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Long-Term Effects of Tillage on Soil Chemical Properties and Grain Yields of a Dryland Winter Wheat–Sorghum/Corn–Fallow Rotation in the Great Plains

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ABSTRACT

Tillage systems and nutrient management influence soil chemical properties that can impact the long-term sustainability of dryland production systems. This study was conducted to compare the effects of no-till (NT) and conventional till (CT) on the soil chemical properties and grain yield of a dryland winter wheat (*Triticum aestivum* L.)–grain sorghum [*Sorghum bicolor* (L.) Moench]/corn (*Zea mays* L.)–fallow rotation. The effects of tillage practice over a 27-yr period (1962–1989) and the effect of the conversion of CT to NT over a 14-yr period (1989–2003) on selected soil chemical properties [pH, cation exchange capacity (CEC), base saturation (BS), soil organic C (SOC), K, Ca, Mg, and Bray-P] at different soil depths was determined. The acidification rate of the NT treatment from 1962 to 2003 was also determined. The study was conducted at North Platte, NE on a Holdrege silt loam (fine-silty, mixed, mesic Typic Argiustolls). In 1989, there were differences in soil chemical properties between CT and NT at some depths after 27 yr. However, in 2003, 14 yr after converting from CT to NT, there were no differences in the soil chemical properties compared with continuous NT. In 1989 and 2003, the soil chemical properties varied with soil depth. The acidification rate from 1962 to 2003 for the NT treatment in the 0- to 15-cm depth was 1.3 kmol H^+ ha^{-1} yr^{-1}. This rate of acidification represents 38% of the total potential acidity from N fertilizer applications over 41 yr. Acidification was attributed to nitrification of ammonium-based fertilizers and leaching of NO_3^-. Long-term winter wheat (1966–1983) and grain sorghum (1964–1988) grain yields were higher for NT (2718 and 4125 kg ha^{-1}) than CT (2421 and 3062 kg ha^{-1}). Retention of soil moisture as a result of increased residue cover under NT likely contributed to higher NT yields. Soil chemical properties in the wheat–sorghum/corn–fallow rotation will likely continue to change as a result of current management practices. Lime additions may become necessary in the future to ensure the sustainability of crop production in this system.

The 2-yr winter wheat–fallow (WF) rotation was the traditional dryland cropping system in the semiarid, central Great Plains in the USA from the time this area was converted to agriculture until the early 1970s. Since then, a 3-yr rotation of winter wheat (Year 1), grain sorghum or corn (Year 2), and fallow (Year 3) (WS/CF) has become a common dryland cropping system (Wicks et al., 1995). Research data showing increased crop yields and profitability of the WS/CF rotation over the WF rotation have facilitated the conversion to the WS/CF rotation (Wicks and Fenster, 1981). This rotation is often called the ecofarming system when it utilizes NT or minimal tillage to conserve soil moisture, which allows more intensive cropping and more stable and higher yields than in the traditional WF rotation (Wicks et al., 1988). Herbicides are applied to winter wheat stubble after grain harvest to keep the field weed free and to conserve soil moisture for grain sorghum or corn that is planted the following spring (Wicks et al., 1995). Some producers still utilize varying degrees of tillage during the fallow period following the row crop to control weeds and facilitate winter wheat planting with conventional drills. The long-term impact of this dryland system, which receives minimal agricultural inputs, on soil properties needs to be assessed. Therefore, it is necessary to assess the differences and changes in soil chemical properties with NT and CT in this rotation.

Studies conducted in semiarid dryland production systems have compared the effects of NT and CT on soil chemical properties. Tillage has been found to decrease SOC compared with NT (Follett and Peterson, 1988). Converting from the traditional WF rotation to more intense cropping systems such as a wheat–corn–fallow (WCF) rotation with NT in the Great Plains can increase SOC in surface soils (Sherrod et al., 2003; Bowman et al., 1999; Wood et al., 1991). The higher SOC under NT was attributed to reducing the amount of tillage and increasing soil water storage, which increases the amount of plant biomass returned to the soil surface. However, in an established WCF rotation in Nebraska, Wicks et al. (1988) found that there were no differences in surface SOC between NT and CT treatments over a 15-yr period (1964–1979). They also concluded that exchangeable K and Ca were found to decrease in both CT and NT over time, mostly due to removal in harvested grain. These nutrients were not replenished with fertilizer or lime applications over the life of the study. Research has shown that exchangeable bases decrease in soil not receiving lime as a result of acidification (Bouman et al., 1995). This is often due to removal of exchangeable bases from the exchange sites on clay and organic matter by H and Al (Singer and Munns, 1999). Differences in acidification between NT and CT can also result in differences in exchangeable bases. There is a need for data on the changes in exchangeable bases due to CT and NT on WS/CF production systems in the Great Plains, which rarely receive lime applications.

