{S_{\text{z}}^2}$$

where S_z^2 is the overall sample variance of the baseline C data and S_u^2 is the variance of the baseline data that is due to all the sources of uncertainty in baseline measurements, estimated independently. These include analytical errors and spatial variability due to imperfect identification of the site locations during resampling (Lark et al., 2006). The S_u^2 values were obtained using sample variograms of the baseline C values. The variograms were calculated and fitted with variogram models using the SAS procedures PROC VARIOGRAM and PROC NLIN. The value of S_u^2 was set to be equal to the fitted variogram value at a 3-m lag distance. This value was considered to be representative of the spatial variability of the baseline C data within a 3-m area around the sampled site. This area was assumed to provide a conservative estimate of the errors in identifying the precise location of the baseline sampling sites. Being a cumulative estimate, S_u^2 accounts for baseline C variability occurring at distances <3 m and includes the analytical errors as well. Conclusions on whether the adjusted regression slopes are different from zero have been reached based on examination of the confidence intervals for the adjusted regression slopes calculated as described by Blomqvist (1977). If the confidence intervals were found to include zero, the regression slope was concluded to be not significantly different from zero.

The intercept for the RTM-adjusted regression equation, $\hat{\beta}_0$, was obtained based on the value of $\hat{\beta}_{\text{adjusted}}$, the mean baseline C value, $\bar{x}$, and the mean value for the C change, $\bar{y}$:

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_{\text{adjusted}}\bar{x}$$

The relationships between the changes in soil C and baseline values presented here are the results obtained after accounting for the RTM effect.

RESULTS

In the Main Site, the mean C contents of contemporary samples (2006) under NT-F (9.9 g C kg^{-1} soil) and CT-cover (9.8 g C kg^{-1} soil) treatments were significantly greater than that of CT-F (8.2 g C kg^{-1} soil) (Table 2). In the Interaction Site, the interaction between tillage and fertilization factors was considered to be statistically significant ($P = 0.07$). Thus we report the results for the individual treatments. The mean contemporary C content of the CT-NF treatment tended to be less than that of the CT-F treatment ($P = 0.09$) but there were no differences among the other treatments (Table 2). The variability in the Interaction Site baseline (1986) C data was found to be much higher than in 2007, which can be explained by different methods used for sample pretreatment and analyses. The soil C content of the virgin sites was much higher than those of the agronomic treatments in both 1986 and 2007 (Table 2).

In none of the treatments of either the Main or Interaction sites did C content increase from the baseline C levels. In the Main Site, the mean changes in C from 1988 to 2006 adjusted for the common level of baseline C values in the eNT-F and CT-cover treatments were not significantly different from zero, indicating no change in the C content over the baseline values. In the CT-F treatment, the mean change was significantly less than zero, indicating C loss. The loss of C in the CT-F treatment was significantly greater than that in the CT-cover treatment, while the NT and CT-cover treatments were not significantly different from each other ($P < 0.1$) (Table 2).

At the Interaction Site, the mean C change in the CT-NF treatment was less than zero and less than those of the NT-F and NT-NF treatments. The mean C changes in the CT-F, NT-F, and NT-NF treatments were not different from zero and not different from each other either. Carbon loss at the virgin site was significantly greater than zero and greater than the losses of the agronomic treatments (Table 2).

At the Main Site, even though all raw regression slopes for the relationships between baseline C and the change in C were negative (data not shown), after RTM adjustment only the regression slope for the CT-cover data was found to be less than zero (Fig. 2a). At the Interaction Site, a significant negative relationship was observed between baseline C values and the change in C values from 1986 to 2007 in all the studied treatments. The plots are shown in Fig. 2b, with fertilization treatments combined for clarity.

Among the studied treatments, a significant positive relationship between changes in C content and the silt + clay content was observed only for the NT-F treatment at the Main Site, with an R^2 value of 0.32, and for the NT-NF treatment at the Interaction Site, with an R^2 value of 0.44 (Table 3).

