Published January, 2009

Long-Term Changes in Mollisol Organic Carbon and Nitrogen

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Conversions of Mollisols from prairie to cropland and subsequent changes in crop production practices in the Midwestern USA have resulted in changes in soil organic matter. Few studies have used archived samples, long-term resampling of soils to a depth of 1 m, and space for time studies to document these changes. We resampled soils by depth (0–100 cm) in fields at 19 locations in central Illinois on poorly drained Mollisols that were in corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) rotations, were tile drained, and had no known history of manure application in recent decades. Three fields were paired with virgin prairie remnants, two had grass borders that were sampled, and 16 had been previously sampled in 1901 to 1904 or 1957 under various land uses (virgin prairie, cultivation, grass cover). The soils had large amounts of C and N in the profile, with mean values of 179 Mg C ha^{-1} and 16.1 Mg N ha^{-1} for the 18 cultivated fields sampled in 2001 and 2002. We confirmed a large reduction in organic C and total N pools from conversion of prairies to annual cultivation and artificial drainage and documented no change in these organic matter pools of cultivated soils during the period of synthetic fertilizer use (1957–2002). Cultivated fields had soil C and N concentrations typically 30 to 50% less than virgin prairie soils. Smaller but significant declines in C and N concentrations were found when comparing 1900s cultivated fields to concentrations in 2002, after another 100 yr of cultivation, and in comparing 1957 grass covered fields that had been converted to annual cultivation before 2002. The reduction in organic matter after cultivation of prairies occurred mostly in the top 50 cm of soil, with evidence of translocation of C and N from these upper layers to the 50- to 100-cm depth, possibly enhanced by tile drainage. For these Mollisols, declines in organic matter were likely completed by the 1950s, with organic matter pools in a steady state under the production practices in place from the late 1950s through 2002.

Humans are a major factor in soil formation, and there is a great need to examine pedology on a decadal time scale to understand slow but important soil changes (Richter, 2007). Alterations in soil organic C and total N due to long-term cultivation and crop production are important because of their impact on greenhouse gases (CO_2 and CH_4) and on the sustainability of agricultural production (Jaynes et al., 2001; USEPA, 2007). Organic C and N concentrations and pools are also a measure of soil quality and productivity due to their influence on physical, chemical, and biological properties. Mass balances of N in agricultural soils and watersheds in the USA have considered N pools to be in a steady state during the recent (last 50 yr) agricultural production period (David and Gentry, 2000; McIsaac et al., 2002), although it was recognized that net mineralization (i.e., reduction in soil organic C and N pools) had previously occurred after initial cultivation of soils (David et al., 2001). Recent N mass balances for the upper Mississippi River Basin, a major part of the tile-drained Corn Belt, suggest that a net depletion of soil organic N may be occurring (McIsaac and Hu, 2004; USEPA, 2007).

Different rates of decline in organic C and total N after cultivation of virgin soils have been reported, but all involve a large reduction in concentrations and content. In the midwestern USA, Jenny (1941) reported losses in organic C and total N of 38 and 35%, respectively, from virgin prairie soils that tended to reach a steady state after 60 yr of cultivation. Haas et al. (1957) reported a decline of 28 to 59% (mean, 42%) and 24 to 60% (mean, 39%) in surface soil organic C and total N, respectively, after 30 to 40 yr of cropping in the Great Plains. Bauer and Black (1981) found that the quantity and rate of decline in organic C and total N were not significantly different from those reported by Haas et al. (1957) after 40 years of further cropping and implied that organic C reached a steady state after 40 yr of cropping. However, recent studies in the Great Plains showed a decline of only 18 to 26% in surface soil organic C and total N after 60 yr of cultivation (Reeder et al., 1998). Mann (1986), using secondary data from 66 cultivated and virgin Mollisols in a meta-analysis, estimated a 33 to 38% decline in surface soil (0–15 cm) organic C concentration due to cultivation. Mikhailova et al. (2000) found that surface organic C and total N concentrations in Chernozem soils (formed on deep loess) declined by 38 to 43% and 45 to 53%, respectively, after cultivation. Also reported by Mikhailova et al. (2000) were significant reductions in organic C and total N to a depth of 80 and 130 cm, respectively, in

Published in J. Environ. Qual. 38:200–211 (2009).
doi:10.2134/jeq2008.0132
Received 17 Mar. 2008.
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Abbreviations: SCS,USDA Soil Conservation Service.

50-yr continuously cropped and continuous fallow fields when compared with virgin grassland.

The effects of texture (Parton et al., 1987), initial C content (Mann, 1986), and tillage and cropping practices (Cambardella and Elliott, 1993; Drinkwater et al., 1998; Wander et al., 1998; Yang and Wander, 1999) on the rate of loss of C and N have been investigated. The importance of the interaction among bulk density, soil organic matter, and sample depth in the effective spatial and temporal comparison of the rate of C decline across soil types was reported by Ellert and Bettany (1995). However, most studies on organic C and N changes were focused on surface soils, with limited consideration given to the changes in the subsurface or in the entire soil profile as influenced by the changes in bulk density. Mann's (1986) estimated 33 to 38% organic C loss declined to 26% when bulk density was incorporated into her analysis. This lack of available data on organic C and N with depth and bulk density may complicate the estimation of changes in organic C inventories after cultivation (Davidson and Ackerman, 1993; Reeder et al., 1998) and N mass balances directed at understanding environmental problems such as nitrate leaching (David and Gentry, 2000; McIsaac and Hu, 2004; USEPA, 2007). Significant changes in organic C and N can occur in subsurface soils (Reeder et al., 1998; Mikhailova et al., 2000), and analyses focused exclusively on the topsoil may result in an incomplete assessment of changes in soil organic C and N pools due to management. Reeder et al. (1998) estimated that 40 to 60% of the observed decrease in surface soil C and total N were due to the mixing of the surface and subsurface layers during long-term cultivation. There is a need to evaluate organic C and total N in the entire soil profile if actual losses of C and N due to cultivation are to be distinguished from vertical redistribution (Blanco-Canqui and Lal, 2008).

The USDA-Natural Resources Conservation Service estimated that about 20.8 × 10^6 hectares of agricultural lands in the Midwest are tile drained, with Illinois alone accounting for 19%, or a total of 4.0 × 10^6 hectares (USDA-NRCS, 1987). This figure represents 35% of all the cropland in Illinois and includes the most productive Mollisols that were native prairie soils. The fate of organic C and total N is partially influenced by drainage due to the affect of aeration and biological activity of the soil. Carbon and N concentrations can be significantly higher in undrained soils than in tile-drained soils (Jacinthe et al., 2001). There is relatively little information on the changes and profile distribution of organic C and total N due to long-term cultivation in artificially drained agricultural soils. The objectives of our study were to use historical and contemporary data to estimate the changes in Mollisol organic C and total N after various time periods of cultivation and to determine how agricultural production practices have affected the loss and re-distribution of organic C and total N in these generally poorly drained soils.

Materials and Methods

At 19 locations across central Illinois, 25 fields were sampled in 2001–2002, including six that had been previously sampled between 1901 and 1904, 10 that had been sampled in 1957, and three remnant prairie-cultivated field pairs that had not been previously sampled (Table 1). All the sampling locations except the remnant prairies were tile drained, which is typical for these poorly drained, nearly level soils in the central part of Illinois (David et al., 2001).

