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Effects of 10 years of conservation tillage on soil properties and productivity in the farming–pastoral ecotone of Inner Mongolia, China

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Abstract

Soil degradation and subsequent yield decline are the main factors limiting further development of agriculture on the farming–pastoral transition zone of China. A 10-year field experiment was conducted in Inner Mongolia to compare the long-term effects of no-tillage with straw cover (NT), subsoiling with straw cover (ST), rototilling with straw cover (RT) and traditional tillage (TT) using ploughs on soil properties and productivity in a spring wheat–oat cropping system. Long-term conservation tillage increased soil organic matter in the top 20 cm by 21.4%, total N by 31.8% and Olsen's P by 34.5% in the 0–5 cm layer compared to traditional tillage. Mean percentage of macro-aggregates (>0.25 mm, +20%) and macroporosity (>60 μm, +52.1%) also improved significantly in the 0–30 cm soil layer ($P < 0.05$). The largest yield improvements coupled with greatest water use efficiency (WUE) were achieved by no-tillage with straw cover. Ten-year mean crop yields increased by 14.0% and WUE improved by 13.5% compared to traditional tillage due to greater soil moisture and improved soil physical and chemical status. These improvements in soil properties and productivity are of considerable importance for the seriously degraded soils in semiarid Inner Mongolia, as well as for food security, sustainable agriculture and carbon storage in the farming–pasture transition regions of China.

Keywords: Conservation tillage, soil fertility, aggregate stability, soil porosity, yield, water use efficiency

Introduction

In semiarid Inner Mongolia, animal husbandry has been the only important agriculture for much of its history. In the last 100 years, large areas of grassland have been converted into cropland due to increased population and food demand (Zhang *et al.*, 1998). The agriculture–pasture transition region has about 32.8 Mha land, representing 27.8% of the total land area of Inner Mongolia (LZU, 2005). In this region, conversion of grassland to cropping, combined with insufficient rainfall and wind erosion have resulted in serious soil nutrient depletion and structural deterioration (Liu *et al.*, 2007; Jin *et al.*, 2008; Markus *et al.*, 2008). In the current cropping system, all the crop residues are removed for fodder after harvest before mouldboard ploughing. Using these traditional practices, farmers seek to produce good seedbeds, conserve water and reduce variability in crop yields. However, in the long term, this traditional tillage tends to increase soil bulk density, reduce both macroporosity and macro-aggregates, resulting in less water and nutrient availability (Zhou, 2004; Qin *et al.*, 2007). Consequently, crop yields become unstable and decline, especially in dry years (Zhao *et al.*, 2007). The extent and impact of soil degradation on crop production in agro-pastoral transition zones also has environmental impacts, for example dust storms pose a risk to crops.

Conservation tillage is defined as any tillage and planting system that leaves ≥30% of crop residue on the soil surface after planting (Uri *et al.*, 1998). No tillage, shallow surface

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tillage, subsoiling, strip rototilling and residue mulching are often included under the umbrella of this definition (Lampurlanes *et al.*, 2002; Gao *et al.*, 2008). The positive effects of conservation tillage on soil physical and chemical properties (Bessam & Mrabet, 2003; Al-Kaisi & Yin, 2005; Peixoto *et al.*, 2006; Thomas *et al.*, 2007) and crop yields (De Vita *et al.*, 2007; He *et al.*, 2007) have been demonstrated in many environments. In China, several long-term experiments (e.g. Li *et al.*, 2006, 2007; Wang *et al.*, 2008) have generally confirmed the improvements in soil quality and productivity achieved by conservation tillage in dryland farming areas. However, results vary due to the variability of climate and time requirements for soils to adapt to a new management system. In the agriculture–pasture transition regions, Qin *et al.* (2007) demonstrated that soil organic matter and available P and K down to 10 cm depth were up to 10% higher in no-tillage than traditional tillage after 4 years in semiarid Inner Mongolia. Rong (2004) conducted a 3-year no-tillage experiment and established that no-tillage increased soil water content by 4% (0–20 cm) and spring wheat yield by 3% compared to traditional ploughing on silt loam soils on the Baishang Plateau in Hebei province. In more arid Inner Mongolia, Zhao *et al.* (2007) compared no-tillage with full residue cover and ploughing with all residues removed. Their results indicate that no-tillage improved mean wheat and potato yields by up to 7% during a 3-year experiment. Apart from these short-term studies, little is known about the long-term effects of conservation tillage practices on soil properties and yields in agriculture–pasture transition regions of China.

