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Soil properties can be altered by tillage and rotation, however, these effects cannot be detected in short-term studies. This study was conducted to assess the long-term (14 years) tillage and rotation impacts on selected soil surface properties. A long-term experimental site comprised of two tillage systems [no tillage (NT) and conventional tillage (CT)], and three crop rotations [corn (*Zeamays*)-soybean (*Glycinemax*), corn-soybean-wheat (*Triticumaestivum*), and corn-soybean-wheat-alfalfa (*Medicagosativa*)] were used for the present analysis. Surface (0-15 cm) soil samples were collected every year from 1991 through 2004 and analyzed for soil organic matter (SOM), available P, available K, and nitrate (NO_3

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[16]. Immobile nutrients such as P could be concentrated at the soil surface as a result of applying NT [17]. Mineralization of SOM may significantly affect the concentration of some nutrients like P and N, but does not affect K concentration Calonego et al. [18] and Karlen et al. [19] found that there was no difference between K concentration under NT and CT system. At the soil surface, nutrients concentrations are higher but they may decrease with depth under NT; however, CT may result in a homogenous distribution of these nutrients with depth [7,13] in their work in Spain found that P and K concentrations at the soil surface (0-15 cm) were higher under NT compared with CT, which could be due to the high SOM concentration under NT as well as maintaining the applied P fertilizers. Further, crop rotation may also impact the distribution of nutrients such as P and K in the soil profile [13] The present study was conducted with the specific objective to assess the long-term (14 years) tillage and crop rotation impacts on soil organic matter and soil nutrients.

Materials and Methods

Experiment location and design

The experimental site is located at the Southeast Research Farm of the South Dakota State University South Dakota located at Clay County (43° 02' 58" N, 96° 53' 30" W), South Dakota (Figure 1). The experiment was initiated in 1990 to assess the impact of different tillage systems and crop rotations on the long term production and economics of cropping systems. The first growing season started in the spring of 1991. The experiment was conducted on Egan soil series (Fine-silty, mixed, superactive, mesic Udic Haplustolls) [20]. The study soil series occupies 3,931,019 acres (or 99.6% of the total area occupied by this soil series in USA), and it is nearly level with a slope of 0-1%. The daily average temperature ranges from -14.1°C in January to 31.8°C in July, and the mean annual precipitation is 627.4 mm [21].

The experimental site has 80 plots distributed randomly in a complete block design. Each plot has a width of 20 m and a length of 100 m. The experimental plots were designed to be large so that field operations could be carried out using commercial sized farm equipment. The experiment had three different tillage systems which were no till (NT), conventional till (CT), and ridge till (RT). Ridge till system had only a two year crop rotation of corn (*Zea . a* L.) – soybean (*G c e. a* L.). In the fall of every year after harvest, residues of corn, soybean, and wheat were disked and chiseled in all of the conventionally tilled plots. The RT plots were excluded from this study because it had only one rotation system. Both NT and CT had three rotation systems, which were a two year rotation of corn-soybean, a three year rotation of corn-soybean-wheat (*T c . ae .* L.), and a four year rotation of corn-soybean-wheat-alfalfa (*Med cag a a* L.) (Figure 1).

Soil sampling and analyses

It is of importance to mention that the data we used here were collected from 1991 to 2004, but they have not been published in scientific journals. Also, not all of the soil properties were analyzed every year; that is why we selected the years that have data of the same soil properties. Soil samples were collected every fall after harvesting the crops from 1991 to 2004 from each plot. Three cores of soil samples from each plot were collected at a depth of 0-15 cm using a 3.5-cmdiameter and 50-cm-tall hand probe(Inc. JMC Soil Samplers) and mixed together to make a composite sample. Composited soil samples were labeled, sealed in plastic zip-lock bags, and transported to the laboratory. Every year, after bringing the soil samples to the laboratory, all of them were air dried, ground, and sieved to pass a 2-mm sieve. All of the analyses were carried out using the soil fine fraction (<2 mm in diameter).

Soil organic matter (SOM) was measured using the loss on ignition (LOI) method [22]. Briefly, 10 g of each soil sample was weighed in an aluminum crucible, transferred to a muffle at a temperature of 450-500°C for 4 h, and then the loss of weight was determined. P was extracted using a 0.5 M $NaHCO_3$ solution and then the extraction was measured colorimetrically [23]. Nitrate was determined using a nitrate-specific ion electrode [24]. Available K was extracted by 1 M NH_4OAc at pH 7.0, and it was determined using an atomic absorption (AA) [25].

