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Thirty-year tillage effects on crop yield and soil fertility indicators

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ABSTRACT

Long-term studies are crucial for quantifying tillage effects on productivity and soil fertility. Moldboard plow, chisel plow, spring disk, ridge-tillage, and no-tillage systems were evaluated after 32 years of a corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation and 27 years of continuous corn in central Iowa, U.S.A. Productivity was quantified using yield, while soil fertility status was evaluated by collecting four, 5-cm diameter soil cores to a depth of 0.9 m from each treatment, dividing them into four depth increments (0–15-, 15–30-, 30–60-, and 60–90-cm), analyzing them for bulk density (BD), NO_3-N, NH_4-N, electrical conductivity (EC), pH, Mehlich-3 extractable P, K, Ca, Mg and DTPA-extractable Cu, Fe, Mn, and Zn, and interpreting the data using Iowa State University (ISU) guidelines. Production costs for each tillage and cropping system were also computed. To account for genetic and agronomic changes during the 30-year study period, yields were examined for establishment, maintenance, and intensification/recovery phases. Rotated corn yield averaged 8.6, 8.8, and 11.6 Mg ha^{-1} and soybean yield averaged 2.7, 3.2, and 3.4 Mg ha^{-1}, respectively, for each of the phases. Continuous corn from 1988 to 2006 averaged 7.5 and 10.1 Mg ha^{-1} for the maintenance and intensification/recovery phases, respectively. Fixed plus variable machinery costs for corn ranged from 233 to 354 USD ha^{-1}, while for soybean they ranged from 194 to 280 USD ha^{-1}. Net returns to land, labor and management ranged from 233 to 269, 560 to 620, and 437 to 483 USD ha^{-1} for continuous corn, rotated corn, and rotated soybean, respectively. Based on 9-year (2003–2011) average grain prices and yields from this study, the corn–soybean rotation was twice as profitable as continuous corn. Soil-test P and K measurements, as well as calculated P and K removal, suggest that nutrient mining occurred during the course of this study. The soil-test data also indicate that further studies are needed regarding plant availability of subsoil K and its impact on fertilizer recommendations. Overall, we conclude that with good nutrient management and crop rotation, yield and soil fertility differences between no-tillage and more intensive tillage systems can be minimized and that no-till production can be profitable on glacial till derived soils.

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1. Introduction

Long-term tillage studies were advocated by Richter et al. (2007) as one way to improve the management of rapidly changing ecosystems. Such studies are also important for agricultural producers because as Coughenour and Chamala (2000) stated, replacing moldboard plowing with conservation- or no-tillage practices, is truly a "cultural" change driven by multiple factors including markets, weather cycles, biological changes (*e.g.* glyphosate resistant crops), agribusiness, and scientific advances. Toliver et al. (2012) evaluated several studies comparing crop yield with and without tillage, and also concluded that soil and climate factors can influence the risk and expected return that farmers may achieve by adopting less intensive tillage practices.

Tillage and/or cropping practices can affect many different soil properties and processes (Karlen et al., 2008, 2011; Stott et al., 2011). For example, soil-test P and K levels and especially their tendency for stratification in response to no-tillage (*e.g.* Holanda et al., 1998; Karlen et al., 2002; Rehm and Fixen, 1990; Shi et al., 2012) have been shown to significantly affect crop productivity.

Long-term studies are even more valuable if the measurement data are accompanied by the management records (Richter et al., 2007). Cultivar, seeding rate, planting and harvest dates, N, P, and K fertilizer applications, pesticide inputs and estimated costs of production for the different systems are frequently of interest to producers considering potential changes for their operations. Such details are also essential for those striving to develop economic, agronomic, and environmental assessment models (*e.g.* Six et al., 2004). Long-term field experiments are also crucial for addressing knowledge gaps that need to be filled to ensure long-term

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sustainability of alternate crop production enterprises (Toliver et al., 2012).

Our objective for this report is to summarize crop yield, soil fertility, and economic response data for five tillage systems evaluated from 1975 to 2006 on the Clarion-Nicollet-Webster/Canisteo soil association in central Iowa, U.S.A. To facilitate comparisons during different phases of this 30-year field experiment, the response data were examined for three phases—establishment (1976–1980), maintenance (1980–2002), and intensification/recovery (2003–2006).

2. Methods and materials

2.1. Site characteristics and general experimental design

This study was initiated at the Iowa State University (ISU) Agronomy/Ag Engineering Research and Education Center (AAEREC) in Boone County, IA (latitude 42°01′N, longitude 93°45′W) in 1975. Three soil series {Canisteo [poorly and very poorly drained Typic Endoaquoll (map unit 507)], Clarion [well drained Typic Hapludolls (map unit 138B)], and Webster [poorly drained Typic Haplaquolls (map unit 107)]} are found at the site. The soils are derived from glacial till (Soil Survey Staff, 2010) and have an elevation difference of approximately 7 m across the 10 ha area (Fig. 1). Initially eight "replicates" of each tillage system were established and managed in a corn and soybean rotation (4 replicates each). The tillage systems, imposed on plots that were 27.4 m wide by 91.4 m long, were: (1) slot plant on ridges which was eventually transitioned to a no-till operation; (2) Spring Disk; (3) Till plant (ridge tillage) where surface soil to a depth of ~5–8 cm is "thrown off" during planting and then the ridges are later rebuilt through cultivation; (4) Fall moldboard plowing; and (5) Fall chisel plowing. From 1976 to 1980, the four replicates in the south half (Field 70) and north half (Field 71) were managed in an alternating corn and soybean rotation. Starting in 1979 and continuing through 2006, the four replicates in Field 70 were used for continuous corn production, while Field 71 was maintained in the corn/soybean rotation with each crop occurring every other year.

2.2. Cultural practices

The five tillage systems were characterized as follows: (1) moldboard plow which was considered the "conventional" system when the study was initiated, and for which corn stalks were generally shredded and disk harrowed before plowing to a depth of approximately 20 cm in the fall. Either corn or soybean was planted the following spring after seedbed preparation with a tandem disk harrow and spike-tooth drag harrow; (2) chisel plow for which the land was chisel plowed to a depth of approximately 20 cm in the fall, after shredding the stalks if following corn. The chisel plow had twisted points spaced 38 cm apart. In the spring, the seedbed was prepared by one field cultivation before planting; (3) spring disk, for which the stalks were shredded if following corn, and the seedbed was prepared by disking one or two times with a tandem disk. The typical disk configuration consisted of 56-cm blades, spaced 23 cm apart, and weighing approximately 57 kg blade^{-1}; (4) till-plant (ridge-till) for which no pre-plant tillage was used, although if the previous crop was corn, stalks were often shredded. Row attachments in front of the double-disk openers removed crop residue and a small amount of soil just before the seeds were planted. Ridges were then rebuilt during the cultivation

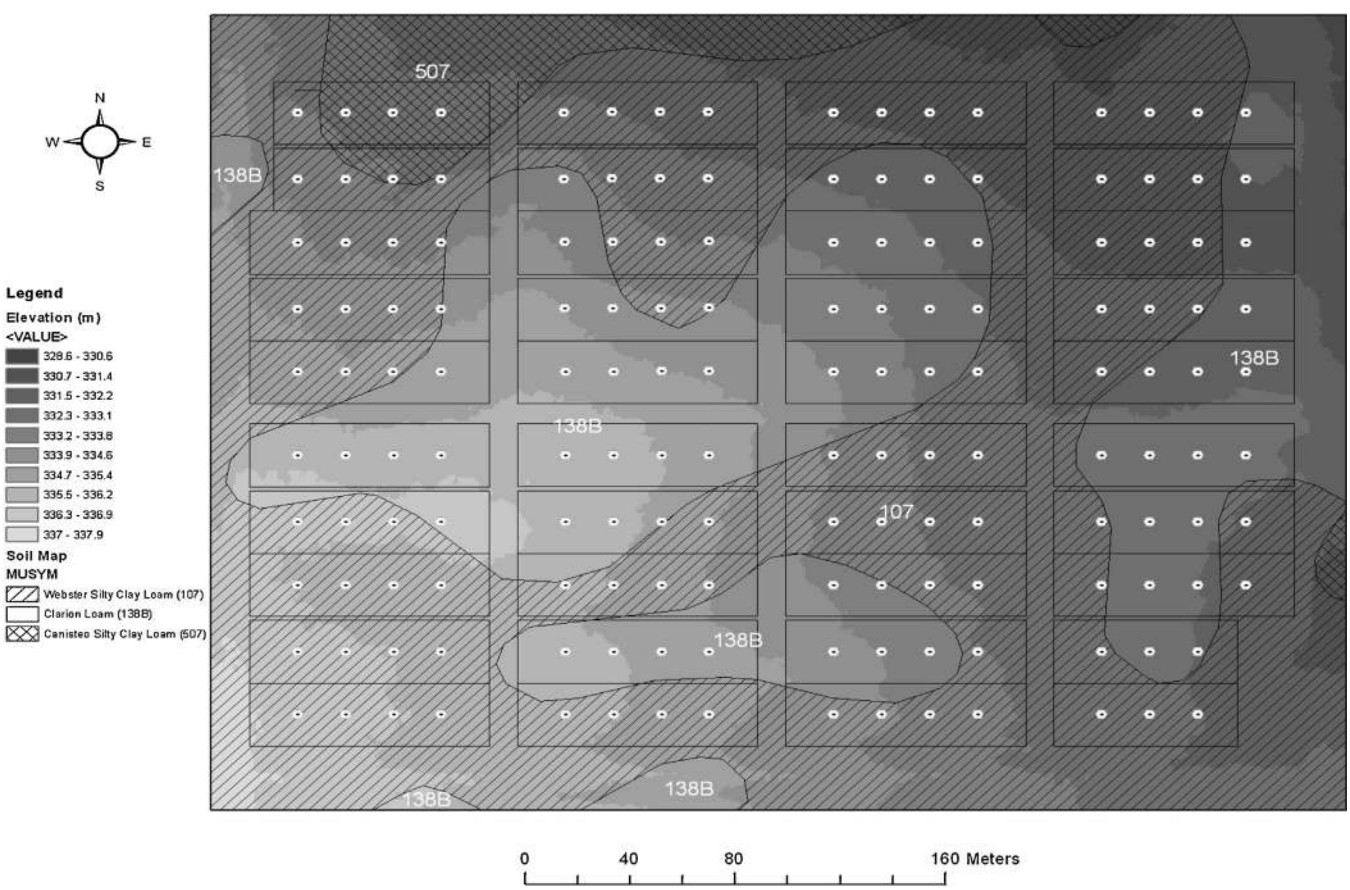

Fig. 1. Elevation, soil series, and plot layout for the long-term tillage evaluations on the ISU Agronomy/Agricultural Engineering Research Center near Boone, Iowa, U.S.A. The bottom half was in continuous corn from 1979 to 2006, while the top half was in a corn and soybean rotation. The points represent the 2005 soil sampling sites.

process each year; and (5) slot-plant (no-tillage) for which there was no pre-plant tillage other than shredding the stalks if the previous crop was corn. The planter was equipped with a single coulter in front of double-disk openers. Small ridges that may have been built through cultivating during the previous season were left undisturbed. It should be noted that because of the longevity of this study, many subtle management changes were made as equipment and herbicide technologies improved. Prior to the mid-1990s, it was common for many no-till studies in central Iowa to be cultivated at least once for improved weed control. In some years it was also necessary to hand-weed the soybean plots for late-season weed control.

Commercially available corn and soybean cultivars (Table 1) were planted in 76 cm rows between late April and early June each year. The planting rate for corn gradually increased from 6.4 to 7.4 seeds m^{-2} (26,000–30,000 seeds $acre^{-1}$) throughout the study period due to improved plant genetics and agronomic practices. The seeding rate for soybean varied much less averaging 44.1 seeds m^{-2} (178,500 seeds $acre^{-1}$). Monthly precipitation and average daily maximum and minimum temperatures at the AAEREC for 1986–2006 are presented in Tables A1 and A2. Seasonal rainfall (April through October) ranged from 356 to 1238 mm with an overall annual average of 682 mm (26.9 inches). These rainfall amounts as well as the mean monthly temperatures were consistent with those reported for the period 1951–1974 (USDA-SCS, 1981).