Historical Records and Site Selection

Fields were selected for soil sampling based on historical soil sampling information from the early 1900s and the 1950s. The early 1900s records were extracted from field and laboratory books of Cyril G. Hopkins stored in archives at the University of Illinois at Urbana-Champaign. These original books contain detailed information, including dates and locations of sampling, maps with X's marking each replicate sample on a field (6–10 individual samples that were composited by depth for analysis), cropping history, drainage conditions, and analytical values of organic C and total N of cultivated soils and their virgin prairie counterparts. We could locate the fields and their sampling locations quite well due to the detailed maps. Data on soils sampled in the 1950s were published by the USDA Soil Conservation Service (SCS) in cooperation with Illinois Agricultural Experiment Station (Survey Investigations Report No. 19; USDA Illinois Agricultural Experiment Station, 1968) and contain detailed site descriptions, soil types, bulk density, and analytical values of C and N (all analyzed at the SCS Lincoln, Nebraska laboratory).

We selected sites in the early 1900s records from central Illinois that were generally poorly drained, had a known date of first soil sampling, had analytical results for C and N, and had notes recorded by Hopkins that described the condition of the site as cultivated or "virgin." Priority was given to locations that contained virgin and cultivated fields. From the 1950s records, priority was given to poorly drained or somewhat poorly drained soils (chiefly Drummer Soil Series: fine-silty, mixed, superactive, mesic Typic Endoaquolls) with recorded analytical values of C and N, bulk density, and land-use history. All fields, with the exception of the virgin prairie remnants, were tile drained. The region of Illinois we sampled includes the most productive agricultural soils in Illinois (that are almost always tile drained) and is typical of tile-drained corn and soybean growing area of the Corn Belt (Fehrenbacher et al., 1984).

All six fields that had been sampled in the 1900s were cultivated at the time of first sampling and have been cultivated for the past 100+ years. Based on Hopkins' notes and our knowledge of farming in this area, they were likely cultivated for 20 to 50 yr by 1901, except perhaps for the Metcalf site, which was described as "virgin prairie soil… being broken and planted in corn for the first time." Two of the six cultivated fields had adjacent uncultivated areas that Hopkins sampled and identified as virgin prairie in the early 1900s (although only the surface 0- to 20-cm soil was sampled by Hopkins). The designation of "virgin" most likely indicated that the field had not previously been cultivated, but these areas most likely had been used for grazing or disturbed in other ways. One of the virgin sites (Normal) was also identified as a "roadside."

Of the 10 locations sampled in 1957, four had been grass covered, and six were cultivated when they were originally sampled.

Table 1. Location, land use, drainage class, year of sampling, and periods of cultivation for fields resampled in 2001 and 2002 and originally sampled in the early 1900s or 1957.

Field location	Latitude N	Longitude W	Historic land use†	Current land use	Soil series	Drainage class‡	Sampling years	Length of cultivation
								yr
1901–1904								
Funk's Grove	40° 22.69′	89° 02.88′	virgin/cropped	cropped	Sable	PD	1901 and 2001	100/100+
Margarity	40° 29.05′	89° 14.42′	pasture	cropped	Peotone	VPD	1903 and 2001	100+
Normal	40° 30.61′	88° 56.55′	virgin/cropped	cropped	Ipava	SWPD	1901 and 2001	100/100+
Mayview	40° 09.18′	88° 07.54′	cropped	cropped	Drummer	PD	1902 and 2002	100+
Metcalf	39° 48.52′	87° 48.41′	cropped	cropped	Flanagan	SWPD	1904 and 2002	100+
Washington	40° 39.96′	89° 24.34′	cropped	cropped	Ipava	SWPD	1904 and 2002	102
1957								
Champaign	40° 05.19′	88° 13.98′	grass	grass/cropped	Drummer	PD	1957 and 2002	50+
Manteno	41° 17.18′	87° 52.67′	cropped	cropped	Reddick	PD	1957 and 2002	50+
Ogden	40° 07.65′	87° 57.71′	cropped	cropped	Drummer	PD	1957 and 2002	50+
Onarga	40° 43.68′	88° 04.06′	cropped	cropped	Drummer	PD	1957 and 2002	50+
Waltham	41° 24.83′	88° 57.33′	cropped	cropped	Drummer	PD	1957 and 2002	50+
Wallace	41° 22.16′	88° 52.16′	grass	cropped	Drummer	PD	1957 and 2002	50+
Round Grove	41° 02.66′	88° 14.95′	grass	grass/cropped	Reddick	PD	1957 and 2002	50+
Roseville	40° 46.37′	90° 41.58′	cropped	cropped	Sable	PD	1957 and 2002	50+
Sheldon	40° 47.37′	87° 34.02′	cropped	cropped	Drummer	PD	1957 and 2002	50+
Waldo	40° 47.02′	88° 52.51′	grass	cropped	Drummer	PD	1957 and 2002	50+
Remnant prairies								
Paxton	40° 26.69′	88° 05.84′	virgin/cultivated		Swygert	SWPD	2002	0/100+
Loda	40° 31.63′	88° 04.49′	virgin/cultivated		Clarence	PD	2002	0/100+
Weston	40° 44.80′	88° 36.80′	virgin/cultivated		Varna	MWD	2002	0/100+

† Virgin/cropped site has both virgin and cropped sampling sites; remnant prairie sites include pairs of preserved prairies in cemeteries with nearby cultivated fields.

‡ MWD, moderately well drained; PD, poorly drained; SWPD, somewhat poorly drained; VPD, very poorly drained.

All the fields cultivated at the time of first sampling have remained cultivated, whereas only two of the four grass-covered locations were still partially under grass at the time of the 2002 sampling; the cultivated and grass-covered portions of these fields were sampled in 2002 (Table 1). Soils at all sites were classified as Mollisols and included Argiudolls and Endoaquolls. The remnant prairies are designated as Illinois nature preserves and have never been cultivated, whereas the adjoining fields, which have the same soil types as their adjacent prairie, have been continuously cultivated for 100+ years. We interviewed owners of each of the properties about cropping history, manure application, and drainage. From these inquiries, none of the fields was known to have received important manure applications in recent decades, although we cannot completely rule this out given the long-term nature of this study and lapses in memory that can occur. However, every attempt was made to sample only fields that were known to the owner to have been in a typical corn–soybean rotation for several decades and that we assume have followed the general trend in cropping patterns in this region of Illinois, as summarized below.

During the first half of the 20th Century, weed control was accomplished with tillage, which included moldboard plowing followed by disk or field cultivation and cultivation of row crops during the growing season. Crop rotations included oats and hay (often with legumes) for draft animals and as a source of N for subsequent crops. It was not uncommon to feed corn stover to livestock. As tractors gradually replaced draft animals, this reduced the demand for oats and hay, which were largely replaced by soybean. Soybean production expanded from a few hectares in 1930 to approximately half of the cropland hectarage in 1980. Additionally, commercial N fertilizer eliminated the need for rotation with legume hay. Nitrogen fertilizer input increased from about 20 kg N ha^{-1} of corn before 1960 to 200 kg N ha^{-1} of corn by 1980 (McIsaac and Hu, 2004), with anhydrous ammonia being the dominant form since its introduction in the 1950s. As corn and soybean production became increasingly profitable, livestock production declined, and the region specialized in the production of feed grains. As chemical herbicides became more effective and as USDA required soil conservation plans, mechanical tillage declined in favor of conservation tillage, especially after 1990. The adoption of glyphosate-tolerant soybeans further enhanced the use of conservation tillage and no-till.

The average annual precipitation in the eastern and central Illinois climate divisions from 1895 to 1957 was 886 mm, compared with 944 mm from 1958 to 2002 (NOAA, 2008). Much of this increase occurred after 1970, a pattern that has been observed throughout much of the eastern USA (McCabe and Wolock, 2002).

