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Crop yield and soil condition under ridge and chisel-plow tillage in the northern Corn Belt, USA

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Abstract

Ridge tillage is a special conservation tillage method, but the long-term effect of this tillage system on crop yield and soil quality in a corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotation is largely unknown in the northern Corn Belt of the USA. Our objectives were to compare crop performance and soil condition at three nitrogen-fertilizer levels under ridge tillage (RT) and conventional tillage (CT). The experiment was started in 1990 at Brookings, SD, on a Barnes clay loam (US soil taxonomy: fine-loamy, mixed Udic Haploboroll; FAO classification: Chernozem). CT included moldboard or chisel plowing, seedbed preparation with tandem disk and field cultivator, and row cultivation. Raised beds under RT were maintained using only row cultivation. Corn grain yield was significantly ($p \leq 0.10$) greater on CT than on RT. Average (11 years and three fertilizer-N rates) corn yield was 6267 kg ha^{-1} with RT and 6500 kg ha^{-1} with CT. Soybean grain yield was not significantly ($p \leq 0.10$) different between RT and CT. Average (11 years and three fertilizer-N rates) soybean yield was 1997 kg ha^{-1} with RT and 2058 kg ha^{-1} with CT. In 9 of 11 years there was a significant soybean-yield response to N-starter fertilizer. There was no significant accumulation of NO_3-N in the top 3 m of soil at the end of 9 years in either tillage treatment (111 kg NO_3-N ha^{-1} under RT and 121 kg NO_3-N ha^{-1} under CT). Soil pH in the top 15 cm was unaffected by tillage (average pH was 6.62). In 1999, soil organic C in the top 0.2 m was significantly greater under CT (56 Mg ha^{-1}) than under RT (52 Mg ha^{-1}). Bulk density in the top 0.2 m was significantly greater under RT (1.52 g cm^{-3}) than under CT (1.44 g cm^{-3}). Tillage did not have a great effect on grain yield or soil properties. RT can protect soil from erosion because crop residues remain relatively undisturbed on the soil surface in contrast to chisel plow. In this respect, we expect RT to be more sustainable over the long term than chisel plow tillage.

Keywords: Corn; Soybean; Crop rotation; Soil quality; Water use; Nitrogen use efficiency; Nitrate nitrogen; Soil organic carbon; Brookings, South Dakota, USA

1. Introduction

Tillage normally incorporates residues or amendments, controls weeds, and prepares soil for seeding. The purpose of tillage for crop production is to create the best possible conditions for crop-seed germination

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and emergence. In an ideal situation, maintaining adequate soil surface cover would minimize soil erosion, crop yields would be maximized by assuring optimum seedbed conditions, and quality of the soil resource would be maintained or improved. Farmers often face field conditions that are less than ideal and consequently manage their land as a compromise between optimum crop-production management and optimum resource-conservation management. Soils in sub-humid northern environments can be especially difficult to manage because of cool and wet conditions. Many farmers in the northern Corn Belt of the USA prefer some type of tillage to accelerate soil warming and drying thereby achieving timely crop establishment.

Increased loss of soil organic matter (SOM) has been associated with increased tillage intensity. In addition, SOM loss from tillage can be expected to be a function of soil type, climate, and cropping practice (Lal et al., 1998). Increased intensity of tillage has been shown to increase short-term CO_2 flux from soils of semi-arid (Ellert and Janzen, 1999) and sub-humid (Reicosky and Lindstrom, 1993) agricultural production systems. The impact of these tillage induced fluxes of CO_2 on atmospheric CO_2 concentration or soil C retention is uncertain. Ellert and Janzen (1999) suggest that the short-term influence of soil tillage on the transfer of soil C to atmospheric CO_2 is small. Based on cropping studies established in the 1930s in the semi-arid Pacific Northwest, USA, Rasmussen et al. (1998) concluded that loss of SOM was related to excessive oxidation and absence of C input during fallow. Decreasing tillage intensity reduced SOM loss, but cropping practice, especially avoiding bare fallow, had a more dramatic effect on SOM status. Similarly, Doran et al. (1998) concluded, from long-term studies on the Central Great Plains, USA, that decline of SOM could be slowed by a more intensive cropping system that reduced time in fallow.

Ridge tillage is "a tillage system in which ridges are reformed atop the planted row by cultivation, and the ensuing row crop is planted into ridges formed the previous growing season" (Soil Science Society of America, 1997). Advantages and disadvantages of ridge tillage (RT) have been reported. In southwestern Ontario, Canada, conservation tillage (RT was included as a conservation tillage method) reduced soil erosion, but increased P loss (Gaynor and Findlay, 1995). Studies in Ohio, USA, showed that older consolidated ridges were more resistant to soil erosion than newly formed ridges (Norton and Brown, 1992). For a corn–soybean rotation in Iowa, USA, Kanwar et al. (1997) found little difference in N or pesticide movement to drain tiles in tillage trials that included ridge till. Wheeltrack compaction was found to be more severe in ridge till compared to moldboard plow trials in Indiana, USA (Larney and Kladivko, 1989). Soil mechanical resistance was greater for ridge tilled corn than for conventional tillage (CT) corn in New York, USA (Cox et al., 1990). No detectable differences due to tillage treatments in total SOM were found following 11 years in Quebec, Canada; however, labile fractions of SOM were maintained or increased by reduced tillage (Angers et al., 1993). Mycorrhizal colonization in corn was greater in fields that were ridge tilled than moldboard plowed in Ontario, Canada (McGonigle and Miller, 1993).