The aim of this study was to improve our understanding of the long-term effects of conservation tillage in Inner Mongolia, in particular to collect sufficient data to enable a quantitative assessment of the potential benefits on soil quality and crop yield. The long-term comparison also examined the combined effects of changing tillage practice and straw management. The experiments were conducted over a period of 10 years (1998–2008) and included comparing several conservation tillage treatments with traditional ploughing after straw removal.

Materials and methods

Site and climatic conditions

The experiment was conducted in the semiarid agriculture–pasture transition region in Shang Tuhe village (41°06′N, 111°27′E), Wuchuan, Inner Mongolia, China, from 1998 to 2008. Wuchuan is located in a temperate continental semiarid monsoon climate at 1500–2000 m above sea level. Annual rainfall is most abundant from June to August, totalling about 360 mm. Annual evaporation is 1848 mm with 110 frost-free days. Figure 1 shows the annual mean monthly rainfall from 1998 to 2007. Average annual temperature and accumulated temperature of ≥10 °C are 2.5 °C and 1951 °C, respectively. In the experimental plots, the soil is a luvic Kastanozem (FAO/UNESCO, 1990). The key physical and chemical properties of the soil (0–20 cm) are listed in Table 1.

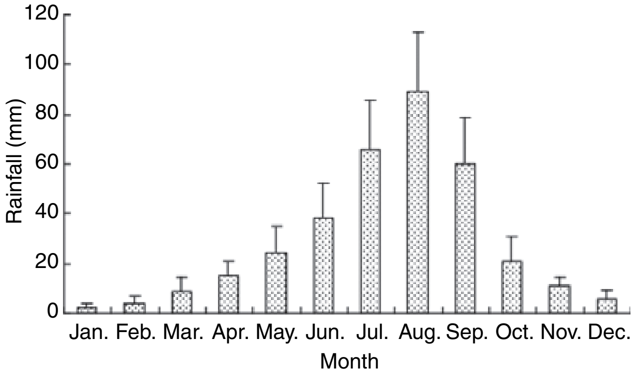

Figure 1 Distribution of mean monthly rainfall at the experimental site from 1998 to 2007. Error bars represent standard deviation.

A 2-year spring wheat–oat rotation is the common cropping system, providing the mean yields of 1.2 t/ha of spring wheat and 1.1 t/ha of oat (Wang *et al.*, 2002), in this part of Wuchuan. Spring wheat (*Triticum aestivum* L.) and oat (*Avena sativa* L.) are planted in early April or late May, respectively, and harvested in early to mid-September. The low yields are attributed to the low soil nutrient status, as well as water stress and cold weather in Wuchuan (Zhou, 2004).

Experimental design

The experimental design was a randomized block with three replications. Each plot was 10 m wide and 100 m long. Before the experiment, soils at the site had been farmed by conventional ploughing (20 cm) and subsequent tillage for seedbed preparation, with straw removal after harvest for over 10 years. At the beginning of the experiment in 1998, the entire field was ploughed to a depth of 40 cm to mix soil thoroughly and ensure uniform soil conditions in each experimental plot. In Wuchuan, no-tillage, subsoiling and rototilling are the most popular tillage practices adopted widely by farmers using conservation tillage. So in our experiment, four treatments were used: no-tillage with straw cover (NT), subsoiling (30–35 cm depth) with straw cover (ST),

Table 1 Physical and chemical properties of the soil (0–20 cm) at the experimental site

Texture (%)			Bulk density (Mg/m^3)	Soil organic matter (g/kg)	Available N (mg/kg)	Available P (mg/kg)	pH
Sand	Silt	Clay					
56	23	21	1.32	16.2	57.2	17.1	8.2

rototilling (5–8 cm depth) with straw cover (RT) and traditional ploughing (20 cm) (TT). The NT system included no-tillage planting and fertilizing in early April for spring wheat or late May for oats, herbicide spraying in early June, and mechanical harvesting in early September for spring wheat or mid-September for oats. The crops were combine harvested in September. Standing stubble of 15–25 cm remained on the field and straw was chopped and spread uniformly across the plots by the combined harvester prior to the conservation tillage treatments. For the traditional treatment a stubble of 5–8 cm was left and all the straw removed. All the tillage treatments were repeated annually.

The same varieties of spring wheat (Mengmai 34) and oat (Beihuang 2) were planted at 150 and 127.5 kg/ha, respectively, throughout the experiment. Fertilizers ($CO(NH_2)_2$ and $(NH_4)_2HPO_4$) were applied at the same rates to each plot and crop every year: 36 kg N/ha and 25 kg P/ha for spring wheat and 29.7 kg N/ha and 17.6 kg P/ha for oats. These applications were considered to be the optimum fertilizer quantities for crop growth and yields according to the study on the relationship between grain yields and fertilizer (N and P) conducted by IAAS (1998) in this part of Wuchuan. For each crop cycle, 2,4-D butylate herbicide was applied at the rate of 0.9 kg a.i./ha using a knapsack sprayer.

