Published July 24, 2015

Soil Profile Transformation after 50 Years of Agricultural Land Use

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Despite a large body of scientific research that shows that soils change on relatively short time scales under different management regimes, classical pedological theory states that we should expect these changes to occur only in the surface few centimeters and that they are not of adequate magnitude to suggest fundamental changes in pedon character over short periods of time. In fact, rarely, do the scientists that make these comparisons report on any properties deeper than 30 to 45 cm in the soil profile. With this study, we evaluate soil transformation to a depth of 150 cm after 50 yr of intensive row-crop agricultural land use in a temperate, humid, continental climate (Iowa, United States), by resampling sites that were initially described by the United States soil survey between 1943 and 1963. We find that, through agricultural land use, humans are accelerating soil formation and transformation to a depth of 100 cm or more by accelerating erosion, sedimentation, acidification, and mineral weathering, and degrading soil structure, while deepening dark-colored, organic-matter rich surface horizons, translocating and accumulating organic matter deeper in the soil profile and lowering the water table. Some of these changes can be considered positive improvements, but many of these changes may have negative effects on the soils' future productive capacity.

Abbreviations: SOC, soil organic carbon.

One third to one half of the earth's land surface has been transformed by humans (Vitousek et al., 1997) via tilling, ripping, transporting, compacting, bulldozing, draining, and more. Yet, classical pedological theory only weakly assesses the effect of humans as primary soil formers. However, a number of researchers have recognized humans as a soil-forming factor (Amundson and Jenny, 1991; Miller et al., 2004; Richter, 2007; Sandor et al., 2005; Yaalon, 2007; Richter and Yaalon, 2012), but there has been little quantification and synthesis of the soil forming processes that humans affect. Many researchers have documented soil change with agricultural land use (Aguilar et al., 1988; Anderson and Browning, 1950; Bouman et al., 1995; Greenland, 1977; Guo et al., 2010; Jenkinson, 1991; Kelly et al., 1988; Mann, 1985). But, although a few have looked at the whole soil profile (Aguilar et al., 1988; Kelly et al., 1988; Follett et al., 2009), rarely, do the scientists that make these comparisons report on any properties deeper than 30 to 45 cm in the soil profile or synthesize a wide range of soil property data (Richter and Yaalon, 2012). In this study, we integrate the effects of 50 yr of row-crop agriculture in Iowa via an extensive field study across the state to understand agriculture's contribution to soil formation.

This research helps to address the two top-ranked priority research questions for soil formation and degradation in the 21st century: 1. "What are the long-term cumulative effects of intensive agricultural management systems on soil?" and 2. "How can we incorporate long-term climatic and geologic processes and con-

Open Access article
Soil Sci. Soc. Am. J. 79:1154–1162
doi:10.2136/sssaj2015.01.0027
Received 19 Jan. 2015.
Accepted 2 May 2015.
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temporary anthropogenic impacts into integrated models of soil properties?" according to Adewopo et al. (2014) and supported by the work of Tugel et al. (2005), Richter et al. (2011), Richter and Yaalon (2012). And this work will also help to address the key questions of anthropogenic soil change that may affect the valuation of the ecosystem services that soil provides (Robinson et al., 2012).

We sampled 82 "representative pedons" in Iowa, representing 46 soil series with a median initial description and sampling date of 1959 (Soil Conservation Service, 1966; Soil Conservation Service, 1978). These sites have been primarily used for corn (*Zea mays* L.) and soybean (*Glycine max* L.) row-crop agriculture, which is typical in Iowa, the central USA and increasingly the world. All of the sites were cultivated for at least some portion of the time period studied. Globally, corn area harvested has increased by 50%, and soybean area harvested has increased by 300% since 1961 (United Nations Food and Agricultural Organization, 2011). Thus, the impacts documented herein could potentially be extrapolated to the region and perhaps the agricultural practice as a whole.

MATERIALS AND METHODS

Historical Database of Soil Properties

The United States National Cooperative Soil Survey has been surveying and cataloguing soils from across the nation since 1899. Soils across the country have been mapped and classified to the soil series level (Natural Resource Conservation Service, 1999). Throughout this time, although higher categories have evolved with changes in U.S. Soil Taxonomy, soil series, and their associated descriptions remain relatively consistent. For each soil series in the USA there is a "type location", a specific location that is considered the representative example of that particular series in that county. For these sites, there is a database of soil information with data from Iowa that began in 1943. We chose to evaluate sites that were described between 1943 and 1963 with a median sampling date of 1959 (Soil Conservation Service, 1966, 1978). The initial data included specific public land survey system locations. We used georeferenced 1930s aerial photos and ArcGIS to convert public land survey system locations to latitude and longitudes. Using these locations and GPS, we were able to relocate the original representative sites, and we sampled 82 representative pedons in 21 counties across Iowa USA (Fig.1) again in 2007 and 2008. Throughout this paper, we refer to these data as the "current" sampling and use the year 2007 as the time of sampling, and we refer to the historic data as the "initial" sampling and use the median sampling year, 1959, as the time of initial sampling.

Land Use History Reconnaissance

The initial soil survey data recorded land use at the time of sampling, and we recorded land use or cover at the time of our sampling. To determine land use change for the interim, we reviewed historical aerial photos, from 1930s, 1950s, 1960s, 1970s, 1980s, 1990s, and 2000s available on the Iowa Geographic Map Server (Iowa State University, 2009). Changes in land use or cover for each landscape position are shown in the pie graphs below the pedon descriptions in Fig. 2. All sites sampled were in some sort of agricultural land use for at least some portion of the time period evaluated.