Ridge tillage offers a compromise between no tillage and other intensive, whole-field tillage systems such as chisel-plow and generally has been viewed as an economically viable tillage/crop production system. Farmer adoption of RT in the Corn Belt of the USA was shown to be a positive step towards low-input cash grain production (Lighthall, 1996). On-farm studies with Practical Farmers of Iowa, found RT without herbicides to be an effective and economical system for row crop production (Exner et al., 1996). Ridge tillage in corn and soybean rotations was thought to be more efficient than cultivation or herbicides used alone because RT integrated mechanical and chemical controls to attack a broad spectrum of weeds (Klein et al., 1996). Evidence suggests improved root growth and lateral root proliferation in ridge tilled corn, e.g. during a hot, dry growing season, RT increased yield for uninfested and rootworm-infested corn plants when compared with yields produced using spring disk tillage (Riedell et al., 1991).

The area devoted to ridge-till in the USA has not increased regardless of reports identifying benefits of RT. The Conservation Technology Information Center (CTIC) reported 1.7 million ha of corn and 1.4 million ha of soybean in South Dakota, USA, during 1998. Of this cropland, RT was practiced on only 1.8% of the hectares in corn and 1.4% of the hectares in soybean (CTIC, 1998). On a national basis in the

USA, RT was practiced on only 1.2% of all crop land in 1998. This percentage has changed little since 1990 when 1.1% of all crop land was ridge tilled.

There is not a definitive set of soil measurements that, when taken together, adequately defines soil quality. We measured soil properties thought to be important in respect to nutrient management and plant growth. Our objectives were to compare corn and soybean yield and soil condition at three nitrogen-fertilizer levels in an RT system and a CT system.

2. Materials and methods

2.1. Experimental site

Our study was located on the Eastern South Dakota Soil and Water Research Farm near Brookings, SD (44°19′N latitude, 96°46′W longitude, and 500 m elevation) on a Barnes clay loam with nearly level topography. Brookings is located in a transition zone between cool (frigid temperature regime) and warm (mesic temperature regime) prairies. Annual precipitation is 580 mm. Soils of this area are Udic Borolls to the north, Udic Ustolls to the south, and Typic Ustolls to the west. Thus, cool soil temperatures and limited soil water can affect adoption of conservation tillage methods. High intensity summer storms and rapid runoff from snowmelt can both cause serious soil erosion. Prior to the start of the experiment in 1990, the field was cropped to soybean in 1988 and spring wheat in 1989.

2.2. Experimental design and management

Whole plots (tillage) in the split plot experiment were arranged as a randomized complete block with three replications. Split plots (or subplots) were nitrogen treatments. Corn was grown in rotation with soybean and each crop was present each year in each tillage trial. Plots were 30 m long and 30 m wide.

On CT plots, primary tillage was with a moldboard or chisel plow in the fall of the year. Primary tillage since 1996 was with a chisel plow. In 1995 and 1996 wet weather conditions precluded fall tillage. RT received only row cultivation for both corn and soybean crops. Cultivation maintained a raised seedbed on RT plots and no effort was made to build or knock down soil ridges. Rows were oriented in the east–west direction for both CT and RT.

Seedbeds for corn and soybean under CT were prepared in spring using a tandem disk and field cultivator. Corn and soybean were no-till planted on the previous crop row in RT. Seeding date, rate, and variety were the same for all tillage and nitrogen treatments in a given year (Table 1). Early-maturing (Maturity Group I) soybean cultivars are recommended for our area. Depending on weather, seeding was as early as 5 May for corn and 11 May for soybean (Table 1). Row spacing for corn and soybean was 76 cm. Both CT and RT plots were cultivated twice during the early growing season for weed control. Urea-N was side-dressed immediately before the 2nd cultivation of corn.

Nitrogen treatments (subplots) termed high N, medium N, and low N were: corn fertilized for a yield goal (YG) of 8.5 Mg grain ha^{-1} (HN), corn fertilized for a YG of 5.3 Mg grain ha^{-1} (MN), and corn not fertilized (LN). Total soil nitrate (TSN) test was used to estimate N fertilizer prescription (NP) for corn (Gerwing and Gelderman, 1996). On each N treatment, NP was calculated as

$$NP = 0.022YG - TSN \quad (1)$$

Adjustment (Gerwing and Gelderman, 1996) to NP for previous crop or sampling date was not made. Nitrogen prescription for each tillage and N treatment, expressed as an average of three replications, was met by applying starter fertilizer with the seed and sidedressing with appropriate amounts of urea as 46–0–0 (elemental N–P–K).

Starter fertilizer for both corn and soybean was applied at seeding and placed 5 cm to the side and 5 cm deeper than seed. Starting with the 1996 crop year, 112 kg ha^{-1} of starter fertilizer as 14–16–11, 7–16–11 and 0–16–11 (elemental N–P–K) were applied on HN, MN, and LN plots, respectively. Prior to 1996, 111 kg ha^{-1} of starter fertilizer was applied to HN and 53 kg ha^{-1} was applied to MN as 13–14–11 (elemental N–P–K). Starter fertilizer was not used on LN plots prior to 1996. Soil phosphorous levels were elevated on all plots prior to spring field work in 1996 with an application of triple super phosphate as 0–20–0 (elemental N–P–K) equivalent to 89 kg ha^{-1} of elemental P.