DISCUSSION

The studied experiments used the same treatments for the entire experiment duration and were located on land with a similar land use history. This is a desirable characteristic for a study addressing the temporal changes in soil C, since many factors, especially historical land use, may affect present soil C levels and, potentially, soil C change rates (Stevens and van Wesemael, 2008). Another advantage of our study is the availability of georeferenced baseline data, which contributed to reducing errors due to spatial variation. Yet another advantage is that at least in one of the two experiments, we were able to use archived samples reanalyzed with the same techniques as those used for contemporary samples.

Overall, the observed changes in C content varied with the management system. At the Main Site, total C under CT management has decreased by 12%. Under NT-F and CT-cover treatments, there were no C losses but there were not any C gains either. Note that in 2006 the total C values under the NT-F treatment and the CT-cover treatment were higher than those of the CT management (Table 2). Thus, if only contemporary data were available, we could have concluded that NT-F and CT-cover managements increased soil C. The observed contemporary differences, however, are essentially reflecting the C losses sustained by the soil under CT-F rather than gains in NT-F and CT-cover. Our results indicate that while contemporary comparisons among management practices provide valuable information on the relative differences generated due to human-induced management, to obtain a comprehensive perspective on soil C changes, the relative differences must be examined along with the absolute changes.

Similar to our study, Hendrix et al. (1998) observed a decline in soil C content from the baseline status under CT at a 0- to 20-cm depth in a 16-yr experiment performed in a fine-loamy soil in Georgia. Doran et al. (1998) observed C losses at 0 to 30 cm in a >20-yr-old experiment in a silt loam soil in Nebraska. Both studies reported that the magnitude of C losses was greater under CT than NT. The lack of C gain under the NT treatment observed in this study was consistent with the results of Puget and Lal (2005) at the 0- to 30-cm depth in an 8-yr-old experiment on a Mollisol of central Ohio; and of Eynard et al. (2005) at the 0- to 20-cm depth in a 16-yr-old experiment on Ustolls of South Dakota. In Mead, NE, on a Typic Argiudoll following the first 8 yr (1984–1992) of gains in soil C in a corn–soybean rotation, Varvel (2006) observed 3 to 5% losses from 1992 to 2002. VandenBygaart et al. (2002) observed C losses in Orthic and Gleyic Luvisols in a majority of sampled sites at four agricultural fields in southern Ontario from 1985 to 2000.

The rate of change in C contents in any management system depends on the balance between soil C inputs through plant residues and C losses, which occur mainly through decomposition. This balance exists for a particular environmental setting that affects decomposition rates, including air and soil temperatures and soil moisture. Because the temperature sensitivity of organic matter decomposition decreases with increasing temperature, soil C losses can be expected to be higher in cold and