Equipment

The 2BMF-7 no-till wheat planter (Figure 2a) matched with a 20 kW class tractor was used for planting spring wheat and oats for NT and ST treatments. This machine used narrow-point openers and presswheels to place and firm seed and fertilizer at depths of 5 and 8 cm, respectively. Residue clearance was maximized by mounting three openers on the front and four on the rear bar of the machine. For this experiment the machine was set to the 16 cm row spacing commonly used by local farmers.

The 2BMFS-5/10 no-till planter (Figure 2b) matched with a 37 kW class tractor was used for the planting of RT treatment. The machine is equipped with five rotary hoe units at 32 cm spacing, to chop the residue and till strips of seedbed to create an 18 cm wide, 8 cm deep tilled zone. Behind the narrow-point openers it places two rows of seed at 5 cm depth and 16 cm spacing and fertilizer at 8 cm depth in each seed row.

Subsoiling to loosen soil without inversion was carried out with a subsoiling chisel point with adjustable wings (Figure 2c). The machine had an anti-blocking front disc which cut crop residues in the subsoiling line to prevent blockage; followed by a soil levelling device.

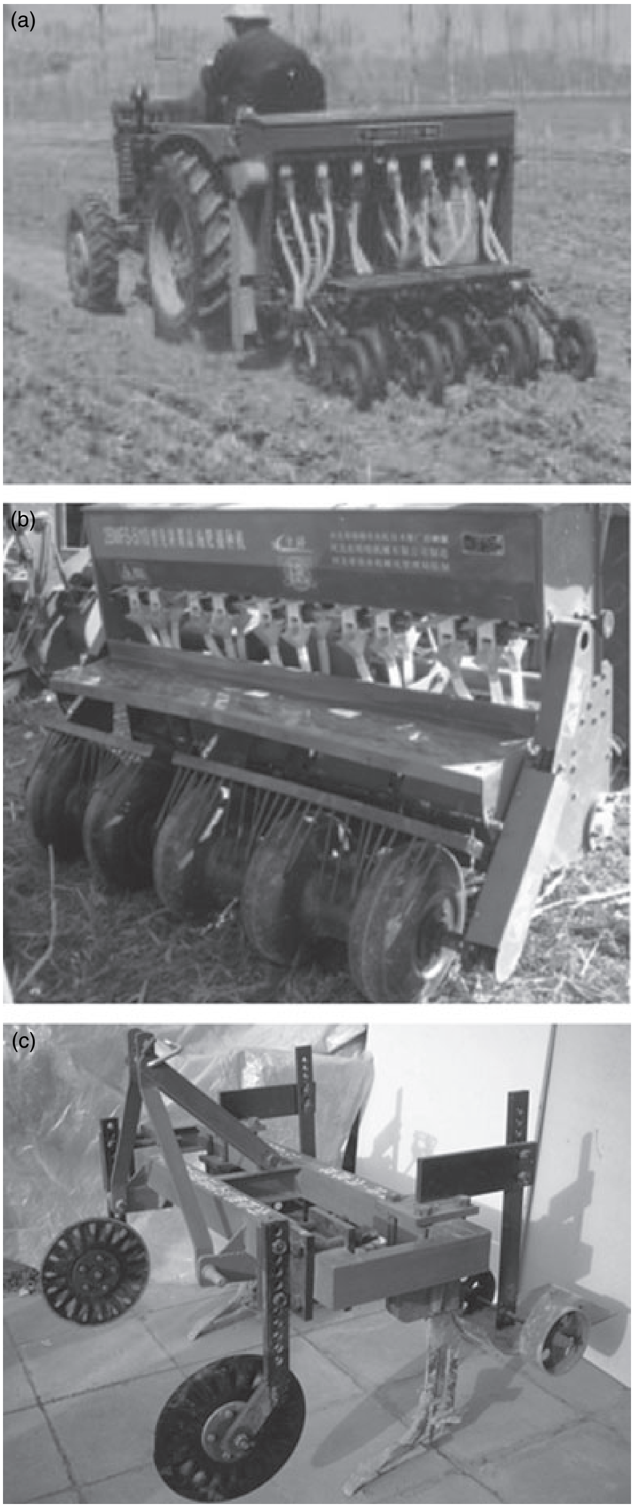

Figure 2 The 2BMF-7 no-till wheat planter (a), the 2BMFS-5/10 no-till planter (b) and subsoiler with adjustable wings (c).