Available N (AN) for the corn crop was defined as mineral sources of N available through additions by N

Table 1
Corn and soybean planting date, variety (Pioneer), seeding rate, date of soil sample for nitrate-N, harvest date, growing season precipitation, and growing degree days (base 10°C) for 1990–2000

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Corn											
Planting date	17 May	8 May	7 May	17 May	10 May	5 May	16 May	8 May	30 April	12 May	3 May
Variety	3737	3737	3737	3737	3737	3769	3769	3769	3751	3751	37H24
Seeds/ha	60 500	65 000	65 000	65 000	65 000	65 000	73 000	75 000	74 000	77 000	72 000
Harvest date	23 October	3 October	19 October	27 October	25 October	30 October	23 October	10 October	8 October	6 October	10 Oct
Soybean											
Planting date	23 May	16 May	12 May	19 May	11 May	24 May	21 May	28 May	14 May	25 May	15 May
Variety	9181	9161	9161	9161	9161	9171	9171	9171	9171	9172	9172
Seeds/ha	399 000	399 000	399 000	399 000	399 000	399 000	447 000	451 000	493 000	493 000	581 000
Harvest date	9 October	23 September	13 October	5 October	11 October	11 October	4 October	30 September	28 September	29 September	26 September
	Sample date for soil nitrate-N										
	None	23 May 1991	21 May 1992	7 May 1993	7 April 1994	30 November 1994	1 May 1996	30 October 1996	17 October 1997	20 October 1998	25 October 1999
	Precipitation[a] (mm)										
April	23	91	45	50	76	69	7	50	46	106	57
May	126	93	30	110	39	115	125	30	39	87	171
June	154	100	203	221	259	69	72	65	52	65	76
July	93	62	94	132	53	174	22	76	40	69	45
August	71	53	119	58	91	113	77	44	89	47	41
September	12	58	47	54	70	100	66	51	19	72	23
Total April–September	479	457	538	625	588	640	369	306	285	446	393
Total year	639	653	678	726	673	822	511	408	475	520	–
	Growing degree days										
April–September	1352	1469	1081	1119	1297	1286	1421	1342	1475	1383	1400

[a] Average precipitation for 1961–1990 for April–September was 459 mm and yearly average was 581 mm. Weather data courtesy of Alan Bender, South Dakota State Climatologist, Brookings, SD.

fertilization and soil nitrate N. Available N does not include N that may be potentially released through mineralization of organic N. Nitrogen use efficiency (NUE) was defined as the ratio of corn grain yield to available N and was used as an indicator of production efficiency within similar N-fertilizer management plans. Apparent N mineralization was estimated as the difference between total N uptake by corn and AN.

Prior to 1996, subplots HN, MN, and LN were termed management input levels for both tillage treatments. Experimental objectives were narrowed in 1995 to include only N as a variable on the sub plots. Primary tillage on CT mainplots varied with input level. Fall moldboard plow was used on HN. An year-to-year rotation between moldboard plow and chisel plow was used on MN. Fall chisel plow was used on LN. Since 1996, only chisel plow has been used on CT mainplots. Whole-field tillage was not used on RT since 1990. Prior to 1995, weed control on HN included herbicide and two row-cultivations and weed control on MN and LN was two row-cultivations. In 1995, management was changed to include herbicide and row cultivation on all plots.

2.3. Soil water content

Soil water content was measured in 1997–2000 using neutron attenuation equipment to determine water storage and use. Neutron equipment was calibrated in a manner described by Pikul and Aase (1998). On each subplot, a permanent access tube was installed enabling volumetric soil water measurements to a depth of 1.8 m at 0.3 m increments. Soil water content was expressed as an average of three replications for each tillage and nitrogen management treatment. Measurements were made at seeding and at crop maturity. Water use was defined as beginning soil water content minus ending soil water content plus precipitation during the growing season. Operationally, this period was defined as 1 June–30 September. For water balance calculations, runoff was assumed to be negligible because the plots are located on nearly level topography. However, at least once per year, we might expect about 25 mm of runoff from a high intensity summer storm. Water drainage beyond 1.8 m was assumed to be negligible among treatments during the growing season. Other researchers have made similar assumptions when estimating soil water depletion by corn and soybean in the northern Corn Belt (Copeland et al., 1993).

2.4. Crop measurements

Corn and soybean grain yield were measured with a Massey Ferguson MF 8-XP Research Plot Combine (Kincaid Equipment Manufacturing,[1] Haven, Kansas) equipped with an electronic weigh bucket. On each plot, eight rows, 30 m long ($\frac{1}{5}$ of the plot area) were harvested for grain yield. Subsamples of combine-harvested grain were retained for grain moisture, test weight, and N content. Prior to 1996, grain yield was measured by transferring harvested grain to a weigh-wagon. Grain moisture and test weight were measured with a Dickey-John GAC 2000 Grain Analysis Computer (Johnston, Iowa). Corn grain yields were adjusted to 15.5% moisture and soybean grain yield adjusted to 10% moisture. Concentration of N and C in grain was measured using a Carlo Erba NA 1500 C-N analyzer (Milan, Italy).