The time it takes to detect changes in soil properties

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Abbreviations: BS, base saturation; CEC, cation exchange capacity; CT, conventional till; NT, no-till; SOC, soil organic carbon; UAN, urea ammonium nitrate; WCF, wheat–corn–fallow; WF, wheat–fallow; WS/CF, wheat–sorghum/corn–fallow; WSF, wheat–sorghum–fallow.

after the conversion from CT to NT varies in the literature. While Dick et al. (1991) found little change after only 2 to 3 yr in Ohio, a number of studies have documented significant changes in some chemical properties over longer time periods. For example, significant increases in SOC were reported for the topsoil layer 4 to 28 yr after conversion to NT (Rhoton, 2000; Blevins et al., 1983; Lai et al., 1994; Ismail et al., 1994; Karathanasis and Wells, 1989; Shuman and Hargrove, 1985). The amount of precipitation in a given area will greatly influence the time it takes to notice changes in soil properties.

Soil acidification is generally more pronounced in areas of higher rainfall and on soils with low buffer capacities (Poss et al., 1995). However, the additions of ammonium- and urea-based fertilizers can result in an acceleration soil acidification compared with no fertilization in arid climates with naturally alkaline soils (Bowman and Halvorson, 1998). After 9 yr, Bowman and Halvorson (1998) reported that in Nebraska, pH values of the surface 5 cm in a WCF rotation were 6.3, 6.2, 5.8, 5.4, and 5.0 after annual applications of 0, 28, 56, 84, and 112 kg N ha^{-1} of either ammonium nitrate or anhydrous ammonia, respectively. The long-term acidification of a calcareous soil under a WC/SF rotation needs to be assessed.

Acidification rates have been reported to range from near 0 to 20 kmol H ha^{-1} in research located in a variety of climates and cropping systems (Poss et al., 1995). Factors affecting the acidification of soils include the effects of C, N, S, Mn, Al, and Fe cycles; addition of alkaline materials (e.g., lime); and addition of acids (e.g., acid rain deposition) (Helyar and Porter, 1989; Poss et al., 1995). In most soils, the contribution of the S, Mn, Al, and Fe cycles to long-term acidification are negligible and are often ignored when determining rates of acidification (Helyar and Porter, 1989). The N cycle plays a large role in the acidification in many agricultural soils, especially when ammonium-based fertilizers are applied (Helyar and Porter, 1989). The acidification of soils receiving ammonium-based fertilizer is driven by nitrification (2 mol of H^+ is produced per mole of NH_4^+) and is influenced by the crop N fertilizer uptake efficiency. The acidity caused by nitrification can only be neutralized by the release of OH^- as NO_3^- is assimilated by plants (Bouman et al., 1995). Acidification occurs when NO_3^- is lost due to leaching from the soil zone (Poss et al., 1995). In a study conducted by Poss et al. (1995), the calculated acidification rate of a wheat cropping system in semiarid Australia was between −1.0 and 1.4 kmol H^+ ha^{-1}. The acidification was based on the top 25 cm of soil receiving an annual application of N as diammonium phosphate and urea at a rate of 157 kg N ha^{-1}. They concluded that the near neutral acidification in the root zone was because of small losses of NO_3^- below the root zone.

Acidification of the soil surface in a WCF rotation has been found to be greater under NT compared with CT (Wicks et al., 1988). Other production systems have come to the same conclusion (Lilienfein et al., 2000; Mahler and Harder, 1984). Differences in acidification of the soil surface in NT and CT systems have been attributed to several factors:

1. Ammonium-based fertilizers are distributed in the soil profile differently (Dick, 1983). In water-limiting environments like the Central Great Plains, it is important to consider the influence of applying greater amounts of N fertilizer to NT systems compared with CT systems on soil pH due to the potential for increased productivity from increased water availability as a result of residue cover in NT systems (Halvorson et al., 1999).
2. Differences in grain yield and biomass production can result in varying C cycle effects. In water-limiting environments, NT has been shown to have higher average crop yields than CT due to the effects of surface residues on soil moisture retention (Bordovsky et al., 1998; Bonfil et al., 1999; Halvorson et al., 2000). The potential differences in production between NT and CT systems can result in greater organic anion exports in grain and accumulation of residue under NT. Differences in residue distribution in the soil profile in the two tillage systems may also influence acidification (Heenan and Taylor, 1995; Lilienfein et al., 2000; Jacobsen and Westerman, 1991).
3. Differences in amount of water leaching through the soil profile. The greater amounts of soil moisture retained under NT may increase NO_3^- leaching through the soil (Bouman et al., 1995). Although the factors listed above have been used to explain differences in surface soil acidification between NT and CT, the same principles influence acidification of soil at deeper depths.

