Soil Biology & Biochemistry

# Agricultural Management and Soil Carbon Storage in Surface vs. Deep Layers

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Soil C sequestration research has historically focused on the top 0 to 30 cm of the soil profile, ignoring deeper portions that might also respond to management. In this study we sampled soils along a 10-treatment management intensity gradient to a 1-m depth to test the hypothesis that C gains in surface soils are offset by losses lower in the profile. Treatments included four annual cropping systems in a corn (*Zea mays*)–soybean (*Glycine max*)– wheat (*Triticum aestivum*) rotation, perennial alfalfa (*Medicago sativa*) and poplar (*Populus* x *euramericana*), and four unmanaged successional systems. The annual grain systems included conventionally tilled, no-tillage, reduced-input, and organic systems. Unmanaged treatments included a 12-yr-old early successional community, two 50-yr-old mid-successional communities, and a mature forest never cleared for agriculture. All treatments were replicated three to six times and all cropping systems were 12 yr post-establishment when sampled. Surface soil C concentrations and total C pools were significantly greater under no-till, organic, early successional, never-tilled mid-successional, and deciduous forest systems than in the conventionally managed cropping system ($p \leq 0.05$, $n = 3$–$6$ replicate sites). We found no consistent differences in soil C at depth, despite intensive sampling (30–60 deep soil cores per treatment). Carbon concentrations in the B/Bt and Bt2/C horizons were lower and two and three times more variable, respectively, than in surface soils. We found no evidence for C gains in the surface soils of no-till and other treatments to be either offset or magnified by carbon change at depth.

**Abbreviations:** CV, coefficient of variation; KBS, W.K. Kellogg Biological Station.

Soils hold approximately 75% of the C stored on land and about twice that stored in the atmosphere, and thus plays a large role in the global C cycle (Swift, 2001). Carbon is sequestered in soil when organic matter accumulates faster than it is respired as $CO_2$ by soil heterotrophs. Soil C storage helps to stabilize atmospheric $CO_2$ concentrations and promotes improved drainage, soil structure, water holding capacity, and other important soil properties that improve agricultural productivity (Lal et al., 2004).

Organic matter shows differential resistance to microbial decomposition depending on the complexity of the organic compounds, with some simple sugars showing resistance for hours and some lignified materials remaining for millennia (Kononova, 1975; Schlesinger, 1977; VanVeen and Paul, 1981). Organic matter can also be sequestered when adsorbed to clay surfaces and captured within soil aggregates (Six et al., 1998; DeGryze et al., 2004; Grandy and Robertson, 2006, 2007). Additionally, microbial decomposition requires appropriate environmental conditions that are conducive to cellular respiration—soils that are too cold or wet inhibit microbial growth and also accumulate C (Schuur et al., 2008).

Agricultural soils are particularly important for C storage because of their potential for C sequestration both now and in the future (Schlesinger, 1995; Murty et al., 2002). Conversion of native ecosystems to agriculture accelerates soil heterotrophic activity and typically leads to 50 to 70% C loss from agricultural soils. The global potential of soil C sequestration in these soils is estimated at 0.6 to

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Soil Sci. Soc. Am. J. 75:92–101
Posted online 17 Nov. 2010
doi:10.2136/sssaj2009.0414
Received 9 Nov. 2009.
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1.2 Pg C $yr^{-1}$ for about 50 yr, with a cumulative sink capacity of 30 to 60 Pg of C (Lal, 2003).

Globally, agricultural soils have contributed approximately 124 Pg of C to the atmosphere from 1850 to 1990 (Houghton and Hackler, 2001). Interest in restoring some part of this lost C as a readily deployable, low cost option to help stabilize atmospheric $CO_2$ concentrations (Caldeira et al., 2004), now increasing at rates >4.1 Pg C $yr^{-1}$ (Canadell et al., 2007), has led to interest in agricultural management techniques that promote C storage. These include reduced or no-tillage practices to slow decomposition, cover crops to add additional residue to soil, and crop rotations that slow decomposition by increasing the biochemical complexity and quantity of crop residue. Other strategies that might increase soil C storage include converting cropland from annual to perennial cropping systems, abandoning agricultural fields to succession, and planting long-rotation tree crops (Angers and Caron, 1998; Martens, 2000; West and Post, 2002; Lal et al., 2004).

Conversion of cropland to perennial crops or to successional communities has been estimated to sequester in soil as much as 60 g C $m^{-2}$ $yr^{-1}$ (Council for Agricultural Science and Technology, 2004), and conversion to no-till annual crops leads to sequestration rates that are about half this rate (West and Post, 2002; Lal, 2003). However, most of these estimates of sequestration capacity are based on studies of soil C change in surface soils, and recent concerns that similar gains may not be occurring or that the soils may be losing C at depth (VandenBygaart et al., 2003; Carter, 2005; Dolan et al., 2006; Baker et al., 2007) call into question the overall value of no-till and other management strategies for storing C.

For example, of 67 studies reviewed by West and Post (2002) in which soil C sequestration was compared across different management systems, in only two studies were soils sampled below 30 cm. Recent studies of deep soil C have shown that soil type (Blanco-Canqui and Lal, 2008; Chatterjee and Lal, 2009; Christopher et al., 2009), landscape position (VandenBygaart et al., 2003), and sampling depth (Don et al., 2009; Gal et al., 2007; Hermle et al., 2008; Yang et al., 2008) can influence conclusions regarding gains or losses of C. For example, some studies comparing tilled vs. no-till systems have found more C storage at depth in the tilled systems due to incorporation of crop residue at depth, where decomposition presumably proceeds more slowly due to lower oxygen and higher soil moisture levels (e.g., Angers et al., 1997; VandenBygaart et al., 2003; Carter, 2005; Dolan et al., 2006). In such cases any C gains in no-till surface soils could be offset by losses at depth, such that no-till would lose much of its value as a $CO_2$ mitigation strategy.

Sampling at depth is more difficult and expensive. It may also be harder to detect C changes at depth because concentrations are lower and are likely be more variable due to pedogenic factors and the absence of homogenization that occurs with tillage (Robertson et al., 1993; Yang et al., 2008). These factors make it more difficult to detect C change at depth, and also make it likely that whole-profile comparisons will fail to detect C change even when present because variability in deep horizons will mask significant treatment differences in surface horizons, where C is less variable and more concentrated; in fact most whole-profile till vs. no-till comparisons lack the statistical power needed to detect significant carbon change at depth (Kravchenko and Robertson, 2010).

Prior research on soil C at our site in southwest Michigan has shown soil C accumulation in surface soils under no-till and perennial crops and in successional systems. Robertson et al. (2000) documented C gains of 30 g C $m^{-2}$ $yr^{-1}$ in the upper 7 cm of no-till surface soil and up to 60 g $m^{-2}$ $yr^{-1}$ in perennial crops. Grandy and Robertson (2007) reported similar gains of soil C under no-till, perennial cropping, and successional systems to a 5-cm depth. Senthilkumar et al. (2009a) compared surface soil (to 15 cm) C values to historical values and also found C levels to be higher in no-till and organic management systems compared with conventional, but also concluded that surface soils under conventional tillage had themselves lost C over the experimental period. Studies of organic systems have shown gains in soil organic C in both animal- and legume-based organic systems (Pimental et al., 2005; Robertson et al., 2000; Grandy and Robertson, 2007; Senthilkumar et al., 2009a).