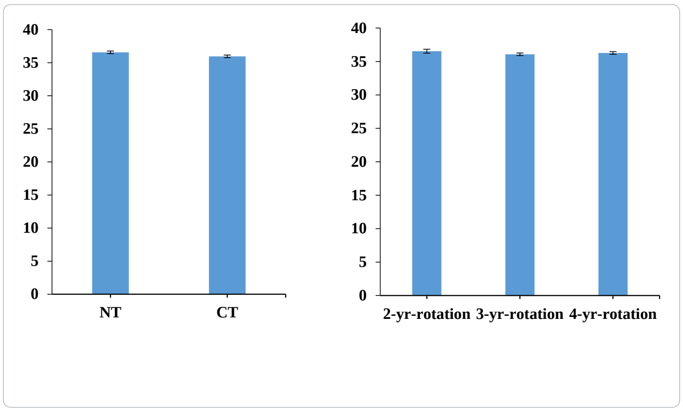
Statistical analysis

Soil organic matter and soil nutrients that measured in all of the tillage and crop rotation systems of each year were analyzed separately and together. An analysis of variance (ANOVA) was conducted using the SAS software (version 9.3, SAS Institute, Cary, NC, USA). An estimate for the least significant difference (Duncan's LSD) between two tillage systems and three crop rotations were obtained using the 'GLIMMIX procedure' in SAS. Statistical differences were declared significant at the$\alpha = 0.05$ level.

Results and Discussion

Tillage and crop rotation impacts on soil organic matter

The NT system increased SOM (37 g kg^{-1}) for the 0-15 cm depth after 14 years compared to CT system (36 g kg^{-1}) (Figure 2A). This was attributed to the mixing of SOM content within the plowing depth (25 cm) and the increased aeration under CT treatment leading to SOM decomposition [26,27]. Compared with SOM concentration under NT in 1991, its concentration significantly increased across the years of the experiment under all of the crop rotation systems. For example, under the 4-year-rotation, the highest and lowest SOM concentrations of 39.3 and 32.6 g kg^{-1} were observed in 2004 and 1991, respectively (Table 1). Furthermore, SOM concentrations under CT followed atrend similar to those under NT (Table 1). In 2002, however, SOM concentration under NT and CT drastically declined, which could be attributed to the higher temperature in that year leading to more oxidation of SOM. Concentrations of SOM under CT were lower than those under NT in almost all of the years of the experiment, which could be due to the mixing action of the surface layer to the depth of the plowing (25 cm) and the increased aeration and oxidation under CT [28] (Table 1).



CT for individual years were mostly not significant especially under the 2 and 3-year-rotations (Table 1). In the 4-year-rotation; however, SOM concentration under NT was significantly higher by 5.4, 4.7, and 4.1% than that under CT in 1994, 1997, and 2004, respectively (Table 1).

Generally, SOM concentrations under the three different crop rotations (corn-soybean, corn-soybean-wheat, and corn-soybean-wheat-alfalfa) were not significantly different among each other (Figure 2B), which agreed with what was observed by Karlen et al. [29]. Moreover, data in Table 2 indicated that there was no impact of the crop rotations under NT system on SOM concentration in almost all of the years [30]. In contrast, crop rotations under CT impacted SOM concentration in some of the years. For example, SOM concentrations under the 2-year-rotation were significantly higher than that under the 3 and 4-year-rotation systems for 1994, 2002, and 2004 (Table 2). The majority of SOM under the 2-year-rotation was sourced from corn. Organic materials sourced from corn have wider C/N ratio and decompose slower compared with those sourced from legumes [30]. That may interpret why the 2-year-rotation had some higher values of SOM under CT compared with those under the other two rotations under CT. Overall, NT system enhanced the accumulation of SOM compared with CT. However, crop rotation systems did not significantly impact SOM concentration.

Tillage and crop rotations impacts on available phosphorus

Averaged across all the years, the available P concentrations under NT vs CT systems were significantly different. For example, available P concentration of 208 mg kg^{-1} under NT was significantly higher (8.4%) compared with that of 191 mg kg^{-1} under CT (Figure 3A). Similar findings were also found by Wyngaard et al. [31]. In their work on tillage effects on soil properties of a Mollisol in Argentina. On a yearly basis, available P concentration was significantly higher under NT vs CT under all of the rotation systems (Table 3). For example, in the 4-year-rotation, P concentrations were higher under NT and these were 40, 30, 22, 32.6, and 21.5% higher than those under CT for 1994, 1995, 1997, 2002, and 2004, respectively. This high concentration of available P under NT vs CT could be due to the application of P fertilizer to crops every year which may cause an accumulation of P at the soil surface as a consequence of the low mobility of P and due to the mixing of the plowing depth, which distributed the P content within a 25 cm depth. In contrast, in the yearly basis in the 2 and 3-year-rotations, NT and CT exhibited no significant impact on available P concentration [32] (Table 3).