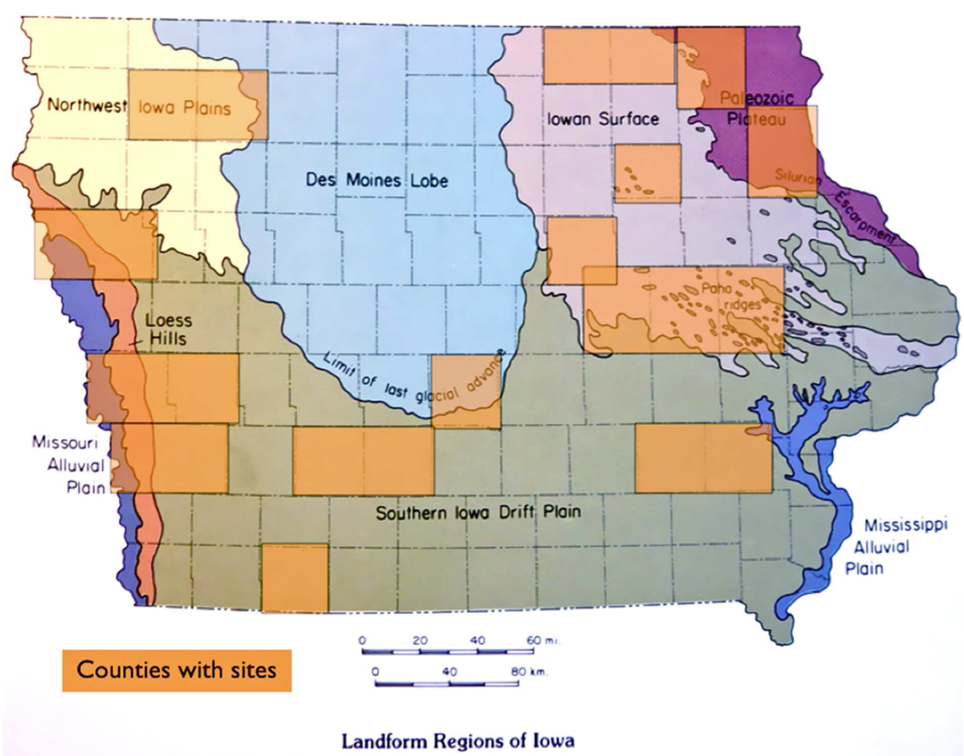

Fig. 1. Iowa counties with sites sampled across landform regions [original map from *Landforms of Iowa*, (Prior, 1991)].

Pedological Context

The climate in Iowa is continental with a mean annual air temperature of 6 to 10°C. The frost-free period is 165 to 200 d long. The average annual precipitation is 58 to 90 cm, and much of the precipitation falls from April to September with snow usually covering the ground from December to March (Soil Survey Staff et al., 2010). Parent materials include loess and glacial till, and the native vegetation is largely perennial grasses.

Soil Sampling

Two 7-cm diam., 150 cm cores, approximately 50 cm apart, were taken at the sites of 82 representative pedons using a truck-mounted hydraulic soil sampler (Gidding's Machine Co., Windsor, CO). While in the field, location, landscape position, and slope were determined for each of the sampling locations (Schoeneberger et al., 2002).

Soil Core Characterization

To assess soil change, we compared morphological, physical, and chemical soil properties to initial data, such as: Munsell color, texture, structure, bulk density, pH, organic C, total N, and depth to carbonates and redoximorphic features to the initial data.

Each soil core was fully characterized according to traditional methods outlined in the Field Book for Describing and Sampling Soils (Schoeneberger et al., 2002). Horizon type, horizon depth, rock fragment content, structure, consistence, presence of cutans, roots, and pores were visually determined for each horizon. Soil matrix and feature color hue, value and chroma were determined by comparing soil samples to a Munsell Soil Color Chart. Gray redoximorphic features were defined as Munsell colors with a value ≥ 5 and a chroma ≤ 2 and red redoximorphic features were defined as Munsell color with a hue of 10YR or redder, a value ≥ 4 and a chroma ≥ 6. Effervescence was determined by dropping 10% (v/v) hydrochloric acid continuously down the soil core to pinpoint the initial depth at which the acid reacted with carbonates and effervesced.

Soil pH was initially and currently determined in 1:1 water dilution following U.S. Soil Survey Method 8C1a (Soil Survey Staff, 1996). Bulk density and total soil organic C and N was also determined for each of the horizons (Table 1).

Several researchers have shown that the Kjeldahl Nitrogen, Ammonia Distillation method (U.S. Soil Survey Method 6B1a) and Total Nitrogen, Dry Combustion method (U.S. Soil Survey Method 6B4a) produce very comparable results (Kowalenko, 2001; Oxenham et al., 1983; Sheldrick, 1986; Soil Survey Staff, 1996).