Fertilizer N, P, and K were applied at rates consistent with ISU recommendations (Table 1). No additional fertilizer was applied for the soybean crop, because throughout the study period and even now, it is assumed that the quantity of nutrients supplied to the corn crop will be sufficient for a subsequent soybean crop. Several different herbicides were used throughout the study period (Tables A3 and A4), each being applied at rates consistent with recommended management practices for its period of use.

2.3. Crop yield and macro-nutrient balance measurements

The long-term crop yield record was divided into segments defined as (1) establishment, (2) maintenance, and (3) recovery/intensification phases. The establishment phase focused solely on the first five years and is a summary of the information reported by Erbach (1982). Unfortunately, yield records for 1981–1987 have been lost, so the maintenance phase in this report covers only the period from 1988 to 2002. The recovery/intensification phase from 2003 to 2006 was so defined because of an increased use of soil testing and plant analysis to determine why grain yields (especially for continuous corn) had fallen below National Agricultural Statistics Service (NASS) County averages (USDA-NASS, 2012).

Throughout the entire period of record, corn and soybean were harvested each year with plot-scale combines and grain yields were recorded (Table A5). Grain weights were taken either directly on the combine when the machines were equipped with weigh tanks or by transferring the grain for each plot to weigh wagons. Grain samples from each plot were collected and analyzed to determine water content (Table A6). Grain yields were then adjusted to a constant water content of 130 or 155 g kg^{-1} for soybean or corn, respectively.

2.4. Machinery operations and estimated costs

The machine operations used to implement the five tillage systems are presented in Table 5. The data were compiled by reviewing annual soil and crop management records for the research site and summarizing the operations according to the frequency that it occurred (*e.g.* 1–4 cultivations). For this evaluation, 2012 fixed (*i.e.* depreciation, interest, insurance, housing) and variable (*i.e.* fuel, oil, repairs) machinery costs (Duffy, 2012a) were used to estimate a cost per hectare for each operation. Total machinery costs were calculated by summing costs for each operation. Average seed and chemical costs for each of the cropping systems were taken from Duffy (2012a). Gross returns were computed by multiplying the average grain yields for 2003 through 2006 (the intensification and recovery phase of the study) by the 9-year average corn (145 USD Mg^{-1}) or soybean (330 USD Mg^{-1}) price (USDA-NASS, 2012). Net returns to land, labor, and management were calculated by subtracting the average machinery and seed/chemical costs for each tillage system from the gross returns.

2.5. Soil profile sampling and analyses

The long-term tillage effects on soil fertility indicators were assessed by collecting 5-cm diameter soil cores to a depth of 0.9 m following the 2005 grain harvest. With the exception of plots on the northwest and southeast corners of the 10 ha research site, where grass waterways resulted in slightly shorter plots (Fig. 1), each tillage plot was approximately 91 m long. A fixed sampling pattern was used, resulting in soil cores being taken 18-, 37-, 49-, and 73-m from the west edge of each plot (Fig. 1). By overlaying the soil survey map (USDA-SCS, 1981), this sampling protocol enabled us to examine not only multiple points within each tillage plot, but also to identify the predominant soil series and thus determine if there were different tillage responses to the two dominant soils. Since the Canisteo silty clay loam differs from the Webster silty clay loam primarily by the presence of free calcium carbonate at the surface, samples for those two series were pooled for statistical analyses and compared with the Clarion loam that is located at slightly higher (~2–3 m) elevations (Fig. 1). This approach resulted in 61 sampling sites classified as Clarion loam and 97 classified as Webster/Canisteo silty clay loam.

Each core was divided into increments of 0–15-, 15–30-, 30–60-, and 60–90-cm. Incremental samples were placed in plastic bags and stored on ice until they could be transported to the lab, where they were refrigerated at 4 °C until processing. Each field-moist sample was weighed and mixed before processing. A 100 g subsample was removed and dried at 105 °C to determine soil water content. The field-moist weight was adjusted to a dry weight and divided by the volume associated with each sample to estimate bulk density (BD). The remaining field-moist soil sample was passed through an 8-mm screen, air-dried, and then crushed to pass a 2 mm sieve. Sub-samples from each depth increment were analyzed for soil pH and electrical conductivity (EC) using a 1:1 soil to water ratio as appropriate for the location (Watson and Brown, 1998; Whitney, 1998a,b). A second sub-sample was extracted with 2 M KCl and analyzed for ammonium (NH_4-N) and nitrate (NO_3-N) concentrations using flow injection analysis (Lachat QC 800; Loveland, CO). A third sub-sample was extracted with Mehlich-3 solution (Mehlich, 1984) and the concentrations of phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in the extracts were determined via inductively coupled plasma-atomic emission spectroscopy (ICP-AES). A fourth sub-sample was extracted with diethylene-triamine-pentaacetic acid (DTPA) as described by Whitney (1998b) and analyzed for Cu, Fe, Mn, and Zn using the ICP-AES.

To calculate individual plot means using the four sampling sites per plot, data from each sample point (approximately 20 m apart) were used to create a 4-m surface using the ArcGIS (ESRI; Redlands, CA) spatial analyst tool spline with barriers. The field boundary was used as the barrier for the spline interpolation to ensure the plot values were constrained to the field area. The spline interpolation was used to make sure estimated values in the

Table 1
Selected cultural practices for the 30-year tillage system comparison study in central Iowa, U.S.A..

Year	Cultivar	Planting date	Planting rate (seeds m^{-2})	Harvest date	N ($kg\,ha^{-1}$)	P ($kg\,ha^{-1}$)	K ($kg\,ha^{-1}$)
Rotated corn (CS)							
1976	Pioneer Brand 3382	May 4	6.4	October 11	140	49	93
1977	Funks 4449	April 27	6.4	October 10	168	49	93
1978	DeKalb XL64	May 3	6.4	October 2	168	49	93
1979	DeKalb XL64	May 14–17	6.4	October 25	179	49	93
1981	Pioneer Brand 3541	May 6	6.5	October 16	179	49	93
1983	Pioneer Brand 3529	May 12	6.5	October 17	179	25	56
1985	Pioneer Brand 3732	May 7	6.4	October 14	179	30	56
1987	Pioneer Brand 3732	April 23	6.8	September 22	179	30	93
1989	Pioneer Brand 3720	May 8–10	6.8	October 9	224	30	56
1991	Pioneer Brand 3732	May 13	6.4	October 22	189	30	56
1993	Pioneer Brand 3394	May 18	6.9	October 28	157	0	0
1995	Pioneer Brand 3394	May 16	6.9	October 27	84	0	0
1997	DeKalb 529SR	May 14	7.0	October 21	174	4	5
1999	Pioneer Brand 33G26	April 30	7.0	November 5	163	0	0
2001	Pioneer Brand 33G26	April 26	7.0	November 6	179	0	0
2003	Pioneer Brand 35P17	April 29	7.2	October 31	213	20	37
2005	Fontenelle 5L381	April 28	7.4	October 27	202	9	28
Rotated soybean (SC)							
1976	Corsoy	May 18	38.9	September 28	0	0	0
1977	Corsoy	May 16	43.2	October 5	0	0	0
1978	Corsoy	May 15–16	45.3	September 27	0	0	0
1979	Harcor	May 22–23	47.5	October 2	0	0	0
1980	Harcor	May 15	47.5	October 9	0	0	0
1982	Corsoy 79	June 7	45.3		0	0	0
1984	Corsoy 79	May 31	45.3	September 21	0	0	0
1986	Corsoy 79	June 12	45.3	October 16	0	0	0
1988	Corsoy 79	May 17	43.2	October 26	0	0	0
1990	Corsoy 79	May 1	45.3	September 28	0	0	0
1992	Corsoy 79	May 13	43.2	October 2	0	0	0
1994	Steine 2250	May 12	40.4	October 22	0	0	0
1996	Steine 2170	June 8	43.1	October 28	0	0	0
1998	Pioneer Brand 9294RR	May 11	45.0	October 1	0	0	0
2000	Asgrow 2601	May 5	43.2		0	0	0
2002	Asgrow 2601	May 20	43.2	October 26	0	0	0
2004	Asgrow 2107	May 7	44.5	September 22	0	0	0
2006	Asgrow 2203	May 9	44.5	September 29	0	0	0
Continuous corn (CC)							
1980	DeKalb XL64	April 23–25	6.5	October 9	179	49	93
1981	Pioneer Brand 3541	May 6	6.5	October 16	179	0	0
1982	Pioneer Brand 3529	May 3	6.5	October 12	179	0	0
1983	Pioneer Brand 3720	May 11	6.5	–	179	25	56
1984	Pioneer Brand 3541	May 17	6.5	October 12	179	0	0
1985	Ames Best SX-37	May 1	7.1	October 14	179	0	0
1986	Pioneer Brand 3475	May 20	6.5	October 7	179	0	0
1987	Pioneer Brand 3720	June 12	6.8	October 19	179	30	93
1988	Pioneer Brand 3720	April 30	6.8	October 26	179	30	56
1989	Pioneer Brand 3720	May 8	6.7	October 18	224	30	56
1990	Pioneer Brand 3475	April 30	6.8	October 9	179	30	56
1991	Pioneer Brand 3379	May 13	6.4	October 21	191	30	56
1992	Pioneer Brand 3417	May 8	7.0	October 26	185	0	0
1993	Pioneer Brand 3417IR	May 17	6.9	October 27	157	0	0
1994	Pioneer Brand 3417IR	May 3	6.9	October 25	202	0	0
1995	Pioneer Brand 3394	May 16	6.9	October 26	84	0	0
1996	Pioneer Brand 3395IR	May 16	7.4	October 28	261	0	0
1997	DeKalb 592SR	May 14	7.0	October 17	201	5	4
1998	DeKalb 550RR	May 4	7.4	October 19	202	0	0
1999	Pioneer Brand 33G26	April 30	7.0	November 4	206	0	0
2000	Asgrow RX686RR	April 26	7.7	September 29	235	17	0
2001	Asgrow RX686RR	April 26	7.0	November 3	225	1	0
2002	Pioneer Brand 35P17	April 26	7.0	November 8	196	0	0
2003	Fontanelle 7797RR	April 28	7.2	October 30	220	24	38
2004	Fontanelle 7797RR	April 27	7.4	October 6	202	0	0
2005	Fontanelle 5L381	April 29	7.4	October 24	202	9	28
2006	Fontanelle 6K547	April 27	7.4	October 12	39	0	28

interpolated cells would not exceed measured values within the core data. A total of 158 soil cores were taken from the 88 plots (Fig. 1), which is 1.8 soil cores per plot. The interpolated surface contained on average 70 interpolated cells per plot. Data summaries for the plots were created using zonal statistics in ArcGIS. The 4-m grided surface for each type of soil measurement was used to create summary statistics based on plot zones.

2.6. Statistical analyses

Crop data from the maintenance and recovery/intensification phases were analyzed separately for the continuous corn and rotated corn/soybean systems. The data were evaluated with the General Linear Model (GLM) procedure from the SAS software packages (SAS Institute, 1990) to determine seasonal, tillage treatment, replicate, and year by tillage interaction effects. Soil data were analyzed by depth increment and evaluated with the SAS GLM procedure to determine tillage system, soil series, replicate and tillage by soil interactions. If the ANOVA F statistic was significant at $P \leq 0.10$, least significant difference (LSD) values were calculated to separate crop and soil indicator means. More conservative statistical approaches could have been used, but since mean yields for the various tillage systems were not agronomically significant, we chose to provide a liberal interpretation of the subtle differences that this unique, long-term record provided to producers and other stakeholders.

3. Results and discussion

3.1. Grain yield response to tillage and crop rotation

Corn and soybean grain yields for this long-term study are shown in Fig. 2, and for potential modeling purposes also presented for the three phases [(1) establishment, (2) maintenance, and (3) recovery/intensification] in Table A5. As stated by Erbach (1982) and verified by the non-significant tillage system difference (Table A5), the establishment phase for this study showed that "growth and yield depressions that commonly occur with continuous corn grown by using conservation tillage systems were not observed when corn was grown following soybeans or when soybeans were grown following corn." Furthermore, except for the 1976 soybean crop, average grain yields during this phase at the AAEREC research site exceeded the Boone County average (USDA-NASS, 2012) for all five tillage systems (Table A5).