There is little information on the long-term effects of NT and CT and annual applications of ammonium-based fertilizers on changes in chemical properties and the acidification rate of soil under the WS/CF rotation. Therefore, our study has four objectives: (i) compare the differences in soil chemical properties after 27 yr of NT and CT (1962–1989), (ii) compare the effects of converting from CT to NT on soil chemical properties over a 14-yr period (1989–2003) in relation to soil under NT for 41 yr, (iii) determine the acidification rate of soil under NT from 1962 to 2003, and (iv) determine the influence of tillage treatments on winter wheat, sorghum, and corn grain yields.

MATERIALS AND METHODS

Experimental Site

The study was conducted on a Holdrege silt loam (fine-silty, mixed, mesic Typic Argiustolls) at the University of Nebraska West Central Research and Extension Center, North Platte, NE. The site was converted from native prairie to a WF rotation under CT in the 1930s. In 1962, a field study was established at the experimental site to assess various weed control strategies in a 3-yr winter wheat–sorghum–fallow (WSF) rotation. This study showed that herbicides could be used to control weeds in NT as effectively as CT (Wicks et al., 1988). The study site consists of three adjacent strips, with each strip containing 1 yr of the 3-yr rotation (three crop-year strips). Grain sorghum was grown in the rotation following winter wheat from 1962 to 1992, and corn was substituted for grain sorghum from 1993 to 2003. Each crop-year strip had five weed management treatments and five replications arranged in a Latin square design. In 1962, the soil had a SOC content of 9.3 g kg^{-1} and a pH of 7.2 (1:1 soil:water) in the surface 15 cm. A complete description of the original experimental design and treatments are provided by Wicks et al. (1988).

Two of the five weed management treatments from each crop-year strip were used in this study (CT and NT). Tillage for the CT treatment included sweep plowing to a depth of approximately 5 cm twice after winter wheat harvest and disking to a depth of approximately 10 cm once in the spring. No herbicides were used in this treatment. The NT treatment used herbicides as the primary weed management strategy and has not been tilled since 1962. The CT and NT treatments were maintained from 1962 to 1989. In 1989, the CT treatment was converted to NT (called the CT to NT treatment). The original NT weed management regime was maintained continuously in the NT treatments from 1962 to 2003.

Both tillage treatments received identical annual N fertilizer inputs from 1962 to 1989 before planting wheat and sorghum as ammonium nitrate at an average annual rate of 48 kg N ha^{-1}. From 1990 to 2003, urea ammonium nitrate (UAN) was applied at an average annual rate of 50 kg N ha^{-1} before planting wheat and corn. A total of 114 kg P ha^{-1} was applied from 1962 to 2003 before planting winter wheat. Fertilizer application rates were based on typical rates adopted by producers using the WS/CF system.

Soil Sampling and Analysis

Soil samples were taken at depth increments of 0 to 5, 5 to 10, 10 to 15, and 15 to 30 cm in the spring of 1989 and 2003 from all replicate plots of the two tillage treatments in the three crop-year strips. Soil samples were air-dried and ground to pass through a 2-mm sieve before analysis. They were analyzed for pH (1:1 soil:water), percentage SOC using the Walkley–Black method (Nelson and Sommers, 1982), basic cations extracted by 1 *M* ammonium acetate (Knudsen et al., 1982), CEC using the Ba replacement method (Sumner and Miller, 1996), and Bray-P (Bray and Kurtz, 1945). Base saturation was calculated by dividing the sum of all bases (cmol kg^{-1}) by the CEC (cmol kg^{-1}) and then multiplying by 100 (Miller and Gardiner, 2001).

Acidification Rate

The acidification rate from 1962 to 2003 for the NT treatment was determined for the 0- to 15-cm depth. The soil pH in the surface 15 cm of the experimental site before implementation of the tillage treatments in 1962 was 7.2 (1:1 soil:water) (Wicks et al., 1988). The acidification rate for the CT treatment was not determined because the bulk density of this treatment was not determined in 1989 when CT was converted to NT (CT to NT). The acidification rate is defined as the rate of H ion accumulation in a defined soil volume and is estimated by the method of Helyar and Porter (1989) as follows:

$$\text{Acidification rate (kmol H}^+\ \text{ha}^{-1}\ \text{yr}^{-1}) =$$
$$\Delta\text{pH} \times \text{pHBC} \times \text{BD} \times V/\text{TP}/1000$$

where ΔpH is the change in pH over the time period, pHBC is the pH buffer capacity of the soil at the end of the time period (mol H^+ kg^{-1} pH $unit^{-1}$), BD is the bulk density of the soil (kg m^{-3}), V is the volume of soil per unit area (m^3 ha^{-1}), and TP is the time period (yr).