Soil sampling and treatment

In April 2008, soil samples were collected from the plots of the four treatments before the planting of spring wheat. In each plot, one composite soil sample consisting of five subsamples was taken at 0–5, 5–10, 10–20 and 20–30 cm depths to determine soil organic matter (SOM), total N and Olsen's P. For aggregate stability a similar soil sample was collected at 0–10, 10–20 and 20–30 cm depths. Each soil sample was first passed through an 8 mm sieve by gently breaking the soil clods, pebbles and stable clods larger than 8 mm were discarded. Before the analyses, soil samples were air-dried for 24 h in the laboratory. For porosity tests, five undisturbed soil cores were obtained from depths of 0–10, 10–20 and 20–30 cm of each plot.

Soil organic matter, total N and Olsen's P

Total organic carbon was measured by dry combustion using a Leco Carbon Analyzer (Nelson & Sommers, 1982). Total N concentration was determined by Kjeldahl digestion. Olsen's phosphorus was extracted with 0.5 M $NaHCO_3$ solution adjusted to pH 8.5. Concentrations of extracted P were determined by the modified Murphy-Riley ascorbic acid procedure (Olsen & Sommers, 1982).

Soil porosity

Soil porosity was measured following the procedure of Bai *et al.* (2008). The classes of pores were distinguished as: macropores of equivalent radius $>60\ \mu m$, mesopores from 0.2 to 60 μm in diameter and micropores $<0.2\ \mu m$. The intact soil cores were saturated by capillary action in a sand and kaolin box before using a laboratory pressure plate extractor to drain them to matric potentials of 0, −5 and −1500 kPa. They were then oven-dried at 105 °C for 24 h. The weight of each sample was recorded at each matric potential and after oven drying to calculate the soil volumetric water content. Macroporosity was taken as the volumetric water content between 0 and −5 kPa matric potential, mesoporosity as the difference in volumetric water content between −5 and −1500 kPa matric potential and microporosity as the volumetric water content at −1500 kPa matric potential.

Soil water-stable aggregates

Size distribution of water-stable aggregates was determined by placing a soil sample on a stack of sieves (2, 1 and 0.25 mm). The stack was then immersed in water and moved up and down by 3.5 cm at a frequency of 30 cycles per minute for 15 min. Proportions of stable aggregates >2, 2–1, 1–0.25 and <0.25 mm were calculated by drying and weighing the soil remaining on the sieves. Micro-aggregates <0.25 mm are those formed by the material that passed through the stack of sieves (Oades & Waters, 1991).

Bulk density and soil water storage

In each plot, five random soil samplers were taken using a 54 mm diameter steel core sampling tube, manually driven into 30 cm depth, immediately after harvest from 1998 to 2007. The soil cores were weighed wet, dried at 105 °C for 48 h, and weighed again to determine bulk density. Soil water storage was calculated for a 30 cm deep profile by multiplying the mean soil volumetric water content by the soil profile depth.

Yield and water use efficiency

Yields were determined by manual harvesting, threshing and air-drying grain from five $1 \times m^2$ areas taken randomly from each plot.

Apparent evapotranspiration (AET) was calculated using the formula:

$$\mathrm{AET} = P - \Delta W \tag{1}$$

where P is growing season rainfall (mm), and ΔW is the change in stored soil water (mm) of the soil profile (0–100 cm depth) from planting to harvest.

Total water use efficiency (WUE) was estimated as the grain yield (kg/ha) divided by the growing-season evapotranspiration (mm):

$$\mathrm{WUE} = \frac{\mathrm{Yield}}{\mathrm{AET}}. \tag{2}$$

Statistical analysis

Mean values were calculated for each of the measured variables and ANOVA was used to assess the statistical effects of conservation tillage on the measured values. When ANOVA indicated a significant F-value, multiple comparisons of annual mean values were performed by the least significant difference method. The SPSS 13.0 analytical software package was used for all the statistical analyses.

Results

Soil organic matter, total N and Olsen's P

Soil organic matter, N and P results are presented in Table 2. The mean SOM in the 0–5 cm soil layer was 17.9 g/kg for the three conservation tillage treatments (NT, ST and RT), which is significantly greater than the 14.3 g/kg observed on the traditional tillage plot. The SOM difference between conservation and traditional tillage declined in the deeper layers, but were still significant at 20 cm depth. Mean SOM of NT was greater in the 0–5 cm layer than ST and RT treatments, but not below 5 cm depth. A similar increase was found for total N on the conservation tillage plots, but differences were only significant for the 0–5 cm layer. The quantity of Olsen's P was 34.5% greater under conservation tillage than under traditional tillage in the 0–5 cm layer (significant at $P < 0.05$). Below 5 cm, this pattern was reversed with TT