Starting in 1981, the south half (*i.e.* Field 70) of this AAEREC research site (Fig. 1) was switched to continuous corn production, while the north half remained in a corn/soybean rotation for the duration of this study. Although yields from 1981 to 1987 were measured, as evidenced by the harvest dates recorded in the management record (Table 1), the yield data have been lost. Therefore, it is not possible to determine how quickly the continuous corn yields began to fall below the NASS Boone County average (Fig. 2), but with the exception of 1990 and 1991, average yields for all five tillage systems were just equal to or less than the NASS values. For the 15 years of available data characterized as Phase 2, moldboard plowing increased the average continuous corn grain yield by 0.8–1.7 Mg ha^{-1} (13–27 bu ac^{-1}) when compared to the other tillage systems. Moldboard plowing also had the highest average grain yield for rotated corn (Table A5), but the differences among tillage systems were smaller ranging from 0.2 to 0.8 and averaging only 0.35 Mg ha^{-1} (5.6 bu ac^{-1}). The moldboard plow treatment also had significantly lower grain moisture at harvest (Table A6) than the other tillage treatments, presumably because the plants had emerged more uniformly, grown more rapidly and matured earlier (data not presented). Grain moisture for the rotated corn was not affected by tillage, presumably because seedling emergence and subsequent plant growth (data not presented) were similar for all five tillage systems.

Visual comparisons between tillage systems (Fig. 2) show that the moldboard plow treatment generally had the highest yield, but actual differences were quite small (Table A5). Fig. 2 also shows that continuous corn had a lower average yield and greater variation due to seasonal weather patterns (Tables A1 and A2). A more detailed comparison of the overall yield averages for the two cropping systems during Phase 2 shows that crop rotation increased grain yield an average 1.3 Mg ha^{-1} (21 bu ac^{-1}) compared to continuous corn production (Table A5). This 17% yield increase is consistent with previous reports (*e.g.* Karlen et al., 1994, 2006, 2011) and re-emphasizes Erbach's 1982 conclusion regarding the importance of crop rotation. Seasonal comparisons

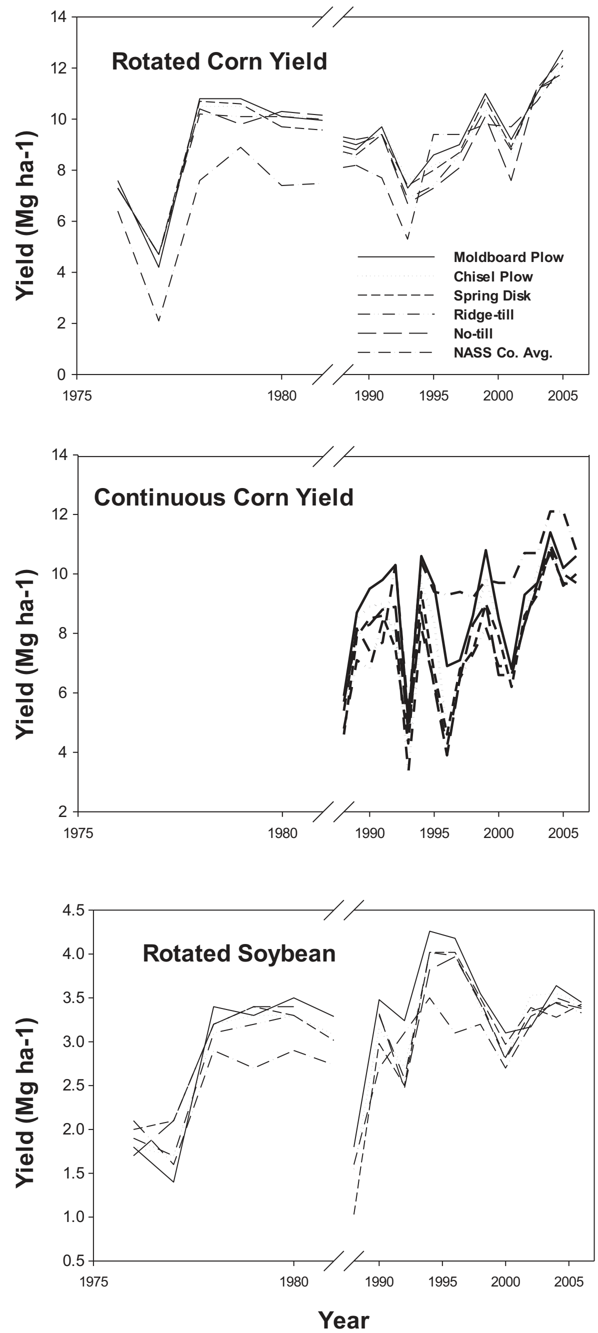

Fig. 2. Crop yield response to long-term tillage treatments on glacial till soils in Central Iowa, U.S.A.

between the NASS County averages and average yields for the five tillage systems showed that with rotation, yields were greater four times and less three times during this period of record (Table A5). Soybean yields during Phase 2 averaged 0.3 Mg ha^{-1} (4.5 bu ac^{-1}) more than the average NASS value and were greater than the NASS values in 6 of 8 seasons. Among tillage systems, the chisel and disk tillage treatment yields were significantly lower than those of the other tillage treatments (Table A5), but the difference was quite small. Soybean grain moisture was relatively consistent, although there was a statistical difference between the disk- and ridge-tillage systems (Table A6) during Phase 2 of this long-term study.

Phase 3 (intensification and recovery) was differentiated from Phase 2 (maintenance) because the management intensity

Table 2
Plant diagnostic analyses used to identify factors limiting ridge- and no-till corn production in a long-term study on glacial till soils in central Iowa, U.S.A.

Tillage	N ($g\,kg^{-1}$)	P ($g\,kg^{-1}$)	K ($g\,kg^{-1}$)	Ca ($g\,kg^{-1}$)	Mg ($g\,kg^{-1}$)	S ($\mu g\,g^{-1}$)	B ($\mu g\,g^{-1}$)	Cu ($\mu g\,g^{-1}$)	Fe ($\mu g\,g^{-1}$)	Mn ($\mu g\,g^{-1}$)	Zn ($\mu g\,g^{-1}$)
Corn "Ear Leaf" analysis											
Critical value	27.5	2.5	17.0	2.0	2.0	1.0	5	3	20	20	25
2003 Rotated corn											
No-tillage	28.2	2.5	10.3	6.0	3.6	1.51	5	10	160	30	14
Ridge-tillage	27.8	2.6	9.5	6.2	3.8	1.59	5	10	161	36	15
$LSD_{(0.1)}$	NS	NS	0.7	NS	NS	0.06	NS	NS	NS	NS	NS
2004 Continuous corn											
No-tillage	27.8	3.0	16.4	8.1	4.0	1.7	7	9	98	71	21
Ridge-tillage	28.0	3.1	15.5	8.8	4.5	1.7	7	9	99	68	22
$LSD_{(0.1)}$	NS	0.1	NS	0.4	0.3	NS	NS	NS	NS	NS	1
2005 Rotated corn											
No-tillage	27.5	2.7	13.5	6.8	4.6	1.5	8	11	139	58	18
Ridge-tillage	27.7	2.9	12.9	7.6	5.2	1.6	9	11	135	65	19
$LSD_{(0.1)}$	NS	0.2	NS	0.4	0.4	NS	NS	NS	NS	NS	NS
2005 Continuous corn											
No-tillage	28.7	2.8	12.9	6.6	4.3	1.6	4	11	134	62	18
Ridge-tillage	29.9	3.0	12.6	7.2	4.8	1.7	7	11	131	62	19
$LSD_{(0.1)}$	0.5	0.1	NS	0.4	0.4	0.1	1	NS	NS	NS	NS
2006 Continuous corn											
No-tillage	27.4	2.2	10.7	8.0	5.4	1.6	4	10	108	56	20
Ridge-tillage	26.7	2.3	10.2	8.4	5.8	1.5	4	9	104	54	18
$LSD_{(0.1)}$	NS	NS	NS	NS	NS	NS	NS	1	NS	NS	2
Corn V6 whole plant analysis											
Critical value	35.0	3.0	25.0	3.0	3.0	2.0	7	7	50	20	20
2004 Continuous corn											
No-tillage	37.2	4.0	28.3	7.8	5.3	2.0	7	12	334	62	32
Ridge-tillage	37.9	3.9	22.9	8.2	5.9	2.1	7	11	356	61	31
$LSD_{(0.1)}$	NS	NS	2.2	0.3	0.3	NS	NS	NS	NS	NS	NS
2005 Continuous corn											
No-tillage	37.4	4.4	18.7	6.8	5.0	2.3	7	11	475	54	43
Ridge-tillage	38.6	4.4	16.4	7.5	5.3	2.3	7	11	510	55	44
$LSD_{(0.1)}$	NS	NS	2.2	0.3	NS	NS	NS	NS	NS	NS	NS
2005 Rotated corn											
No-tillage	42.4	4.1	28.6	7.4	5.0	2.2	8	13	749	65	43
Ridge-tillage	41.8	4.2	20.7	8.1	5.8	2.3	9	13	1125	79	50
$LSD_{(0.1)}$	NS	NS	4.1	0.4	0.5	0.1	0.4	NS	145	6	5
2006 Continuous corn											
No-tillage	58.6	5.1	25.6	8.8	5.9	2.0	9	6	160	62	44
Ridge-tillage	29.4	5.0	19.3	8.7	6.9	2.0	10	6	170	70	46
$LSD_{(0.1)}$	NS	NS	3.1	NS	1.0	NS	NS	NS	NS	NS	2

increased substantially through the use of yearly soil testing and plant tissue analyses. Preliminary investigations of the long-term management record (Colvin et al., 2001) had raised several questions regarding consistently lower yields under the ridge- and no-till systems, than under the moldboard plow system. Recognizing that soil fertility and/or plant nutritional differences could account for the "yield penalty" associated with continuous corn production, early season (V6) whole plant and leaf samples during pollination (R2) were collected from ridge- and no-till treatments during 2003–2006 (Table 2). The plant tissue samples indicated that during pollination, K concentrations were generally below the critical level (Mills and Jones, 1996), and therefore, K was likely one factor contributing to lower grain yields. These results differed from those of Shi et al. (2012), however, since V6 samples from ridge-till plots in both continuous and rotated corn production systems in 2004–2006 were always below the critical level (25 $g\,kg^{-1}$), while with no-till, the K concentration at V6 was sufficient except for continuous corn in 2005. Samples collected from the moldboard plow treatments for both rotated (16.8 $g\,kg^{-1}$) and continuous (17.0 $g\,kg^{-1}$) corn ear-leaf K concentrations at pollination were also at or just below the critical level of 17.0 $g\,kg^{-1}$ indicating that K fertilizer rates were probably insufficient for the higher plant populations (Table 1) and yield potential during the latter years of study (Table 3).

To complement the plant analysis data, soil-test data were also collected from the ridge- and no-tillage treatments in 2003 and 2004. Those samples (Table 4) indicated substantial stratification of both P and K, with K values below 10 cm being classified as low or very low (Sawyer et al., 2011). According to the basic cation saturation ratio (BCSR) as described by Eckert (1987), K saturation in soil below a 5-cm depth was less than the 2–5% suggested as being appropriate for Midwestern soils. This was consistent with other mid-Iowa studies on similar soils (Karlen et al., 2002). Based on this information, sub-plot studies focusing on P and K fertilizer placement (Karlen and Kovar, 2005) were conducted, and the rate of P and K fertilizer application for the overall tillage study was also increased (Table 1) during Phase 3.

Fertilizer N, P, and K application rates throughout the study averaged 174, 25, and 50 $kg\,ha^{-1}\,yr^{-1}$ for rotated corn and 186, 10, and 21 $kg\,ha^{-1}\,yr^{-1}$ for continuous corn. Therefore, to determine whether the macronutrient balance could explain why the average corn yields were at or below the NASS Boone County Average during Phases 2 and 3, when they had been 32% higher during Phase 1 (Table 2), the crop grain yield data were multiplied by

Table 3
Near-surface soil-test analyses used to help identify factors limiting ridge- and no-till corn production in a long-term study on glacial till soils in central Iowa, U.S.A.