Documenting potential change in the entire soil profile is important for understanding the total effect of management on C sequestration and overall nutrient cycling, especially if decreases in C pools at depth due to changes in nutrient cycling might offset increases in surface soil C pools.

Our objective is to examine changes in the accumulation of soil C at depth (to 1 m) under different management regimes, and additionally to test the hypothesis that C gains that might be observed in surface soils of various systems are offset by losses lower in the profile. Specifically, we hypothesize that (i) conventional management will store less C than no-till management, (ii) organic and reduced input systems will store more C than conventional management systems, (iii) perennial cropping systems will store more C than any annual cropping system, (iv) native successional systems will store more C than perennial or annual cropping systems, and (v) increases in soil N will co-occur with increases in soil C. A large range of experimental treatments have been included to show the full range of management options that could be employed to sequester C in soils, from annual cropping systems to native forest systems.

## MATERIALS AND METHODS

### Site Description

We collected soil cores from a field experiment that was established at the W.K. Kellogg Biological Station (KBS) in 1988. W.K. Kellogg Biological Station is located in Southwest Michigan, USA, within the northern portion of the U.S. corn belt (85° 24′ W long., 42° 24′ N lat.). The site lies on Kalamazoo (fine loamy) and Oshtemo (coarse loamy) soil series that are mixed, mesic Typic Hapludalfs that co-occur and developed on glacial outwash (Table 1). The two series mainly differ in the thickness of the B/Bt horizon; the Kalamazoo series has a somewhat thicker upper B/Bt horizon than the Oshtemo. Annual rainfall at KBS is 920 mm yr$^{-1}$, distributed evenly through the year. The water holding capacity of these soils is approximately 150-mm to 1.5-m depth (Crum and Collins, 1995).

**Table 1. Soil profile characteristics at the W.K. Kellogg Biological Station Long-Term Ecological Research (KBS LTER) site. The dominant KBS soil series are Kalamazoo (fine-loamy, semiactive, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, active, mixed, mesic Typic Hapludalfs) series. Data are from Crum and Collins (1995).**

| Horizon | Depth | Texture | | | Bulk Density | pH† |
|---|---|---|---|---|---|---|
| | | Sand | Silt | Clay | | |
| | cm | % | | | Mg m$^{-3}$ | |
| Kalamazoo Series | | | | | | |
| Ap | 0–30 | 43 | 38 | 19 | 1.6 | 5.5 |
| E | 30–41 | 39 | 41 | 20 | 1.7 | 5.7 |
| Bt1 | 41–69 | 48 | 23 | 29 | 1.8 | 5.3 |
| 2Bt2 | 69–88 | 79 | 4 | 17 | nd‡ | 5.2 |
| 2E/Bt | 88–152 | 93 | 0 | 7 | nd | 5.6 |
| Oshtemo Series | | | | | | |
| Ap | 0–25 | 59 | 27 | 14 | 1.6 | 5.7 |
| E | 25–41 | 64 | 22 | 14 | 1.7 | 5.7 |
| Bt1 | 41–57 | 67 | 13 | 20 | 1.8 | 5.8 |
| 2Bt2 | 57–97 | 83 | 4 | 13 | nd | 5.8 |
| 2E/Bt | 97–152 | 92 | 0 | 8 | nd | 6.0 |

†Measured with a soil/water ratio of 15 g field moist soil to 30 mL deionized water.

‡ nd = not determined.

## Experimental Design

Seven experimental cropping system treatments were established in 1989 in replicated 1-ha plots organized in a complete block design (*n* = 6 replications, Table 2). Additional successional communities were added in 1991 as described below (*n* = 3–4 replications), for a total of 10 experimental treatments. Annual cropping systems include four corn–soybean–wheat rotations managed either (i) with conventional inputs and tillage, (ii) with conventional inputs and no tillage, (iii) with tillage and reduced chemical inputs, or (iv) organically with tillage and no chemical inputs. The latter two treatments include a leguminous winter cover crop grown following the corn and wheat portions of the rotation to provide N to the following grain crops. All cropping systems were planted with the same variety and harvested during the same periods each year. Fertilizer application rates for the conventional input systems were based on Michigan State University Extension recommendations and soil-test recommendations. The reduced input system received 1/3 of the N and pesticide applied to the conventional systems, banded within rows rather than broadcast. Details on N application rates, chemical applications, tillage, planting, and harvesting can be found at http://lter.kbs.msu.edu/datatables/16 (verified 26 Oct. 2010).

From 1989 to 1992, the conventional tillage and no-till systems were in a corn–soybean rotation, and the reduced-input and biologically based organic systems were in a corn–soybean–wheat rotation. Since 1993, all four of the annual grain crops have been in a corn–soybean–wheat rotation. The conventional, reduced-input, and organic systems received primary tillage, which consisted of moldboard plowing from 1989 to 1998 and chisel plowing from 1999 onward, all in the spring. Secondary tillage consisted of disking before wheat planting, field conditioning with a soil finisher before soybean and corn planting, and interrow cultivation for soybean and corn. The reduced input and organic systems received additional interrow cultivation and rotary hoeing as needed for weed control.

The two perennial systems included alfalfa and fast growing clonal poplar trees. The alfalfa was harvested 3 to 4 times per year, and was reestablished once during the study period. Fertilizer (P, K, B, and lime) and pesticides were applied according to Michigan State University Extension recommendations and soil test results. Poplar trees were planted in 1989, and starter fertilizer (only) was added at that time. Creeping red fescue (*Festuca rubra*) was used as a cover crop to prevent soil erosion. Poplar trees were harvested in 1999, and allowed to coppice (regrow from cut stems).

The four unmanaged successional systems included: (i) an early successional system that was abandoned from agriculture in 1989 (*n* = 6), (ii) a historically tilled, mid-successional system that was released from agriculture in the 1950s (*n* = 3), (iii) a never tilled successional community that was cleared from forest in 1960 (*n* = 4), and (iv) a

**Table 2. Management summaries for cropping systems and successional communities at the Kellogg Biological Station Long-Term Ecological Research Site.**

| | Replicates | Tillage | Nitrogen fertilizer† | Weed control |
|---|---|---|---|---|
| Annual crops (corn-soybean-wheat rotation) | | | | |
| Conventional | 6 | Conventional | Conventional | Chemical (Conventional Rate) and mechanical |
| No-Till | 6 | None | Conventional | Chemical (Conventional Rate) |
| Reduced Input | 6 | Conventional | 1/3 Conventional with cover crop | Chemical (1/3 Conventional Rate) and mechanical |
| Organic | 6 | Conventional | Cover crop | Mechanical |
| Perennial crops | | | | |
| Alfalfa | 6 | None | None | None |
| Poplar | 6 | None | Starter‡ | None |
| Unmanaged communities | | | | |
| Early Successional | 6 | None | None | None |
| Mid-Successional (HT) § | 3 | None | None | None |
| Mid-Successional (NT) § | 4 | None | None | None |
| Deciduous Forest | 3 | None | None | None |

† Conventional refers to the recommended rate based on soil testing and best management practices.