Samples to determine corn phytomass and N uptake were taken when the crop was mature and just prior to combine harvest. All plant material was cut from four rows 1 m long. Bundles were dried and weighed. Grain was separated from stover and weighed. Stover yield was determined as the difference between mass of bundle and mass of grain. Stover was shredded, subsampled and ground for C and N analysis using a Carlo Erba NA 1500 C-N analyzer. Soybean phytomass was sampled just before leaf drop.

2.5. Soil measurements

Samples for soil nitrate-N were collected in the fall or spring, depending on weather conditions (Table 1). Samples for 1991–1996 crops were taken from 0 to 15 and 15 to 60 cm depths. After 1996, samples were taken to a depth of 120 cm at increments of 0–15, 15–30, 30–60, 60–90 and 90–120 cm. Three soil samples were taken from each depth on each plot. Core diameter was 3.2 cm. Samples were dried at 40°C immediately after sampling, ground through a 2 mm sieve, and subsampled. Measurements of nitrate-N in

[1] Mention of trade names is for the benefit of the reader and does not constitute endorsement by the US Department of Agriculture over other products not mentioned.

samples collected in 1991–1995 were made using a nitrate electrode procedure (Gelderman et al., 1995). After 1995, nitrate-N was measured using a 2 M KCl extraction and automated copperized Cd reduction column procedure (Zellweger Analytics, 1992).

In addition to the yearly soil sampling for TSN, selected soil attributes were measured in 1989, 1996, 1998 and 1999. In 1989, prior to establishment of this tillage study, the experimental area was sampled on a 30 m × 30 m grid (Maursetter, 1992). Samples were taken in August after a wheat crop. Intact soil cores 5.0 cm in diameter were taken from the 0 to 15 cm depth. Soil pH, P, K, bulk density, and organic carbon (determined by loss on ignition) were measured (Gelderman et al., 1995). Extractable P (Olsen P) was determined using the $NaHCO_3$ method (Olsen et al., 1954).

In 1996, three soil samples were taken from the 0 to 15 cm depth of each plot. Core diameter was 3.2 cm. Soil pH, Olsen P, and K were measured.

In 1998, prior to corn seeding, 14 cores were taken from the top 20 cm of each plot. Soil core diameter was 3.1 cm. Cores were randomly taken from CT treatments and from ridge positions of RT treatments. Olsen P, soil organic carbon, total soil N, mineralizable N, bulk density and pH were measured. Soil organic carbon and total N were determined by combustion using a Carlo Erba NA 1500 C-N analyzer. Soil bulk density, adjusted to a dry basis, was calculated from the mass and volume of the bulked soil samples. Soil pH was measured using 0.01 M $CaCl_2$ and a soil:solution (weight basis) ratio of 1:2. Potentially mineralizable N was estimated using a modified aerobic incubation method (Stanford and Smith, 1972). Samples were processed for aerobic incubation on the same day of sample collection and incubated for 189 days. Carpenter-Boggs et al. (2000) provides details of this methodology.

To determine if there were unusual accumulations of nitrate-N in the top 3 m, plots were sampled to a depth of 3 m at 0.3 m depth increments in spring 1998. Three cores were bulked per depth from each plot. Samples were processed for N measurement as previously described.

In 1999, prior to corn seeding, 12 cores were taken from the top 20 cm of each plot. Soil core diameter was 3.1 cm. Cores were randomly taken from CT treatments. On RT, six cores were from ridge positions (rows) and six cores were taken between rows. Soil bulk density and organic C were measured as previously described.

Statistical comparisons of all measurements were made using analysis of variance and multiple factor analysis of variance (MINITAB Release 12, 1998). The split plot arrangement within randomized blocks was such that factor 1 was tillage (whole plot).

3. Results and discussion

3.1. Crop yield

Our field trials covered some of the wettest and coldest periods in the South Dakota climate record (Table 1). Precipitation totals from 1991 to 1995 were the greatest in more than 100 years and the 1992 and 1993 summers were the coldest consecutive summer seasons on record beginning in 1890 (Alan Bender, South Dakota State Climatologist, Brookings, SD). Corn and soybean yields were lowest in 1992 and 1993 compared with other years in the study (Table 2). However, even during these adverse growing seasons, corn and soybean yields on RT were equal to CT (Table 2).

In the first year of the study (Table 2, year 1990) there was no significant difference in corn yield between tillage systems, but there was a significant response to N fertilizer. The HN treatment resulted in 2220 kg ha^{-1} more grain than LN treatment. Results were important because they showed that our test site was responsive to N fertilizer.

Corn grown using CT significantly $(p \leq 0.10)$ outyielded corn grown using RT by an average of 233 kg grain ha^{-1} (4%) during 11 years (Table 2). However, only in 2 of 11 years was corn yield with CT significantly $(p \leq 0.10)$ greater than corn yield with RT (Table 2). In 5 years, average plant population on RT was significantly $(p \leq 0.10)$ greater than plant population on CT by 2000 plants ha^{-1} (Table 3). Often, there are not clear relations between tillage intensity and crop yield and our findings are typical of other cropping and tillage studies. Moldboard plow tillage resulted in the highest corn yield in a 10-year tillage study conducted in Iowa, USA (Chase and Duffy, 1991). Corn produced with no tillage yielded less than corn produced with plowing following

Table 2
Mean corn yield (15.5% grain moisture) and soybean yield (10.0% grain moisture) for RT and CT