Depth (cm)	Bulk density (g cm^{-3})	pH	Bray P (mg kg^{-1})	Exch. K	Exch. Ca	Exch. Mg
Field 71–2003						
0–5	1.19	6.53	52	176	2916	392
5–10	1.24	6.61	29	96	2940	361
10–20	1.58	6.28	19	65	2899	392
$LSD_{(0.1)}$	0.05	0.15	8	21	NS	NS
Field 71–2004						
0–5	1.16	6.56	43	192	3479	459
5–10	1.26	6.49	34	119	3667	439
10–20	1.42	6.32	17	107	3874	480
$LSD_{(0.1)}$	0.14	NS	8	18	NS	NS
Field 70–2004						
0–5	1.15	6.24	50	199	3511	441
5–10	1.35	6.32	38	119	3258	399
10–20	1.42	6.16	14	83	3663	471
$LSD_{(0.1)}$	0.13	NS	10	18	NS	NS

Table 4
Machinery operations and 2012 estimated costs (U.S. \$ ha^{-1}) for corn and soybean production using the five tillage systems evaluated in central Iowa U.S.A.

Operation	Unit cost (\$ ha^{-1})	Moldboard plow	Chisel plow	Spring disk	Ridge-Till	No-till
Continuous (CC) or rotated (CS) corn						
Chop stalks (CC only)	26.68	26.68	26.68	26.68	26.68	26.68
Broadcast fertilizer	8.75	8.75	8.75	8.75	8.75	8.75
Moldboard plow	49.40	49.40				
Chisel plow	21.24		21.24			
Tandem disk	16.55	16.55–33.10		16.55–33.10		
Harrow	9.63	9.63		9.63		
Field cultivate	13.59		13.59–27.18			
Sprayer	9.88	9.88	9.88	9.88	19.76	19.76
Planter	28.16	28.16	28.16	28.16		
No-till planter	31.62				31.62	31.62
Rotary hoe	6.92	6.92	6.92	6.92		
Cultivator	10.13	10.13–20.26	10.13–20.26	10.13–20.26	20.26–40.52	20.26–30.39
Sidedress fertilizer	24.70	24.70	24.70	24.70	24.70	24.70
Combine	79.04	79.04	79.04	79.04	79.04	79.04
Grain cart	22.23	22.23	22.23	22.23	22.23	22.23
Grain hauling[a]	(0.0032 kg^{-1})	34.99	34.29	33.81	28.85	33.44
Total machine cost		327–354	286–309	276–303	262–282	233–243
Seed & chemicals cost[b]		931	931	931	931	931
Gross return[c] continuous corn		1526	1482	1453	1467	1438
Net return ha^{-1} to land, labor, & management[d]		255	254	233	264	269
Total machine cost		327–354	286–309	276–303	262–282	233–243
Seed & chemicals cost		813	813	813	813	813
Gross return rotated corn		1714	1700	1714	1656	1671
Net return ha^{-1} to land, labor, & management		560	590	612	571	620
Rotated soybean (SC)						
Chop corn stalks	26.68	26.68	26.68	26.68	26.68	26.68
Moldboard plow	49.40	49.40				
Chisel plow	21.24		21.24			
Tandem disk	16.55	33.10		33.10		
Harrow	9.63	9.63		9.63		
Field cultivate	13.59		13.59–27.18			
Sprayer	9.88	9.88	9.88	9.88	19.76	19.76
Planter	28.16	28.16	28.16	28.16		
No-till planter	31.62				31.62	31.62
Rotary hoe	6.92	6.92	6.92	6.92		
Cultivator	10.13	10.13–20.26	10.13–20.26	10.13–20.26	20.26–40.52	20.26–30.39
Combine	62.49	62.49	62.49	62.49	62.49	62.49
Grain cart	22.23	22.23	22.23	22.23	22.23	22.23
Grain hauling[a]	(0.0032 kg^{-1})	11.33	11.17	10.75	10.88	10.94
Total machine cost		270-280	212-236	220-230	194-214	194-204
Seed & chemicals cost		447	447	447	447	447
Gross return soybean		1168	1152	1109	1122	1129
Net return ha^{-1} to land, labor & management[d]		446	481	437	471	483

[a] Grain hauling cost estimates are based on the average grain yield from Phase 4 of the study (2003–2006).
[b] From Duffy (2012a).
[c] Gross returns calculated by multiplying the average 2003–2006 yields from this study by the 9-year average prices given in NASS (2012).
[d] Net returns to land, labor, and management calculated by subtracting the average machinery costs plus the seed and chemical costs from the gross returns.

estimates of N, P, and K content (IPNI; http://www.ipni.net/nutrientremoval). The calculations showed that for continuous corn (1980–2006), N, P, and K removal accounted for 55, 234 and 155%, respectively, of the applied fertilizer nutrients (Table 1). Similar calculations showed that nutrient removal from the rotation treatments during the corn phase alone accounted for 69, 116, and 77%, respectively, of the applied nutrients. Estimated N removal during the soybean phase totaled 3463 kg ha^{-1} which, by difference, indicates that at least 2556 kg ha^{-1} had to come from fixation or residual total soil N supplies. With regard to P and K, estimated removal via soybean seed totaled 337 and 983 kg ha^{-1}, respectively. Collectively P and K removal by both crops grown in the rotation treatment was almost twice (196 and 192%, respectively) the level applied as fertilizer. Based on these calculations, there was indeed a high probability that nutrient mining created a yield limiting situation.

3.2. Machinery operations, estimated costs, gross and net returns

Machinery operations and estimated costs for each at 2012 prices (Duffy, 2012a) are summarized in Table 4. Estimates for seed and chemical input costs associated with each of the cropping systems from Duffy (2012a) are also presented. For continuous or rotated corn, average machinery costs for the five tillage systems ranged from 238 to 340 USD ha^{-1}, while for soybean following corn, they ranged from 199 to 275 USD ha^{-1}. As expected, the primary tillage costs and number of secondary tillage operations associated with each are the major factors accounting for differences between the tillage treatments.

Based on ISU Extension information (Duffy, 2012b), machinery costs during the course of this 30-year study increased by approximately 250% for soybean and 275% for corn. This increase, however, was not the largest factor affecting overall costs of production as the cost for seed/chemicals/fertilizer and land costs increased by 358 and 447%, respectively.

Net returns to land, labor and management ranged from 233 to 269, 560 to 620, and 437 to 483 USD ha^{-1} for continuous corn, rotated corn, and rotated soybean, respectively. For all three cropping systems, net returns were higher for no-tillage than for the other tillage treatments. For rotated soybean, the smallest difference (2 USD ha^{-1}) was noted for the comparison between the no-till and chisel plow treatments. Minimum tillage system differences for continuous and rotated corn were 5 and 9 USD ha^{-1}, respectively.

3.3. Tillage and soil series effects on soil properties

An analysis of variance by depth increment for the various soil properties [bulk density (BD), NO_3-N, NH_4-N, electrical conductivity (EC), pH, Mehlich-3 extractable P, K, Ca, Mg and DTPA-extractable Cu, Fe, Mn, and Zn] measured to characterize long-term effects of five tillage systems and two crop rotations showed several statistically significant differences due to tillage system, soil series, and replicate, as well as several tillage by soil series interactions (Table A7). Differences among mean pH, P and K values illustrate that although the differences are statistically significant, they are neither large nor of real agronomic importance (Table 5).

Collectively, these data show that soil pH in the top 15 cm and even into the 15–30 cm increment was beginning to drop to a level that could have an agronomic impact. According to the management records, agricultural lime was applied only once (1987) during the long-term study at a rate of 6.7 Mg ha^{-1} effective calcium carbonate. Acidification is generally not a major agronomic production issue for glacial-till derived soils in central Iowa, U.S.A. because of the calcareous subsoil below 60 cm (Table 5).

Table 5
Long-term tillage system and soil series effects on selected soil properties measured at four depth increments in soils derived from glacial till in central Iowa, U.S.A.

Factor	pH	Soil-test P ($\mu g\,g^{-1}$)	Soil-test K ($\mu g\,g^{-1}$)
Tillage system (0–0.15 m)			
Moldboard plow	6.2	22	107
Chisel plow	6.0	35	112
Spring disk	6.1	33	125
Ridge-tillage	6.2	31	115
No-tillage	6.2	33	130
$LSD_{(0.1)}$	NS	6	14
Tillage system (0.15–0.30 m)			
Moldboard plow	6.3	14	104
Chisel plow	5.9	11	97
Spring disk	5.9	9	103
Ridge-tillage	6.0	10	99
No-tillage	6.1	12	105
$LSD_{(0.1)}$	0.2	3	NS
Tillage system (0.3–0.6 m)			
Moldboard plow	6.5	2	109
Chisel plow	6.2	3	110
Spring disk	6.3	4	114
Ridge-tillage	6.4	3	114
No-tillage	6.5	4	112
$LSD_{(0.1)}$	0.2	1	NS
Tillage system (0.6–0.9 m)			
Moldboard plow	7.2	1	100
Chisel plow	7.1	2	94
Spring disk	6.9	2	101
Ridge-tillage	7.0	2	103
No-tillage	7.2	3	109
$LSD_{(0.1)}$	0.2	NS	NS
Soil series (0–0.15 m)			
Clarion loam (138B)	6.2	25	110
Webster (107) & Canisteo (503) silty clay loam	6.1	35	122
$LSD_{(0.1)}$	NS	4	NS
Soil series (0.15–0.30 m)			
Clarion loam (138B)	6.0	11	95
Webster (107) & Canisteo (503) silty clay loam	6.1	12	106
$LSD_{(0.1)}$	NS	NS	5
Soil series (0.3–0.6 m)			
Clarion loam (138B)	6.3	4	104
Webster (107) & Canisteo (503) silty clay loam	6.5	3	117
$LSD_{(0.1)}$	0.1	0.7	6
Soil series (0.6–0.9 m)			
Clarion loam (138B)	7.0	2	96
Webster (107) & Canisteo (503) silty clay loam	7.1	2	105
$LSD_{(0.1)}$	NS	NS	NS

The spatial variability of soil-test P and K across the entire research site is illustrated in Figs. 3 and 4, respectively. The contour intervals for K are aligned with the ISU relative values used for soil-test K interpretation (Sawyer et al., 2011) and generally show higher levels in the Webster/Canisteo silty clay loam soils than in the Clarion loam. Areas with high levels in the surface are more likely to show higher concentrations in the lower depth increments, but there does not appear to be any pattern associated with the long-term tillage treatments. Subsoil soil-test P concentrations were so low that the contour interval for a “very low” ISU rating (0–15 mg kg^{-1}) was split into two and the top interval included values that would be rated as both high and very high. The relatively low soil-test P concentrations support the nutrient mining hypothesis based on crop yield and nutrient composition and also indicate that P levels certainly were not a potential environmental problem at this site.