‡ 60 kg N ha$^{21}$ in 1989 only.

§ HT = historically tilled, NT = never tilled.

late-successional eastern deciduous forest that has never been cleared or plowed ($n = 3$). The early successional system has been burned annually in the spring since 1997, and the never-tilled successional system is mown every fall with mown biomass left in place. All systems are located within 2 km of one another on the same soil series.

## Soil Carbon Sequestration Estimation

Soil C sequestration was estimated by measuring differences between treatments in soil C levels 12 yr after the establishment of agronomic treatments. Plots were arranged into a randomized complete block design to distribute the treatments across the field and account for any underlying spatial variability in soil C levels. The 60-ha field had been managed under conventional tillage (including moldboard plowing) for decades before the 1989 initiation of this experiment, homogenizing much of the underlying soil C variability. Carbon sequestration is calculated as the difference in soil C pool between any given treatment and that in the conventional tillage system. This space-for-time substitution assumes no (Robertson et al., 2000) or little change in C levels in the conventional treatment since other treatments were initiated in 1989. All sequestration rates in our study are thus normalized against rates in the conventional tillage system.

## Soil Sampling and Analysis

Soil samples from all sites were taken sequentially by replicate from 31 May to 19 Oct. 2001 with a hydraulic sampler (Geoprobe, Salina, KS) that collected 6-cm diam. intact cores to a 1-m depth. Soil C concentrations could change over the course of the season, and sampling by replicate helped to eliminate any bias by treatment of sampling across the 4.5-mo period. Cores were taken using the direct push method, which uses vibratory driving to avoid compaction. Each core was removed from the soil in its own clear acrylic sleeve and taken into the lab for classification into soil horizons. Two cores were taken at each of five long-term sampling stations within each replicate plot, for a total of 60 cores per treatment in the annual grain systems, alfalfa, poplar, and early successional systems; 40 in the midsuccessional never-tilled treatment; and 30 in the deciduous and mid-successional historically tilled treatments.

Soil profiles were classified according to soil horizon, and each horizon was measured for length and then split into individual profile segments. Soil segments were individually dried, weighed and analyzed for bulk density, C, and N. Segments were first passed through a 4-mm sieve and mixed. A subsample was then oven dried. Duplicate subsamples from each dried sample were then finely ground in a roller mill and 10-mg aliquots weighed into each of three tin foil cups, which were placed in dessicators before CN analysis. Each was then analyzed for C and N using a Carlo Erba NA1500 Series II C N Analyzer (Carlo-Erba Instruments, Milan, Italy).

For all analytical replicates the coefficient of variation (CV) was ≤0.05; triplicate samples that exceeded 0.05 CV were re-analyzed. We used for soil calibration the standards O519 and O559 provided by USDA-ARS, Pendleton, OR. For 440 of the 800 samples of different treatments and depths, subsamples were reacted with hydrochloric acid to test for the presence of carbonates. A pressure transducer was used to measure changes in pressure due to the presence of carbonate minerals (Evangelou et al., 1984; Loeppert and Suarez, 1996), with a detection limit of <0.1% inorganic C. Detectable levels of inorganic C were not found in any cores.

## Statistical Analysis

The experiment was analyzed as a completely randomized design (CRD) analysis of variance (ANOVA), with 11 treatments and 3 to 6 replicates of each treatment. It was analyzed in this fashion due to the successional sites that were included in the analysis that were not part of the Long-Term Ecological Research main site plots. Treatments were compared based on bulk density, horizon length, C concentrations, and total C pools in each horizon as well as total C pool to 1 m. Total C was calculated by multiplying the C concentration times the bulk density and horizon length for each depth increment. The average bulk density and horizon length was used for those treatments that were not statistically different for each horizon. All comparisons were completed using SAS (SAS Version 8.2, SAS Institute, 2003). The PROC MIXED procedure was used with the LSMEANS statement to determine treatment differences. Differences were determined to be statistically significant at the $p < 0.05$ level.

# RESULTS

## Horizon Depth

A/Ap horizon depths ranged from 14.2 to 22.3 cm and differed little by treatment except among plots that differed in plowing history (Table 3). All sites that had been plowed previously were not significantly different in A/Ap horizon depths, with an average of 20.8 ± 0.3 (s.e.) cm, whereas the A/Ap horizons in the never-tilled mid-successional and deciduous forest systems had significantly smaller ($p \leq 0.05$) mean depths of 14.2 ± 0.2 cm and 16.9 ± 1.3 cm, respectively. The B/Bt horizon lengths were not significantly different among any treatments (mean 35.9 ± 0.6). There were also no significant differences ($p > 0.05$) in Bt2/C horizon lengths, with all treatments having an overall mean of 42.2 ± 0.8 cm to 1-m depth.

## Bulk Density

Bulk density was generally lower at the surface than in lower profile positions in all systems (Table 3). A/Ap bulk density was significantly lower in the never-tilled successional system ($1.20 \pm 0.03$ g cm$^{-3}$, $p \leq 0.05$) than in all other systems (mean 1.47 g cm$^{-3}$ ± 0.03). The bulk densities of B/Bt and Bt2/C horizon soils were not significantly different among treatments.

## Soil Carbon Concentrations

Soil C concentrations ranged from 0.5 to 29.5 g C kg soil$^{-1}$ (Table 4, Fig. 1). Concentrations were higher at the surface than at lower soil horizons, and also showed a pattern of increasing variability with depth. We found highest C concentrations in the A/Ap horizons of the never tilled successional community and the lowest in the conventional row crop system. Among the annual cropping systems, the no-till and organic systems had significantly greater C concentrations in the A/Ap horizon