	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	Average
Corn yield (kg ha^{-1})												
Tillage (T)												
RT	8450	8320	4400	2160	5050	5360	7500	6750	7620	6290	7041	6267
CT	8050	8300	4190	2240	6080	5800	8260	6930	7870	6540	7239	6500
Fertilizer (N)[a]												
H	9130	9800	6440	3880	8780	7160	9090	7280	8690	6800	8003	7732
M	8710	9580	4690	2520	5840	5070	7710	7220	7880	6920	7300	6676
L	6910	5540	1750	200	2070	4510	6840	6020	6660	5520	6116	4741
p-Value T	ns	ns	ns	ns	ns	ns	0.057	ns	0.076	ns	ns	0.084
p-Value N	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.004	0.001	0.002	0.001	0.001
p-Value T × N	0.061	ns	ns	0.047	0.031	ns	ns	ns	0.008	ns	0.046	ns
Soybean yield (kg ha^{-1})												
Tillage (T)												
RT	2080	2160	1555	1207	1739	1830	2528	2517	2093	2061	2195	1997
CT	2230	2073	1565	1652	2008	2050	2668	2090	2094	1918	2293	2058
Fertilizer (N)[a]												
H	2398	2487	1999	1810	2779	2302	2615	2408	2187	2082	2249	2301
M	2053	2042	1774	1370	1586	1758	2694	2268	2008	1974	2298	1984
L	2014	1821	908	1108	1256	1759	2485	2236	2086	1913	2184	1797
p-Value T	ns	ns	ns	ns	ns	ns	0.077	0.026	ns	ns	ns	ns
p-Value N	0.081	0.001	0.001	0.001	0.001	0.001	0.011	0.060	ns	0.029	ns	0.001
p-Value T × N	ns	ns	ns	ns	ns	0.017	ns	ns	ns	ns	ns	ns

[a] Nitrogen treatments for soybean were starter fertilizer only. Starter was applied to corn and soybean as 14–16–11, 7–16–11 and 0–16–11 (N–P–K) on H, M, and L treatments, respectively, at 112 kg ha^{-1}. Corn N fertilizer treatments were corn fertilized for a yield of 8.5 Mg ha^{-1} (H), corn fertilized for a yield of 5.3 Mg ha^{-1} (M), and corn not fertilized (L). Soybean grain moisture was not measured in 1994 and 1995.

soybean in Indiana, USA (West et al., 1996). In contrast, corn yields were not affected by tillage systems in Wisconsin, USA (Buhler, 1992). Similarly, corn yields were not affected by tillage in Ontario, Canada (McGonigle and Miller, 1993).

There was a significant corn-yield response to N during each year of the study (Table 2). However, there was not a consistent tillage × N interaction every year. Tillage could be expected to change distribution and concentration of N, soil temperature, and soil water content on a yearly basis and these factors could have contributed to variable interactions between tillage and N fertilizer on grain yield. There was no difference due to tillage in soil temperature following corn planting in 1999 (data not shown).

In 4 years, there was no significant difference in water use by corn between tillage systems, but there was a significant ($p \leq 0.10$) response to fertilizer N (Table 3). On average, corn grown under HN used 19 mm (6%) more water than corn grown under LN. There were significant ($p \leq 0.10$) differences in water use by soybean for both tillage and fertilizer N treatments. On average, soybean grown under RT used 20 mm (6%) more water than soybean grown under CT. Water use by corn averaged 335 mm and water use by soybean averaged 347 mm (Table 3). For comparison, on a rotation study located 160 km east of Brookings, Copeland et al. (1993) found that corn used 272 mm of water and soybean used 256 mm of water.

Average yield of soybean was 61 kg grain ha^{-1} greater (3%) with CT than with RT during the 11 years (Table 2). Only twice in 11 years was there a significant ($p \leq 0.10$) difference in yield due to tillage. In 1996, yield of soybean was 5% greater with CT than with RT. But, in 1997, yield of soybean was 17% greater with RT than with CT (Table 2). We do not have an explanation for soybean yield response to

Table 3
Corn and soybean plant population and water use for RT and CT

	Plant population (plants/ha)						Water use (mm)				
	1996	1997	1998	1999	2000	Average	1997	1998	1999	2000	Average
Corn											
Tillage (T)											
RT	75000	65000	80000	80000	80000	76000	346	344	334	319	336
CT	72000	66000	77000	79000	77000	74000	354	346	329	307	334
Fertilizer (N)											
H	72000	66000	78000	78000	77000	74000	351	360	338	320	342
M	76000	67000	80000	79000	79000	76000	358	349	335	317	340
L	73000	63000	77000	80000	80000	74000	342	327	323	302	323
p-Value T	ns	ns	0.094	ns	ns	0.072	ns	ns	ns	ns	ns
p-Value N	ns	ns	0.053	ns	ns	0.068	ns	0.041	ns	0.020	0.001
p-Value T × N	ns	ns	ns	0.093	ns	ns	ns	ns	ns	0.039	0.015
Soybean											
Tillage (T)											
RT	308000	414000	447000	452000	482000	420000	338	343	361	387	357
CT	285000	370000	422000	461000	474000	403000	324	331	343	351	337
Fertilizer (N)[a]											
H	304000	383000	432000	458000	488000	413000	345	343	354	370	353
M	282000	395000	433000	460000	468000	408000	326	327	344	368	341
L	304000	399000	438000	451000	477000	414000	322	340	359	369	348
p-Value T	ns	0.062	0.064	ns	ns	ns	ns	ns	ns	0.049	0.032
p-Value N	0.058	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.045
p-Value T × N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.055