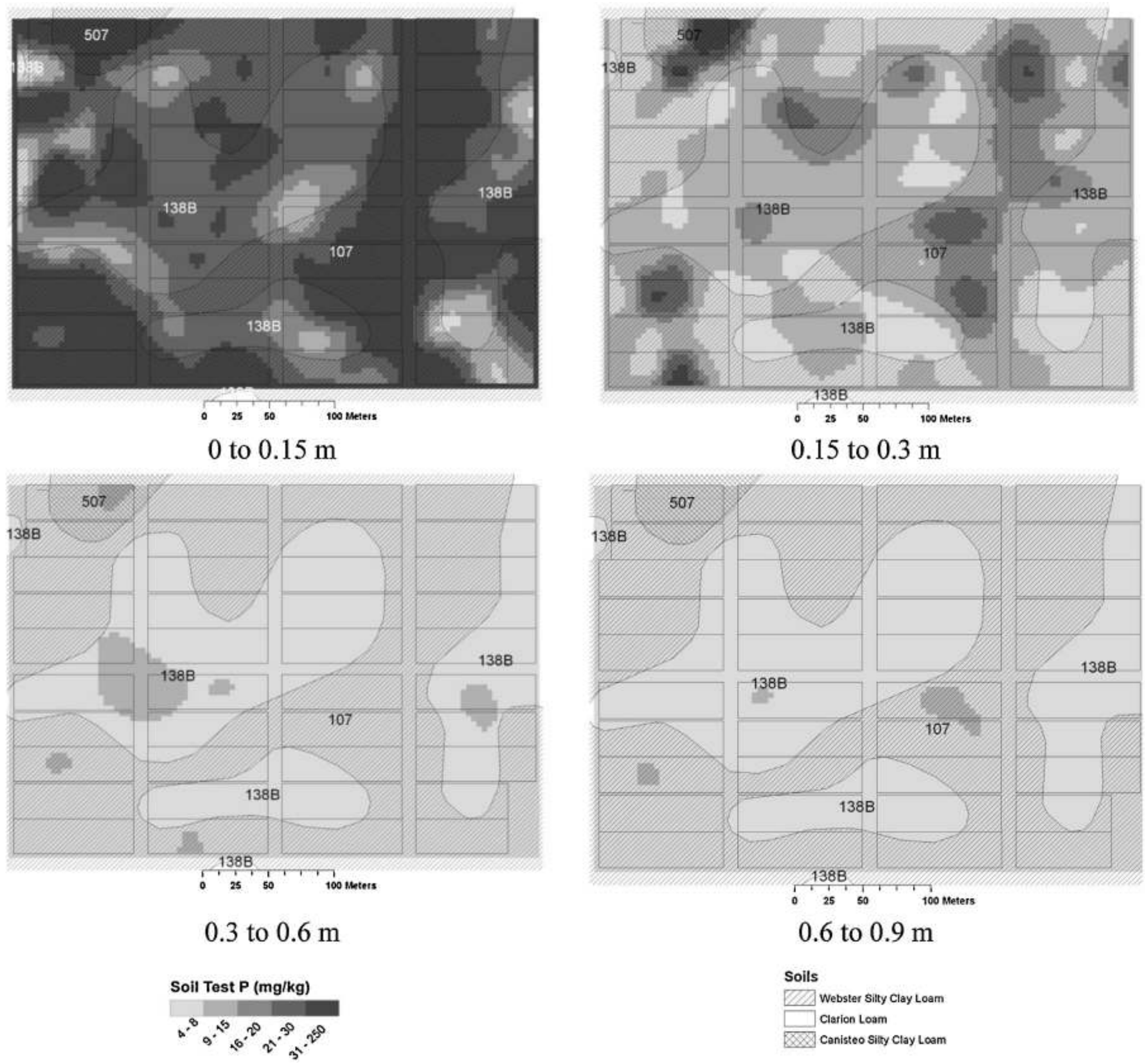

Fig. 3. Spatial variability of soil-test P after long-term tillage and cropping system evaluations on glacial-till derived soils in central Iowa, U.S.A.

Mean soil-test P and K concentrations at the various depth increments are also presented in Table 5. Among the five tillage systems, the moldboard plow treatment had a significantly lower surface (0–15 cm) P concentration than any other system. Conversely, within the 15–30 cm increment, soil-test P was higher than for the other tillage treatments, presumably reflecting physical movement downward through the annual inversion process. Statistical differences were found within the 15–30- and 30–60-cm increments, but all of the soil-test P levels are considered very low (Sawyer et al., 2011), so there was really no agronomic difference among treatments. Comparing the two soil series shows that surface P levels in the Clarion loam were lower than for the Webster/Canisteo series. Soil-test P concentrations at the lower depth increments are all considered very low (Sawyer et al., 2011) and although there were some statistical differences, we do not consider them to be important from an agronomic perspective.

The plow treatment also had the lowest surface soil-test K concentration, but presumably due in part to spatial variability (Fig. 4), the average value was significantly different from only the disk and no-tillage treatments. There were no significant differences among tillage systems within the lower depth increments. Between the two soil series, K concentrations were always the lowest for the Clarion loam but the differences were statistically significant only for the 15–30-cm and 30–60-cm depth increments (Table 5).

The value of maintaining and collecting data from long-term soil and crop management studies is often debated, especially when human and fiscal resources become limited. A primary argument for doing so is the opportunity to examine the data for unanticipated questions. This study is no exception, especially since crop yield, nutrient applications, and estimated nutrient removal data can be combined with information from an intensive soil profile coring (Fig. 1) and subsequent soil sample analyses. For example, according to Sawyer et al. (2011), Clarion, Canisteo and Webster soils in central Iowa, U.S.A. generally have low subsoil P ($\leq$8 μg g^{-1} at the 76 cm depth) and low subsoil K ($\leq$50 μg g^{-1} at the 30–60 cm depth) levels. At this site, the low subsoil P status was confirmed, but subsoil K concentrations were nearly twice as high as the current value (*i.e.* 50 μg g^{-1}) used to differentiate low and high subsoil K levels.

Having the correct classification (*i.e.* low or high subsoil concentrations) is important because subsoil K influences interpretation of surface K concentrations with regard to K fertilizer application rates (Sawyer et al., 2011). Assuming a low subsoil K rating, the surface soil-test K concentrations for all five tillage systems would be classified as low, but if subsoil K is classified as high, only the moldboard plow treatment would be classified as

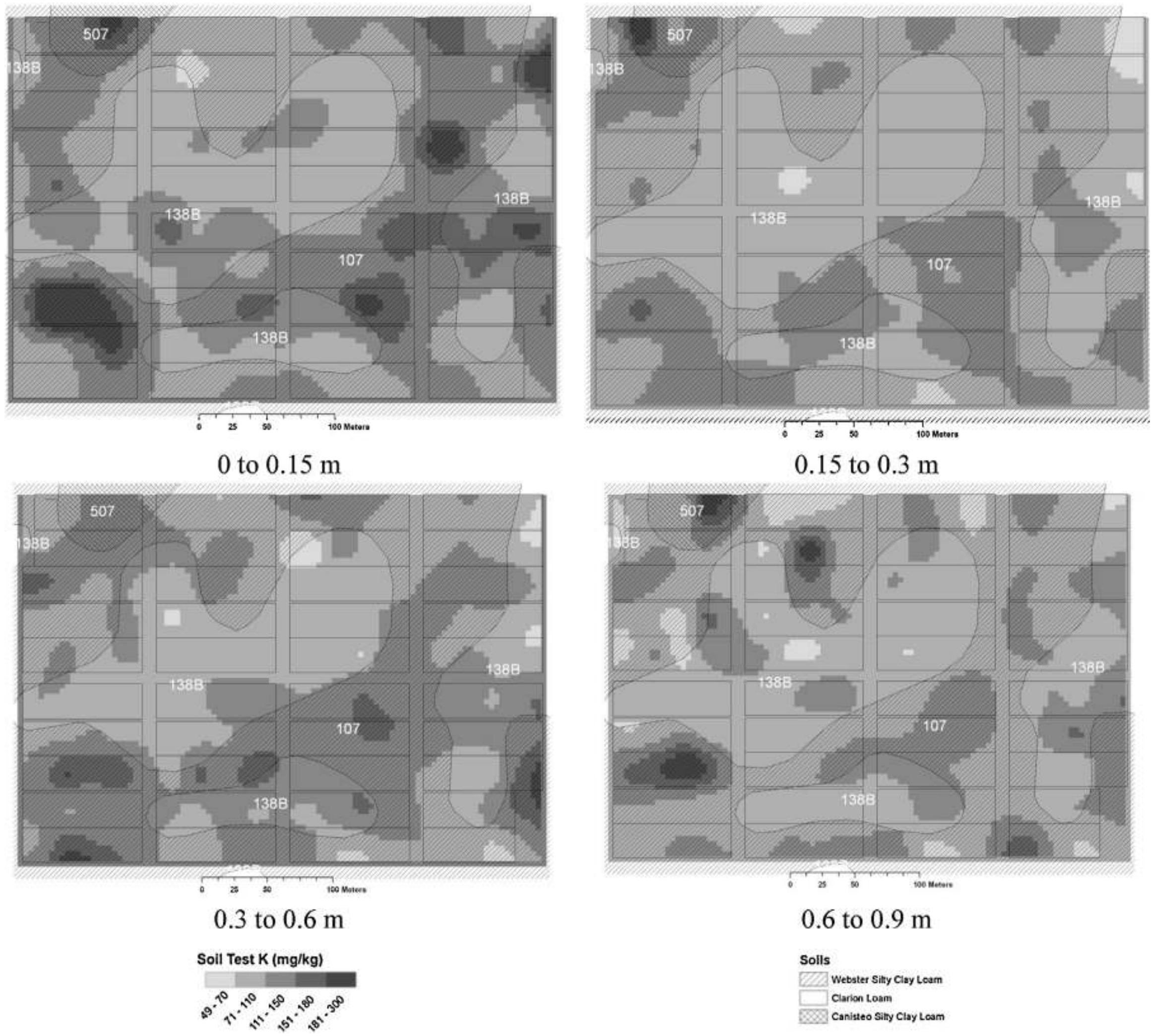

Fig. 4. Spatial variability of soil-test K after long-term tillage and cropping system evaluations on glacial-till derived soils in central Iowa, U.S.A.

low. The other four systems would be considered to have optimum soil-test K. This soil-test interpretation dilemma is beyond the scope of this study, but because plant K concentrations were frequently below the critical level specified by Mills and Jones (1996) and because calculated K removal was twice the level applied through fertilization (Table 1), it is an issue that warrants further investigation on glacial till soils.

4. Summary and conclusions

Long-term evaluations of soil and crop production systems are essential for quantifying subtle effects of tillage and as a source of data for subsequent simulation modeling. This study examines 30-year effects of five tillage systems used for a corn/soybean rotation or continuous corn production on glacial-till derived soils in central Iowa, U.S.A. Crop yields, estimated nutrient removal by grain harvest, machinery operations and costs, and changes in profile soil-test levels are reviewed. Appendices are also included to provide available rainfall, temperature, pesticide application, yield, and grain moisture data for those who may want to use this long-term record for model development and/or validation.

The analyses show that crop rotation increased corn grain yield by 17% compared to growing continuous corn. Calculated nutrient removal for continuous corn (1980–2006) accounted for 55, 234 and 155% of the applied fertilizer N, P, and K, respectively. Similar calculations for the rotated corn and soybean treatment indicated that almost twice as much P and K were removed (196 and 192%, respectively) as had been applied as fertilizer. For continuous or rotated corn, average machinery costs for the five tillage systems ranged from 238 to 340 USD ha^{-1}, while for the rotated treatment, they ranged from 199 to 275 USD ha^{-1}. As expected, the major factor accounting for cost differences among the tillage treatments was the intensity of primary tillage and the number of secondary tillage operations needed to prepare the seedbed. Net returns to land, labor, and management for the no-till production were greater than for tilled systems even though actual grain yields were slightly lower. An intensive soil sampling and profile analysis after 29 years showed statistically significant tillage, soil series, replicate, and interactions between tillage and soil series, but numerically the differences were small and with the exception of pH, P and K were of minimal agronomic importance. Soil K concentrations at the lower depth increments were "high" by current ISU soil-test interpretations, but until annual K fertilization rates were much greater than current recommendations based on the "high" subsoil rating, plant tissue analyses indicated plant available K was inadequate. This suggests further investigations are needed to improve soil-test K interpretations for glacial-till derived soils in central Iowa, U.S.A. Overall, we conclude that no-tillage can be successfully and profitably implemented on these soils by using improved nutrient management and crop rotation.

Acknowledgements

Numerous USDA-ARS and Iowa State University (ISU) research support personnel have contributed to the care and maintenance of the plots and data associated with this long-term assessment. Without their dedication, this type of long-term, tillage system evaluation would not have been feasible.

Appendix A

See Tables A1–A7.

Table A1
Monthly rainfall (mm) at the AAEREC near Boone, Iowa, U.S.A.

Year	April	May	June	July	August	September	October	Total
1986	99	127	172	130	85	164	120	897
1987	54	86	68	125	308	44	28	713
1988	36	38	140	340	59	335	27	975
1989	251	397	337	58	40	82	73	1238
1990	50	207	197	183	100	25	45	807
1991	216	97	97	14	52	1	45	522
1992	92	24	16	298	52	98	52	632
1993	80	154	180	350	266	82	31	1143
1994	65	42	144	80	77	104	75	587
1995	0	0	67	109	70	61	49	356
1996	31	191	120	97	119	79	69	706
1997	78	56	91	94	31	57	12	419
1998	68	96	249	64	80	25	88	670
1999	191	134	171	146	144	53	8	847
2000	26	106	101	67	31	23	42	396
2001	85	159	42	43	64	134	57	584
2002	86	112	71	134	118	32	70	623
2003	81	113	134	159	32	87	21	627
2004	60	179	81	43	115	30	36	544
2005	58	106	115	97	163	93	3	635
2006	58	58	13	80	59	90	53	411
Average	84	118	124	129	98	81	48	682

Table A2
Mean monthly temperatures (°C) at AAEREC near Boone, Iowa, U.S.A.