Available P concentrations differed significantly among all of the three crop rotations. For example, its concentration under the 2-year-rotation of 236 mg kg^{-1} was significantly higher than that under the 3-year-rotation of 211 mg kg^{-1}, which was higher than that of 172 mg kg^{-1} under the 4-year-rotation (Figure 3B), similar results were found in Canada [30], Across the years of the experiment under NT and for the 4-year-rotation, P concentration under NT significantly decreased from 1991 to 1997, but significantly increased in both 2002 and 2004 (Table 4). However, in the 2 and 3-year-rotations under NT, available P concentration generally increased from 1991 to 2004 (Table 4). In contrast, available P concentration generally increased from the beginning of the experiment to 2004 under NT and CT in both the 2 and 3-year-rotations (Table 4). Data in Table 4 under NT revealed that there was almost no significant difference in available P concentrations under all of the three crop rotations. However, under CT, available

P concentrations under the 4-year-rotation were signi cantly lower compared with those under the other two crop rotations (Table 4), which could be attributed to the higher demand of P for the [33] under the 4-year-rotation than that under the other two crop rotations.

Tillage and crop rotations impacts on soil nitrate (NO_3^- -N)

In general, averaged across all of the years, the nitrate (NO_3^-) concentrations for the soil surface (0-15 cm) under the two tillage

	1991	1994	1995	1997	2002	2004
	17.8a†	19.3a	15.0a	20.7a	20.8a	17.5a
	17.2ab	16.4a	11.1b	15.7b	13.3b	15.7ab
	13.5b	15.3a	11.5b	12.1b	12.9b	12.8b
	19.9a	15.0b	11.0a	18.3a	17.9a	20.8a
	22.1a	19.4a	10.5a	16.8a	18.0a	19.0a
	12.3Bb	16.2ab	12.8a	15.6a	14.9a	20.3a

†Means with different letters within a column under each tillage system are significantly different at P<0.05.

Soil nitrate (NO_3^-) concentrations as impacted by crop rotations under no tillage and conventional tillage at the soil surface layer (0-15 cm).

	1991	1994	1995	1997	2002	2004
	419bA†	412bA	472aA	372cA	326dA	275eA
	359abB	336bcB	364aB	317cB	311cA	315cA
	351aA	362aA	379aA	313bA	286bcA	277cB
	351abA	387aA	380aA	340bcA	308cA	329bcA
NT	390bA	451aA	389bA	337cA	275dA	270dA
CT	357bA	433aA	412aA	333bA	322bcA	293cA

†Means with different lower case letters within a row are significantly different at P<0.05. Higher case letters show the differences between NT and CT for each year and under each crop rotation separately.

Soil potassium (K) concentration differences between no tillage and conventional tillage under three rotation systems for the soil surface layer (0-15 cm).

	1991	1994	1995	1997	2002	2004
	419a†	412a	472a	372a	326a	275a
	351b	362b	379b	313b	286b	277a
	390a	451a	389b	337ab	275b	270a
	359a	336b	364b	317a	311a	315a
	351a	387ab	380b	340a	308a	329a
	357a	433a	412a	333a	322a	293a

†Means with different letters within a column under each tillage system are significantly different at P<0.05.

Soil available potassium (K) concentrations as impacted by crop rotations under no tillage and conventional tillage at the soil surface layer (0-15 cm).

rotation for each separate year, however, available K concentration under NT and CT was not signi cantly di erent (Table 7). Within the crop rotations, the 3-year-rotation had the lowest concentration of available K (340 mg kg^{-1}) which was signi cantly di erent from the other two rotations, and there was no signi cant di erence between its concentration in the 2-year-rotation (365 mg kg^{-1}) and 4-year-rotation (357 mg kg^{-1}) (Figure 5B). Data in Table 8 indicated that the available K concentrations under NT in each separate year were signi cantly lower under the 3-year-rotation system than those under the other two rotations. However, under the CT system, the available K concentrations were not signi cantly di erent among the three crop rotation systems.

Conclusions

In the long term experiment (14 years) data showed that the SOM concentration at a depth of 0-15 cm under NT system was signi cantly higher than that under CT. However, there was no signi cant di erence in SOM concentrations between under crop rotations. Soil P concentration under NT was signi cantly higher compared with that under CT. e 2-year-rotation had the highest P concentration followed by the 3-year-rotaion, and the lowest concentration was observed in the 4-year-rotation. Nitrate concentration under NT was not signi cantly di erent from that under CT; however, the 4-year-rotation had the highest NO_3^- concentration followed by the 3-year-rotation, and the lowest concentration was observed in the 2-year-rotation. e K concentration was not signi cantly di erent under NT and CT; however, the 3-year-rotation had the lowest K concentration compared with the other two rotations.

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