**Table 3. Cropping system and successional community effects on soil horizon thickness and bulk density to a 100-cm soil depth at the Kellogg Biological Station Long-Term Ecological Research site. Results are shown as mean (standard error). Replication is *n* = 6 plots for annual crops, alfalfa (*Medicago sativa*), poplar (*Populus × euramericana)*, and early successional communities; *n* = 4 mid-successional never-tilled (NT) sites, and *n* = 3 sites for the mid-successional historically tilled (HT) communities and deciduous forest.**

| | A/Ap | | B/Bt | | Bt2/C | |
|---|---|---|---|---|---|---|
| | Thickness | Bulk Density | Thickness | Bulk Density | Thickness to 1 m | Bulk Density |
| | cm | g cm$^{-3}$ | cm | g cm$^{-3}$ | cm | g cm$^{-3}$ |
| | | | Annual crops (corn-soybean-wheat rotation) | | | |
| Conventional | 19.9 (2.30)$^{ab\dagger}$ | 1.6 (0.05)$^{a}$ | 35.8 (3.85)$^{ab}$ | 1.7 (0.05)$^{ab}$ | 43.0 (2.31)$^{a}$ | 1.6 (0.03)$^{a}$ |
| No-till | 20.0 (0.97)$^{ab}$ | 1.5 (0.05)$^{a}$ | 35.8 (1.99)$^{ab}$ | 1.6 (0.03)$^{b}$ | 41.3 (1.86)$^{a}$ | 1.6 (0.03)$^{a}$ |
| Reduced Input | 21.6 (1.43)$^{a}$ | 1.5 (0.02)$^{a}$ | 36.2 (3.24)$^{ab}$ | 1.6 (0.03)$^{b}$ | 40.1 (2.76)$^{a}$ | 1.7 (0.03$^{)b}$ |
| Organic | 19.5 (1.43)$^{ab}$ | 1.5 (0.04)$^{a}$ | 36.7 (3.43)$^{ab}$ | 1.6 (0.04)$^{ab}$ | 41.6 (2.41)$^{a}$ | 1.6 (0.04)$^{ab}$ |
| | | | Perennial crops | | | |
| Alfalfa | 21.2 (1.97)$^{ab}$ | 1.5 (0.04)$^{ab}$ | 35.9 (2.44)$^{ab}$ | 1.7 (0.05)$^{ab}$ | 40.5 (3.34)$^{a}$ | 1.6 (0.05)$^{ab}$ |
| Poplar | 21.3 (2.65)$^{ab}$ | 1.4 (0.05)$^{ab}$ | 30.0 (2.21)$^{b}$ | 1.7 (0.03)$^{ab}$ | 46.1 (3.95)$^{a}$ | 1.7 (0.03)$^{b}$ |
| | | | Successional communities | | | |
| Early Succession | 22.3 (1.67)$^{a}$ | 1.5 (0.03)$^{ab}$ | 35.8 (3.39)$^{ab}$ | 1.6 (0.04)$^{bc}$ | 41.1 (2.19)$^{a}$ | 1.6 (0.03)$^{a}$ |
| Mid- Successional (HT) | 20.8 (2.21)$^{ab}$ | 1.5 (0.04)$^{ab}$ | 33.2 (3.86)$^{ab}$ | 1.8 (0.09)$^{a}$ | 38.9 (6.54)$^{a}$ | 1.7 (0.01)$^{b}$ |
| Mid- Successional (NT) | 14.2 (0.20)$^{c}$ | 1.2 (0.03)$^{c}$ | 35.0 (1.06)$^{a}$ | 1.6 (0.02)$^{b}$ | 47.9 (2.80)$^{a}$ | 1.5 (0.02)$^{c}$ |
| Deciduous Forest | 16.9 (1.25)$^{b}$ | 1.3 (0.02)$^{b}$ | 40.0 (4.26)$^{a}$ | 1.7 (0.08)$^{ab}$ | 40.6 (4.13)$^{a}$ | 1.7 (0.02)$^{b}$ |

†Systems with different lowercase letters within columns are significantly different ($p \leq 0.05$).

than the conventional system; the reduced input system was intermediate to these.

In the B/Bt horizon, C concentrations were statistically similar among all annual and perennial systems. In the Bt2/C horizon there were no statistically significant differences in C concentrations in the annual and perennial systems. In the Bt2/C horizon, the historically tilled mid-successional system had lower soil C concentrations than the early or never-tilled successional systems, but concentrations were not statistically different from those in the deciduous forest system.

Variability in C concentrations was lowest in the A/Ap horizon, with a mean CV of 0.18 ± 0.14 (Table 5). In the B/Bt horizon, CVs for C concentrations were about twice those in the A/Ap horizon (mean 0.37 ± 0.15). Variability in C concentrations was highest in the deepest horizon, the Bt2/C horizon; CVs here were more than three times those in the A/Ap horizon (mean 0.61 ± 0.31). Throughout the entire profile, the systems with fewer replicates (*n* = 3 replicate sites, deciduous forest and historically tilled mid-successional system) showed higher variation in C concentrations than the other systems (*n* = 6 replicate plots).

**Table 4. Cropping system and successional community effects on soil carbon concentrations (g C kg soil$^{-1}$) and pools (kg C m$^{-2}$) to a 100-cm soil depth at the Kellogg Biological Station Long-Term Ecological Research site in 2001. Results are shown as mean (standard error). Replication is *n* = 6 plots for annual crops, alfalfa (*Medicago sativa*), poplar (*Populus × euramericana)*, and early successional communities; *n* = 4 mid-successional never-tilled (NT) sites, and *n* = 3 sites for the mid-successional historically tilled (HT) communities and deciduous forest. Systems with different lowercase letters within columns are significantly different ($p \leq 0.05$).**

| | A/Ap | | B/Bt | | Bt2/C | | Total |
|---|---|---|---|---|---|---|---|
| | g C kg soil$^{-1}$ | kg C m$^{-2}$ | g C kg soil$^{-1}$ | kg C m$^{-2}$ | g C kg soil$^{-1}$ | kg C m$^{-2}$ to 1 m | kg C m$^{-2}$ to 1 m |
| | | | Annual crops (corn-soybean-wheat rotation) | | | | |
| Conventional | 10.4 (0.3)$^{a\dagger}$ | 3.2 (0.1)$^{a}$ | 4.2 (0.7)$^{abc}$ | 2.4 (0.4)$^{abc}$ | 1.8 (0.2)$^{a}$ | 1.2 (0.2)$^{a}$ | 6.9 (0.6)$^{ab}$ |
| No-till | 11.5 (0.4)$^{b}$ | 3.6 (0.1)$^{b}$ | 4.4 (0.5)$^{ab}$ | 2.5 (0.3)$^{ab}$ | 3.5 (1.4)$^{ab}$ | 2.4 (0.9)$^{ab}$ | 8.5 (0.9)$^{ac}$ |
| Reduced Input | 11.1 (1.2)$^{ab}$ | 3.5 (0.4)$^{ab}$ | 3.5 (0.5)$^{bc}$ | 2.0 (0.3)$^{bc}$ | 1.5 (0.3)$^{ab}$ | 1.0 (0.2)$^{ab}$ | 6.5 (0.8)$^{a}$ |
| Organic | 12.2 (0.4)$^{b}$ | 3.8 (0.1)$^{b}$ | 4.6 (0.5)$^{ab}$ | 2.7 (0.3)$^{ab}$ | 2.7 (0.9)$^{a}$ | 1.9 (0.6)$^{a}$ | 8.3 (0.8)$^{ac}$ |
| | | | Perennial crops | | | | |
| Alfalfa | 11.6 (0.1)$^{b}$ | 3.6 (0.3)$^{ab}$ | 4.5 (0.7)$^{ab}$ | 2.6 (0.4)$^{ab}$ | 6.0 (2.2)$^{a}$ | 4.1 (1.6)$^{a}$ | 10.4 (1.5)$^{bc}$ |
| Poplar | 9.8 (1.6)$^{b}$ | 3.0 (0.5)$^{ab}$ | 3.9 (0.9)$^{abc}$ | 2.3 (0.5)$^{abc}$ | 5.2 (2.3)$^{ab}$ | 3.6 (1.5)$^{ab}$ | 8.9 (0.8)$^{bc}$ |
| | | | Successional communities | | | | |
| Early Successional | 14.3 (0.5)$^{c}$ | 4.5 (0.1)$^{c}$ | 4.8 (0.3)$^{a}$ | 2.8 (0.2)$^{a}$ | 1.9 (0.2)$^{a}$ | 1.3 (0.2)$^{a}$ | 8.6 (0.3)$^{c}$ |
| Mid-Success. (HT) | 12.7 (2.9)$^{ab}$ | 3.9 (0.9)$^{abcd}$ | 2.6 (0.6)$^{c}$ | 1.5 (0.4)$^{c}$ | 0.9 (0.1)$^{bc}$ | 0.6 (0.1)$^{bc}$ | 6.1 (1.3)$^{a}$ |
| Mid-Success. (NT) | 29.5 (1.1)$^{d}$ | 5.7 (0.2)$^{d}$ | 4.3 (0.4)$^{ab}$ | 2.6 (0.3)$^{ab}$ | 1.7 (0.4)$^{a}$ | 1.2 (0.3)$^{a}$ | 9.6 (0.7)$^{c}$ |
| Deciduous Forest | 24.0 (3.4)$^{d}$ | 4.7 (0.7)$^{bcd}$ | 4.0 (1.0)$^{abc}$ | 2.5 (0.6)$^{abc}$ | 1.3 (0.4)$^{abc}$ | 0.9 (0.3)$^{abc}$ | 8.1 (1.5)$^{ac}$ |