Year	April		May		June		July		August		September		October	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1986	5.2	18.2	10.8	22.7	16.1	28.0	18.5	30.4	14.0	25.8	13.3	24.3	5.2	16.6
1987	4.7	20.4	12.1	26.4	15.8	30.0	18.6	30.7	14.8	26.5	10.7	24.5	1.6	15.6
1988	2.2	18.2	13.2	27.1	20.8	28.2	23.2	31.9	22.6	31.3	16.4	23.4	7.2	14.0
1989	3.1	18.1	8.8	23.7	15.4	27.0	18.3	30.1	16.7	28.2	9.9	23.1	4.3	18.5
1990	2.2	15.8	8.8	19.8	17.0	27.0	18.4	27.7	19.0	29.2	13.8	26.1	3.6	17.6
1991	6.0	17.7	15.2	26.4	18.6	28.6	18.2	29.6	18.0	27.9	10.6	24.1	3.7	17.5
1992	2.4	13.2	9.1	22.4	14.2	26.9	15.4	24.2	13.1	24.2	10.0	22.7	3.9	17.1
1993	2.5	13.4	10.6	20.4	14.8	24.9	17.1	28.9	16.4	30.3	9.1	23.9	3.9	17.4
1994	3.0	16.2	9.9	23.1	15.8	27.0	15.8	27.6	14.6	26.6	11.9	25.3	6.9	17.7
1995	1.5	12.3	8.6	17.9	15.5	25.5	17.4	27.3	19.0	30.0	9.2	23.2	4.8	16.6
1996	1.3	16.4	9.4	19.0	16.0	27.1	16.0	27.2	16.0	26.8	10.2	22.0	4.2	17.4
1997	0.8	13.5	7.0	20.2	15.8	28.4	17.4	29.0	15.8	26.8	11.8	25.2	5.9	17.3
1998	4.9	15.2	12.5	24.7	14.5	24.4	18.1	28.7	18.2	27.8	13.5	27.4	6.4	17.0
1999	4.7	15.0	10.8	21.0	15.8	25.5	19.8	30.6	16.0	26.6	8.9	23.0	3.2	18.0
2000	2.7	17.2	10.8	24.2	14.1	25.8	17.2	27.4	17.1	28.4	10.9	26.1	6.8	18.9
2001	5.0	18.6	10.9	21.1	15.2	26.8	18.8	29.5	17.0	28.1	10.4	22.3	4.0	16.3
2002	2.9	15.3	7.6	20.9	16.8	28.3	18.6	30.1	15.7	27.0	11.9	25.5	2.0	12.5
2003	4.0	16.4	9.2	20.4	14.0	25.6	17.0	28.0	16.9	28.8	8.9	22.9	4.4	18.7
2004	3.5	17.8	10.4	21.9	13.6	24.7	16.0	26.2	13.1	24.2	12.1	26.6	5.3	16.5
2005	5.7	18.3	8.5	20.5	16.6	28.0	17.3	29.0	15.6	27.4	12.6	26.8	4.3	18.0
2006	5.6	18.4	10.6	22.1	15.8	27.7	18.4	29.8	17.3	27.1	9.9	21.6	3.4	14.3
Average	3.5	16.5	10.2	22.2	15.8	26.9	17.9	28.8	16.5	27.6	11.2	24.3	4.5	16.8

Table A3
Pesticide inputs over the course of a 30-year tillage system comparison study in central Iowa, U.S.A.

Year	Pesticide trade name[a]	Applied to	Rate	Date
Rotated corn (CS)				
1976	Lasso	All	4.6 L ha^{-1}	May 20
1976	Sencor	All	0.4 kg ha^{-1}	May 20
1976	Sevin	All	2.3 L ha^{-1}	May 21

Table A3 (*Continued*)

Year	Pesticide trade name[a]	Applied to	Rate	Date
1976	Carbofuran	All	1.1 kg ha^{-1}	June 25
1976	Carbofuran	All	1.1 kg ha^{-1}	July 7
1977	Bladex	All	4.6 L ha^{-1}	April 28
1977	Lasso	All	4.6 L ha^{-1}	April 28
1977	Carbofuran	All	1.1 kg ha^{-1}	June 13
1978	Paraquot	Ridge-till & No-till	2.3 L ha^{-1}	May 4
1978	Bladex	All	4.6 L ha^{-1}	May 5
1978	Lasso	All	4.6 L ha^{-1}	May 5
1978	2-4-D	All	1.2 L ha^{-1}	June 2
1978	Carbofuran	All	1.1 kg ha^{-1}	June 19
1978	Carbofuran	Ridge-till	1.1 kg ha^{-1}	August 4
1979	Bladex	All	4.6 L ha^{-1}	May 17–21
1979	Lasso	All	4.6 L ha^{-1}	May 17–21
1979	Paraquot	Ridge-till & No-till	2.3 L ha^{-1}	May 17
1979	2-4-D	All	1.2 L ha^{-1}	June 11
1979	Carbofuran	All	1.1 kg ha^{-1}	June 23
1980	Paraquot	No-till	2.3 L ha^{-1}	April 25
1980	Bladex	All	4.6 L ha^{-1}	April 25
1980	Lasso	All	4.6 L ha^{-1}	April 25
1980	Atrazine + oil	No-till	1.1 kg + 2.3 L ha^{-1}	May 20
1980	Basagran	Moldboard, Chisel, & Disk	2.3 L ha^{-1}	May 23
1980	Carbofuran	Ridge-till & No-till	1.1 kg ha^{-1}	June 17
1981	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 7
1981	Bladex	All	4.6 L ha^{-1}	May 7
1981	Lasso	All	4.6 L ha^{-1}	May 7
1983	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 13
1983	Bladex	All	4.6 L ha^{-1}	May 13
1983	Lasso	All	4.6 L ha^{-1}	May 13
1983	2-4-D	All	1.2 L ha^{-1}	June 9
1985	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 6
1985	2-4-D	Ridge-till & No-till	1.2 L ha^{-1}	May 6
1985	Bladex	All	4.6 L ha^{-1}	May 8
1985	Dual	All	4.6 L ha^{-1}	May 8
1987	No herbicides applied	–	–	–
1989	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 8
1989	2-4-D + crop oil	Ridge-till & No-till	1.2 + 2.3 L ha^{-1}	May 8
1989	Bladex	All	4.6 L ha^{-1}	May 8
1989	Lasso	All	4.6 L ha^{-1}	May 8
1991	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 13
1991	2-4-D + crop oil	Ridge-till & No-till	2.3 + 2.3 L ha^{-1}	May 13
1991	Bladex 4L	All	4.6 L ha^{-1}	May 13
1991	Lasso	All	4.6 L ha^{-1}	May 13
1991	Buctril	(Spot sprayed)	1.2 L ha^{-1}	June 20
1991	Atrazine	(Spot sprayed)	1.1 kg ha^{-1}	June 20
1991	Accent	(Spot sprayed)	49 mL ha^{-1}	June 20
1993	Glyphosate	Ridge-till & No-till	1.2 L ha^{-1}	April 30
1993	2-4-D + crop oil	Ridge-till & No-till	1.8 + 2.3 L ha^{-1}	April 30
1993	Bladex 90 DF	All	2.5 kg ha^{-1}	May 18
1993	Lasso	All	4.6 L ha^{-1}	May 18
1993	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 20
1993	2-4-D + crop oil	Ridge-till & No-till	1.2 + 2.3 L ha^{-1}	May 20
1995	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 12
1995	2-4-D	Ridge-till & No-till	1.2 L ha^{-1}	May 12
1995	Lasso	All	7.0 L ha^{-1}	May 16
1995	Accent	(spot treatment)	49 mL ha^{-1}	June 20
1995	Buctril	All	1.2 L ha^{-1}	June 21
1997	Glyphosate	All	2.3 L ha^{-1}	May 17
1997	Poast Plus	All	876 mL ha^{-1}	June 18
1997	Sencor	All	36 mL ha^{-1}	June 20
1997	Buctril	All	1.75 L ha^{-1}	June 20
1999	Glyphosate	All	2.3 L ha^{-1}	April 28
1999	2-4-D	All	1.2 L ha^{-1}	April 28
1999	Balance	All	150 mL ha^{-1}	April 30
1999	Sencor	All	150 mL ha^{-1}	June 7
1999	Buctril	All	0.6 L ha^{-1}	June 7
1999	Accent	All	24 mL ha^{-1}	June 14
2001	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	April 30
2001	Dual Magnum	All	1.8 L ha^{-1}	April 30
2001	Buctril	All	0.3 L ha^{-1}	June 15–19
2003	Glyphosate	All	1.9 L ha^{-1}	April 29
2003	Dual II Magnum	All	1.8 L ha^{-1}	April 29
2003	Liberty	All	2.0 L ha^{-1}	June 16
2005	Lumax	All	5.8 L ha^{-1}	April 25–May 3
2005	Glyphosate	All	1.6 L ha^{-1}	May 3
Rotated soybean (SC)				
1976	Paraquot	Ridge-till	1.8 L ha^{-1}	May 21
1977	Paraquot	Ridge-till	3.5 L ha^{-1}	May 17

Table A3 (*Continued*)

Year	Pesticide trade name[a]	Applied to	Rate	Date
1977	Lasso	All	4.6 L ha^{-1}	May 18
1977	Amiben	All	4.6 L ha^{-1}	May 18
1978	Glyphosate	Ridge-till & No-till	4.6 L ha^{-1}	May 15
1978	Lasso	All	4.6 L ha^{-1}	May 17
1978	Sencor	All	0.6 kg ha^{-1}	May 17
1978	Basagran	All	2.3 L ha^{-1}	June 2
1979	Paraquot	Ridge-till & No-till	1.2 L ha^{-1}	May 24
1979	Lasso	All	4.6 L ha^{-1}	May 24
1979	Sencor	All	0.6 kg ha^{-1}	May 24
1979	Basagran	All	2.3 L ha^{-1}	June 15
1980	Glyphosate	No-till	4.6 L ha^{-1}	May 20
1980	Lasso	All	4.6 L ha^{-1}	May 20–21
1980	Amiben	All	4.6 L ha^{-1}	May 20–21
1980	Basagran	All	2.3 L ha^{-1}	June 17
1980	Hoelon	Moldboard & Chisel Plow	3.5 L ha^{-1}	June 26
1982	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	June 7
1982	Lasso	All	4.6 L ha^{-1}	June 7–8
1982	Amiben	All	9.2 L ha^{-1}	June 7–8
1982	Hoelon	Ridge-till	3.1 L ha^{-1}	June 25
1982	Basagran	All	2.3 L ha^{-1}	June 28
1982	Carbofuran	Moldboard & Chisel Plow	1.1 kg ha^{-1}	July 8
1984	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 18
1984	Lasso	All	2.3 L ha^{-1}	May 18
1984	Amiben	All	9.2 L ha^{-1}	May 18
1984	Basagran	All	2.3 L ha^{-1}	June 19
1986	Lasso	Ridge-till & No-till	5.8 L ha^{-1}	April 24
1986	Amiben	Ridge-till & No-till	9.2 L ha^{-1}	April 24
1986	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	June 12
1986	Dual	Ridge-till & No-till	2.3 L ha^{-1}	June 12
1986	Amiben	Ridge-till & No-till	9.2 L ha^{-1}	June 12
1986	Basagran	All	2.3 L ha^{-1}	July 3
1988	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 17
1988	Lasso	All	2.3 L ha^{-1}	May 17
1988	Amiben	All	9.2 L ha^{-1}	May 17
1990	Glyphosate	No-till	2.3 L ha^{-1}	May 1
1990	Lasso	No-till	4.6 L ha^{-1}	May 1
1990	Amiben	No-till	9.2 L ha^{-1}	May 1
1992	Glyphosate	Ridge-till & No-till	1.2 L ha^{-1}	April 15
1992	2-4-D	Ridge-till & No-till	1.8 L ha^{-1}	April 15
1992	Lasso	All	4.6 L ha^{-1}	May 13
1992	Pursuit	All	0.3 L ha^{-1}	May 13
1994	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	April 14
1994	2-4-D	Ridge-till & No-till	1.2 L ha^{-1}	April 14
1994	Glyphosate	Ridge-till & No-till	3.5 L ha^{-1}	May 12
1994	2-4-D	Ridge-till & No-till	1.8 L ha^{-1}	May 12
1994	Lasso	All	4.6 L ha^{-1}	May 12
1994	Pursuit	All	0.3 L ha^{-1}	May 12
1994	Basagran	All	1.2 L ha^{-1}	June 12
1996	Glyphosate	All	2.9 L ha^{-1}	June 7
1996	2-4-D	All	0.6 L ha^{-1}	June 7
1996	Pursuit	All	0.3 L ha^{-1}	June 2
1998	Glyphosate	All	2.3 L ha^{-1}	May 18
2000	Glyphosate	Ridge-till & No-till	1.9 L ha^{-1}	April 29
2000	Glyphosate	All	1.8 L ha^{-1}	June 13
2002	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 24
2002	Glyphosate	All	2.3 L ha^{-1}	June 12
2002	Glyphosate	All	2.0 L ha^{-1}	September 6
2004	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 20
2004	Glyphosate	All	1.6 L ha^{-1}	June 12
2004	Glyphosate	All	1.8 L ha^{-1}	August 13
2006	Dual	Moldboard, Chisel, Disk	1.8 L ha^{-1}	May 18
2006	Glyphosate	All	2.0 L ha^{-1}	May 26
2006	Glyphosate	All	2.0 L ha^{-1}	June 22
Continuous corn (CC)				
1980	Paraquot	No-till	2.3 L ha^{-1}	April 25
1980	Bladex	All	4.6 L ha^{-1}	April 25
1980	Lasso	All	4.6 L ha^{-1}	April 25
1980	Atrazine + oil	No-till	1.1 kg + 2.3 L ha^{-1}	May 20
1980	Basagran	Moldboard, Chisel, & Disk	2.3 L ha^{-1}	May 23
1980	Carbofuran	Ridge-till & No-till	1.1 kg ha^{-1}	June 17
1981	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 7
1981	Bladex	All	4.6 L ha^{-1}	May 7
1981	Lasso	All	4.6 L ha^{-1}	May 7
1981	Carbofuran	All	1.1 kg ha^{-1}	June 23
1982	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 7
1982	Bladex	All	4.6 L ha^{-1}	May 7
1982	Lasso	All	4.6 L ha^{-1}	May 7