Deposition and erosion can affect soil organic matter pools, and we attempted to minimize this effect by our selection of sampling locations within a field. The sample sites were carefully selected to avoid such problems as sedimentation or erosion while matching as close as possible the sites sampled by Hopkins. Fencerows, depressions, and eroded swales were avoided. The slopes of the sample sites were in general <2%, so important amounts of erosion were not expected, and any surface irregularities that would indicate active erosion or deposition were avoided. Hopkins' detailed field notes located the sites down to the ¼, ¼, ¼ section, and, given the permanent grid that is described by the roads in this portion of the Midwest, it was relatively easy to reoccupy Hopkins' sites. The virgin prairie sites were chosen to replicate the nearby cultivated areas while avoiding confounding areas such as fence rows.

Soil Sampling and Laboratory Analyses

The fields were sampled or re-sampled in the summers of 2001 and 2002. In each of the fields, three replicate sampling locations approximately 10 m apart were delimited within the specific soil mapping unit that contained the original sampling location. At sites where we sampled from a prairie remnant or grassed border and the neighboring cultivated field, these sample sets were also taken within a single soil mapping unit. Within a sampling location, three soil samples were taken at depth intervals of 0 to 20, 20 to 35, 35 to 50, and 50 to 100 cm using a 3.2-cm-diameter probe and bulked to make composite samples by depth. The depth increments were chosen to correspond as much as possible to the sampling depths used in the early 1900s and 1957. In the 1957 sampling procedure, samples were taken from grass-covered or cultivated fields but not both in any one sampling location. In the current sampling procedure, the grass and the neighboring cultivated fields were sampled in fields where only the grass-covered fields had been sampled in 1957. In the early 1900s, soils were originally sampled at 6 to 10 locations and three depths, which were composited by depth for chemical analysis (Hopkins and Pettit, 1908). The original 1957 samples were collected using standard Soil Conservation Service methods, with a single composite sample sent to the SCS Lincoln Laboratory for analysis and additional samples for bulk densities measured at the soil testing laboratory at the University of Illinois, Urbana, using the core method.

Our composite samples (three replicates per depth for each field) were put in sealed plastic bags, labeled, and taken to the laboratory for further processing and analyses. In the laboratory, soil moisture content was determined on field moist subsamples. Bulk density was calculated from sections of the cores; we sampled when soil moisture allowed sampling with minimal compaction. For C and N analyses, the soil was air dried and crushed to pass through a 2-mm sieve, further ground to powder, and oven dried at 105°C. Total C and N concentrations in the prepared samples were measured by dry combustion using a CE440 CNS analyzer (Exeter Analytical, Inc., North Chelmsford, MA). Replicate analyses and standard soils with known C and N concentrations were used to document the data quality. These standard soils indicated that the dry combustion analyzer was not able to always give high-quality data for total N with soil concentrations <0.05%. Therefore, all samples below this concentration were reanalyzed using a Kjeldahl digestion followed by colorimetric determination of ammonium using a Lachat QuickChem 8000 Flow Injection Analysis system (Hach Co., Loveland, CO). Because no inorganic C was found in any of our samples, we considered total C equal to organic C and used organic C in our data analysis. Mass per unit area of total organic C and total N in the profile was calculated by multiplying soil C and N concentration in each depth increment by the corresponding bulk densities and summing all depth increments (Ellert and Bettany, 1995). To simplify the data analysis and discussion, we lumped depth values from 20 to 35 and 35 to 50 cm, weighting by bulk density. We also lumped various soil depths from the 1900s and 1957 to obtain matching depth values with our sampling. To estimate the mass of C and N in the 1900s virgin prairie soils where no bulk density values were available (0–10 cm depth only), we used the average bulk density for this soil depth from the three virgin prairies we sampled in 2002. The changes due to cultivation were determined by comparing the current and historical values of C and N in the surface, subsurface, and the entire profile across the different land-use types and time periods.

There are different perspectives on how to appropriately compare the C and N content of undisturbed prairie soils to long-term cultivated soils, with some comparisons made on an equivalent mass basis. When sampled to the same depth of 1 m, the higher bulk density and lower organic matter of the cultivated fields lead to a greater quantity of mineral soil content in the sample volume, which can be viewed as the equivalent of sampling deeper into the undisturbed soil profile. Some researchers consider this a biased sample and suggest that the soils should be sampled to an equivalent soil horizon. This was not possible in our study, but to estimate the magnitude of using this approach, we developed an estimate of soil organic C and N content in three cultivated fields on the basis of an equivalent soil mineral content of the soil samples taken from the neighboring undisturbed prairie. We multiplied the organic C concentration by 2 (Nelson and Sommers, 1996) to estimate the organic matter and mineral fractions of each soil layer sampled. We calculated the mineral soil content of the prairie soil sampled to 1 m depth. From the organic matter content and bulk densities of the cultivated soils, we then estimated the depth of the cultivated soil that would produce an equal amount of mineral soil, assuming that the properties in the 50- to 100-cm depth segment were uniform with depth. We then estimated the C and N content of the cultivated sample at this reduced depth assuming that the C and N content of the 50- to 100-cm depth was uniform.

The early 1900s sites that we resampled in 2001 and 2002 were a subset of the fields that had been sampled between 1901 and 1907 (Hopkins and Pettit, 1908). In our discussion of the results, we used data from Hopkins and Pettit (1908) from central Illinois that included, as characterized by the authors, black clay loams on flat prairie (11 profiles) and brown silt loams on undulating prairie (31 profiles). These correspond directly to the range of fields and locations we sampled in 2002. Hopkins and Pettit (1908) had used standard soil mass values of 0.91 million kg ha^{-1} for the 0- to 18-cm depth, 1.81 million kg ha^{-1} for the 18- to 51-cm depth, and 2.72 million kg ha^{-1} for the 51- to 102-cm depth, equivalent to bulk densities of 1.26, 1.36, and 1.32 Mg m^{-3}, respectively.

Re-analysis of Historical Samples

Because datasets in this study were obtained at different times using different techniques, we compared our analytical methods with those used previously. For C, dry combustion was used in the early 1900s, with CO_2 likely quantified by gravimetric weighing after combustion that was common in this period (Warrington and Peake, 1880; Cameron and Breazeale, 1904) to yield organic C. Historically, total N was determined by Kjeldahl digestion, followed by distillation and titration,

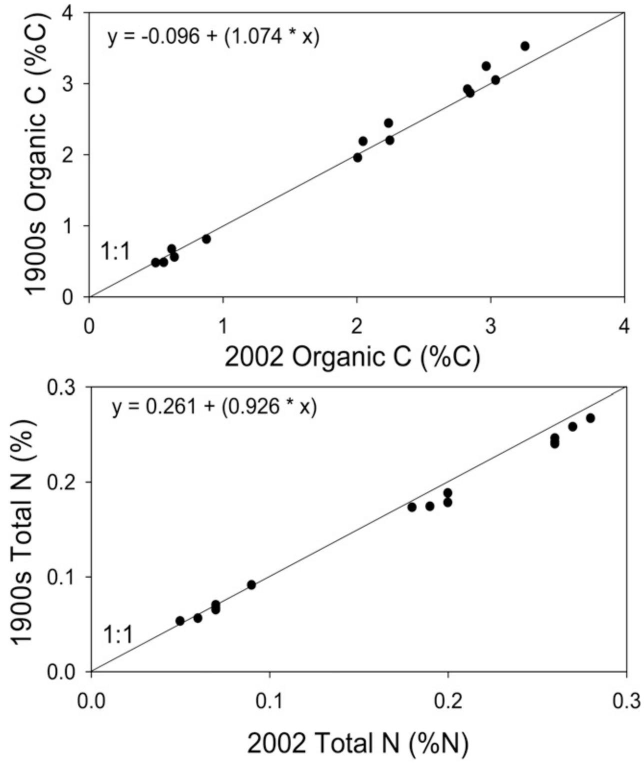

Fig. 1. Comparison of organic C and total N concentrations in archived soil samples from 1901 to 1910 measured at the time of sampling and again in 2002.