Table 2 Soil organic matter (SOM), total N and Olsen's P

	Soil depths (cm)	Treatments			
		NT	ST	RT	TT
SOM (g/kg)	0-5	18.8^{a}	17.9^{ab}	17.0^{b}	14.3^{c}
	5-10	14.1^{a}	13.9^{a}	14.0^{a}	12.4^{b}
	10-20	9.6^{a}	9.1^{a}	9.8^{a}	7.4^{b}
	20-30	7.0^{a}	7.2^{a}	6.8^{a}	6.5^{a}
Total N (g/kg)	0-5	0.60^{a}	0.58^{a}	0.56^{a}	0.44^{b}
	5-10	0.44^{a}	0.42^{a}	0.45^{a}	0.40^{a}
	10-20	0.30^{a}	0.29^{a}	0.26^{a}	0.24^{a}
	20-30	0.25^{a}	0.23^{a}	0.26^{a}	0.27^{a}
Olsen's P (mg/kg)	0-5	20.23^{a}	22.63^{a}	21.24^{a}	15.89^{b}
	5-10	13.71^{a}	14.15^{a}	13.98^{a}	16.56^{b}
	10-20	8.32^{a}	7.94^{a}	8.21^{a}	10.12^{b}
	20-30	5.34^{a}	5.89^{a}	6.30^{a}	6.31^{a}

Values within a row in the same depth followed by the same letters are not significantly different ($P < 0.05$). NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

containing 8.0–24% more Olsen's P than conservation tillage.

Bulk density, porosity and water-stable aggregates

Bulk density measurements from 1998 to 2007 are shown in Figure 3. Significant differences between treatments emerged only after 3–7 years and were less obvious than for SOM, N and P. On all treatments, bulk density increased initially, and soil bulk density to 30 cm depth was greater for NT than for traditional tillage during the first 5 years of the experiment (1998–2002). However, the increase on the conservation tillage plots plateaued after about 5 years, while traditional tillage kept increasing. After 10 years, bulk density on the TT plot was significantly greater than on the conservation tillage plots. Differences between the conservation tillage practices were not significant.

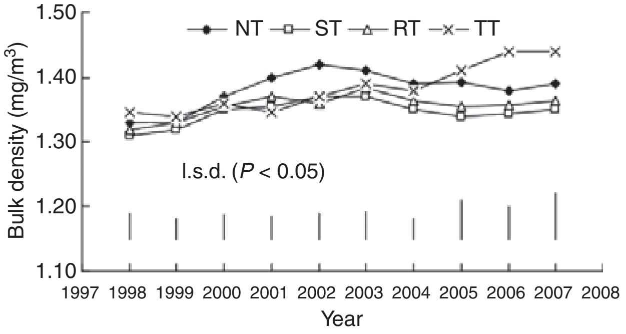

Figure 3 Mean bulk density for the four treatments in the 0–30 cm soil profile. Samples were taken immediately after harvest from 1998 to 2007. NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

Pore size distributions of the four treatments in 2008 are shown in Figure 4. Mean total porosity was 42% on conservation tillage plots and 38% on traditional tillage plots ($P < 0.05$). The increased porosity was largely due to an increase in macroporosity and mesoporosity on the conservation tillage plots. In the 0–10 cm soil layer, macroporosity and mesoporosity on conservation tillage plots were 14% (significant at $P < 0.05$ level) and 4.6% greater, but microporosity was 5.9% less than on TT. In deeper soil layers, conservation tillage treatments also had significantly ($P < 0.05$) greater (75%) macroporosity in the 10–20 cm soil layer, as well as a 17% increase in mesoporosity in the 20–30 cm soil layer. Mean microporosity in the 10–30 cm soil layer was reduced by 19.5%.

The size distribution of water-stable aggregates is shown in Table 3. Differences between treatments in 2008 were similar to those of pore size distribution. Soils from conservation tillage plots contained more macro-aggregates (13–37%) than those under traditional tillage throughout the soil profile. The percentage of micro-aggregates was 25–59% greater in traditional tilled soils.

Soil water storage, crop yield and water use efficiency

Table 4 shows the soil water storage (0–30 cm) at planting time of spring wheat and oats. At the start of the experiment (1998), soil water storage was similar for the four treatments. However, 3–4 years later differences between tillage treatments started to emerge. During the test period, mean soil water storage in the 0–30 cm layer was about 10% greater on the conservation tillage plots (59 mm) than on traditional tillage (54 mm). In the dry years of 2003, 2006 and 2007, soil water storage in conservation tillage plots increased on average by 8 mm (19%).