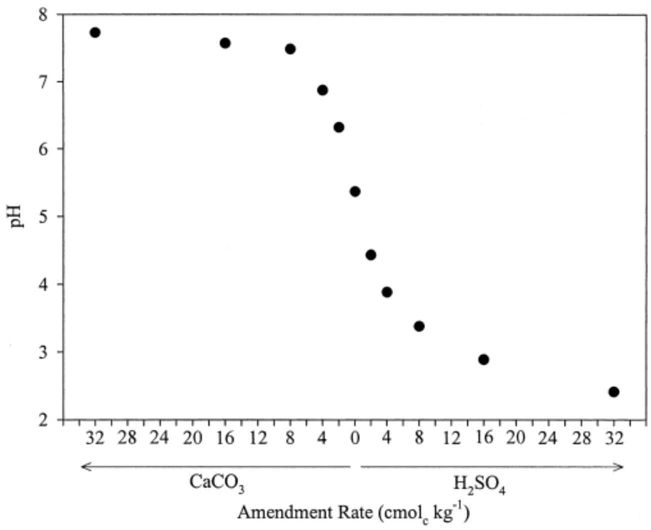

Fig. 1. Titration curve for the no-till treatment. Each point is averaged over depth (0–5, 5–10, and 10–15 cm), four replications, and three crop-year strips.

To determine the pH buffer capacity of the NT treatment and to check for variability in the pH buffer capacity across the experimental plots, buffer capacities were determined at each depth for Replications 1 through 4. The pH buffer capacities were determined by titrating 50 g of each soil sample (air-dried and passed through a 2-mm sieve) in sealable polyethylene bags with H_2SO_4 and $CaCO_3$ applied at rates of 0, 2, 4, 8, 16, and 32 cmol (H^+ or $1/2Ca^{2+}$) kg^{-1} (Magdoff and Bartlett, 1985). The rates of $CaCO_3$ were added to the soils as a suspension in distilled water. After amendments were added, they were mixed with the soil. Distilled water was added to each treated soil sample to reach field capacity, and then the bags were sealed and stored at room temperature for 1 mo. After 1 mo, the treated soil samples were air-dried and ground to pass through a 2-mm sieve for determination of pH (1:1 soil:water). The buffer capacities varied little between replications and depths. Therefore, pH readings at each H_2SO_4 and $CaCO_3$ rate were averaged over replication and depth to determine the final pH buffer capacity curve (Fig. 1).

Grain Yields

At maturity, grain from each tillage treatment within crop-year strips was harvested and removed each year of the study since 1962 although grain yields were not recorded in some years. Crop residues were not removed from the plots.

Grain yields for winter wheat, sorghum, and corn were recorded 26 out of 41, 18 out of 30, and 9 out of 10 yr, respectively.

Statistical Analysis Methods

Analysis of variance was conducted using the Randomized Complete Block Model from Statistix 8 (Analytical Software, 2003). Fifteen replicate plots were used in the statistical analysis of each tillage treatment (five replicate plots for three crop-year strips). Reported values were the means of 15 soil samples. Long-term effects of tillage treatments on soil properties were assessed for the 1962 to 1989 period based on comparison of the soil samples from CT and NT treatments that were taken in 1989. Changes in soil properties due to conversion of CT to NT in relation to the long-term NT treatment were evaluated from the soil samples taken from the CT to NT and NT plots in 2003. Analysis of variance was used to

Table 1. Effect of tillage treatments on soil chemical properties at depths of 0 to 5, 5 to 10, 10 to 15, and 15 to 30 cm for 1989 and 2003. Values are the average of five replications of the three crop-year strips (15 replications).

Year	Sample depth	Tillage†	pH	CEC‡	BS§	SOC¶	K	Ca	Mg	Bray-P
	cm			$cmol_c\ kg^{-1}$	%	$g\ kg^{-1}$	$mg\ kg^{-1}$			
1989	0–5	NT	5.1 a	15.6 a	46.3 a	10.7 a	670 a	803 a	171	79.4 a
		CT	5.6 b	13.0 b	64.9 b	10.2 a	770 b	959 b	196	71.8 b
	5–10	NT	5.9 a	13.0 a	76.6 a	7.7 a	546 a	1317 a	223	43.4 a
		CT	5.7 b	13.3 a	71.6 b	8.7 b	602 b	1209 b	214	51.5 b
	10–15	NT	6.5 a	12.8 a	97.5 a	7.4 a	526 a	1749 a	291	22.5 a
		CT	6.3 b	13.2 a	92.2 b	7.9 a	554 a	1659 a	286	26.6 a
	15–30	NT	6.8 a	12.8 a	99.6 a	5.6 a	436 a	1812 a	312	12.7 a
		CT	6.9 a	12.9 a	99.1 a	5.8 a	432 a	1806 a	322	13.1 a
				Analysis of variance						
Tillage			NS#	NS	NS	NS	***	NS	NS	NS
Depth			***	***	***	***	***	***	***	***
Tillage × depth††			***	***	***	**	***	**	NS	***
2003	0–5	NT	5.2	15.6	48.0	10.6	635	878	158	62.5
		CT to NT	5.2	15.4	48.6	10.2	703	845	157	63.1
	5–10	NT	5.4	15.5	60.8	7.7	546	1241	193	41.3
		CT to NT	5.4	14.6	65.6	7.5	590	1232	194	41.2
	10–15	NT	5.9	14.7	82.9	7.8	554	1689	255	20.5
		CT to NT	6.0	14.8	85.9	7.4	586	1769	275	18.0
	15–30	NT	6.6	14.3	98.6	5.8	506	2013	324	9.3
		CT to NT	6.5	14.6	97.1	5.7	526	2008	335	8.2
				Analysis of variance						
Tillage			NS	NS	NS	NS	***	NS	NS	NS
Depth			***	*	***	***	***	***	***	***
Tillage × depth			NS	NS	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† NT, no-tillage; CT, conventional tillage.
‡ CEC, cation exchange capacity.
§ BS, base saturation.
¶ SOC, soil organic carbon.
# NS, not significant at the 0.05 probability level.
†† Mean separations (LSD) between tillage treatments for each depth were determined for significant tillage × depth interactions. For each depth, tillage treatments with different letters are significantly different at the 0.05 probability level.