However, comparing the two carbon methods to each other is more difficult (Mikhailova et al., 2003; Nelson and Sommers, 1982). Some researchers have shown that the Walkley Black Modified Acid Dichromate Digestion, $FeSO_4$ Titration (6A1a) of determining soil organic carbon (SOC) to the Dry

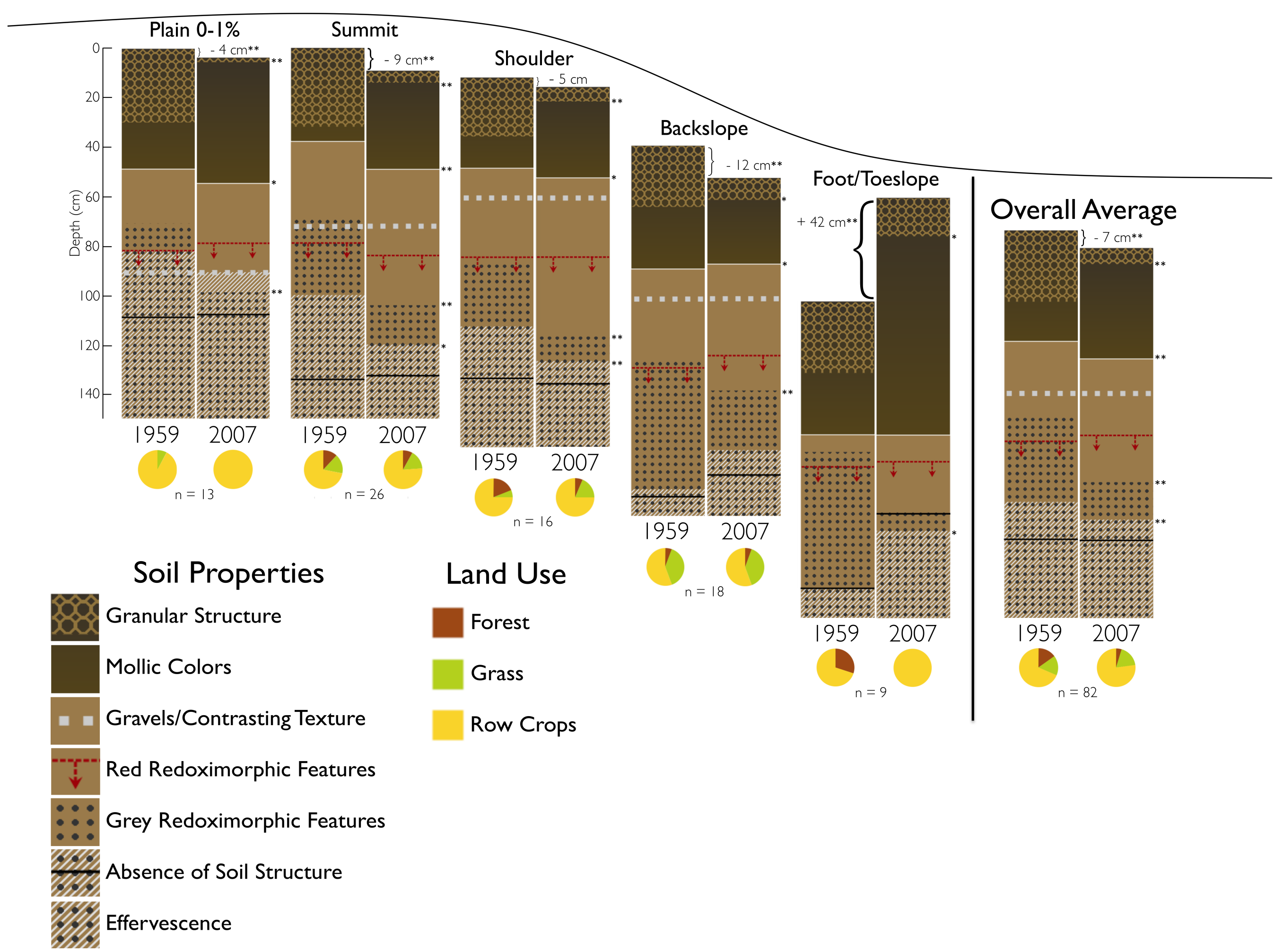

Fig. 2. A visual representation of the changes in soil properties reported in Table 2 arranged such that the most stable reference depth is aligned for comparison. The depth to gravels or contrasting texture is aligned in the images of the pedons from the plain (0–1% slope), summit, shoulder, backslope, and overall averages, and the depth to mollic colors (Munsell colors with a value and chroma ≤ 3) is aligned in the foot/toeslope position. *Indicates that the depth to the feature is statistically significantly different when using the depth to gravels/contrasting texture as the reference depth (or depth to mollic colors in the foot/toeslope position), where **a = 0.1 and *a = 0.2. See Table 2 for specific P values. Pie graphs below each example pedon indicate the percentages of sampled pedons in each type of land use, row crops, grass or forest, for the initial sampling date and current sampling date.

Table 1. Initial and current methods for soil C, N, and bulk density. Method codes from USDA Soil Survey Laboratory Manual (Soil Survey Staff, 1996).

Soil property	Initial method	Current method
C	6A1a Walkley Black Modified Acid Dichromate Digestion, $FeSO_4$ Titration	6A2a Total Carbon, Dry Combustion
N	6B1a Kjeldahl Nitrogen, Ammonia Distillation	6B4a Total Nitrogen, Dry Combustion
Bulk Density	3B1c† Bulk Density Saran Coated Clods Oven Dry	3B6 Bulk Density from Soil Cores

†Originally reported method as method 4A1h, an obsolete method code.