[a] Nitrogen treatments for soybean were starter fertilizer only. Starter was applied to corn and soybean as 14–16–11, 7–16–11 and 0–16–11 (N–P–K) on H, M, and L treatments, respectively, at 112 kg ha^{-1}. Corn N fertilizer treatments were corn fertilized for a yield of 8.5 Mg ha^{-1} (H), corn fertilized for a yield of 5.3 Mg ha^{-1} (M), and corn not fertilized (L).

tillage in 1996. In 1997, we attribute significant yield improvement to superior stand establishment with RT. Spring 1997 turned unusually dry and the seedbed under CT dried out. Soybean was planted on 28 May, but there was no significant rainfall until 19 June. Consequently, emergence under CT was delayed until late June following a series of rain storms that re-wetted the seed zone.

Delayed emergence of soybean under CT in 1997 mimicked a date-of-planting test. But, date of planting has been shown to be less important than environmental condition following planting as a determinant of yield in soybean. Kane et al. (1997) stated that ''Early planting may be a disadvantage for early-maturing cultivars in seasons with favorable rainfall, particularly if canopy development is inhibited by cool temperatures during vegetative growth. If moisture is not limiting, delayed planting of early-maturing cultivars may be advantageous''. Stand counts revealed delayed emergence of soybean under CT. On 18 June, before the rains, there were 412 000 seedlings ha^{-1} under RT and only 62 000 seedlings ha^{-1} under CT (data not shown). On 1 July, following 58 mm of rain, there were 446 000 seedlings ha^{-1} under RT and 421 000 seedlings ha^{-1} under CT (Table 3). Good stand establishment with RT led to increased phytomass and, presumably, increased yield under RT. At maturity, average phytomass was 5200 kg ha^{-1} with RT and 4000 kg ha^{-1} with CT (data not shown). In respect to our plot research, where planting date was not a variable, favorable seedbed conditions under RT compared to CT have generally led to rapid and uniform stand establishment.

There was a significant soybean yield response in 3 of the last 5 years to low rates of N fertilizer applied as starter at seeding time (Table 2). Inspection of Table 2

Table 4
Soil pH, Olsen P (bicarbonate method), and K for RT and CT

	Soil pH				Olsen P (kg ha^{-1})				K (kg ha^{-1})			
	1989	1996	1998	Average	1989	1996	1998	Average	1989	1996	1998	Average
Tillage (T)												
RT	6.7	6.8	6.5	6.7	18.4	18.4	42.1	26.3	390.2	333.8	361.5	361.8
CT	6.6	6.6	6.6	6.6	21.2	14.4	43.5	26.4	360.9	299.3	345.8	335.3
Fertilizer (N)[a]												
H	6.6	6.6	6.4	6.5	21.9	17.2	55.6	31.6	350.1	323.7	365.8	346.5
M	6.6	6.2	6.5	6.6	19.2	22.0	32.5	24.6	388.2	311.4	349.0	349.7
L	6.7	6.8	6.7	6.7	18.2	10.1	40.3	22.9	388.2	314.3	346.5	349.7
p-Value T	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.042
p-Value N	ns	ns	ns	0.02	0.005	0.067	ns	ns	ns	ns	ns	ns
p-Value year				ns				0.015				0.026
p-Value T × N	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Nitrogen treatments for soybean were starter fertilizer only. Starter was applied to corn and soybean as 14–16–11, 7–16–11 and 0–16–11 (N–P–K) on H, M, and L treatments, respectively, at 112 kg ha^{-1}. Corn N fertilizer treatments were corn fertilized for a yield of 8.5 Mg ha^{-1} (H), corn fertilized for a yield of 5.3 Mg ha^{-1} (M), and corn not fertilized (L).

also reveals that in 9 of 11 years we found a significant fertilizer response. We think that starter N can improve soybean yield. Small amounts of N at seeding may promote rapid and early stand establishment and this could be important in northern climates. However, we cannot discount that yield response to fertilizer in 1990–1995 was actually a response to P rather than N. There was a slight but significant difference in soil P among fertilizer treatments at the start of the experiment in 1990 (Table 4, soil P values for 1989). By spring of 1996, soil P on LN decreased to about one half that of HN (Table 4). Soil P levels were elevated with P fertilization on all plots prior to crop planting in 1996 and these elevated levels were apparent in 1998 (Table 4). Tests from 1998 show no difference in soil P among fertilizer treatments and support our claim that starter N may stimulate soybean yield, especially in respect to soybean yield from 1996 to 2000. There was no difference in soil pH or K between tillage or fertilizer treatments (Table 4).

There is controversy in the literature concerning effect of N fertilizer on soybean yield. Peterson and Varvel (1989) found that soybean following sorghum [*Sorghum bicolor* (L.) Moench] responded positively to N application, but soybean following corn did not respond to N application. Roder et al. (1989) reported no increase in soybean yield to N application. On late planted double-cropped soybean, 50 kg ha^{-1} of starter N increased soybean yield 0.15 Mg ha^{-1} in south-eastern USA (Starling et al., 1998). Our highest N application rate for soybean was about 16 kg ha^{-1} (HN fertilizer treatment) which was less than the lowest rate of N applied in the previous mentioned reports. Our findings are consistent with recent research from northern Minnesota, USA, where soybean yield has been improved by starter N (George Rehm, personal communication).