Table A3 (*Continued*)

Year	Pesticide trade name[a]	Applied to	Rate	Date
1982	2-4-D	All	1.2 L ha^{-1}	June 11
1982	Carbofuran	All	1.1 kg ha^{-1}	June 24
1982	Atrazine & crop oil	Moldboard and Chisel	4.6 + 2.3 L ha^{-1}	June 25
1983	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 12
1983	Bladex	All	4.6 L ha^{-1}	May 12
1983	Lasso	All	4.6 L ha^{-1}	May 12
1983	2-4-D	All	1.2 L ha^{-1}	June 9
1984	Glyphosate	Ridge-till, No-till, Disk	2.3 L ha^{-1}	May 18
1984	Bladex	All	4.6 L ha^{-1}	May 18
1984	Lasso	All	4.6 L ha^{-1}	May 18
1985	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 1
1985	2-4-D	Ridge-till & No-till	1.2 L ha^{-1}	May 1
1985	Bladex	All	4.6 L ha^{-1}	May 1
1985	Lasso	All	4.6 L ha^{-1}	May 1
1986	Bladex	Ridge-till, No-till, Disk	5.8 L ha^{-1}	April 24
1986	Lasso	Ridge-till, No-till, Disk	4.6 L ha^{-1}	April 24
1986	Glyphosate	All	2.3 L ha^{-1}	May 20
1986	2-4-D	All	1.2 L ha^{-1}	May 20
1986	Bladex	All	2.3 L ha^{-1}	May 20
1987	(not sprayed)	–	–	–
1988	Lorsban	All	10 kg ha^{-1} (banded)	May 6
1988	Glyphosate	Ridge-till, No-till, Disk	2.3 L ha^{-1}	May 29
1988	Bladex	All	4.6 L ha^{-1}	May 29
1988	Lasso	All	4.6 L ha^{-1}	May 29
1989	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 8
1989	2-4-D + crop oil	Ridge-till & No-till	1.2 + 2.3 L ha^{-1}	May 8
1989	Bladex	All	4.6 L ha^{-1}	May 8
1989	Lasso	All	4.6 L ha^{-1}	May 8
1990	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	April 30
1990	2-4-D + crop oil	Ridge-till & No-till	2.3 + 2.3 L ha^{-1}	April 30
1990	Bladex	All	4.6 L ha^{-1}	April 30
1990	Lasso	All	4.6 L ha^{-1}	April 30
1991	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 13
1991	2-4-D + crop oil	Ridge-till & No-till	2.3 + 2.3 L ha^{-1}	May 13
1991	Bladex 4L	All	4.6 L ha^{-1}	May 13
1991	Lasso	All	4.6 L ha^{-1}	May 13
1991	Buctril	(spot sprayed)	1.2 L ha^{-1}	June 20
1991	Atrazine	(spot sprayed)	1.1 kg ha^{-1}	June 20
1991	Accent	(spot sprayed)	49 mL ha^{-1}	June 20
1992	Glyphosate	Ridge-till & No-till	1.2 L ha^{-1}	April 15
1992	2-4-D + crop oil	Ridge-till & No-till	1.8 + 2.3 L ha^{-1}	April 15
1992	Bladex	All	4.6 L ha^{-1}	May 8
1992	Lasso	All	4.6 L ha^{-1}	May 8
1993	Glyphosate	Ridge-till & No-till	1.2 L ha^{-1}	April 30
1993	2-4-D + crop oil	Ridge-till & No-till	1.8 + 2.3 L ha^{-1}	April 30
1993	Lasso	All	4.6 L ha^{-1}	May 18
1993	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 20
1993	2-4-D + crop oil	Ridge-till & No-till	1.2 + 2.3 L ha^{-1}	May 20
1993	Pursuit	All	0.3 L ha^{-1}	June 11
1994	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	April 14
1994	2-4-D	Ridge-till & No-till	1.2 L ha^{-1}	April 14
1994	Bladex 90 DF	All	2.5 kg ha^{-1}	May 2
1994	Lasso	All	4.6 L ha^{-1}	May 2
1994	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 2
1994	2-4-D + crop oil	Ridge-till & No-till	1.2 + 2.3 L ha^{-1}	May 2
1994	Buctril + crop oil	All	1.8 + 2.3 L ha^{-1}	June 3
1995	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 12
1995	2-4-D	Ridge-till & No-till	1.2 L ha^{-1}	May 12
1995	Lasso	All	7.0 L ha^{-1}	May 16
1995	Accent	(spot treatment)	49 mL ha^{-1}	June 20
1995	Buctril	All	1.2 L ha^{-1}	June 21
1996	Pursuit	All	0.1 L ha^{-1}	June 11
1997	Glyphosate	All	2.3 L ha^{-1}	May 17
1997	Poast Plus	All	876 mL ha^{-1}	June 18
1997	Sencor	All	36 mL ha^{-1}	June 20
1997	Buctril	All	1.5 L ha^{-1}	June 20
1998	Glyphosate	Ridge-till & No-till	2.3 L ha^{-1}	May 19
1998	Glyphosate	All	1.8 L ha^{-1}	June 10
1999	Glyphosate	All	2.3 L ha^{-1}	April 29
1999	2-4-D	All	1.2 L ha^{-1}	April 29
1999	Balance	All	150 mL ha^{-1}	April 30
1999	Sencor	All	150 mL ha^{-1}	June 7
1999	Buctril	All	0.6 L ha^{-1}	June 7
2000	Glyphosate	All	2.3 L ha^{-1}	May 9
2000	2-4-D	All	0.6 L ha^{-1}	May 9
2000	Glyphosate	All	1.8 L ha^{-1}	May 20
2000	Glyphosate	All	1.8 L ha^{-1}	June 6

Table A3 (*Continued*)

Year	Pesticide trade name[a]	Applied to	Rate	Date
2000	Glyphosate	All	2.3 L ha^{-1}	July 7
2001	Glyphosate	All	2.3 L ha^{-1}	May 18
2001	Balance	All	0.1 L ha^{-1}	June 18
2001	Glyphosate	All	1.8 L ha^{-1}	June 19
2002	Glyphosate	Ridge-till & No-till	1.9 L ha^{-1}	May 5
2002	Dual II Magnum	All	1.8 L ha^{-1}	May 5
2002	Liberty	All	2.0 L ha^{-1}	June 5
2003	Glyphosate	Ridge-till & No-till	1.9 L ha^{-1}	April 29
2003	Dual II Magnum	All	1.8 L ha^{-1}	April 29
2004	Aztec	All	7.7 kg ha^{-1}	April 27
2004	Glyphosate	All	2.3 L ha^{-1}	May 20
2004	Glyphosate	All	1.6 L ha^{-1}	July 8
2005	Lumax	All	5.8 L ha^{-1}	April 25–May 3
2005	Glyphosate	All	1.6 L ha^{-1}	May 3
2006	Dual Magnum	All	1.8 L ha^{-1}	May 3
2006	Glyphosate	Ridge-till & No-till	2.0 L ha^{-1}	May 26
2006	Glyphosate	All	2.0 L ha^{-1}	June 7

[a] Chemical names are listed in Table A4.

Table A4
Chemical names for pesticides used in a 30-year tillage system study in central Iowa, U.S.A.

Trade name	Chemical name
Accent	3-Pyridimecarboxamide,2-[[(4,6-Dimethoxy-pyrimidin-2-yl)amino-carbonyl]aminosulfonyl]-N,N-dimethyl
Amiben	3-Amino-2,5-dichlorobenzoic acid
Atrazine	2-Chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine
Balance	5-Cyclopropyl-1,2-oxazol-4-yl)(α,α,α-trifluoro-2-mesyl-*p*-tolyl)methanone
Basagran	3-(1-Methylethyl)-1H-2,1,3-benzothiadiazin-4-(3H)-one 2,2-dioxide
Bladex	2-[(4-Chloro-6-(ethylamino)-S-triazin-2-yl) amino)]-2-methylpropionitrile
Buctril	3,5-Dibromo-4-hydroxybenzonitrile
Carbofuran	2,3-Dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate
Dual/Dual Magnum	(*RS*)-2-Chloro-*N*-(2-ethyl-6-methyl-phenyl)-*N*-(1-methoxypropan-2-yl)acetamide
Glyphosate	N-(Phosphonomethyl) glycine
Hoelon	Diclofop-methyl: methyl 2-[4-(2,4-dichlorophenoxy) phenoxy]propanoate
Lasso	2-Chloro-2′-6′-diethyl-N-(methoxymethyl)-acetanilide
Liberty	2-Amino-4-(hydroxymethylphosphinyl)butanoic acid
Lorsban	*O*,*O*-Diethyl *O*-3,5,6-trichloropyridin-2-yl phosphorothioate
Lumax	2-Chloro-4-ethylamino-6-isopropylamino-s-triazine
Paraquot	*N*,*N*′-Dimethyl-4,4′-bipyridinium dichloride
Poast Plus	2-[1-(Ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cycloxexen-1-one
Pursuit	(+)-2-4,5-Dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-y1|-5-ethyl-3-pyridinecarboxylic acid
Sencor	4-Amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one
Sevin (Carbaryl)	1-Naphthyl methylcarbamate
2-4-D	2,4-Dichlorophenoxyacetic acid

Table A5
Phase one[a] (1976–1980), two[b] (1988–2002) and three (2003–2006) crop yield response to long-term tillage treatments on glacial till soils in Central Iowa, U.S.A.