Mean spring wheat and oat yields for the four treatments were similar to the values of crop yields reported by Wang *et al.* (2002) Wuchuan, but fluctuated widely from year to year due to the seasonal and annual variation of rainfall (Table 5). On average, the yields on conservation tillage treatments were greater than those on the traditional tillage plot, with significant differences ($P < 0.05$) in 6 of 10 years. It is interesting to note that the mean yield advantage of conservation tillage was relatively small (6%) in the first 4 years of the experiment, but this increased to a mean value of 13% in the subsequent 6 years.

The benefits of conservation tillage become even more obvious for WUE (Table 5). WUE ranged from 3.8 to 5.4 kg/ha/mm for conservation tillage and from 3.6 to 4.5 kg/ha/mm for traditional tillage. Similar to yields, WUE in NT plots was better than in the TT plots during the dry years of 1999, 2003 and 2006. The maximum difference

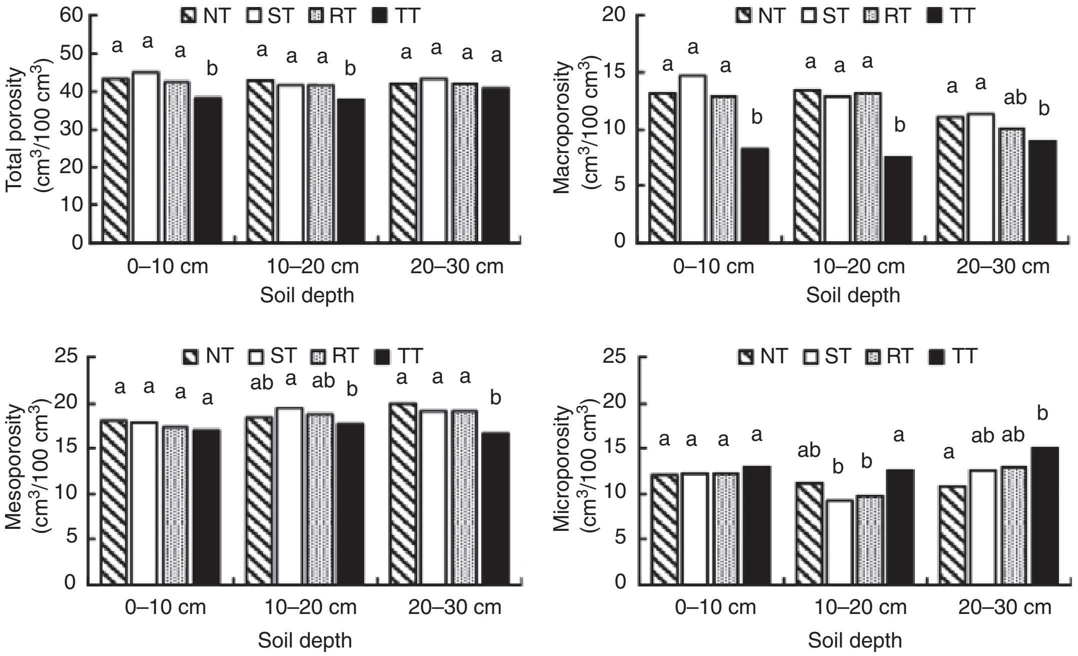

Figure 4 Mean soil porosity in the 0–30 cm soil layer. Means in the same soil profile followed by same letters are not significant ($P < 0.05$). NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

Table 3 Stable aggregate size classes

Soil depth (cm)	Treatment	Aggregate size classes (%) Macro-aggregates (> 0.25 mm) > 2 mm	2–1 mm	1–0.25 mm	Micro-aggregates (< 0.25 mm) < 0.25 mm
0-10	NT	19.2^{a}	17.5^{ab}	35.1^{a}	28.2^{a}
	ST	17.3^{ab}	19.1^{a}	33.3^{ab}	30.3^{a}
	RT	16.8^{b}	16.2^{b}	30.7^{b}	36.3^{b}
	TT	11.6^{c}	10.5^{c}	27.7^{c}	50.2^{c}
10-20	NT	20.1^{a}	20.5^{a}	33.2^{ab}	26.2^{a}
	ST	18.5^{a}	17.0^{bc}	34.9^{a}	29.6^{b}
	RT	18.8^{a}	17.5^{bc}	33.5^{ab}	30.2^{b}
	TT	13.9^{b}	15.4^{c}	30.5^{b}	40.2^{c}
20-30	NT	22.8^{a}	23.0^{a}	30.4^{a}	23.8^{a}
	ST	21.2^{a}	21.8^{ab}	31.6^{a}	25.4^{a}
	RT	22.0^{a}	22.4^{ab}	30.8^{a}	24.8^{a}
	TT	17.8^{b}	19.6^{b}	29.5^{a}	30.8^{b}

Values within a column in the same depth followed by the same letters are not significantly different ($P < 0.05$). NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

between NT and TT of 1.1 kg/ha/mm (5.2 vs. 4.1 kg/ha/mm) occurred in 2006, a year with only 290 mm rainfall.