and we found a methods manual written by Hopkins and Pettit (1910) that supported that this was the method used for our samples. We obtained 15 original soil samples collected between 1901 and 1910 that were archived and stored in sealed glass jars and had analytical results in the original laboratory notebooks. Samples were chosen to provide a range of organic C and total N concentrations. These samples were reanalyzed using our modern CNS dry combustion instrument, with the exception of one sample for C that was found to have inorganic C present. The original 1900s organic C and total N concentrations compared well with our modern reanalysis (Fig. 1) and gave us confidence in comparing our new samples with those analyzed in the 1900s. The linear regression r^2 values were 0.992 and 0.997 for organic C and total N, respectively, with slopes of 1.07 and 0.93, respectively. These slopes were significantly different than 1 ($p < 0.01$), so we adjusted the 1900s samples C and N concentrations using the regression equations.

In the 1950s, the Walkley and Black (1934) method was used with the assumption that 77% of the organic C was quantified by the measurement (from Walkley, 1935), and values were adjusted accordingly to estimate organic C (SCS, 1972). To test this recovery assumption, 20 of our new soil samples from various depths and with a range in C concentrations (as determined by the CE440 CNS) were randomly selected and analyzed for organic C using the Walkley and Black (1934) method. Between 72 and 78% (mean, 75%) of the organic C in the current samples was recovered by using the Walkley and Black (1934) wet digestion method (data not shown). Walkley and Black (1934) reported average recoverable organic C at 76% (range, 60–86%; correction factor, 1.32) of the total organic C determined by the dry combustion method, similar to our results. Therefore, the 1957 and current data were compared without adjustment.

Statistics

We did not have replicate values for the 1900s and 1957 samples, so we could not statistically compare individual site values. However, we could compare all site pairs together of a given type and soil depth using paired *t* tests. We also could compare remnant prairie and cultivated fields and grassed boarders and cultivated fields using ANOVA. In addition, if we consider each sampling location as a replicate, we had replicate profile analyses for prairie ($n = 3$), cultivated fields sampled by Hopkins and Pettit (1908) between 1901 and 1907 ($n = 41$), cultivated fields in 1957 ($n = 6$), and cultivated fields in 2002 ($n = 18$). These data were compared using the GLM procedure, with mean separation using LSD at the 0.05 level. All statistical analyses were completed using SAS v. 9.1.

Results

Soil Bulk Density

In the remnant prairies, soil bulk density in the 0- to 20-cm depth was 0.95 Mg m^{-3}, which was on average 41% less than the bulk densities in the neighboring cultivated fields (Table 2). In the fields that had been in grass in 1957, bulk density in the 0- to 20-cm depth was 1.2 Mg m^{-3}, which was 13% less than the value for same field currently under cultivation. For the 20- to 50-cm depths, the bulk densities of the remnant prairies and 1957 grassed fields were similar (average 1.28 Mg m^{-3}) and on average were 17% less than the corresponding cultivated fields. Bulk densities for the 50- and 100-cm depth were similar regardless of time or vegetative cover. The differences in surface bulk density could be due to soil compaction and a reduction in organic matter associated with long-term cultivation and artificial drainage of these fields.

Soil Organic Carbon and Total Nitrogen Concentrations

We compared soil organic C and total N concentrations in three soil depths down to 100 cm (Table 2; Fig. 2). Virgin prairie soils had between 38.6 and 58.6 g kg^{-1} organic C in the upper 0 to 20 cm of soil and 3.8 to 4.7 g kg^{-1} total N. One field (Margarity) with peat deposits had much higher concentrations of C and N (organic C was 319 and 302 g kg^{-1} in the 0- to 20-cm and 20- to 50-cm depths, respectively), but this was atypical and was not included in further analysis. Although this area was under cultivation, field notes of Hopkins and comments of the owner indicated that crop planting, production, and harvesting in this portion of the field were often limited by excess soil moisture. One field (Waldo) that was in grass in 1957 had C and N concentrations in the 0- to 20-cm depth that were similar to the prairie remnants, and one of the 1900s cultivated fields (Washington) had historical N concentration similar to the prairie remnants. All other fields, including the two identified as virgin in 1900, had lower C and N concentrations than the prairie remnants in

Table 2. Mean concentration of soil organic C, total N, and bulk density by depth for fields resampled in 2001 and 2002 and originally sampled in the early 1900s or 1957.