Combustion method (6A2a) of determining total carbon are strongly correlated (Kowalenko, 2001; Sheldrick, 1986; Soon and Abboud, 1991). To carefully compare Walkley–Black soil organic carbon values (WBC) to dry combustion total soil carbon, we assumed that dry combustion total carbon was equal to soil organic carbon in any horizon that did not show evidence of effervescence and thus excluded any horizon that showed evidence of effervescence from the from the SOC analysis. Several researchers have used linear regressions of WBC values against dry combustion total soil carbon values to standardize SOC values across methods (Wills et al., 2013; Meersmans et al., 2009). Similar to Wills et al. (2013), using the U.S. National Cooperative Soil Survey Characterization Database (NCSS, 2015), we analyzed all of the horizons sampled in Iowa with no evidence of carbonates that had both WBC and dry combustion total soil carbon values (292 horizons). From these data, we created the following linear regression: SOC = 0.9782WBC + 0.0383, R^2 = 0.96765. We then applied this regression equation to our initial WBC data to convert it to a comparable dry combustion SOC value.

For purposes of comparison the data were organized into depth increments of 0 to 5, 5 to 15, 15 to 30, 30 to 50, 50 to 75, 75 to 100, 100 to 125, and 125 to 150 cm. Mean total profile C (kg C m^{-2}) was calculated using the following formula:

$$\text{Total Profile Carbon} = 10\left(\sum_{i=0}^{n}\overline{TC_i}\,\overline{\rho_i}\,d_i\right)$$

$\overline{TC_i}$ equals mean concentration of carbon (g 100 g $^{-1}$) for each depth increment; $\overline{\rho_i}$ equals mean bulk density (g cm^{-3}) for each depth increment; d_i equals thickness of depth increment (cm).Total Profile Nitrogen (kg N m^{-2}) was calculated in the same manner.

Soil particle-size distributions (<2 mm) by the pipette method were determined for the horizons from a subset of 33 soil cores (U.S. Soil Survey Methods 6N2, 6O2, 6P2, 6Q2, 6H5a, 3A1 as described in Soil Survey Staff, 1996). The depth to a gravel layer or a contrasting texture was determined from texture by feel analysis. We define the depth to gravels or contrasting texture as an increase rock fragments or significant change in soil texture (increase in sand content or clay content). Examples of contrasting textures are silty textures over loamy textures or large increases (>15%) in clay content between two adjacent horizons. Pedologically speaking these features were evidence of a stone line, lithologic discontinuity, etc. and were often recognized as such in the initial National Cooperative Soil Survey descriptions.

Reference Levels

Defining a baseline condition from which to measure change is more difficult within soil profiles than generally thought. The standard choice is the soil surface, yet the soil surface is dynamic by way of erosion and deposition, organic matter addition, etc. Likewise the depth to the C horizon is popular, but the depth to the upper C boundary is open to interpretation. Here we report changes in soil profile properties using three reference levels, (i) the soil surface; (ii) the depth to gravels or contrasting texture; and (iii) the maximum depth of mollic colors (dark organic-matter-rich soil, matrix Munsell colors with a value and chroma ≤ 3).

We use the soil surface because it is the standard reference level, and by using this depth all 82 of our sampled pedons can be analyzed. However, given compaction, erosion, sedimentation, or other changes the soil surface is unstable and it is likely to have become deeper or shallower depending on landscape position and land use. Hence, we needed an alternative reference level, a point that was unlikely to be changed with human uses, natural pedon evolution or subject to differing interpretations. We decided that the depth to a unique stationary feature, such as gravels or a contrasting texture, is a better choice for a reference level. So, we also report changes in soil property depths using the depth to gravels or contrasting texture as the reference level.

However, in the foot/toeslope position only two of the nine pedons sampled had a depth to gravels or contrasting texture for comparison, so given that these are usually sediment-gaining positions we use the maximum depth of mollic colors as the most stable reference depth for this landscape position.

Example calculation for the change in property depth, using an alternative reference depth:

$$\Delta d_p = (d_{ai} - d_{pi}) - (d_{ac} - d_{pc})$$

where Δd_p equals change in depth to soil property; d_{ai} equals initial depth from soil surface to alternative reference level; d_{pi} equals initial depth from soil surface to soil property; d_{ac} equals current depth from soil surface to alternative reference level; d_{pc} equals current depth from soil surface to soil property. Where a positive change in depth to the soil property (Δd_p) indicates that the soil property is deeper than it was in the initial samples, and a negative change indicates that the soil property is shallower than it was in the initial samples.

Fifty of the eighty-two pedons we sampled have properties that qualify for the appropriate alternative reference level. To analyze the data from all 82 pedons, the overall average depths of soil properties were visually represented and arranged in Fig. 2 such that the average depth to gravels or contrasting texture is aligned in the images of the pedons from the plain (0–1% slope), summit, shoulder, backslope, and overall averages, and the depth to mollic colors is aligned in the foot/toeslope position. This allows for a visual assessment of the changes in soil properties of all of the pedons sampled using the average depth of the alternative, more stable, reference depth for comparison.

Statistical Analysis

The data were analyzed statistically by applying a paired *t* test to each set of soil characteristics, comparing inital data with current measurements for each soil property in each depth increment in a two-tailed test, using the JMP 8.0.2 statistical program (SAS, Inc., Cary, NC). P values were reported throughout. In the visual data summary, Fig. 2, $^{**}\alpha = 0.1$ and $^{*}\alpha = 0.2$ were used.