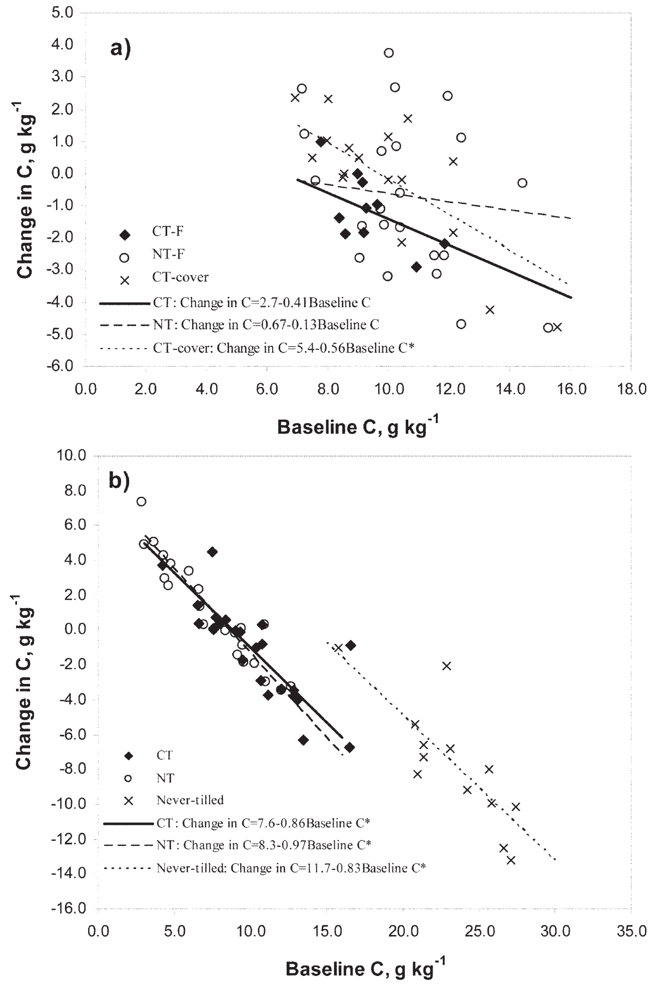

Fig. 2. Changes in total soil C plotted vs. baseline total soil C values for (a) the Main Site experiment (1988–2006) and (b) the Interaction Site experiment (1986–2007). Symbols represent observed data (CT, chisel plow; NT, no-till; F, fertilizer added; CT-cover, chisel plow with cover crops; Never-tilled, virgin grassland). The lines represents the regression equation plots adjusted for the regression-to-the-mean effect. *Regression equations where the slopes are significantly different from zero.

temperate regions than in the tropics (Kirschbaum, 1995, 2000). An increase in global temperature by 1°C could lead to a loss of >10% of soil C in regions with an annual mean temperature of 5°C (Kirschbaum, 1995). In Michigan, the mean air temperature has increased during the last century from 8.1°C (1876–1905 average) to 8.7°C (1962–1991 average; USEPA, 1997). During the next century, however, predictions of the Intergovernmental Panel on Climate Change (IPCC) and the UK Hadley Centre's climate model (HadCM2) project an increase in mean air temperature of 2.2°C (USEPA,1997). Data from the LTER weather station adjacent to the studied experiments indeed indicate a recent winter warming trend. The number of days per year with minimum daily temperature above freezing has been steadily increasing during the past 15 yr (Fig. 3). Even though it cannot be unequivocally concluded from this study that the recent warming trends are the cause of the observed C losses, there is undoubtedly an association between the two. This is especially true for the virgin grassland. The warming trend appears to be the only recently changed influence on this treatment, which otherwise remains managed in the same manner since the 1960s.

Table 3. Relationships between changes in soil C and soil silt + clay contents.

Treatment†	Regression model‡	R^2
Main site experiment		
CT-F	$\Delta C = -0.11 - 0.00003$(silt + clay)	NS§
NT-F	$\Delta C = -0.68 + 0.01$(silt + clay)	0.32
CT-cover	$\Delta C = -0.12 + 0.002$(silt + clay)	NS
Interaction site experiment		
CT-F	$\Delta C = -1.8 + 0.03$(silt + clay)	NS
CT-NF	$\Delta C = 1.22 - 0.023$(silt + clay)	NS
NT-F	$\Delta C = -0.24 + 0.003$(silt + clay)	NS
NT-NF	$\Delta C = -4.3 + 0.08$(silt + clay)	0.44
Virgin grassland	$\Delta C = -0.49 + 0.004$(silt + clay)	NS

† The agronomic treatments are chisel-plow (CT) or no-till (NT) in a corn–soybean–wheat rotation either with (F) or without (NF) fertilization; CT-cover is a certified organic treatment with leguminous cover crops; the virgin grassland was mowed annually since 1960s.

‡ ΔC = C content in 2006 or 2007 minus C content in 1986 or 1988.

§ NS, regression slope is not significantly greater than zero at $\alpha = 0.05$.

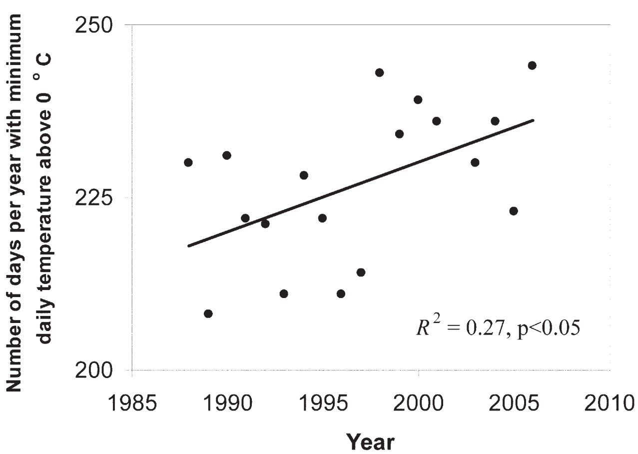

Fig. 3. Number of days per year with minimum air temperatures above 0°C recorded by the weather station at the Kellogg Biological Station Long-Term Ecological Research site from 1988 to 2006.