Field location	Sampling depth	Organic C		Total N		Bulk density		ΔC†	ΔN	ΔBD
		Remnant	Cultivated	Remnant	Cultivated	Remnant	Cultivated			
Prairies	cm	g kg^{-1} soil				Mg m^{-3}		%		
Paxton	0–20	51.8	18.1	4.1	1.6	0.95	1.30	−65	−62	+36
	20–50	20.5	9.0	1.8	0.92	1.37	1.52	−56	−47	+11
	50–100	5.8	5.7	0.69	0.52	1.46	1.61	−2	−25	+10
Loda	0–20	58.6	28.6	4.7	2.6	0.95	1.43	−51	−46	+51
	20–50	28.1	14.3	2.3	1.5	1.29	1.43	−49	−37	+11
	50–100	6.4	7.3	0.99	0.69	1.65	1.44	+15	−31	−13
Weston	0–20	53.4	31.1	4.3	2.5	0.95	1.30	−42	−44	+36
	20–50	25.9	14.2	2.3	1.2	1.16	1.46	−45	−47	+25
	50–100	8.3	6.6	0.75	0.54	1.50	1.48	−21	−28	−0
1901–1904		Historic	Current	Historic	Current	Historic	Current			
Funk's Grove	0–20	38.6‡	27.0§	3.8	2.4	NA¶	–	−30	−37	–
	0–20	35.6	23.4	3.5	2.1	NA	1.14	−34	−39	–
	20–50	19.4	14.7	1.8	1.4	NA	1.35	−24	−24	–
	50–100	3.6	5.3	0.40	0.64	NA	1.32	+46	+59	–
Margarity	0–20	319	266	34.8	24.5	NA	1.20	−17	−30	–
	20–50	302	316	34.8	28.4	NA	1.38	+5	−18	–
Normal	0–20	44.5†	–	4.1	–	NA	–	–	–	–
	0–20	32.6	20.3	3.1	1.9	NA	1.27	−38	−39	–
	20–50	22.0	11.7	1.8	1.2	NA	1.40	−47	−35	–
	50–100	6.7	5.1	0.52	0.57	NA	1.42	−24	+9	–
Mayview	0–20	42.4	23.7	3.9	2.1	NA	1.36	−44	−46	–
	20–50	24.7	10.9	2.2	1.0	NA	1.41	−56	−56	–
	50–100	3.4	5.9	0.42	0.42	NA	1.46	+71	0	–
Metcalf	0–20	34.4	24.1	3.6	2.3	NA	1.24	−30	−36	–
	20–50	20.3	12.5	2.2	1.3	NA	1.45	−38	−40	–
	50–100	3.5	5.1	0.45	0.6	NA	1.57	+44	+34	–
Washington	0–20	41.4	19.5	4.2	1.8	NA	1.32	−53	−57	–
	20–50	26.7	11.5	2.7	1.1	NA	1.29	−57	−59	–
	50–100	4.2	4.0	0.58	0.51	NA	1.42	−4	−11	–
1957 (Grass)										
Champaign	0–20	40.8	31.7	3.2	2.5	1.18	1.53	−22	−21	+30
	20–50	24.7	20.5	1.9	1.6	1.25	1.67	−17	−15	+33
	50–100	3.7	7.4	0.34	0.66	1.35	1.49	+101	+95	+10
Round Grove	0–20	40.5	25.4	3.4	2.4	1.28	1.39	−37	−29	+8
	20–50	8.4	10.2	0.84	1.0	1.45	1.65	+21	+22	+14
	50–100	2.1	4.0	0.21	0.40	1.54	1.34	+92	+89	−13
Waldo	0–20	58.8	29.1	4.5	2.5	1.18	1.33	−51	−44	+13
	20–50	21.5	15.5	1.8	1.4	1.23	1.43	−28	−25	+16
	50–100	6.4	6.9	0.57	0.65	1.47	1.53	+8	+15	+4
Wallace	0–20	43.1	31.1	3.1	2.6	1.15	1.20	−28	−18	+4
	20–50	15.7	11.8	1.4	1.1	1.24	1.33	−24	−19	+7
	50–100	2.5	4.0	0.24	0.40	1.40	1.39	+63	+67	0
1957 (Cultivated)										
Manteno	0–20	38.0	30.0	2.8	2.6	1.30	1.29	−21	−7	−1
	20–50	11.9	10.6	1.0	1.1	1.36	1.50	−10	+5	+10
	50–100	3.2	4.9	0.20	0.47	1.45	1.43	+2	+131	−2
Ogden	0–20	30.7	22.5	2.7	2.2	1.20	1.46	−27	−20	+21
	20–50	7.1	9.1	0.98	0.82	1.32	1.58	+29	−16	+20
	50–100	2.2	5.1	0.23	0.36	1.50	1.49	+133	+56	−1
Onarga	0–20	39.3	28.7	3.1	2.6	1.26	1.34	−27	−14	+6
	20–50	9.9	15.4	0.86	1.5	1.62	1.58	+56	+70	−2
	50–100	3.0	5.1	0.33	0.48	1.48	1.55	+70	+46	+5
Roseville	0–20	32.2	32.3	2.2	2.5	1.21	1.30	0	+13	+8
	20–50	25.2	20.5	1.7	1.5	1.22	1.48	−19	−10	+21
	50–100	5.8	4.6	0.35	0.44	1.30	1.36	−20	+26	+5
Sheldon	0–20	39.7	29.3	3.3	2.5	1.17	1.30	−26	−23	+12
	20–50	11.3	15.0	1.1	1.4	1.32	1.46	+33	+22	+10
	50–100	3.1	5.5	0.38	0.60	1.64	1.54	+77	+57	−6
Waltham	0–20	29.4	36.7	2.3	3.1	1.36	1.23	+25	+37	−9
	20–50	10.3	23.2	0.89	2.0	1.41	1.37	+125	+124	−2
	50–100	2.9	5.8	0.29	0.60	1.47	1.46	+98	+111	−1

† Change in C, N, and bulk density.
‡ Virgin in 1902.
§ Formerly virgin.
¶ NA, not available from historical data.

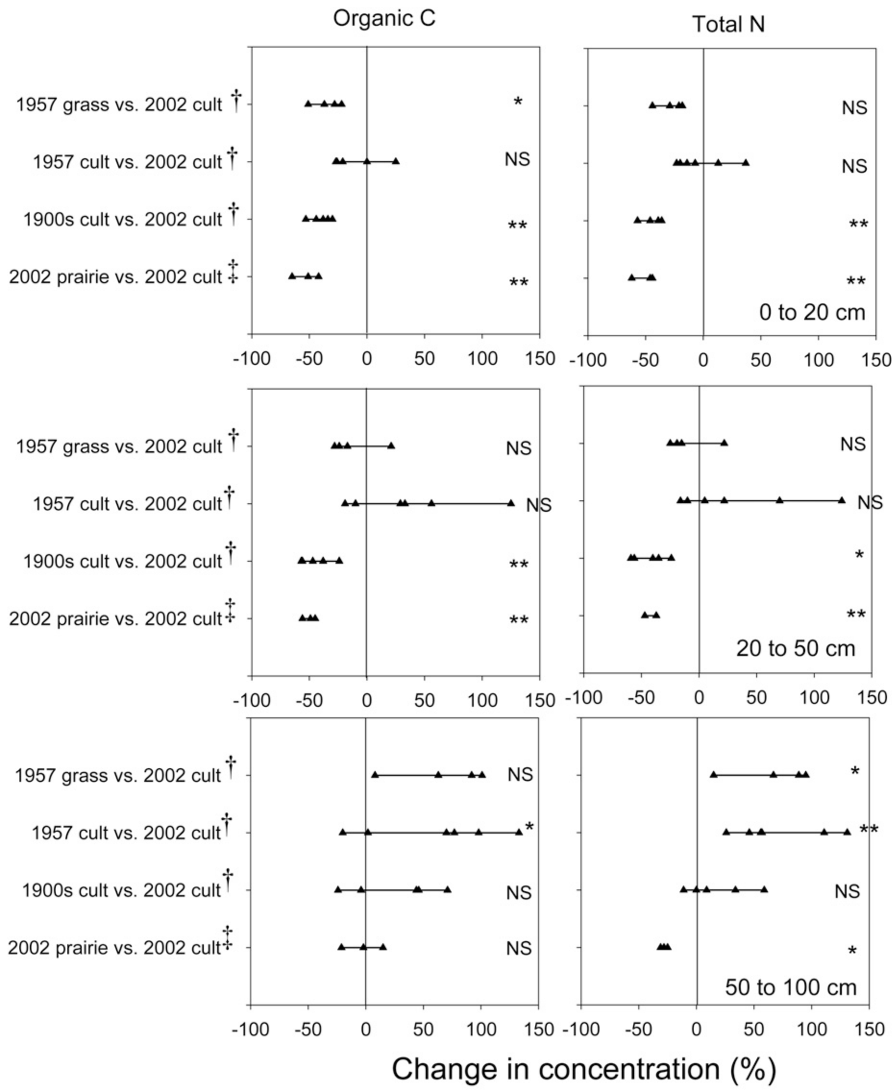

Fig. 2. Percentage differences in soil organic C and N concentrations between original and recent sampling and between grass or prairie soils and paired cultivated fields by sample groups and soil depth. Triangles indicate individual site differences; lines illustrate the range. For each comparison type and within a depth, mean of site differences significantly different from zero at $p < 0.05$ shown with *; $p < 0.01$ shown with **. NS, not significantly different ($p > 0.05$). † Paired *t* tests used. ‡ ANOVA used.

2002. Unlike the sites considered virgin in 1900, the prairie remnants have been protected from grazing and other disturbances for several decades. Additionally, productivity in the prairie remnants may have increased as a result of increased atmospheric N deposition and precipitation in recent decades.

The largest apparent change in C and N concentrations were found in surface soils (0–20 cm) of prairies (original in 1900 or remnant) compared with neighboring cultivated fields. Differences in C and N concentrations were typically 30 to 50% less in the cultivated fields compared with virgin prairie. Similar large declines in C and N concentrations were found in the 1900s cultivated fields after another 100 yr of cultivation and in 1957 grass-covered fields that were now cultivated. The only surface soils that generally had no clear change in C and N concentrations were fields that were cultivated in 1957 and 2002. Three of these fields had declines in C concentrations for the surface soils, two had increases, and one had no change, with a similar pattern for N. When cultivated fields in 1957 and 2002 were compared as a group (Fig. 2), there were no significant changes at any depth in C or N concentrations.