RESULTS AND DISCUSSION

Overall, depths to gravels/contrasting texture and the absence of structure are 7 cm shallower than they were initially ($P = 0.01$, Table 2). We attribute these changes to erosion and not compaction, because bulk densities are the same or lower now than originally (Table 3). The greatest soil loss is in the backslope position, a 12 cm decrease (Table 2, $P = 0.04$). Alternately, the foot/toeslope positions gained 42 cm ($P = 0.04$, Fig. 2, Table 2) based on changes in depth to mollic colors. Corresponding erosion rates are extrapolated in Veenstra (2010).

Despite evidence of soil loss in most landscape positions, maximum depth of mollic soil colors (dark organic-matter-rich soil, matrix Munsell colors with a value and chroma ≤ 3) did not change accordingly. Rather, the maximum depth of mollic soil colors increases in the summit, shoulder and relatively flat (plain, 0–1% slope) landscape positions (Fig. 2, Table 4). But the overall organic C and total N contents of the surface soil horizons decrease (Table 5, Table 6). Although soil has been lost through erosion, we speculate that deep tillage, even if it is infrequent, mixes organic-matter-rich soil material more deeply in the soil profile, increasing the depth of mollic colors and diffusing the overall organic C and total N contents of the surface soil horizons (Fig. 2, Table 5, Table 6), and thus, increasing the melanization rate of deeper soil horizons.

While physical mixing with tillage is one explanation for the overall decreases in organic C and total N in the surface soil, it is more likely a combination of (i) physical mixing, (ii) shorter crop rotations that provide fewer organic matter additions, (iii) accelerated decomposition rates, and (iv) the dissolution and translocation of organic matter. Across the state, crop rotations have changed from multi-year rotations including deeply rooting perennial plants (corn, alfalfa, [*Medicago sativa*], oats [*Avena sativa*], and soybean), to continuous corn or a 2-yr corn–soybean rotation without small grains or perennials. It is also likely

Table 2. Changes in the mean minimum depth (cm) to soil properties using the soil surface as the reference depth. Mollic colors and granular structure reported as total thickness. A positive change indicates that the soil property is deeper than it once was, and a negative change indicates that the soil property is shallower than it once was.

	1959	2007	Change‡	Std. err.	*n*	P
			Overall average			
Gravels/contrasting texture	66	59	-7	2	43	0.01
Absence of soil structure	125	118	-7	5	49	0.14
Granular structure†	29	7	-22	2	82	<0.01
Blocky structure	15	1	-14	2	82	<0.01
Mollic colors†	45	45	0	3	81	0.94
Gray redoximorphic features	76	95	+19	5	56	<0.01
Red redoximorphic features	80	76	-4	6	67	0.43
Effervescence	110	110	0	5	52	0.99
			Plain 0–1% slope			
Gravels/contrasting texture	91	87	-4	5	8	0.50
Absence of soil structure	109	104	-5	6	8	0.42
Granular structure†	30	2	-28	5	13	<0.01
Blocky structure	12	2	-10	4	13	0.04
Mollic colors†	49	51	+2	5	13	0.76
Gray redoximorphic features	71	95	+24	7	10	<0.01
Red redoximorphic features	82	75	-7	11	11	0.55
Effervescence	82	87	+5	6	13	0.47
			Summit			
Gravels/contrasting texture	72	63	-9	4	12	0.07
Absence of soil structure	134	120	-14	11	10	0.22
Granular structure†	32	5	-27	5	26	<0.01
Blocky structure	14	1	-13	4	26	<0.01
Mollic colors†	38	40	+2	2	25	0.30
Gray redoximorphic features	69	95	+27	9	16	<0.01
Red redoximorphic features	79	75	-4	11	18	0.68
Effervescence	100	111	+11	7	13	0.17
			Shoulder			
Gravels/contrasting texture	49	45	-5	4	12	0.24
Absence of soil structure	122	120	-1	15	15	0.87
Granular structure†	24	6	-18	3	16	<0.01
Blocky structure	10	0	-9	3	16	0.01
Mollic colors†	37	37	0	4	16	0.95
Gray redoximorphic features	76	101	+26	8	11	0.01
Red redoximorphic features	73	69	-4	12	15	0.74
Effervescence	101	111	+10	6	13	0.11
			Backslope			
Gravels/contrasting texture	62	49	-12	5	9	0.04
Absence of soil structure	142	117	-24	10	9	0.04
Granular structure†	25	9	-17	4	18	<0.01
Blocky structure	18	0	-18	4	18	<0.01
Mollic colors†	50	35	-15	7	18	0.05
Gray redoximorphic features	87	83	-5	7	16	0.53
Red redoximorphic features	90	72	-18	12	17	0.14
Effervescence	139	110	-15	7	18	0.05
			Foot/toeslope			
Gravels/contrasting texture	54	59	+5	6	2	0.56
Absence of soil structure	116	128	+12	18	7	0.52
Granular structure†	29	16	-13	9	9	0.19
Blocky structure	20	1	-19	5	9	<0.01
Mollic colors†	54	96	+42	16	8	0.04
Gray redoximorphic features	61	127	+66	16	3	0.06
Red redoximorphic features	67	107	+39	15	6	0.05
Effervescence	116	135	+19	8	5	0.09

†Maximum thickness (cm) is reported for these soil properties.
‡Change in depth using the soil surface as the reference depth.