3.2. Nitrogen use

Testing for TSN is a key N management tool for corn producers in eastern South Dakota and western Minnesota (Gerwing and Gelderman, 1996; Rehm et al., 1994). In the past 5 years, there was little difference in TSN due to tillage treatments following soybean, averaging 40 kg N ha^{-1} to a depth of 1.2 m (Table 5). In 4 of the past 5 years, there were small, but significant, differences in TSN due to N fertilization. Average TSN in the top 1.2 m of soil was 46 kg ha^{-1} on HN and 36 kg ha^{-1} on LN (Table 5).

There was a significant and consistent difference in TSN due to fertilization of corn. In the past 5 years, average TSN was 34 kg ha^{-1} greater HN than under LN (Table 5). In 1 out of 5 years TSN was significantly greater under RT than under CT. We are uncertain of the effect of TSN on soybean production. However, it

Table 5
Soil nitrate-N in the top 1.2 m following corn or soybean for RT and CT

	1995	1996	1997	1998	1999	Average
Nitrate-N following corn (kg ha^{-1})						
Tillage (T)						
RT	39.1	21.9	75.7	55.3	45.2	47.3
CT	30.9	24.7	35.1	42.8	54.3	37.6
Fertilizer (N)[a]						
H	44.1	30.8	81.8	73.8	74.3	61.0
M	31.7	18.6	57.9	44.1	47.9	40.0
L	29.1	20.4	26.5	29.3	27.0	26.5
p-Value T	ns	ns	0.049	ns	ns	ns
p-Value N	0.019	0.014	0.010	0.005	0.001	0.001
p-Value T × N	ns	ns	0.068	ns	ns	ns
Nitrate-N following soybean (kg ha^{-1})						
Tillage (T)						
RT	42.7	27.8	36.3	57.7	35.8	40.1
CT	40.3	29.2	28.2	55.7	43.1	39.3
Fertilizer (N)[a]						
H	43.6	32.5	35.2	71.1	44.9	45.5
M	39.7	25.4	32.2	53.5	38.4	37.8
L	41.1	27.6	29.4	45.4	35.1	35.8
p-Value T	ns	ns	0.062	ns	0.061	ns
p-Value N	ns	0.026	0.007	0.002	0.003	0.003
p-Value T × N	ns	ns	ns	0.091	ns	ns

[a] Nitrogen treatments for soybean were starter fertilizer only. Starter was applied to corn and soybean as 14–16–11, 7–16–11, and 0–16–11 (N–P–K) on H, M, and L treatments, respectively, at 112 kg ha^{-1}. Corn N fertilizer treatments were corn fertilized for a yield of 8.5 Mg ha^{-1} (H), corn fertilized for a yield of 5.3 Mg ha^{-1} (M), and corn not fertilized (L).

is commonly thought that nitrate-N inhibits nodulation in soybean thereby reducing fixation of atmospheric N.

There were no differences in NUE due to tillage treatments (data not shown). Average NUE for the past 5 years for both tillage systems was about 45 kg corn/kg N on HN plots, which is nearly identical to the values used in the South Dakota and Minnesota fertilizer management guides (Gerwing and Gelderman, 1996; Rehm et al., 1994). Other long-term experiments in the central Great Plains of the USA suggest 43 kg corn/kg N (Merle Vigil, personal communication).

Efficient use of N can minimize potential for ground water contamination by leached nitrate. We did not detect significant differences in TSN to a depth of 3 m between RT and CT at the end of 8 years (Table 6). Increased N fertilization significantly increased TSN to a depth of 3 m, but only by 29 kg N ha^{-1}. Estimates of apparent N mineralization show a small net positive uptake of 15 kg N ha^{-1} under RT and 28 kg N ha^{-1} under CT (Table 7). A negative value in Table 7 indicates that above-ground plant N (grain and stover) was less than available N (TSN and fertilizer N). Average apparent N mineralization was 62 kg ha^{-1} under LN and −19 kg ha^{-1} under HN (Table 7). Measurements do not include N in the plant root system, denitrification, volatilization, or loss of N to runoff and deep percolation. Estimates of apparent N mineralization and measurement of deep soil N together show that plots were not over fertilized.

3.3. Soil condition

Soil organic matter is an important source of inorganic nutrients for plant production. Mineralizable N, a component of organic matter, is important for improving N prescription and also evaluating soil

Table 6
Selected soil quality attributes for RT and CT

	Organic C (Mg ha^{-1})			Bulk density (g cm^{-3})			C/N ratio, 1998	N (kg ha^{-1})	
	1989[a]	1998[b]	1999[c]	1989	1998	1999		N-min, 1998	N-NO_3 at 0–3 m, 1998
Tillage (T)									
RT	50.82	53.24	51.89	1.52	1.38	1.52	11.10	177	111
CT	53.65	39.68	55.95	1.56	1.08	1.44	10.92	156	121
Fertilizer (N)[d]									
H	51.38	46.12	53.99	1.55	1.24	1.49	11.00	159	134
M	51.92	46.96	55.01	1.50	1.25	1.46	10.95	168	110
L	53.41	46.31	52.75	1.57	1.20	1.50	11.08	171	105
Year (Y)									
p-Value T	ns	0.038	0.049	ns	0.006	0.065	ns	0.080	ns
p-Value N	ns	ns	ns	ns	ns	ns	ns	ns	0.004
p-Value T × N	ns	ns	ns	ns	ns	ns	ns	ns	ns

[a] Initial soil samples taken from the Ap soil horizon (approximately the top 15 cm of soil) in August 1989 after wheat harvest and prior to establishing tillage and fertilizer treatments.