The 20- to 50-cm soil depth was similar to surface soil in its decline in organic C and total N concentrations, indicating that the depletion in organic matter occurred immediately below the plow layer. The 50- to 100-cm soil depth showed a different response. In this large mass of soil, concentrations at most sites increased, including all of the sites that had been in grass in 1957 and subsequently converted to row crops. The exception was the remnant prairie/cultivated field comparison, where all deep soils had declines in total N concentrations (and the mean decline was statistically significant at $p < 0.05$), and two of the fields had declines in organic C concentrations. Within the 1957 cultivated fields, there were significant increases in C ($p < 0.05$) and N ($p < 0.01$) concentrations, and the site at which C seemed to decrease (Roseville) had the highest C concentration in 1957.

It is possible that this site had been brought under cultivation later than the other sites. In the 1900s cultivated fields, C and N concentrations increased in three of the five sites, but the average difference was not statistically greater than zero. In all these subsoils, C and N concentrations were much lower than the upper soil, and small absolute differences in the concentration led to large percentage differences.

Soil Organic Carbon and Total Nitrogen Contents

These imperfectly drained, cultivated Mollisols had large amounts of C and N in the 100-cm soil profile in 2001 and 2002. Mean C and N contents were 179 and 16.1 Mg C or N ha^{-1}, respectively, for the 18 cultivated fields sampled (Tables 3 and 4). In contrast, the mean C and N contents of the three prairie remnants were 249 and 22.6 Mg C or N ha^{-1}. Overall C/N ratios (mass basis) for the cultivated profiles in 2001 and 2002 averaged 11.1 (range, 9.7–12.6), with little change from previous land use (mean prairie, grass 1957, and cultivated 1957 profile C/N ratios were 11.1, 12.1, and 12.0, respectively).

The effects of long-term cultivation were examined for soil mass contents of organic C and total N for the 0- to 20-cm soil depth and for the 100-cm profile (Fig. 3 and 4). The cultivated fields adjacent to the three remnant prairies had organic C contents in the 0- to 20-cm depth ranging from 21 to 52% less than the prairie and N contents ranging from 19 to 48% less than the prairie. These differences are less than the decline in concentrations due to the increase in surface bulk densities. For the 100-cm profile, declines were 24 to 40% and 28 to 38% of organic C and total N contents, respectively, in the three cultivated fields adjacent to remnant prairies. These whole profile declines were, on average, statistically greater than zero ($p < 0.05$).

Because the prairies had lower bulk density and higher organic matter content than the cultivated fields, sampling all sites to 1 m depth results in sampling greater mineral soil in the cultivated fields, which may be considered equivalent of sampling to a deeper depth in the prairie profile. To estimate the C and N content of the cultivated field at an equivalent mineral soil horizon, we calculated hypothetical sampling depths in the cultivated fields that would contain an equal quantity of mineral soil as had been sampled in the neighboring prairie remnant. The resulting equivalent sampling depths were 87, 97, and 89 cm for the Paxton, Loda, and Weston prairies, respectively. The estimated C contents in the cultivated fields for these equivalent depths were 46, 30, and 29% less than the value for the prairie soil, and the N contents were 43, 29, and 32% less. Although sampling an equivalent quantity of mineral soil increased the apparent loss of organic C and N due to cultivation compared with sampling to an equal depth, the overall difference in the two approaches was relatively small.

The organic C and N content of the two grassed borders that were sampled in 2002 were as large as or larger than that of the prairie remnants. The organic C content in the 0- to 20-cm depth in the adjacent cultivated fields were 8 and 12% less than the grass borders, whereas total N was 10 and 16% less (Table 3). For the 100-cm profile at Round Grove, the C and N contents under cultivation were 35 and 33% less than the grass border, respectively, which is statistically significant and similar to the differences observed between the prairie remnants and cultivated fields. For the Champaign site, the difference between the cultivated field and grass border was 6% for C content and 15% for N content and was not statistically significant. This is partly due to the unusually high bulk density of the cultivated soil at this site (Table 2). If sampled to an equivalent mineral soil horizon, the estimated differences between the cultivated field and grass border would increase to approximately 14% for C and 23% for N. The management history of the site is not known.

Declines in surface and profile C and N contents were observed for the cultivated fields that had been in cultivation in the early 1900s when compared with contents in 2002 and for three of the four fields that were grass in 1957 and cultivated in 2002 (Table 4). The one site for which an increase was observed (Champaign) is explained by higher bulk density in the cultivated portion of the field. An increase was observed for fields that were cultivated in 1957 and in 2002, with all fields increasing in profile total N content (0.8–8.3 Mg N ha^{-1}, with all but one site <2.2 Mg N ha^{-1}) and all but one increasing in organic C (−16 to 83.5 Mg C ha^{-1}). However, when compared as a group using a paired *t* test with sites as the replication (Fig. 3), changes in total profile C or N between 1957 and 2002 were not statistically significant ($p > 0.05$). On an annual basis, individual fields increased in total N between 18 and 184 kg N ha^{-1} yr^{-1} during the 45 yr between 1957 and 2002. One of these fields (Waltham) had the largest increases in C and N throughout the profile and, when calculated on an annual basis, accumulated N at 184 kg N ha^{-1} yr^{-1}, whereas the next largest field accumulated at 49 kg N ha^{-1} yr^{-1}. We have no explanation for why this field had such a large increase; it may be due to manure additions or earth moving operations before the knowledge period of the current owners or to assigning an incorrect location of the field in our resampling in addition to random sampling variation.

Discussion

Our results are consistent with previous studies that documented large declines in surface soil C and N concentrations from conversion of prairies to cultivated land (Jenny, 1933; Mann, 1986; Davidson and Ackerman, 1993). Although we observed losses of C and N from the upper profile, since 1957, concentrations significantly increased in the lower 50 to 100 cm of cultivated soils (based on the comparison of 1957 and 2002 samples). It seems likely that much of this response was due to translocation of C and N after initial plowing and tile drainage from the upper profile to deeper soil depths. These soils are quite retentive of dissolved organic C, as leaching losses average about 9.5 kg C ha^{-1} yr^{-1} (Kovacic et al., 2000; Royer and David, 2005). Artificial drainage enhanced and increased water percolation through the profile (most tile drains are 1–1.5 m in depth) and seems to have led to a redistribution of some of the upper profile C and N pools and to have improved the soil environment for root productivity. Productivity of the agricultural fields

Table 3. Mean mass of soil organic C and total N for surface soil (0–20 cm) and profile (0–100 cm) for remnant prairies, grass borders, and adjacent cultivated fields sampled in 2002. For organic C or total N cultivated and uncultivated pairs, 0–20 cm or profile, means with an * are significantly different at the 0.05 level. For organic C or total N, cultivated or uncultivated and 0–20 cm or profile, means followed by the same letter(s) are not significantly different at the 0.05 level.