Table 3. Bulk density (g cm^{-3}) by depth using the soil surface as the reference depth.

Depth	1959	2007	Change	Std. err.	*n*	*P*
0–5 cm	1.46	1.37	-0.09	0.02	27	<0.01
5–15 cm	1.47	1.36	-0.11	0.03	26	<0.01
15–30 cm	1.47	1.37	-0.10	0.02	27	<0.01
30–50 cm	1.54	1.37	-0.17	0.03	26	<0.01
50–75 cm	1.60	1.48	-0.11	0.04	23	<0.01
75–100 cm	1.67	1.64	-0.03	0.05	24	0.55
100–125 cm	1.71	1.71	0	0.04	18	0.96
125–150 cm	1.72	1.76	+0.03	0.04	12	0.48

that decomposition rates have accelerated since the initial sampling date, because the molecular complexity of organic matter is decreasing as crop rotations are becoming simpler, C/N ratios are decreasing (Table 7), temperatures are warming, and tile drainage has increased which increases oxygen availability at depth (Swift et al., 1979). Thus, a complex of factors appears to be speeding decomposition.

These decreases in organic matter content are confined to the upper 50 cm of the soil profile. In soil horizons > 50 cm, we document an accumulation of organic C (Table 5), and a 2% increase on a whole-profile basis (Table 6). Follett et al. (2009) found similar results in their comparison of the soil C contents by depth in natively vegetated vs. cropped sites across the USA. They found a loss of C stocks in the 0- to 30-cm depth, and associated increases in C stocks in the 30- to 100-cm depths in 9 of their 16 sites where corn and soybeans were the primary crops. All of their sites that were sampled in Iowa, Minnesota, and Ohio showed this trend of loss at the surface and accumulation in the deeper soil depths (Follett et al., 2009). We attribute this accumulation of deep soil C to have been dissolved, translocated, and precipitated from surface horizons, according to the model proposed by Kaiser and Kalbitz (2012). Water movement, microbial activity, and dramatic variations in pH are likely drivers of this process. Drastic short-term fluctuations in pH (pH 9 to pH 6 in a matter of days) are associated with inorganic N fertilization (Court et al., 1962; Duisberg and Bueher, 1954), and inorganic N fertilization has increased by three times in Iowa and five times in the USA since the 1960s (Economic Research Service, 2008; United Nations–Food and Agriculture Organization, 2011). Organic matter dissolves in both low and high pH (Kalbitz et al., 2000). Once it is dissolved, it is transported by moving water to deeper in the profile, perhaps through process of chelation with iron and aluminum. The organic matter precipitates as secondary soil organic matter when water flow ceases and pH increases with depth (McKeague et al., 1983, Kaiser and Kalbitz, 2012).

In addition to causing short-term fluctuations in pH, inorganic N fertilization acidifies soil (Bouman et al., 1995; Guo et al., 2010; Jenkinson, 1991). The average soil pH throughout the profiles has decreased (Table 8) but remains within the optimal range for corn and soybean production

Table 4. Changes in the mean minimum depth (cm) to soil properties using the more stable alternative reference depths: the depth to gravels or contrasting texture as the reference depth for the overall average, plain (0–1% slope), summit, shoulder, and backslope and the maximum depth of mollic colors as the reference depth for the foot/toeslope position. The maximum depth of mollic colors was chosen for the foot/toeslope position because of the paucity of depth to gravel or contrasting textures data and because the foot/toeslope is usually a sediment gaining position, therefore the maximum depth of mollic colors is more likely to be stable here, than in other landscape positions. Values reported for 1959 and 2007 represent the mean of (the depth from the soil surface to the alternative reference depth– depth from the soil surface to the soil property) in centimeters. A positive change indicates that the soil property is deeper than it once was, and a negative change indicates that the soil property is shallower than it once was.