[b] Soil samples taken from the top 20 cm of soil on 28 April 1998. CT plots were chiseled on 20 October 1997 and disked on 15 April 1998. There was 18 mm of rainfall between 15 April and 28 April 1998. Samples taken randomly on CT and from row positions on RT.

[c] Soil samples taken from the top 20 cm of soil on 11 May 1999. CT plots were chiseled on 23 October 1998 and disked on 1 April 1999. There was 154 mm of rainfall between 1 April and 11 May 1999. Samples taken randomly on CT and from both row and between row positions on RT.

[d] Starter was applied to corn and soybean as 14–16–11, 7–16–11 and 0–16–11 (N–P–K) on H, M, and L treatments, respectively, at 112 kg ha^{-1}. Corn N fertilizer treatments were corn fertilized for a yield of 8.5 Mg ha^{-1} (H), corn fertilized for a yield of 5.3 Mg ha^{-1} (M), and corn not fertilized (L).

Table 7
Apparent N mineralization (difference between corn-plant N and available N) for RT and CT[a]

	1996	1997	1998	1999	Average
Tillage (T)					
RT	31.6	21.9	12.3	−8.0	14.5
CT	43.4	27.6	39.5	0.4	27.7
Fertilizer (N)[b]					
H	23.9	−34.4	−19.2	−47.6	−19.3
M	26.8	31.4	22.8	1.2	20.6
L	61.7	77.3	74.1	35.1	62.0
p-Value T	ns	ns	0.001	ns	0.071
p-Value N	0.001	0.001	0.001	0.001	0.001
p-Value T × N	ns	ns	ns	ns	ns

[a] The values of tillage and fertilizer were expressed in kg N ha^{-1}.

[b] Corn N fertilizer treatments were corn fertilized for a yield of 8.5 Mg ha^{-1} (H), corn fertilized for a yield of 5.3 Mg ha^{-1} (M), and corn not fertilized (L). Available N is the sum of nitrate-N in the top 1.2 m of soil and applied fertilizer N. A negative value indicates N in aboveground plant material was less than available N.

function. Laboratory mineralizable N was unaffected by N treatment (Table 6). Potentially mineralizable N was significantly different between tillage treatments with 177 kg N ha^{-1} under RT and 156 kg N ha^{-1} under CT (Table 6).

Differences in mineralizable N between tillage treatments must be interpreted carefully because soil used for the 1998 incubation (Table 6) did not represent a field average. Soil cores were taken only from ridge positions of RT and soil bulk density of the recently tilled CT plots was about 22% less than that of RT (Table 6, 1998 sample date). Soil bulk density is necessary for conversion of N concentration to kilogram N per hectare. Consequently, the volumetric fraction of mineralizable N and organic C reported for 1998 (Table 6) largely reflects a difference in bulk density between RT and CT. Soil C/N ratio was not significantly different between tillage treatments (Table 6).

A stratified sampling for soil OC in 1999 revealed a small but significant difference in OC between CT and RT treatments. Rainfall of 154 mm reconsolidated the surface 20 cm of CT following secondary disk-tillage on 1 April. This rainfall was fortuitous because soil bulk density, at sampling on 11 May, was nearly the same for both CT and RT (Table 6, 1999 sample date). Soil organic C was significantly greater (7%) under CT compared with RT in 1999. However, at the start of the experiment in 1989, soil organic C was also 5% greater on CT plots compared with RT plots (Table 6). Analysis of variance of the differences in OC between 1989 and 1999 among tillage and fertilizer treatments showed that there were no significant differences among treatments in respect to gain or loss of OC (data not shown). A laboratory test revealed negligible differences in analytical results when OC was determined by loss on ignition (1989 analysis) or OC was determined by combustion (1999 analysis).

It is important to identify trend in soil condition because this will ultimately define whether a given management practice is sustainable. In many studies, soil organic C has been identified as an important soil quality indicator and lack of tillage has been identified as having a profound effect on carbon cycling. Methodology of sampling and soil physical condition at time of sampling are key factors important to arriving at valid conclusions concerning long-term effects of tillage management on soil OC. This simple fact was illustrated by the differences in OC obtained for the sampling methods and soil conditions of 1998 and 1999 (Table 6).

4. Summary and conclusion

Corn yield, averaged across 11 years, was 4% greater under CT than under RT. Similarly, soybean yield was 3% greater under CT than under RT. In the past 5 years, soybean fertilized with starter N at seeding yielded significantly ($p = 0.008$) more grain (6%) than soybean not fertilized with N. There was little difference in NUE, water use efficiency, soil nitrate accumulation, soil pH, soil P, or soil K due to tillage. In dry years, such as the spring of 1997, RT boosted soybean grain yield over CT due to early and improved stand establishment. Soil OC of the top 20 cm was significantly greater (7%) under CT compared with RT in 1999. There was no difference in soil OC among fertilizer treatments. It is important to seek management practices that sustain the soil resource while maintaining competitive grain yields. Keeping the soil in place is the best defense against soil degradation. Ridge tillage can protect soil from erosion, without sacrifice of crop yield, because crop residues remain undisturbed on the soil surface in contrast to chisel tillage where residue was incorporated.

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