Field location	Sampling depth	Organic C		Total N		ΔC	ΔN
		Remnant	Cultivated	Remnant	Cultivated		
		Mg C ha^{-1}		Mg N ha^{-1}		%	
Prairies							
Paxton	0–20 cm	99.6bc*	47.4c	7.9b*	4.1c	−52	−48
	profile	223c*	134c	19.9b*	12.5c	−40	−38
Loda	0–20 cm	111a*	81.6b	9.0a	7.3ab	−26	−19
	profile	270a*	196b	26.1a	18.6a	−27	−29
Weston	0–20 cm	102ab*	80.9b	8.3ab*	6.3b	−21	−24
	profile	254ab*	192b	21.9ab*	15.7b	−24	−28
Grass		Border	Cultivated	Border	Cultivated		
Champaign	0–20 cm	105ab	97.1a	9.2a	7.7a	−8	−16
	profile	271a	255a	24.2ab	20.6a	−6	−15
Round Grove	0–20 cm	91.6c*	81.0b	8.6ab*	7.8a	−12	−10
	profile	231bc*	150c	22.0ab*	14.7bc	−35	−33

increased over time, partly due to improved crop genetics and N fertilizer and other inputs but also due to increased precipitation. To estimate the long-term changes in C and N that occurred in the conversion of central Illinois prairies to cropland, we took means of the remnant prairies and the fields under cultivation in the 1900s, 1957, and 2002 cultivated fields (Fig. 5). Our results suggest that a significant loss occurred in profile C and N from initial cultivation of prairie soils and continued through the early 1900s and 1957, but there was no change during the 45 yr of further cultivation between 1957 and 2002. This observation is consistent with Jenny (1933, 1941), who concluded that most of the decline in C and N in paired fields he studied occurred dur-

Table 4. Mean mass of soil organic C and total N for surface soil (0–20 cm) and profile (0–100 cm) for fields resampled in 2001 and 2002 and originally sampled in the early 1900s or 1957.

Field location	Sampling depth (cm)	Organic C		Total N		ΔC‡	ΔN
		Historic	Current	Historic	Current		
		Mg C ha^{-1}		Mg N ha^{-1}		%	
1901–1904							
Funk's Grove	0–20 cm†	73.3	64.4§	7.2	5.7	−12	−21
Normal	0–20 cm†	84.6	51.8	7.8	4.8	−39	−39
Mayview	0–20 cm		64.3		5.7		
	profile		153		13.1		
Metcalf	0–20 cm		59.6		5.7		
	profile		154		15.9		
Washington	0–20 cm		51.5		4.7		
	profile		125		12.5		
1957 (grass)							
Champaign	0–20 cm	86.7	97.1	6.7	7.7	+12	+14
	profile	217	255	17.2	20.6	+18	+20
Wallace	0–20 cm	102	74.5	7.2	6.2	−27	−14
	profile	170	149	13.6	13.4	−12	−1
Round Grove	0–20 cm	119	81.0	10.1	7.8	−32	−23
	profile	166	150	14.8	14.7	−10	−1
Waldo	0–20 cm	139	77.5	10.7	6.7	−44	−37
	profile	266	197	21.9	17.8	−26	−19
1957 (cultivated)							
Manteno	0–20 cm	98.6	77.2	7.3	6.7	−22	−8
	profile	177	161	14.1	14.9	−9	+6
Ogden	0–20 cm	66.9	65.9	6.0	6.4	−2	+8
	profile	128	156	11.9	14.1	+22	+19
Onarga	0–20 cm	95.2	76.7	7.5	7.1	−19	−5
	profile	184	189	15.7	17.8	+2	+13
Roseville	0–20 cm	86.3	83.9	5.9	6.5	−3	+10
	profile	202	206	14.1	16.3	+2	+15
Sheldon	0–20 cm	92.9	76.3	7.6	6.6	−18	−14
	profile	167	182	15.5	16.9	+9	+9
Waltham	0–20 cm	80.0	90.6	6.2	7.7	+13	+24
	profile	142	225	11.8	20.1	+59	+70

† Formerly virgin sampled in 2001.

‡ Change in C and N.

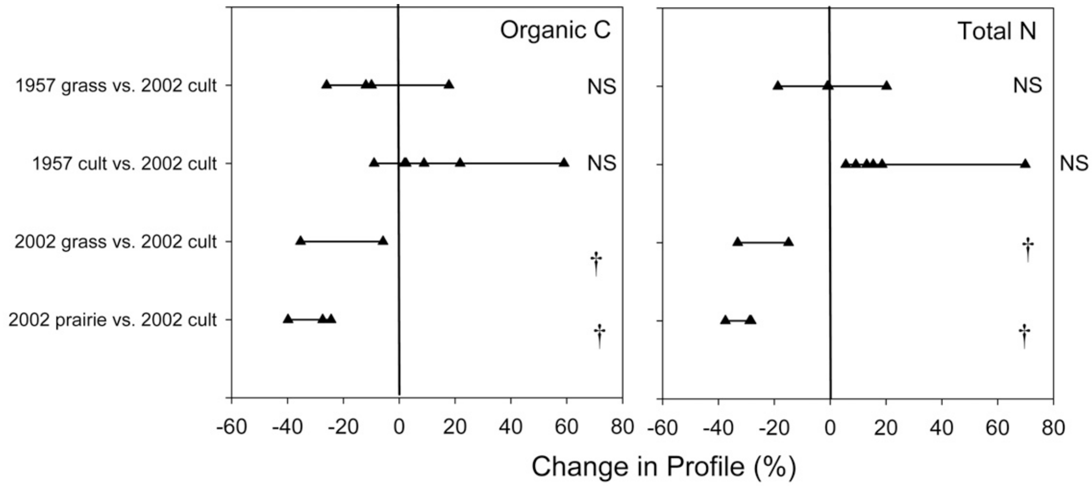

Fig. 3. Percentage differences in organic C and total N contents in the soil profile (0–100 cm) between original and recent sampling and between grass or prairie soils and paired cultivated fields by sample groups. Triangles indicate individual site values; lines illustrate the range. NS, mean of site differences not significantly different from zero (*p* > 0.05) using paired *t* test for each comparison type. † Statistical comparison is available in Table 3.

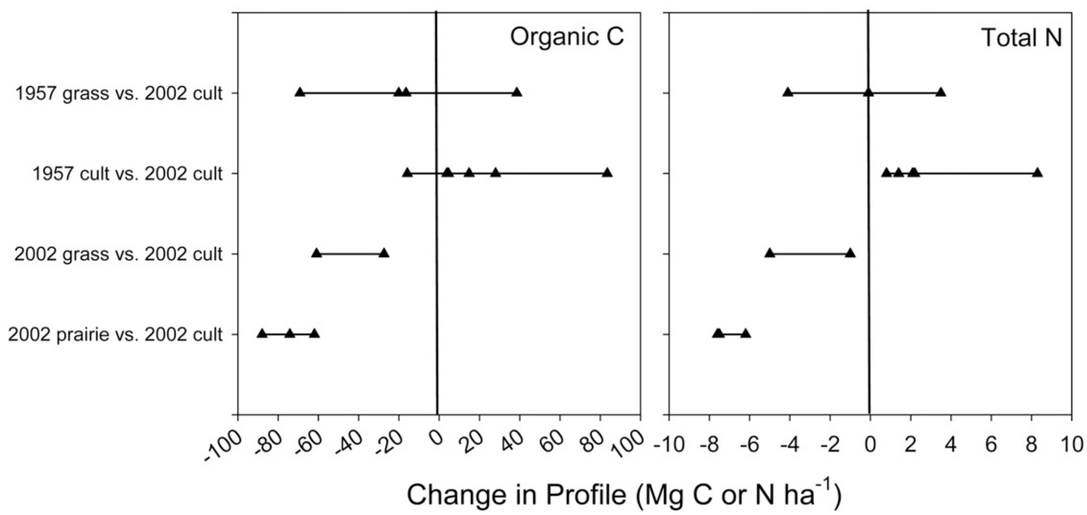

Fig. 4. Mass differences by sample groups for organic C and total N in the soil profile (0–100 cm) between original and recent sampling and between grass or prairie soils and paired cultivated fields. Triangles indicate individual site values; lines illustrate the range.

ing the first 60 yr after cultivation. These data also support the analysis of David et al. (2001), who estimated net mineralization and depletion of soil N for all soils in Illinois from 1860 to 2000 using these assumptions.