†Systems with different lowercase letters within columns are significantly different ($p \leq 0.05$).

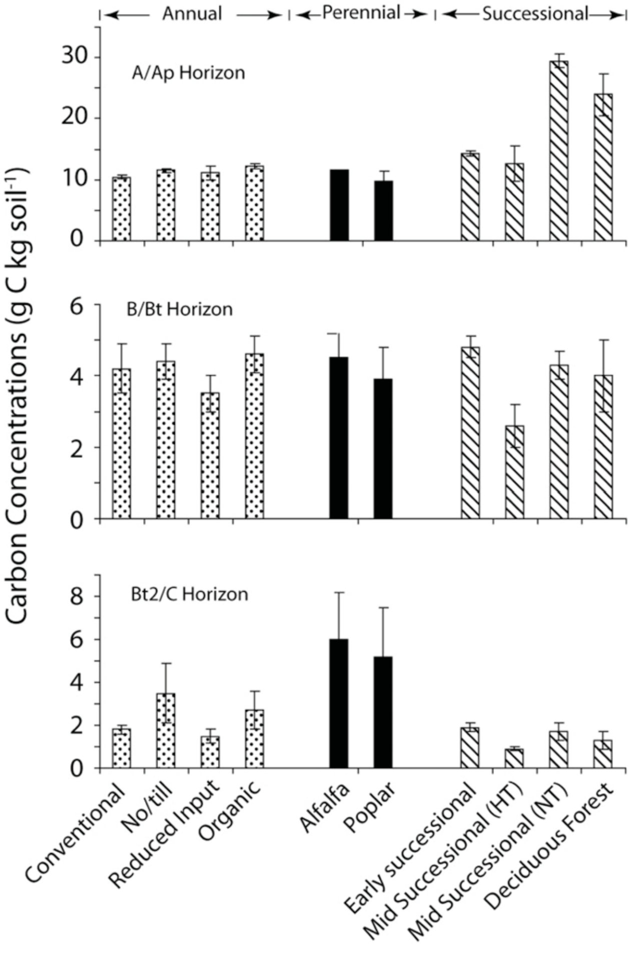

**Fig. 1. Carbon concentrations in the A/Ap, B/Bt, and Bt2/C horizons in the W.K. Kellogg Biological Station Long-Term Ecological Research (KBS LTER) treatments (in g C kg soil$^{-1}$). Error bars represent standard errors. HT is historically tilled, and NT is never tilled.**

## Total Carbon Pool

Total soil C pool is a function of bulk density, horizon length, and C concentration. Management changed the distribution of soil C throughout the soil profile (Table 4, Fig. 2). In the A/Ap horizon, soil C pools in the conventional system were significantly lower than in all the other systems except the reduced input annual system and mid-successional historically tilled system. B/Bt carbon pools in the annual and perennial treatments were not significantly different. The early successional and never-tilled mid-successional systems had significantly higher B/Bt carbon pools than the historically tilled mid-successional system, but none differed significantly from the deciduous forest system. In the Bt2/C horizon, C pools in the annual treatments were not significantly different from one another, and there were no significant differences among perennial treatments.

Over the entire profile to 1 m, all of the annual treatments were not significantly different from one another, nor were there any significant differences among perennial systems. The early successional and never-tilled mid-successional systems had significantly greater C pools than the historically tilled mid-successional system, but none had statistically different C pools from the deciduous forest.

Variability of total soil C pool was also greater at depth than at the surface (Table 5). In the A/Ap horizon, CVs for total C (mean 0.19 ± 0.13) were generally lower than those for deeper in the profile: variability in total C in the B/Bt horizon was about twice as high (mean 0.38 ± 0.14), and in the Bt2/C horizon CVs for total C were more than three times greater (mean 0.61 ± 0.26). Variation across the entire soil profile in total C to 1 m was intermediate to that of the individual profile layers (mean CV = 0.25 ± 0.09).

## Percentage of Nitrogen and Carbon to Nitrogen Ratios

There were no significant differences in soil N concentrations in the A/Ap horizon among the annual and perennial treatments (Table 6). The never tilled mid-successional field and deciduous forest had significantly higher N concentrations than did any

**Table 5. Cropping system and successional community effects on coefficients of variation (CVs) of C concentrations and C pools to a 100-cm soil depth at the Kellogg Biological Station Long-Term Ecological Research site in 2001.**

| | | Coefficients of Variation (CV) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | A/Ap | | B/Bt | | Bt2/C | | Total |
| | Replicates | g C kg soil$^{-1}$ | kg C m$^{-2}$ | g C kg soil$^{-1}$ | kg C m$^{-2}$ | g C kg soil$^{-1}$ | kg C m$^{-2}$ | kg C m$^{-2}$ to 1 m |
| | | | Annual crops (corn-soybean-wheat rotation) | | | | | |
| Conventional | 6 | 0.07 | 0.08 | 0.41 | 0.41 | 0.27 | 0.41 | 0.21 |
| No-till | 6 | 0.09 | 0.07 | 0.28 | 0.29 | 0.98 | 0.92 | 0.26 |
| Reduced Input | 6 | 0.26 | 0.28 | 0.35 | 0.37 | 0.49 | 0.49 | 0.30 |
| Organic | 6 | 0.08 | 0.06 | 0.27 | 0.27 | 0.82 | 0.77 | 0.24 |
| Perennial Crops | | | | | | | | |
| Alfalfa | 6 | 0.02 | 0.20 | 0.38 | 0.38 | 0.90 | 0.96 | 0.35 |
| Poplar | 6 | 0.40 | 0.41 | 0.57 | 0.53 | 1.08 | 1.02 | 0.22 |
| | | | Successional communities | | | | | |
| Early Successional | 6 | 0.09 | 0.05 | 0.15 | 0.17 | 0.26 | 0.38 | 0.09 |
| Mid-Success. (HT)† | 3 | 0.40 | 0.40 | 0.40 | 0.46 | 0.19 | 0.29 | 0.37 |
| Mid-Success. (NT) † | 4 | 0.07 | 0.07 | 0.19 | 0.23 | 0.47 | 0.50 | 0.15 |
| Deciduous Forest | 3 | 0.25 | 0.26 | 0.43 | 0.42 | 0.53 | 0.58 | 0.32 |

†HT = historically tilled, NT = never tilled.