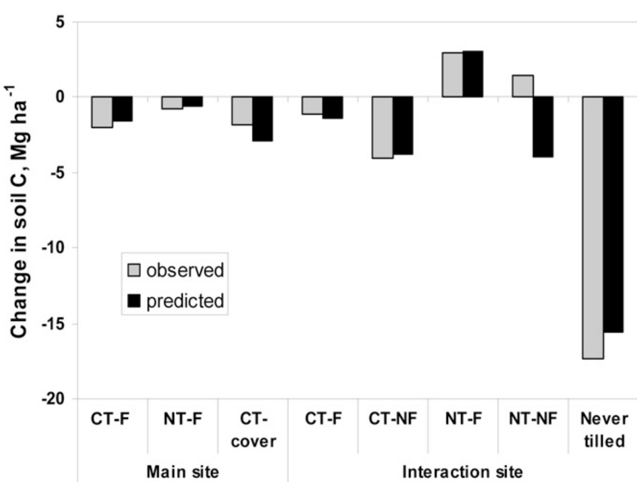

Fig. 4. The observed changes in total C at the Main Site and Interaction Site experiments and the predictions obtained using SALUS (CT, chisel plow; NT, no-till; F, fertilizer added; NF, no fertilizer added; CT-cover, chisel plow with cover crops; Never-tilled, virgin grassland). At the Main Site, the changes were from 1988 to 2006 at the 0- to 15-cm depth, and at the Interaction Site the changes were from 1986 to 2007 at the 0- to 20-cm depth.

The predictions of soil C changes obtained using SALUS were consistent with the observed results (Fig. 4). The model predictions were in excellent agreement with the observed data in the CT-F and NT-F treatments of both the Main Site and Interaction Site experiments. The model also predicted well the observed large soil C loss in CT-NF treatment of the Interaction Site experiment. The model slightly overestimated C losses in the CT-cover treatment. For the NT-NF treatment, the model predicted losses of C that were comparable with the prediction for the CT-NF treatment; however, the observations for this treatment indicated no statistically significant change. One of the reasons for the discrepancy between the model and observed results is that the NT-NF data from 1986 had a relatively large proportion of sites with very low C. In 1986 in this treatment, four out of a total of 11 observations had total C < 0.5%, while the other treatments had one or at most two observations with total C < 0.5%. It is possible that SALUS did not correctly model soil C related processes in such extreme settings of very low initial C values with no fertilization and its further assessments at such settings are necessary.

The observed results and model predictions of this study agree well with the study of the potential effects of global warming on soil C storage under CT and NT management practices at the LTER by Paustian et al. (1995). They evaluated soil C storage projections under the scenario of the mean annual temperature increasing by 2°C by 2050 based on IPCC estimates using the Century model. The simulation assumed that no changes in management or in C input levels were made in the conventional tillage system. The model predicted a decline in C storage from the baseline status under CT by taking baseline C values as 3 kg C m^{-2} for 0 to 20 cm observed in the mid-1980s.

Baseline Carbon Levels

Negative relationships between baseline C and the change in C content observed in this study were consistent with the results of VandenBygaart et al. (2002) and Bellamy et al. (2005) as well as with other studies that looked at the effects of conservation management practices in relation to baseline C (Tan et al., 2006). Stevens and van Wesemael (2008) also observed greater losses in soil C in the Belgian Ardennes associated with higher initial C content values, and C gains at sites with lower initial C contents. As in this study, their regression results were corrected for the RTM phenomenon. The virgin soils of this study that had twice as much C as agricultural soils in 1986 lost 33% of their initial C, compared with an average of 10% loss observed in the conventionally tilled and conventionally managed agricultural systems of this study.