Discussion

The results of the long-term (10 years) test on the effects of conservation tillage practices on soil quality and productivity in the farming–pastoral transition zone of Wuchuan demonstrate that a significant improvement can be achieved. All relevant soil properties (SOM, N and P content, bulk density, porosity, aggregate size) improved and led to higher yields and greater WUE. Overall, the benefits of conservation tillage were greater with the no-tillage with straw cover option than for subsoiling or rototilling with straw cover.

The SOM increases resulting from conservation tillage are attributed to the greater straw input and reduced biological oxidation associated with less soil disturbance by tillage (Chan *et al.*, 2002). Improved aggregate stability under conservation tillage, particularly under NT management, was also a consequence of increased SOM and reduced disturbance of the soil by tillage (Oyedele *et al.*, 1999; Zhang *et al.*, 2007). Tillage-induced changes in soil organic N are also directly related to changes in soil organic C (Zibilske *et al.*, 2002). In our study, total N increased by 27–36% on NT, ST and RT in the top 5 cm depth, but not below 5 cm. Olsen's P at 0–5 cm also increased under NT, ST and RT, confirming the findings of Wang *et al.* (2008). The topsoil accumulation of N and P in NT, ST and RT is attributed to the concentration of fertilizers and crop residues in the surface layer. Similar limited vertical movement of particle-bound P in no-till and minimum-till soils and the upward movement of nutrients from deeper layers through root

Table 4 Soil water storage (0-30 cm) at time of planting spring wheat and oats

Treatment	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean
NT	41.3^{a}	50.9^{a}	68.8^{ab}	66.8^{a}	63.6^{a}	49.8^{a}	83.5^{ab}	71.7^{a}	55.5^{a}	50.1^{a}	60.2
ST	42.2^{a}	52.2^{a}	71.2^{a}	63.1^{ab}	60.3^{ab}	45.3^{ab}	85.2^{a}	72.8^{a}	51.9^{a}	48.1^{a}	59.2
RT	39.9^{a}	50.6^{a}	69.3^{ab}	59.4^{bc}	61.7^{a}	44.7^{b}	80.1^{bc}	69.4^{a}	52.5^{a}	46.9^{a}	57.5
TT	40.7^{a}	50.2^{a}	65.9^{b}	56.2^{c}	56.6^{b}	38.7^{c}	78.1^{c}	63.6^{b}	45.2^{b}	40.6^{b}	53.6

Values are expressed in mm. Values within a column in the same year followed by the same letters are not significantly different ($P < 0.05$). NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

Table 5 Crop yields and water use efficiencies (WUE) from 1998 to 2007

		ΔW (mm)				Yield (kg/ha)				WUE (kg/ha/mm)			
Year	P (mm)	NT	ST	RT	TT	NT	ST	RT	TT	NT	ST	RT	TT
1998	159.1	−81.8	−83.3	−80.3	−77.8	1181^{a}	1204^{a}	1098^{a}	1071^{a}	4.9^{a}	5.0^{a}	4.6^{a}	4.5^{a}
1999	190.0	−69.5	−67.7	−72.2	−75.9	1324^{a}	1221^{ab}	1198^{ab}	1142^{b}	5.1^{a}	4.7^{ab}	4.6^{ab}	4.3^{b}
2000	274.9	−55.4	−62.2	−46.8	−47.9	1420^{a}	1368^{a}	1328^{a}	1365^{a}	4.3^{a}	4.1^{a}	4.1^{a}	4.2^{a}
2001	268.9	−52.8	−50.2	−49.8	−55.8	1348^{a}	1254^{a}	1308^{a}	1234^{a}	4.2^{a}	3.9^{a}	4.1^{a}	3.8^{a}
2002	254.9	−54.1	−53.4	−60.8	−58.3	1478^{a}	1506^{a}	1382^{ab}	1321^{b}	4.8^{a}	4.9^{a}	4.4^{a}	4.2^{a}
2003	167.2	−79.9	−80.8	−74.7	−72.1	1326^{a}	1188^{ab}	1168^{b}	1057^{b}	5.4^{a}	4.8^{ab}	4.8^{ab}	4.4^{b}
2004	309.7	−49.8	−52.8	−44.3	−46.8	1511^{a}	1598^{a}	1534^{a}	1486^{a}	4.2^{a}	4.4^{a}	4.3^{a}	4.2^{a}
2005	286.4	−78.8	−71.8	−70.1	−73.8	1511^{a}	1382^{b}	1356^{b}	1289^{b}	4.1^{a}	3.9^{a}	3.8^{a}	3.6^{a}
2006	206.1	−66.0	−63.5	−66.9	−68.8	1426^{a}	1330^{ab}	1268^{b}	1116^{b}	5.2^{a}	4.9^{ab}	4.6^{ab}	4.1^{b}
2007	192.6	−83.4	−70.8	−82.6	−71.0	1365^{a}	1298^{a}	1278^{a}	1104^{b}	4.9^{a}	4.9^{a}	4.6^{a}	4.2^{a}
Mean	231.0	−67.2	−65.7	−64.9	64.8	1389	1335	1292	1219	4.7	4.6	4.4	4.2