‡Systems with different lowercase letters within columns are significantly different ($p \leq 0.05$).

of the other treatments. The C/N ratio of the A/Ap horizon was significantly greater in the deciduous forest and mid-successional never-tilled systems than in any of the annual or perennial systems. In the B/Bt horizon, the alfalfa system had significantly higher soil N concentrations than any of the annual systems or the poplars. The C/N ratio of the B/Bt horizon was more variable than in the A/Ap horizon, and the C/N ratio of the Bt2/C horizon was more variable than either the A/Ap or B/Bt2 horizons (Table 6).

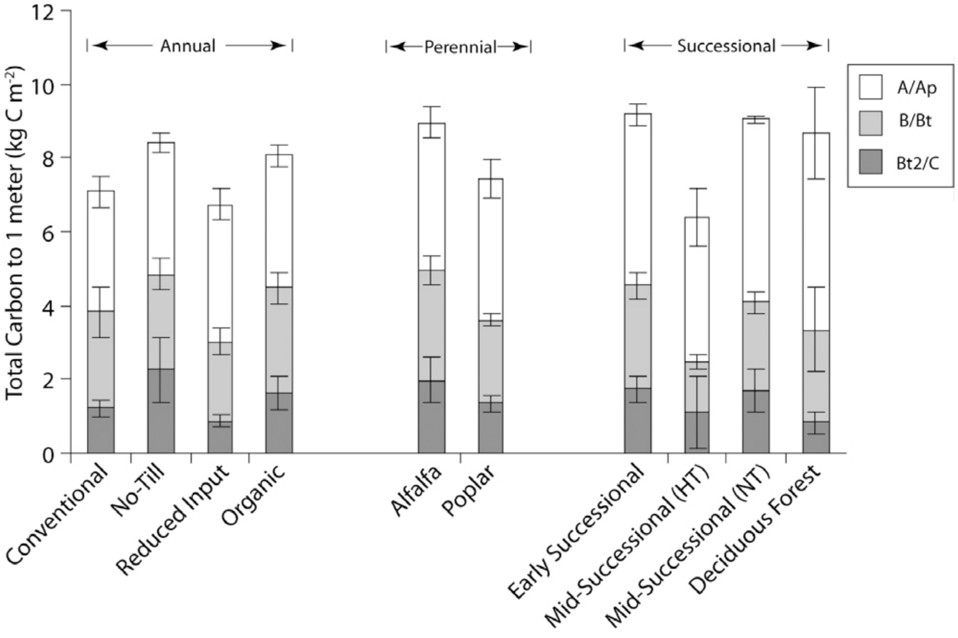

**Fig. 2. Total C in the A/Ap, B/Bt, and Bt2/C horizons to 1 m in W.K. Kellogg Biological Station Long-Term Ecological Research (KBS LTER) treatments (in kg C m$^{-2}$). Error bars represent standard errors. HT is historically tilled, and NT is never tilled.**

# DISCUSSION

In general we found that surface soil C concentrations and total C pools differed significantly among our different systems (Table 7). We also found more variability in C concentrations, total C pools, and C to N ratios in the deeper soil horizons than in the surface soil horizons. Whole-profile C differed significantly among systems only when horizon differences were analyzed separately from one another.

## Annual Cropping Systems

Among the annual cropping systems, differences in C concentrations and total C pools were significant only in surface horizons. Surface soils in the no-till and organic systems had significantly greater concentrations of C than in the conventionally managed system, while the reduced input system had intermediate levels not significantly different from the others. In total C, too, the no-till and organic systems had significantly greater C pools than did the conventional systems, while the reduced input system had intermediate levels not significantly different from the other systems. At all other depths, including to 1 m, we found no significant differences among treatments. This does not support our first hypothesis that C gains in surface soils are offset by losses lower in the profile, though it does support the hypothesis that conventional management will store less C than no-till management or organic systems.

Robertson et al. (2000), Grandy and Robertson (2007), and Senthilkumar et al. (2009a, 2009b) also found that no-till systems had higher surface C than did the conventionally tilled system at this site, although in these studies surface soils were

**Table 6. Cropping system and successional community effects on soil N concentrations and C/N ratios to a 100-cm soil depth at the Kellogg Biological Station Long-Term Ecological Research site in 2001. Results are shown as mean (standard error). Replication is *n* = 6 plots for annual crops, alfalfa (*Medicago sativa*), poplar (*Populus × euramericana*), and early successional communities; *n* = 4 mid-successional never-tilled (NT) sites, and *n* = 3 sites for the mid-successional historically tilled (HT) communities and deciduous forest.**