test tillage and soil depth main effects and the tillage × depth interactions in 1989 and 2003. Least significant difference (LSD) was used to determine the differences between tillage treatment means for each depth in 1989 and 2003 for soil properties with significant tillage × depth interactions. The soil acidification rate in the NT treatment was estimated from soil samples taken in 2003 and using soil analysis results as recorded in Wicks et al. (1988). Changes in exchangeable bases for the different soil depths in the NT and CT to NT treatments were determined by soil samples taken in 1989 and 2003. Analysis of variance was used to test for differences between years for each tillage treatment and soil depth. Grain yield data were analyzed to determine the effects of tillage treatments on productivity. Analysis of variance was used to test year and tillage main effects and the year × tillage interactions for winter wheat, sorghum, and corn grain yields. Due to significant year × tillage interactions, LSD was used to determine the differences between tillage treatment means for each year. Significance was determined for all analysis at the 0.05 probability level.

RESULTS AND DISCUSSION

Treatment Effects on Soil Properties from 1962 to 1989

In 1989, there were differences in soil properties between sampling depths when averaged over tillage practices (Table 1). For both NT and CT, soil pH increased with depth (Table 1). This may be partially attributed to acidification from nitrification of ammonium-based fertilizer in the surface soil layers. Tillage influenced the soil properties at some sampling depths. In 1989, there were no differences in soil properties due to tillage practices when averaged over the 0- to 30-cm depth except for extractable K. However, there were significant tillage × depth interactions for pH, CEC, BS, SOC, K, Ca, and Bray-P. Soil pH was lower for NT (5.1) compared with CT (5.6) in the 0- to 5-cm depth. This can be attributed to the lack of redistribution of higher-pH subsoils and ammonium-based fertilizer deeper in the soil profile from tillage under NT. However, at the 5- to 10-cm depth, the pH from CT (5.7) was significantly lower than NT (5.9). Redistribution of lower-pH surface soil and ammonium-based fertilizers by tillage into the 5- to 10-cm depth due to tillage was likely the reason for the difference. There were no differences in pH between NT and CT at depths greater than 10 cm. The pH for NT and CT averaged 6.4 and 6.9 at the 10- to 15- and 15-to 30-cm depths, respectively. Mahler and Harder (1984) also found differences in soil pH between NT and CT. Their results reported greatest acidification with NT at the 0- to 7.5-cm depth, whereas for CT it occurred at the 7.5- to 15-cm depth. They concluded that the placement of the N fertilizers under the different tillage systems and subsequent nitrification resulted in these differences.

The significant tillage × depth interaction for SOC was due to greater SOC in CT at the 5- to 10-cm depth compared with NT (Table 1). This difference was also likely the result of mixing crop residues by tillage in the

CT treatment. There was no difference in SOC between CT and NT in the 0- to 5-cm depth. This was contrary to past research results, which show significantly higher SOC levels in NT compared with CT (Dick, 1983). However, these results agree with observations by Wicks et al. (1988) on a WCF rotation.

In our study, the NT treatment had a 20% higher CEC in the 0- to 5-cm depth compared with CT (Table 1). Other research has shown increases in CEC in the surface soils of NT systems compared with CT due to increased SOC (Jaiyeoba, 2003; Ciotta et al., 2003). However, in this study, there were no significant differences in SOC between NT and CT in the soil surface. It is unclear why NT had a higher CEC than CT in the 0- to 5-cm depth. A more in-depth investigation is needed to determine the cause of this observation. The 0- to 5- and 5- to 10-cm layers had less extractable K and Ca in NT compared with CT, and although not statistically significant, the 0- to 5-cm layer also had less extractable Mg in NT than in CT, and the relative magnitude of differences for these cations was considerably larger than at lower depths. The higher yields and acidification under NT likely resulted in greater removal of these cations in harvested grain and displacement of the cations from the cation exchange sites by H and Al over time compared with CT. Base saturation of the NT treatment was reduced compared with the CT at the 0- to 5-cm depth, which was consistent with the lower extractable bases and pH in this layer (Table 1).