Climate change could also be affecting C dynamics in soils, and mineralization or sequestration of the large pool of C present in soils could be an important positive feedback mechanism if soil warming were occurring (Cox et al., 2000). A recent study in England suggested that for soils with an organic C concentration >30 g kg^{-1} in the upper 0 to 15 cm, a relatively rapid depletion of C occurred between sampling in 1978 and resampling in 2003 (Bellamy et al., 2005). In contrast, soils with an organic C concentration <30 g kg^{-1} showed a small increase during this period. Bellamy et al. (2005) concluded that the decline in overall surface organic C was due to climate change. However, Smith et al. (2007) pointed out many problems with and limitations of the Bellamy et al. (2005) data and concluded that climate change could be responsible for at most 10 to 20% of the observed losses. They point out problems in using calculated bulk densities (measured ones were not available), examining only the top 0 to 15 cm of soil, and other large-scale changes that are occurring throughout England. In our work, most surface soils were <30 g kg^{-1} organic C, and we suggest that management effects would overwhelm any subtle climate change response that might be occurring. In addition, we have measured bulk densities for all but the early 1900s sampling locations, so we did not need to estimate them from organic matter concentrations.

Because of the interest in using mass balances to examine N fluxes in the Mississippi River basin (David and Gentry, 2000; McIsaac et al., 2002; USEPA, 2007), we were particularly interested in profile changes between 1957 and 2002. During this period, inorganic fertilizers and corn and soybean rotations without other crops became dominant practices in the region (David and Gentry, 2000; David et al., 2001). These mass bal-

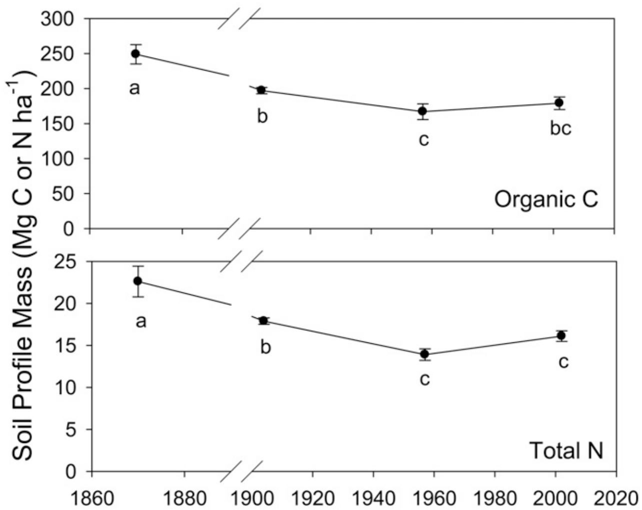

Fig. 5. Mean organic C and total N profile mass by time period, with standard errors. The 1870 are virgin prairies sampled in 2002 (*n* = 3), 1904 is the mean mass calculated by Hopkins and Pettit (1908) for cultivated black clay loams (flat prairie) and brown silt loams (undulating prairie) sampled between 1901 and 1907 in central Illinois (*n* = 41), 1957 represents the cultivated fields from USDA (1968) data (*n* = 6), and 2002 is the mean of each of our cultivated fields (*n* = 18). The break indicates that the 1870 virgin prairie date is uncertain and represents precultivation conditions. Means followed by the same letter are not significantly different at the 0.05 level.

ances have typically assumed a steady state for soil N pools, with annual mineralization equal to immobilization (McIsaac et al., 2002). Our resampling results suggest that although we measured an increase in profile total N pools in the range of 18 to 49 kg N ha^{-1} yr^{-1} (this excludes Waltham, which had large increases inconsistent with the other sites), the average change was not statistically different from zero; thus, our results support the previous assumption that, during the period of modern production practices, soil N pools have been in a steady state.

Across the fields under cultivation in 1957 that we sampled in 2002, average changes in organic C content in the 100-cm soil profile were not statistically significant (Fig. 3). Excluding Waltham, profile organic C pools were on average 5% larger in 2002, but the differences among sites were not statistically different from zero ($p > 0.05$). Khan et al. (2007) interpreted soil organic carbon data from one location in central Illinois (the Morrow Plots) as indicating a significant decline (18%) in soil C (0- to 46-cm depth) after 40 to 50 yr of high rates of synthetic fertilization (336 kg N ha^{-1} yr^{-1} to corn). This loss was slightly greater than any observed in our 1957 to 2002 cultivated field analysis. However, this rate of N fertilization is not typical for the region. Khan et al. (2007) also reported a nonsignificant change in soil organic C (using the dichromate oxidation technique of Mebius [1960]) for the upper 0 to 46 cm of the soil profile with recommended fertilization rates for corn (from 168 to 224 kg N ha^{-1} yr^{-1}) and oats (28 kg N ha^{-1} yr^{-1}), transitioning to a corn–soybean rotation. In this treatment, soil organic C declined from 118 to 112 Mg C ha^{-1} (4.4% decrease). This is within the range of the results from the five 1957 fields under cultivation that we resampled, where average organic C in the upper 0 to 50 cm (excluding the Waltham site) was 140 Mg ha^{-1} in 1957 and 2002. Three of our fields had little change in the C pool for this depth (2–3%), whereas one increased by 14% and one decreased by 15%. When the 100-cm profile was considered, the greatest C loss observed in these fields was 9%. Some of the C losses in the top 46 cm of soil reported by Khan et al. (2007) may have been similarly offset by gains in the subsoil. We conclude from this analysis that under recommended and commonly used fertility rates, tile drainage, and a corn and soybean rotation (typical of much of central Illinois agriculture), little change in soil C pools has occurred during the last 50 yr in central Illinois and that Morrow plot results in this category (a decrease in organic C of 4.4%) reported by Khan et al. (2007) are consistent with our results.

Conclusions

Our sampling of prairie remnants and neighboring cultivated fields in central Illinois confirmed a large reduction in organic C and total N pools from poorly drained Mollisols undergoing cultivation (as well as artificial drainage). Our resampling of fields that had been sampled in two earlier time periods with varying land uses suggested that some decline occurred after 1908, but, during the period of synthetic fertilizer use (1957–2002), changes in these pools averaged across six sites could not be statistically distinguished from zero. The reduction in organic matter stored by prairies occurred mostly in the top 50 cm of soil, although significant reduction in total N was observed in the 50- to 100-cm depth. After 1957, there seems to have been a significant increase in C and N in the subsoils that had been under cultivation, which may be evidence of translocation of C and N from these upper layers to the 50- to 100-cm depth, possibly enhanced by tile drainage. This contributed to a smaller reduction (compared with prairie remnants) in C and N pools than is reflected in the upper soil layers alone. The most productive agricultural soils of Illinois are greatly altered from their prairie beginnings. However, the major declines in organic matter were likely completed by the 1950s, and based on the sampling presented herein, these soils seem to have been in a steady state under production practices in place from the late 1950s through 2002.

Acknowledgments

Funding was provided by the State of Illinois through the Illinois Council on Food and Agricultural Research (C-FAR), Water Quality Strategic Research Initiative. We thank Karen Starks for laboratory assistance.

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