	1959	2007	Change‡	Std. err.	*n*	*P*
Overall average						
Absence of soil structure	-61	-57	+4	6	29	0.47
Granular structure†	35	54	-19	4	43	<0.01
Blocky structure	49	58	-9	3	43	<0.01
Mollic colors†	25	15	+10	3	42	<0.01
Gray redoximorphic features	-13	-43	+30	5	33	<0.01
Red redoximorphic features	-16	-15	+1	7	37	0.92
Effervescence	-50	-39	+12	5	36	0.02
Plain 0–1% slope						
Absence of soil structure	4	-6	+10	5	4	0.12
Granular structure†	61	81	-20	10	8	0.08
Blocky structure	73	81	-8	6	8	0.21
Mollic colors†	47	39	+8	5	8	0.14
Gray redoximorphic features	26	-6	+30	14	5	0.09
Red redoximorphic features	11	10	+1	15	6	0.95
Effervescence	28	17	+11	13	6	0.44
Summit						
Absence of soil structure	-61	-64	+4	12	6	0.78
Granular structure†	32	59	-27	11	12	0.03
Blocky structure	53	62	-9	5	12	0.13
Mollic colors†	22	12	+10	4	11	0.04
Gray redoximorphic features	-12	-52	+39	9	9	<0.01
Red redoximorphic features	-30	-16	-14	17	9	0.46
Effervescence	-40	-53	+13	8	11	0.13
Shoulder						
Absence of soil structure	-78	-75	-3	9	12	0.75
Granular structure†	22	38	-17	6	12	0.01
Blocky structure	41	45	-4	7	12	0.52
Mollic colors†	11	2	+9	6	12	0.17
Gray redoximorphic features	-29	-56	+27	10	10	0.03
Red redoximorphic features	-24	-22	-2	15	11	0.91
Effervescence	-58	-74	+16	9	10	0.09
Backslope						
Absence of soil structure	-71	-55	-16	22	5	0.51
Granular structure†	36	43	-7	8	9	0.42
Blocky structure	39	49	-10	6	9	0.16
Mollic colors†	29	18	+11	7	9	0.16
Gray redoximorphic features	-20	-37	+17	7	8	0.05
Red redoximorphic features	-14	-25	+11	9	9	0.42
Effervescence	-62	-69	+7	15	7	0.69
Foot/toeslope§						
Absence of soil structure	-61	-47	-14	28	7	0.63
Granular structure†	33	69	-36	24	9	0.17
Blocky structure	42	84	-42	24	9	0.12
Gray redoximorphic features	-25	-43	+18	27	3	0.57
Red redoximorphic features	-18	-8	-10	15	6	0.52
Effervescence	-69	-32	-37	18	5	0.11

† Maximum depth (cm) is reported for these soil properties.
‡ Change in depth using the depth to gravels/contrasting texture as the reference depth.
§ Change in depth using the depth to the base of mollic colors as the reference depth.

Table 5. Total organic C and total N (g 100 g^{-1} soil) by depth using the soil surface as the reference depth.

	Total organic C (g C 100 g^{-1} soil)						Total N (g C 100 g^{-1} soil)					
Depth	1959	2007	Change	Std. err.	*n*	*P*	1959	2007	Change	Std. err.	*n*	*P*
0–5 cm	2.98	2.73	-0.25	0.11	64	0.03	0.25	0.25	0	0.01	58	0.92
5–15 cm	2.52	2.13	-0.39	0.10	65	<0.01	0.22	0.20	-0.02	0.01	59	0.01
15–30 cm	1.42	1.42	0	0.10	64	0.99	0.13	0.14	0.01	0.01	60	0.22
30–50 cm	0.74	0.87	0.14	0.09	61	0.14	0.07	0.10	0.02	0.01	60	0.01
50–75 cm	0.43	0.58	0.14	0.08	56	0.06	0.04	0.07	0.01	0.01	31	0.06
75–100 cm	0.28	0.41	0.13	0.05	46	0.11	0.04	0.04	0	0	13	0.35
100–125 cm	0.21	0.35	0.14	0.05	34	<0.01	0.04	0.04	0.01	0	10	0.23
125–150 cm	0.17	0.23	0.07	0.02	17	<0.01	0.04	0.03	0.02	0.01	2	n/a

Table 6. Total profile organic C and total profile N (kg C m^{-2}) by depth using the soil surface as the reference depth.

	Total Profile OC (kg C m^{-2})			Total Profile N (kg N m^{-2})		
Total depth	1959	2007	% Δ	1959	2007	% Δ
5 cm	2.2	1.9	-14%	0.18	0.17	-6%
15 cm	5.9	4.8	-19%	0.51	0.45	-13%
30 cm	10.0	8.7	-14%	0.80	0.74	-8%
50 cm	12.9	11.7	-9%	1.02	1.00	-3%
75 cm	14.5	13.7	-6%	1.17	1.26	+8%
100 cm	15.7	15.2	-3%	1.32	1.42	+8%
125 cm	16.5	16.7	+1%	1.47	1.59	+8%
150 cm	17.2	17.7	+2%	1.65	1.70	+3%

Table 7. Carbon/Nitrogen ratio by depth using the soil surface as the reference depth.

Depth	1959	2007	Change	Std. err.	*n*	*P*
0–5 cm	12	11	-1	0.15	58	<0.01
5–15 cm	12	11	-1	0.19	58	<0.01
15–30 cm	11	10	-1	0.20	59	<0.01
30–50 cm	10	9	-1	0.26	56	<0.01
50–75 cm	9	8	-1	0.34	26	<0.01
75–100 cm	8	7	1	0.39	11	<0.01
100–125 cm	6	7	1	0.65	6	0.45
125–150 cm	n/a	n/a	n/a	n/a	n/a	n/a

Table 8. pH by depth using the soil surface as the reference depth.

Depth	1959	2007	Change	Std. err.	*n*	*P*
0–5 cm	6.10	5.85	-0.25	0.09	77	0.01
5–15 cm	5.89	5.76	-0.13	0.09	77	0.14
15–30 cm	5.77	5.59	-0.17	0.08	78	0.03
30–50 cm	6.18	5.64	-0.54	0.36	77	0.14
50–75 cm	6.21	6.02	-0.19	0.09	77	0.03
75–100 cm	6.73	6.55	-0.18	0.10	75	0.07
100–125 cm	7.05	6.88	-0.17	0.11	64	0.14
125–150 cm	7.34	7.20	-0.14	0.13	41	0.28

(pH 5.5 to 7.0, Havlin et al., 1999). However, a number of sites have soil horizons with a pH below 5.5, and the number of sites with soil horizons outside the optimal pH range has increased (Table 9). Farmers routinely test soil pH and manage for soil acidification by applying lime. Our results show that despite monitoring and management, soils across Iowa are acidifying.