Treatment Effects on Soil Properties from 1989 to 2003

The conversion of CT to NT in 1989 produced similar environments in the soils in 2003 as in the treatment with continuous NT since 1962. For all soil properties measured, there were no significant tillage $\times$ depth interactions in 2003 (Table 1). In 2003, there were still differences in soil properties between sampling depths when averaged over tillage practices, and there were no differences between tillage practices when averaged over the 0- to 30-cm depth except for the amount of extractable K, which resulted from the CT treatment imposed from 1962 to 1989 (Table 1).

Comparisons between soil properties in 1989 and 2003 show that for both tillage treatments, pH decreased at all depths, except the 0- to 5-cm depth in the NT treatment, which increased slightly. Soil organic C did not increase over the 14-yr period in both tillage treatments. This supports the results above, which showed that after 27 yr of NT, SOC was not different than CT. Extractable K and Ca appear to be leaching through the soil profile in both tillage treatments. In 2003, the extractable K and Ca were higher in the 15- to 30-cm depth than in 1989 for both tillage treatments (Table 2). In the CT to NT treatment, the extractable K, Ca, and Mg are lower in the soil surface in 2003. This is likely a result of crop grain removal and/or leaching. Removal of P in harvested grain is likely the reason for the decreased concentrations of Bray-P at most sampling depths for both tillage treatments (Table 2). The average decline of Bray-P over all depths was 0.44 and 0.58 mg Bray-extractable P kg^{-1} yr^{-1} for the NT and CT to NT treatments, respectively. During 1989 and 2003, only 30 kg P_2O_5 ha^{-1} was applied to all treatment plots. In both 1989 and 2003, pH, BS, Ca, and Mg increased with depth while SOC, K, and Bray P decreased with depth for NT, CT, and CT to NT treatments (Table 1).

Acidification Rate

A titration curve was developed to determine the pH buffer capacity of the NT treatment in 2003 for the 0- to 15-cm soil depth (Fig. 1). The soils in this study were highly buffered above pH 7 and below pH 4. Between pH values of 4 and 7, the relationship between pH and $cmol_c$ addition kg^{-1} was mostly linear, and therefore, linear regression was used to determine the pH buffer capacity [mol_c (H^+) kg^{-1} unit change in pH^{-1}] of the NT treatment within this pH range. Based on this linear regression, the pH buffer capacity was 0.025 mol H^+ kg^{-1} unit change in pH^{-1} between pH values of 4 and 7 (r^2 = 0.99). For soil depths 0 to 5, 5 to10, and 10 to 15 cm, the buffer capacities varied only by a range of 0.004 mol H^+ kg^{-1} unit change in pH^{-1} (0.027, 0.025, and 0.023 mol H^+ kg^{-1} unit change in pH^{-1}, respectively). The acidification rate for NT from 1962 to 2003 in the 0- to 15-cm soil layer was 1.3 kmol H^+ ha^{-1} yr^{-1}. Values for the acidification rate calculation were

$$\Delta\text{pH} = 1.7\ [7.2 - 5.5(\text{Table1})]$$

$$\text{pHBC (mol H}^+\ \text{kg}^{-1}\ \text{pH unit}^{-1}) = 0.025$$

$$\text{BD (kg m}^{-3}) = 850.9$$

$$V(\text{m}^3\ \text{ha}^{-1}) = 1500$$

$$\text{TP (yr)} = 41$$

The acidification rate in this study was comparable to calculated acidification rates ranging from –1 to 1.4 kmol H^+ ha^{-1} yr^{-1} in the semiarid southeast Australia wheat belt (Poss et al., 1995). The objective of the research by Poss et al. (1995) was to determine the components of the proton budget and the net acidification rate that occur under wheat cultivation in Australia. The approach determines the inputs and outputs of protons (H^+) to and from the soil. The proton budget included effects from the N cycle, C cycle, Mn cycle, Al cycle, and acid additions. Poss et al. (1995) reported that the major factor in the acidification was loss of NO_3^- below the root zone. It is possible this may be the case in this study as well, but we did not measure NO_3^- leaching losses and therefore cannot confirm this finding. However, using a computer model that calculated the daily soil water balance of the WCF rotation over a 10-yr period (1990–2000), the average percentage of water from precipitation (average = 454 mm yr^{-1}) moving below the 30-cm depth was 35% (unpublished data, 2005). We do not have the data to calculate the water balance for the entire 41-yr period, but these data show that there was water moving below the 15-cm depth in the experimental plots that can leach NO_3^-. Also, data showing leaching of basic cations provide support that NO_3^- not being immobilized or taken up by crops is

Table 2. Comparison of selected soil properties between 1989 and 2003 for the no-tillage (NT) and conventional tillage (CT) to NT treatments. Analysis of variance is based on 15 replications (five replications from each of the three crop-year strips) for each tillage treatment. Values are presented in Table 1.