One possible mechanism behind the negative relationship between baseline C levels and C change might be related to a soil's saturation with C (Hassink, 1997; Six et al., 2002). Carbon saturation capacity is defined as the maximum amount of C that can be sequestered by a soil under specific climatic and management conditions (Hassink, 1997; Six et al., 2002). Saturation capacity depends on the sizes of protected and unprotected soil C pools. In soils with lower baseline C content, the sites able to protect soil C by physical and chemical mechanisms might be undersaturated with C. In soils with higher baseline C contents, most of the protective sites might be already saturated with C. Thus, more C is being stored there in labile forms as light fractions and particulate organic matter (POM), the forms that could be physically protected only within soil aggregates. The amount of unprotected C being held at equilibrium with the environment is more strongly affected by variations in environmental factors affecting decomposition, which prevents substantial increases in C storage in unprotected forms. Limited or no increase in soil C with increased organic residue inputs observed in soils with relatively high baseline C in several experiments supports the saturation capacity hypothesis (Hassink and Whitmore, 1997; Six et al., 2002). Soils with both low and high baseline C values, when subjected to an increase in temperature or heavy soil disturbance, will lose C; however, high-baseline-C soils, which have more unprotected C, will lose more C than lower baseline C soils.

In soils under agricultural management, soil C losses due to an increase in the decomposition rate could be partly compensated by increases in agricultural productivity due to improvement in crop cultivars and the use of external chemical inputs. In Michigan, annual agricultural productivity was reported to increase by about 2.6% per year during 1960 to 1999 (www.ers.usda.gov/Data/AgProductivity; verified 7 Sept. 2009). There might not be such compensation at virgin sites, where the productivity remained stable during the studied time period. Paustian et al. (1995) predicted that baseline C can be sustained or marginally increased if the agricultural productivity increases annually by 1.4%, which might result in 40% more residue return compared with the present residue return rate.

Effect of Soil Texture

Positive correlations between changes in soil C and the silt + clay contents in the NT treatments and no significant relationships in the plowed treatments (CT and CT-cover) observed in this study are consistent with literature reports of the relationships between soil texture and soil total or organic C (Needelman et al., 1999; Hao and Kravchenko, 2007). Besides other mechanisms, greater silt + clay content contributes to greater soil C storage also through enhancing the formation of micro- and macroaggregates, which provide greater stability and protection to soil organic matter.

The soil environment under NT is much more conducive to aggregate formation than that of conventionally tilled soils. Tillage limits the soil's potential to protect C within aggregates, since aggregate formation is greatly disrupted by plowing (Puget et al., 1995; Paustian et al., 1997). For example, Beare et al. (1994) observed that the pool of physically protected C in macroaggregates accounted only for 10% of soil C stocks in a tilled soil but 19% in NT soils. The lack of relationship between C and soil texture in the CT-cover treatment could be further due to the fact that the greater C contents of organic-based systems are often mainly attributed to increases in POM. For example, an organic-based system has been reported to have 30 to 40% more POM than a conventional system (Marriott and Wander, 2006). The POM content, however, typically is found not to be directly related to soil texture (Plante et al., 2006; Franzluebbers and Arshad, 1997; Puget and Lal, 2005).

CONCLUSIONS

The results of this study indicate that in the past 18 to 20 yr, the total C in soil under continuous, conventional, chisel-plowed management has declined. Carbon losses were the greatest in conventionally tilled soil without N fertilization. No C gains were observed in either of the two agricultural managements that are regarded as conservational practices, i.e., NT and organic management with cover crops. That is, the conservation management practices appeared only to have prevented total C losses compared with conventional tillage management. Greater losses were often associated with greater baseline C values, while gains were more likely to be observed where baseline C was low. Soil under virgin continuous grassland, which in 1986 had more than twice as much C as soils of the agricultural part of the study, experienced the greatest loss. Changes in soil C were positively correlated with the silt + clay content in NT, but not in the CT treatments.

Associated with the observed C losses, a tendency for higher winter temperatures was observed during the last two decades of weather recorded by the weather station located in the study area. An increase in temperature might be one of the factors that contributed to the soil C losses. With the projected increase in global temperature, the adoption of NT or the inclusion of cover crops in the crop rotation may be one of the prerequisites to sustaining the present soil C levels.

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