| | **A/Ap** | | **B/Bt** | | **Bt2/C** | |
|---|---|---|---|---|---|---|
| | g N kg soil$^{-1}$ | C/N ratio | g N kg soil$^{-1}$ | C/N ratio | g N kg soil$^{-1}$ | C/N ratio |
| | | | Annual crops (corn-soybean-wheat rotation) | | | |
| Conventional | 1.12 (0.05) $^{ab\dagger}$ | 9.44 (0.37) $^{a}$ | 0.64 (0.09) $^{abd}$ | 6.66 (0.51) $^{a}$ | 0.41 (0.07) $^{abc}$ | 5.52 (1.02) $^{abc}$ |
| No-till | 1.21 (0.02) $^{ac}$ | 9.57 (0.32) $^{a}$ | 0.67 (0.02) $^{b}$ | 6.87 (0.65) $^{abc}$ | 0.39 (0.04) $^{abc}$ | 13.15 (5.16) $^{abc}$ |
| Reduced Input | 1.24 (0.06) $^{abc}$ | 10.14 (0.47) $^{ab}$ | 0.60 (0.06) $^{bcd}$ | 7.51 (1.03) $^{abc}$ | 0.36 (0.05) $^{ab}$ | 6.70 (2.06) $^{ab}$ |
| Organic | 1.17 (0.06) $^{ac}$ | 10.59 (0.42) $^{b}$ | 0.55 (0.05) $^{acd}$ | 9.10 (1.14) $^{bc}$ | 0.32 (0.03) $^{ad}$ | 11.52 (2.61) $^{ad}$ |
| | | | Perennial crops | | | |
| Alfalfa | 1.35 (0.04) $^{bc}$ | 9.40 (0.17) $^{a}$ | 0.73 (0.06) $^{b}$ | 6.95 (0.35) $^{a}$ | 0.47 (0.06) $^{bc}$ | 9.10 (2.96) $^{b}$ |
| Poplar | 1.17 (0.07) $^{ac}$ | 10.75 (0.32) $^{bc}$ | 0.63 (0.06) $^{bcd}$ | 8.19 (0.69) $^{ab}$ | 0.35 (0.03) $^{a}$ | 6.39 (0.63) $^{ab}$ |
| | | | Successional communities | | | |
| Early Successional | 1.30 (0.05) $^{c}$ | 11.04 (0.10) $^{c}$ | 0.59 (0.03) $^{d}$ | 8.45 (0.36) $^{bc}$ | 0.32 (0.02) $^{abe}$ | 8.21 (1.06) $^{acd}$ |
| Mid-Success. (HT) | 1.36 (0.17) $^{ac}$ | 11.51 (0.96) $^{cd}$ | 0.45 (0.04) $^{a}$ | 8.83 (1.89) $^{c}$ | 0.24 (0.03) $^{ce}$ | 10.35 (5.11) $^{de}$ |
| Mid-Success. (NT) | 2.48 (0.16) $^{d}$ | 11.92 (0.42) $^{d}$ | 0.72 (0.05) $^{b}$ | 6.43 (0.29) $^{a}$ | 0.53 (0.06) $^{c}$ | 4.46 (0.84) $^{c}$ |
| Deciduous Forest | 2.05 (0.19) $^{d}$ | 12.42 (0.41) $^{d}$ | 0.50 (0.10) $^{abd}$ | 10.73 (2.33) $^{abc}$ | 0.31 (0.03) $^{abe}$ | 7.98 (2.57) $^{ad}$ |

†Systems with different lowercase letters within columns are significantly different ($p \leq 0.05$).

**Table 7. Cropping system and successional community effects on soil carbon sequestration to 100 cm soil depth at the Kellogg Biological Station Long-Term Ecological Research site in 2001. Results are shown as mean difference from the conventional system, standard error.**

| | Replicates | Time since establishment | Soil C sequestration in A/Ap Horizon | Soil C sequestration to 1 m |
|---|---|---|---|---|
| | | yr | —— kg C $m^{-2}$ —— | |
| | | Annual crops (corn-soybean-wheat rotation) | | |
| Conventional | 6 | 12 | 0.0 (0.1) $^{a\S}$ | 0.0 (0.6) $^{ab}$ |
| No-till | 6 | 12 | 0.4 (0.1) $^{b}$ | 1.6 (0.9) $^{ac}$ |
| Reduced Input | 6 | 12 | 0.3 (0.4) $^{ab}$ | −0.4 (0.8) $^{a}$ |
| Organic | 6 | 12 | 0.6 (0.1) $^{b}$ | 1.4 (0.8) $^{ac}$ |
| | | Perennial crops | | |
| Alfalfa | 6 | 12 | 0.4 (0.3) $^{ab}$ | 3.5 (1.5) $^{bc}$ |
| Poplar | 6 | 12 | −0.2 (0.5) $^{ab}$ | 2.0 (0.8) $^{bc}$ |
| | | Successional communities | | |
| Early Successional | 6 | 12 | 1.3 (0.1) $^{c}$ | 1.7 (0.3) $^{c}$ |
| Mid-Success. (HT)† | 3 | 51 | 0.7 (0.9) $^{abcd}$ | −0.6 (1.3) $^{a}$ |
| Mid-Success. (NT) † | 4 | 51 | 2.5 (0.2) $^{d}$ | 2.7 (0.7) $^{c}$ |
| Deciduous Forest‡ | 3 | n/a | 1.5 (0.7) $^{bcd}$ | 1.2 (1.5) $^{ac}$ |

† HT = historically tilled, NT = never tilled

‡ Deciduous forest is the native system and these sites have never been harvested. is never tilled.

§ Systems with different lowercase letters within columns are significantly different ($p \leq 0.05$).

sampled to a defined depth as opposed to sampling the entire A/Ap horizon. Our findings are also consistent with global meta-analyses of other long-term studies that have shown that no-till systems accumulate surface soil C relative to conventional tillage systems (Franzluebbers, 2004; Puget and Lal, 2005). On average, our no till and organic systems sequestered C (relative to the conventional system) at a rate of 33 and 50 g C $m^{-2}$ $yr^{-1}$, respectively (Table 7).

We found no significant differences in total profile C pools among annual treatments, due mainly to high variability in soil C at depth. In the B/Bt and Bt2/C horizons, variability among plots in total C was two to three times greater than in the A/Ap horizon (CV = 0.19 in the A/Ap horizon vs. 0.38 in the B/Bt and 0.61 in the Bt2/C horizon). The changes in total profile C pool, if any, were too small to be detected given the high variability. Whether change is occurring at depth or not, our finding that C is accumulating in these systems mainly via changes in surface soils is not diminished. That other studies and reviews have also failed to find whole-profile C gains under no-till (Powlson and Jenkinson, 1981; Machado et al., 2003; VandenBygaart et al., 2003; Carter, 2005; Dolan et al., 2006; Baker et al., 2007) is not surprising given the statistical power required to document change in lower, more spatially variable deep horizons (Kravchenko and Robertson, 2010).

The relatively large C gain in our organic system is surprising given that these soils receive no compost or manure and are exposed to more frequent mechanical disturbance that breaks apart aggregates and exposes C therein to microbial attacks (Grandy and Robertson, 2007). Nevertheless, our results are consistent with early studies at our site (Robertson et al., 2000; Grandy and Robertson, 2007; Senthilkumar, 2009a). Soils in this system may be gaining C due to cover crop composition. The fact that the reduced input system is accumulating C more slowly (or not at all), despite having the same cover crops as the organic system, may be due to an interaction with N fertilizer that could be accelerating the decomposition of plant residue relative to rates of decomposition in the unfertilized soils of the organic system.

It seems reasonable to assume that the soil C pool in the conventional till treatment is at equilibrium, that is, that it has already lost all of the C it is likely to lose while row-cropped, and is maintaining its current C levels, since this system has been tilled for over a hundred years. If this is the case, then the C differences between the conventional system and the no-till and organic systems represent absolute sequestration rates of at least 33 and 50 g C $m^{-2}$ $yr^{-1}$ in the A/Ap horizon over the 12 yr since these systems were established. If, on the other hand, the conventional system is still slowly losing C (Senthilkumar, 2009a) then differences between these systems represent net sequestration. In this case, C in the no-till and organic systems would also be losing C more slowly than in the conventional system. In either case, no-till and organic management in these soils would still represent effective $CO_2$ mitigation strategies.