Tillage	Sample depth	pH	SOC†	K	Ca	Mg	Bray-P
	cm						
NT	0–5	*	NS	NS	NS	NS	***
	5–10	***	NS	NS	NS	**	NS
	10–15	**	NS	NS	NS	NS	NS
	15–30	***	NS	***	***	NS	***
CT to NT	0–5	***	NS	*	***	***	**
	5–10	***	**	NS	NS	**	**
	10–15	*	NS	*	NS	NS	*
	15–30	***	NS	***	**	NS	***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† SOC, soil organic carbon.

Table 3. Quantity of ammonium nitrate and urea ammonium nitrate (UAN) applied to each tillage treatment from 1962 to 2003 and their potential acidity and lime equivalent.

N source	N applied 1962–1989	N applied 1990–2003	Total	Potential acidity†	AOAC lime equivalent‡
	kg N ha^{-1}			kmol H$^+$ ha^{-1}	kg $CaCO_3$
Ammonium nitrate	1290	0	1290	92	2320
UAN§	23	650	673	48	1210
			Total =	140	3530

† Calculated based on the assumption that all fertilizer N was oxidized to NO_3^- and 1 mol of NH_4^+ and $(NH_2)_2CO$ each results in the production of 2 mol of H$^+$. (Based on total N applied, 1 mol of total N is equal to 1 mol of H$^+$.)
‡ Amount of $CaCO_3$ ($CaCO_3$ equivalent = 100%) required to neutralize acidity created by N fertilizer. [Based on 1.8 kg $CaCO_3$ per kg N for ammonium nitrate and UAN (Rasmussen and Rohde, 1989; Spies and Harms, 2004).]
§ 32% N.

leaching as well. Further research would help determine the exact causes of the acidification in this soil.

During the course of this study, a total of 1963 kg N ha^{-1} was applied in all treatment plots since 1962 (Table 3). The production of H$^+$ from nitrification of NH_4^+ from ammonium nitrate and urea from UAN is shown in the following reactions (Bouman et al., 1995; Tisdale et al., 1993):

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O \quad [1]$$

$$(NH_2)_2CO + 4O_2 \rightarrow 2NO_3^- + 2H + CO_2 + H_2O \quad [2]$$

Because the NO_3^- in ammonium nitrate does not produce H$^+$, and assuming that all N fertilizer was oxidized to NO_3^-, each kmol of total N applied is equal to 1 kmol H$^+$. The total amount of potential acidity from total applied N was equivalent to 140 kmol of H$^+$ ha^{-1} in the 41 yr since 1962. In contrast, about 53 kmol H$^+$ ha^{-1} (1.3 kmol H$^+$ ha^{-1} yr^{-1} × 41 yr) accumulated in the surface 15 cm of the NT plots during this time (Table 3). This amount of soil acidification represents 38% of the potential acidity that would accrue from the application of N fertilizer and is equivalent to 724 kg N ha^{-1} contributing 100% to soil acidification over the 41 yr (18.6 kg N ha^{-1} yr^{-1}) based on the assumptions listed above. Crop uptake of fertilizer N was most likely the major reason why not all of the potential acidity from N fertilizer ended up as accumulated H$^+$. Denitrification was probably less of a factor.

Grain Yields

No-till increased long-term average winter wheat and grain sorghum yields compared with CT (Table 4). There were significant differences in average winter wheat grain yields from 1966 to 1983 and in average sorghum grain yields from 1964 to 1988 between CT and NT. No-till increased the average winter wheat and sorghum grain yields compared with CT by 300 and 1060 kg ha^{-1}, respectively. In general, numerous studies have demonstrated that increased crop yields from NT were attributed to greater soil moisture storage due to residue cover in cropping systems in arid and semiarid environments (Bordovsky et al., 1998; Bonfil et al., 1999; Halvorson et al., 2000). After CT treatment plots were converted to NT in 1989, there was a significant residual effect on grain yields of corn and winter wheat in the first year grain yields were measured (Table 5). Thereafter, yields in converted and continuous NT treatments were similar. The winter wheat and corn yields from 1994 to 2003 averaged over tillage were 2880 and 6100 kg ha^{-1}, respectively. The effects of soil properties on grain yield cannot be clarified due to potential influences of tillage practice on soil moisture storage.

CONCLUSIONS

Differences in tillage practices (NT and CT) over a 27-yr period resulted in differences in soil chemical properties of a WSF rotation in the Central Great Plains at some depths to 30 cm. However, within 14 yr after converting CT to NT, there were no longer differences in the soil chemical properties compared with long-term NT (41 yr). After 27 yr, NT had lower soil surface pH, extractable K, Ca, and BS compared with NT. However, NT did not increase the SOC levels in the 0- to 5-cm soil depth. Increased winter wheat and sorghum grain

Table 4. Sorghum and winter wheat grain yields from 1964 to 1988 as affected by tillage system. Values are the average of five replications.