The fluctuations in pH that allow for the dissolution of organic matter also allow for the dissolution of carbonate minerals, which then reprecipitate deeper in the soil profile (Fig. 2). We interpret this to reflect that the partial pressure of CO_2 is now greater than it was when the pedons were initially sampled because of increased aerobic decomposition of translocated organic matter deep in the soil profile (Buyanovsky and Wagner, 1983). This shows that agricultural practices (especially the effects of fertilizer additions) may be increasing mineral weathering rates (Perrin et al., 2008).

We found lower surface bulk densities than initially measured (Table 3). The lower bulk density at the surface may be the result of differences in bulk density methods. The clod method generally produces higher bulk density numbers than the core method (Blake and Hartge, 1986; Van Remortel and Shields, 1993). However, if there has been a decrease in bulk density at the surface, the combination of lower surface bulk density and blockier structure (Table 2, Table 3, Table 4) may be evidence of lower particle density and increased mineral weathering rates (Blanco-Canqui et al., 2006). The loss of granular structure suggests that, with the associated loss of porosity, bulk density should be higher than it was initially. Lower particle density could account for the simultaneous lower bulk density and blockier soil structure. Variation in particle density can be evidence of changes in mineralogy over a relatively short period of time with differ-

Table 9. Number of sites sampled that had a pH below 5.5† in each depth using the soil surface as the reference depth.

Depth	1959		2007		% Increase
	Number of sites with pH < 5.5	% of sites sampled	Number of sites with pH < 5.5	% of sites sampled	
0–5 cm	7	9%	27	33%	285%
5–15 cm	15	18%	34	41%	127%
15–30 cm	32	39%	47	57%	46%
30–50 cm	28	34%	36	44%	29%
50–75 cm	9	11%	15	18%	67%
75–100 cm	5	6%	7	9%	40%
100–125 cm	3	4%	2	2%	-33%

†The lower limit of the optimal range in pH for corn and soybean growth.

ent agricultural systems promoting the loss or gain of minerals of different densities (Blanco-Canqui et al., 2006).

The maximum depth of granular structure is much shallower in each of the landscape positions than it was when the soils were initially sampled (Fig. 2, Table 2, Table 4). The shift from granular to blocky structure can be linked to the removal of perennial grasses from the crop rotations which mean there are fewer fine roots to promote the formation and maintenance of granular structure (Tisdall and Oades, 1982). Also, with the increasing loads associated with larger equipment and heavier wheel traffic, granules are compressed and forced to expand to fill the space available to them, expanding against one another forming blocks. Another explanation for the loss of granular structure could simply be that the horizons with granular structure were eroded and the horizons with blocky structure were left behind. The shift from granular to blocky soil structure likely results in fewer macropores and more micropores because blocks pack more closely than granules. These changes in porosity should negatively affect infiltration, aeration, and plant rooting behavior (Topp et al., 1997).

Our sampling also shows evidence for lower water tables. The depth to gray redoximorphic features (Munsell value ≥ 5 and chroma ≤ 2) is deeper across all landscape positions, by as few as 17 cm (P = 0.05, Table 4) in the backslope position to as many as 39 cm (P = < 0.01, Table 4) in the summit position. Interestingly, the depth to red redoximorphic features (Munsell hue 10YR or redder, value ≥ 4 and chroma ≥ 6) has remained unchanged (P > 0.42, Fig. 2, Table 4). Since the 1800s, farmers have been increasingly using tile drainage (Beauchamp, 1987). The sole goal of drainage is to lower the water table and increase oxygen in the rooting zone. Ergo, it is logical that this speeds oxidation and changes the distribution of redoximorphic soil features in the profile. The Fe(II) is oxidized causing gray soils to redden. The red soils already had Fe(III) thus remain unchanged. Hayes and Vepraskas, (2000) showed that the same process was occurring in a ditch drainage system in North Carolina.

In this region, short-term human activities are driving long-term soil change. Some of these changes may improve soil productivity and quality over the short-term, such as a lower water tables, deeper organic-matter-rich surface horizons, and deep storage of organic matter. However, many of the changes may be unanticipated or are likely to be detrimental to crop production over the long term: for example, acidification, accelerated weathering of primary minerals, degradation of soil structure, and lower concentrations of organic matter in the primary root zone. In most of the profiles in this study, these impacts extended to at least 100 cm. Some of these soil changes may be irreversible. However, this study demonstrates that humans accelerate soil formation rates, and in so doing many of these soil changes could, indeed, be reversible depending on the actions we take. More work must be done to continue to document and assess the long-term impacts of human activities on soils.

ACKNOWLEDGMENTS

Thanks to the landowners that allowed us to sample their soils, and B. Oneal, M. Ibrahim, M. Lampo, B. Smith, J. Tucker, A. Norton, M. Tiedeman, J. Seeman, M. Streeter, G. Klever, Y. Lisbeht Vergara and D. McGranahan for their help in the field and the lab. Thanks to P. Dyess for library assitance. Thanks to S. Wills for accessing and sharing NCSS data, and thanks to the reviewers for their thoughtful suggestions for improving this manuscript. The funding for this work was provided by the Iowa State University Agronomy Department.

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