## Perennial Cropping Systems

Although the perennial systems had significantly higher C concentrations in the A/Ap horizon than did the conventional annual systems, the perennial systems did not significantly differ in total C pools from any of the annual systems at any depth. However, the distribution of C through the profile in the perennial cropping systems was strikingly different from many of the other systems. In the alfalfa and poplars, for example, C was much more evenly distributed with depth compared with the annual and successional systems.

Previous studies at this site have shown that both the alfalfa and poplar crops have higher surface C levels than the annual cropping systems (to 7 cm, Robertson et al. [2000]; to 5 cm, Grandy and Robertson [2007]). Our lower stores of soil C in poplars may be related to accelerated soil C oxidation in the year following cutting: earlier studies reported C contents before a 10-yr harvest event (Robertson et al., 2000; Grandy and Robertson, 2007), while our findings represent C values in the summer of 2001, about 18 mo after harvest in the winter of 1999. Soils during this period would likely have been warmer and wetter due to less shading and less transpiration before canopy closure in 2002, and therefore would have experienced accelerated decomposition of accumulated inputs similar to what has been seen in other clear cut forest systems (e.g., Kim, 2008; Lytle and Cronan, 1998). This finding has significant negative implications for soil C storage in short-rotation woody biomass plantations grown for biofuels.

## Successional Communities

Three of our four successional communities contained significantly more total C in the A/Ap horizon than did the conventional annual cropping system; the exception was the mid-successional historically tilled community. Surface soil C was highest in the mid-successional never-tilled and mature forest sites, which together had on average 2 kg C $m^{-2}$ more C than the conventional annual cropping system. This value likely represents the total C lost from the conventional annual crop surface horizon since the onset of agriculture in this area.

That the early successional community has surface soil C pool similar to that of the mature forest is a function of soil bulk density. The forest has greater soil C concentrations (24.0 vs. 14.3 g C kg $soil^{-1}$). The deeper A/Ap horizon in the successional field (22.3 vs. 16.9 cm) and the higher bulk density (1.5 vs. 1.3 g $cm^{-3}$) offset the lower C concentration. This suggests that as C concentrations increase with time in the early successional community, the successional community may accumulate more C than the mature forest it replaced approximately 150 yr ago. Previous studies at this site have shown that the successional systems have higher surface C pools than did the annual and perennial systems (Robertson et al., 2000; Grandy and Robertson, 2007).

## Soil Nitrogen and Carbon to Nitrogen Ratios

In the surface soils, N concentrations were significantly higher in the never-tilled mid-successional system and deciduous forest system than in all the other systems. These two systems also contained the highest soil C concentrations. Soil N and C concentrations were higher in the A/Ap horizon than in the B/Bt or Bt2/C horizon. Nitrogen concentrations and C/ N ratios were also more variable at depth, and few statistically significant differences were found among treatments in the B/Bt or Bt2/C horizon.

## Spatial Variability at Different Depths

Soil C was more spatially variable at depth in all treatments. In the Bt2/C horizon, C concentrations were three times more variable than in the A/Ap horizon, which led to more variability in soil C pool at depth. Carbon concentrations tended to be lower at depth, and the higher variability combined with lower concentrations led to very few statistically significant treatment differences at depth. This in turn led to difficulty in finding statistically significant differences among treatments when the entire profile to 1 m was considered. In the surface horizon, on the other hand, lower variability combined with higher concentrations made treatment differences more detectable.

Overcoming the difficulty of documenting subtle C change at depth requires increasing statistical power (Yang et al., 2008; Kravchenko and Robertson, 2010). This can be achieved either by increasing the sample size or increasing the effect size, that is, the difference between the treatment groups. In the case of soil C, both options are important. The effect size can be increased by waiting additional time for C levels to change, perhaps decades. The other option is increasing replication. In our study, a retrospective power analysis (Kravchenko and Robertson, 2010) suggests that more than 40 soil cores per plot would have been needed to achieve a 40% chance of documenting a statistically significant management effect in Bt2/C horizon soils, with a change of 20% in the annual treatments and 30% in the perennial and successional systems.

This issue of variability merits further study, particularly if soil C sequestration is to be used as a mitigation option for climate change. However, the absence of detectable C change at depth does not discount the importance of change at the surface from the standpoint of mitigation. We found no evidence for differential C loss at depth. Rather, the risk appears to be in overlooking significant C gain at depth due to inadequate sampling intensity, particularly for deep-rooted perennial systems. Future studies should include more extensive sampling at depth to better understand the partitioning and variability of C in cropped soils.

## Policy Implications

Our results have at least two important implications for tracking soil C for offset or other market-based C compensation schemes. First, sampling at depth is important but not likely to provide detectable change in most soils without an exhaustive sampling strategy. Because subsurface soil sampling is substantially more time-consuming and costly than surface soil sampling, and because changes it presents will be spatially variable and small, an appropriate intensity will not likely be economically feasible on a large scale.

Second, notwithstanding the difficulty of documenting change at depth—either gains or losses of C—changes in surface soils are quantifiable, and represent genuine mitigation potentials to the extent that C can be stored indefinitely.

# CONCLUSIONS

1. Twelve years post-establishment, our no-till and organic systems had higher C concentrations and total C in the surface soil (A/Ap horizon) compared with the conventionally managed system, with sequestration rates of more than 33 and 50 g C $m^{-2}$ $yr^{-1}$ in the no-till and organic systems, respectively;
2. The alfalfa and poplar perennial systems did not have significantly different C concentrations or C pools than the conventional system, possibly because of C loss following the re-establishment of long-term rotations.
3. The early successional, never tilled mid-successional, and deciduous forest system had higher soil C concentrations and total C than the conventionally managed system in surface soils, with a sequestration rate of 108 g C $m^{-2}$ $yr^{-1}$ in the A/Ap horizon of the early successional system.
4. In general, soil C concentrations were three to four times more variable in our deepest horizon, the Bt2/C, than in the A/Ap horizon, requiring more intensive sampling to detect statistically significant differences between treatments; and
5. Soil N concentrations were highest in the A/Ap horizon of the never-tilled mid-successional and deciduous forest systems, which also had the highest soil C concentrations. Higher soil N levels were associated with higher soil C concentrations.

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Published July 14, 2014

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**Soil Sci. Soc. Am. J. 75:92-101**
**doi:10.2136/sssaj2009.0414**

The following acknowledgments should be included in the article:

The authors thank S. VanderWulp, S. Bohm, S. Sippel, C. McMinn, and many others for assistance in the field and lab. We also thank A.N. Kravchenko, S. K. Hamilton, M. J. Klug, A. J. M. Smucker, and S. M. Swinton for many helpful suggestions and insightful comments. Financial support was provided by the U.S. National Science Foundation LTER Program (DEB 1027253), the U.S. DOE Office of Science (DE-FCO2-07ER64494) and Office of Energy Efficiency and Renewable Energy (DE-ACO5-76RL01830), Michigan Sustainable Agriculture Research and Education Program, and MSU AgBioResearch.

Soil Sci. Soc. Am. J.
doi:10.2136/sssaj2009.0414er
Received 2 July 2013.
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