Year	Sorghum† CT	Sorghum† NT	Winter wheat CT	Winter wheat NT	Annual precipitation
	kg ha^{-1}				cm
1964	3258 a‡	3648 b	–	–	47.5
1965	4115 a	4596 a	–	–	68.1
1966	3832 a	4786 a	3062 a	3013 a	44.7
1967	2470 a	3448 b	3022 a	2966 a	44.0
1968	4579 a	5610 a	1798 a	2024 a	51.4
1969	1012 a	1543 a	2160 a	2514 a	43.0
1970	2014 a	3287 b	1445 a	1634 b	35.4
1971	1616 a	4796 b	1855 a	2356 a	58.9
1972	1373 a	2059 b	2511 a	2926 a	45.8
1973	2693 a	4623 b	2325 a	2693 a	54.1
1974	2970 a	3180 a	2955 a	3021 a	32.5
1975§	966	3118	2439 a	2966 b	45.3
1976§	192	3321	1812 a	2795 b	44.7
1977	1834 a	3919 b	2631 a	3014 a	57.3
1978	2875 a	4592 b	1430 a	1689 a	38.0
1979	–	–	3060 a	3875 a	57.5
1980	–	–	2357 a	2787 a	41.0
1981	5361 a	6994 b	2843 a	2773 a	61.9
1982	–	–	3261 a	3290 a	57.8
1983	4358 a	3674 b	2608 a	2584 a	48.2
1988	4635 a	5248 a	–	–	51.6
Average	3062	4125	2421	2718	
	Analysis of variance				
Year	***		***		
Tillage	***		***		
Year × tillage	***		**		

** Significant at the $P = 0.01$ level.
*** Significant at the $P = 0.001$ level.
† CT, conventional tillage; NT, no-tillage.
‡ Mean separations (LSD) between tillage treatments for each year were determined due to a significant year × tillage interaction. For each crop and year, tillage treatments with different letters are significantly different at the 0.05 probability level.
§ Plot management error resulted in low sorghum grain yields under CT. These yields were not included in the statistical analysis.

Table 5. Corn and wheat grain yields from 1993 to 2003 as affected by tillage system. Values are the average of five replications.

Year	Corn CT to NT†	Corn NT	Winter wheat CT to NT	Winter wheat NT	Annual precipitation
	kg ha^{-1}				cm
1993	7068 a‡	7646 b	–	–	70.0
1994	8569 a	8851 a	2365 a	2452 b	43.4
1995	4037 a	4678 a	2779 a	2838 a	48.7
1997	7841 a	8486 a	3236 a	3364 a	50.7
1998	8585 a	7052 b	3926 a	3676 a	51.0
1999	6895 a	6754 a	3185 a	3264 a	48.2
2000	1668 a	1807 a	2091 a	2136 a	43.0
2002	7726 a	7924 a	2463 a	2515 a	23.7
2003	3329 a	3388 a	2801 a	2922 a	42.9
Average	6081	6117	2856	2896	
	Analysis of variance				
Year	***		***		
Tillage	NS		NS		
Year × tillage	***		***		

*** Significant at the $P = 0.001$ level.
† CT, conventional tillage; NT, no-tillage.
‡ Mean separations (LSD) between tillage treatments for each year were determined due to a significant year × tillage interaction. For each crop and year, tillage treatments with different letters are significantly different at the 0.05 probability level.

yields and a higher export of bases in grain were likely the reason for lower exchangeable K and Ca in the soil surface under NT. Findings from this study have agreed with past research that has shown lower pH in the soil surface under NT compared with CT. Differences in the soil pH between NT and CT after 27 yr were likely due to the redistribution of soil and N fertilizers with tillage. The WC/SF rotation under NT acidified at a rate of 1.3 kmol H^{+} ha^{-1} yr^{-1} in the surface 15 cm from 1962 to 2003. In this system, only 38% of the potential acidity from the total applied N was realized. The applications of ammonium-based fertilizers and subsequent nitrification and leaching of NO_3^- may have been the primary cause of acidification in this soil. The apparent movement of soil water below the sampling depth and the leaching of bases in this soil over time provide evidence that NO_3^- leaching may have contributed to the acidification of the NT system. It appears that if management practices remain the same, the soil will continue to slowly acidify. Low pH in the soil surface may lead to the inactivation of certain herbicides resulting in a need to apply lime. At this rate of acidification, lime applications to prevent Al and Mn toxicity may be needed in the future on this soil.

No-till in this cropping system increased long-term grain yield averages for winter wheat and grain sorghum compared with CT. Sorghum grain yields increased under NT compared with CT to a greater extent than winter wheat. This study was not able to differentiate between the influences of soil moisture status and changes in soil chemical properties on grain yield under CT and NT. Therefore, more research is needed to determine the role of changing soil chemical properties over time on crop yields.

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