Year	Moldboard plow (Mg ha^{-1})	Chisel plow	Spring disk	Ridge-till	No-till	Seasonal average	NASS boone county average
Phase 1–Establishment (rotated corn)							
1976	7.6	7.5	7.3	7.3	7.3	7.4	6.4
1977	4.2	4.7	4.7	4.7	4.7	4.6	2.1
1978	10.8	10.5	10.7	10.2	10.4	10.5	7.6
1979	10.8	10.5	10.6	10.1	9.8	10.4	8.9
1980	10.1	10.2	9.7	10.1	10.3	10.1	7.4
Average	8.7	8.7	8.6	8.5	8.5	8.6	6.5
Phase 1 Tillage $LSD_{(0.05)}$ for corn = NS							
Phase 1–Establishment (rotated soybean)							
1976	1.8	1.8	2.0	1.9	1.7	1.8	2.1
1977	1.4	1.7	2.1	1.7	2.1	1.8	1.6
1978	3.4	3.2	3.2	3.1	3.2	3.2	2.9
1979	3.3	3.3	3.4	3.2	3.4	3.3	2.7
1980	3.5	3.3	3.3	3.3	3.4	3.4	2.9
Average	2.7	2.7	2.8	2.6	2.7	2.7	2.4
Phase 1 Tillage $LSD_{(0.05)}$ for soybean = NS							
Phase 2–Maintenance (continuous corn)							
1988	5.9	5.5	4.6	4.8	5.7	5.3	5.4
1989	8.7	8.5	7.9	7.1	8.1	8.1	8.2
1990	9.5	8.9	8.5	6.8	8.3	8.4	7.4
1991	9.8	9.0	8.6	8.4	8.8	8.9	7.7
1992	10.3	7.9	7.5	8.3	8.9	8.6	10.3

Table A5 (*Continued*)

Year	Moldboard plow (Mg ha^{-1})	Chisel plow	Spring disk	Ridge-till	No-till	Seasonal average	NASS boone county average
1993	5.0	4.5	4.3	3.3	4.7	4.4	5.3
1994	10.6	9.7	9.4	8.2	8.7	9.3	10.4
1995	9.6	8.4	6.7	6.3	6.2	7.4	9.4
1996	6.9	4.6	4.6	4.2	3.9	4.8	9.3
1997	7.1	6.6	6.8	6.5	6.5	6.7	9.4
1998	8.6	8.3	7.4	7.3	8.3	8.0	9.2
1999	10.8	9.8	9.0	8.2	9.0	9.3	9.8
2000	8.5	8.4	7.9	6.9	6.6	8.2	9.7
2001	6.8	6.3	6.2	6.9	6.6	6.6	9.7
2002	9.3	8.6	8.6	8.3	8.3	8.6	10.7
Average	8.5	7.7	7.2	6.8	7.4	7.5	8.8
Phase 2 Tillage LSD$_{(0.1)}$ for continuous corn = 0.3							
Phase 2–Maintenance (rotated corn)							
1989	8.8	8.5	8.6	9.2	9.0	8.8	8.2
1991	9.7	9.8	9.4	9.4	9.4	9.6	7.7
1993	7.3	7.6	7.4	6.9	6.7	7.2	5.3
1995	8.6	8.2	8.0	7.4	7.3	7.9	9.4
1997	9.0	8.6	8.7	8.6	8.1	8.6	9.4
1999	11.0	10.8	10.8	10.4	10.1	10.6	9.8
2001	9.2	8.7	8.9	8.8	7.6	8.6	9.7
Average	9.1	8.9	8.8	8.7	8.3	8.8	8.5
Phase 2 Tillage LSD$_{(0.1)}$ for rotated corn = 0.2							
Phase 2–Maintenance (rotated soybean)							
1988	1.80	1.55	1.03	–	–	1.46	1.6
1990	3.48	3.15	2.98	3.30	3.32	3.24	2.7
1992	3.24	2.71	2.50	2.58	2.47	4.04	3.1
1994	4.26	3.99	4.02	4.02	3.82	2.70	3.5
1996	4.18	4.05	4.02	3.98	3.97	4.02	3.1
1998	3.55	3.38	3.50	3.46	3.44	3.46	3.2
2000	3.10	2.84	2.97	2.82	2.80	2.91	2.7
2002	3.17	3.53	3.39	3.35	3.29	3.35	3.2
Average	3.34	3.15	3.05	3.36	3.30	3.24	2.9
Phase 2 Tillage LSD$_{(0.1)}$ for rotated soybean = 0.09							
Phase 3–Intensification and Recovery (continuous corn)							
2003	9.7	10.1	9.3	0.6	9.7	9.7	10.7
2004	11.4	11.1	10.9	11.0	10.7	11.0	12.1
2005	10.2	9.6	9.6	10.0	9.7	9.8	12.1
2006	10.6	10.1	10.0	9.7	9.6	10.0	10.8
Average	10.5	10.2	10.0	10.1	9.9	10.1	11.4
Phase 3 Tillage LSD$_{(0.1)}$ for continuous corn = 0.2							
Phase 3–Intensification and Recovery (rotated corn)							
2003	11.0	11.2	11.2	11.2	11.2	11.2	10.7
2005	12.7	12.2	12.4	11.6	11.8	12.1	12.1
Average	11.8	11.7	11.8	11.4	11.5	11.6	11.4
Phase 3 Tillage LSD$_{(0.1)}$ for rotated corn = 0.2							
Phase 3–Intensification and Recovery (rotated soybean)							
2004	3.64	3.55	3.28	3.44	3.45	3.48	3.5
2006	3.45	3.44	3.43	3.33	3.38	3.40	3.4
Average	3.54	3.49	3.36	3.40	3.42	3.44	3.4
Phase 3 Tillage LSD$_{(0.1)}$ for rotated soybean = 0.12							

[a] Phase one yields are reprinted from Erbach, D.C. 1982.
[b] Crop yield data for 1981 through 1987 were collected as evidenced by the management records, but unfortunately due to retirements of both ISU and ARS personnel, the data have been lost.

Table A6
Long-term tillage and crop rotation effects on grain moisture (g kg^{-1}).

Year	Moldboard plow	Chisel plow	Disk	Ridge-till	No-Till	Average
Phase 2–Maintenance (continuous corn)						
1988	156	158	157	157	158	157
1989	159	164	164	166	174	165
1990	179	188	180	186	182	183
1991	174	167	171	171	174	171
1992	203	213	225	200	204	209
1993	206	217	214	219	220	215
1994	168	168	170	170	168	169
1995	151	152	154	153	152	152
1996	172	169	169	166	162	168
1997	152	160	162	160	149	157
1998	151	153	158	158	151	154
1999	147	146	150	149	149	148
2000	138	138	143	137	137	139

Table A6 (*Continued*)

Year	Moldboard plow	Chisel plow	Disk	Ridge-till	No-Till	Average
2001	160	157	158	160	156	158
2002	167	168	168	168	166	168
Average	165	168	170	168	167	168
Phase 3 Tillage $LSD_{(0.1)}$ for continuous corn = 2						
Phase 2–Maintenance (rotated corn)						
1989	173	173	176	172	187	176
1991	169	173	171	171	171	171
1993	230	223	226	234	228	228
1995	167	168	168	166	160	168
1997	136	134	136	141	136	137
1999	144	144	144	145	146	144
2001	162	162	164	161	165	163
Average	169	168	169	170	170	169
Phase 3 Tillage $LSD_{(0.1)}$ for rotated corn = NS						
Phase 2–Maintenance (rotated soybean)						
1988	97	103	107	–	–	102
1990	92	101	102	85	89	94
1992	130	121	126	118	118	122
1994	133	126	131	128	126	129
1996	119	119	120	113	120	118
1998	116	114	116	117	113	115
2000	90	90	89	87	90	89
2002	108	106	107	107	106	107
Average	110	110	112	108	109	110
Phase 3 Tillage $LSD_{(0.1)}$ for rotated soybean = 3						
Phase 3–Intensification and Recovery (continuous corn)						
2003	146	148	146	147	149	147
2004	199	196	193	200	202	198
2005	162	164	164	153	154	159
2006	174	176	177	177	179	176
Average	170	171	170	169	171	170
Phase 4 Tillage $LSD_{(0.1)}$ for continuous corn = NS						
Phase 3–Intensification and Recovery (rotated corn)						
2003	160	160	161	160	161	160
2005	159	156	158	162	161	159
Average	159	158	160	161	161	160
Phase 4 Tillage $LSD_{(0.1)}$ for rotated corn = 1						
Phase 3–Intensification and Recovery (rotated soybean)						
2004	–	–	–	–	–	–
2006	107	106	108	107	106	106

Table A7
Profile ANOVA results for selected soil quality indicators measured in autumn 2005 at the long-term site used for tillage system comparisons in central Iowa, U.S.A.

Indicator	Tillage	Map Unit (MU)	Rep	Tillage*MU
Probability > *F*				
0–0.15 m				
Bulk density (BD)	0.3323	0.1747	0.4597	0.0936
Nitrate N (NO_3-N)	0.0049	0.0530	0.4060	0.4669
Ammonium N (NH_4-N)	0.3747	0.6297	0.0181	0.3022
Electrical Conductivity (EC)	0.2410	<0.0001	0.0032	0.3010
pH	0.4101	0.3010	0.0723	0.2602
Mehlich III Extractable P	0.0126	0.0018	0.4065	0.3060
Mehlich III Extractable K	0.0458	0.1275	0.0285	0.6249
Mehlich III Extractable Ca	0.4653	<0.0001	0.0080	0.4564
Mehlich III Extractable Mg	0.6461	<0.0001	<0.0001	0.0190
DTPA Extractable Cu	0.6333	0.2078	0.1303	0.0452
DTPA Extractable Fe	0.1524	<0.0001	0.2459	0.0295
DTPA Extractable Mn	0.0601	0.8346	0.0500	0.1437
DTPA Extractable Zn	0.9365	0.1152	0.0982	0.1693
0.15–0.30 m				
Bulk density (BD)	0.0495	0.0143	0.1621	0.9095
Nitrate N (NO_3-N)	<0.0001	0.6143	0.9399	0.9128
Ammonium N (NH_4-N)	0.3231	0.7807	0.3060	0.4025
Electrical Conductivity (EC)	0.3381	<0.0001	0.0341	0.1624
pH	0.0085	0.8665	0.0045	0.9416
Mehlich III Extractable P	0.0410	0.2709	0.9993	0.5473
Mehlich III Extractable K	0.2468	0.0033	0.3259	0.7707
Mehlich III Extractable Ca	0.9885	<0.0001	0.0055	0.2115
Mehlich III Extractable Mg	0.7051	<0.0001	0.0053	0.1815
DTPA Extractable Cu	0.9248	0.4472	0.5290	0.7641

Table A7 (*Continued*)

Indicator	Tillage	Map Unit (MU)	Rep	Tillage*MU
DTPA Extractable Fe	0.1597	0.0401	0.0029	0.1362
DTPA Extractable Mn	0.1597	0.0051	0.1454	0.7327
DTPA Extractable Zn	0.9482	0.1097	0.6302	0.8225
0.30–0.60 m				
Bulk density (BD)	0.4754	<0.0001	0.0522	0.2101
Nitrate N (NO_3-N)	0.0024	0.3849	0.5072	0.3075
Ammonium N (NH_4-N)	0.1549	0.9402	0.3169	0.3064
Electrical Conductivity (EC)	0.9436	<0.0001	0.0653	0.2009
pH	0.0389	0.0631	0.0007	0.9999
Mehlich III Extractable P	0.0153	0.0239	0.4889	0.0518
Mehlich III Extractable K	0.8207	0.0031	0.7458	0.1305
Mehlich III Extractable Ca	0.9575	<0.0001	0.0691	0.7605
Mehlich III Extractable Mg	0.8866	<0.0001	0.0893	0.6125
DTPA Extractable Cu	0.3428	0.2333	0.9578	0.0216
DTPA Extractable Fe	0.0678	0.0005	0.0397	0.0265
DTPA Extractable Mn	0.9333	0.0595	0.2632	0.2676
DTPA Extractable Zn	0.2138	0.0515	0.9804	0.0873
0.60–0.90 m				
Bulk density (BD)	0.8480	0.1481	0.2711	0.1402
Nitrate N (NO_3-N)	0.7976	0.2529	0.4672	0.0788
Ammonium N (NH_4-N)	0.1177	0.7769	0.0026	0.7774
Electrical Conductivity (EC)	0.3655	0.0066	0.1403	0.8840
pH	0.0984	0.6889	0.0620	0.2792
Mehlich III Extractable P	0.1420	0.4697	0.2554	0.0984
Mehlich III Extractable K	0.3698	0.1146	0.9235	0.8923
Mehlich III Extractable Ca	0.0145	0.9937	0.0441	0.9935
Mehlich III Extractable Mg	0.6438	0.0003	0.2227	0.5887
DTPA Extractable Cu	0.5369	0.8206	0.4366	0.0012
DTPA Extractable Fe	0.0671	0.0058	0.6307	0.4864
DTPA Extractable Mn	0.9686	0.0153	0.0311	0.0575
DTPA Extractable Zn	0.3877	0.7453	0.5529	0.0049

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