Values within a row followed by the same letters are not significantly different ($P < 0.05$). Spring wheat was planted in 1998, 2000, 2002, 2004 and 2006. Oat was planted in 1999, 2001, 2003, 2005 and 2007. ΔW, change in stored soil water of the soil profile (0–100 cm depth) from planting to harvest; NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

uptake have been reported by Urioste *et al.* (2006). The lack of soil inversion also explains the smaller amount of Olsen's P in conservation tillage treatments below 5 cm depth compared to traditional tillage.

The increase in nutrients on the conservation tillage treatments is consistent with other studies (e.g. Roldan *et al.*, 2005; Li *et al.*, 2007). However, in our study the increase (SOM: 25%; total N: 32%; Olsen's P: 35%) in the 0–5 cm depth appears to be greater than in short-term tests. For example, Qin *et al.* (2007) in Inner Mongolia recorded that after 4 years the SOM, total N and Olsen's P to 5 cm depth under no-tillage was only 17, 8 and 1% more than for traditional tillage, respectively.

Continuous conservation tillage also limited soil compaction of the top 30 cm of the soil profile. In our study, TT initially decreased bulk density, but NT had a lower bulk density than traditional tillage by the end of the experiment. These results suggest that the increased soil bulk density of the early years on NT plots was balanced over time by other changes in the soil, for example the greater amount of soil organic C and greater aggregate stability (Karlen *et al.*, 1994). On the TT treatment, traditional ploughing reduced bulk density only at the beginning of the experiment. After several years, negative effects, such as the formation of a plough pan, emerged. Our data agree with the results Li *et al.* (2007) obtained on the Loess Plateau – that no-tillage with residues retained reduced mean bulk density by 0.06 Mg/m^3 on silt loam soils.

Conservation tillage treatments also had positive effects on pore size distribution. Mean macro-porosity in the top 0–30 cm improved significantly compared to traditional tillage. The effects on mesoporosity were smaller, but consistently positive and statistically significant ($P < 0.05$). Accordingly, microporosity of conservation tillage soils is consistently smaller than on TT plots. These results are consistent with those of Benjamin (1993) and demonstrate the negative long-term effects of traditional tillage on macropore and mesopore volumes after the introduction of crop farming on formerly pastoral land. The benefits of conservation tillage for porosity in our test were more pronounced than those of shorter term experiments conducted in semiarid China. For example, Zhang *et al.* (2006) found an increase in mesoporosity in the 0–10 cm soil layer of only 1.6% compared to ploughing during a 3-year test in western Liaoning.

Water storage increased as a consequence of the improved soil structure and porosity. The 10-year mean soil water storage in the 0–30 cm soil profile of NT, ST and RT was

7–12% greater than on traditional tillage. For the conservation tillage treatments, soil water storage followed the order NT > ST > RT, demonstrating that subsoiling and strip rototilling resulted in less soil water retention capacity and greater soil moisture loss than no-tillage. These might be explained by smaller number of macropores and mesopores, the greater surface area for evaporation and greater gas permeability after annual subsoiling and strip rototilling. In semiarid areas with frequent droughts and where farmland has been converted to pasture, the observed increase in soil water is of particular importance for stabilizing and improving crop yields. It is interesting to note that the yield increases due to conservation tillage were less in wetter years (rainfall > 300 mm) than in drier years (rainfall < 300 mm) (Figure 5). Considering these five dry years, the mean yield of conservation tillage was 14.6% greater than from traditional tillage with the maximum difference of 28% in 2006, when rainfall was only 290 mm. Similar yield improvements from conservation tillage have been reported by Zhao *et al.* (2007) in Inner Mongolia.

Conclusions

Continuous 10-year conservation tillage practices in semiarid Inner Mongolia of China resulted in significant positive effects on soil properties and productivity. The benefits were most pronounced for the no-tillage with straw cover and included significantly greater organic matter content and improved nutrient status, increased macro-aggregate stability, higher proportions of macropores and mesopores, and increased soil water storage. Consequently, crop yield and WUE for the NT treatment were improved by up to 14.0% compared to plots with traditional tillage.

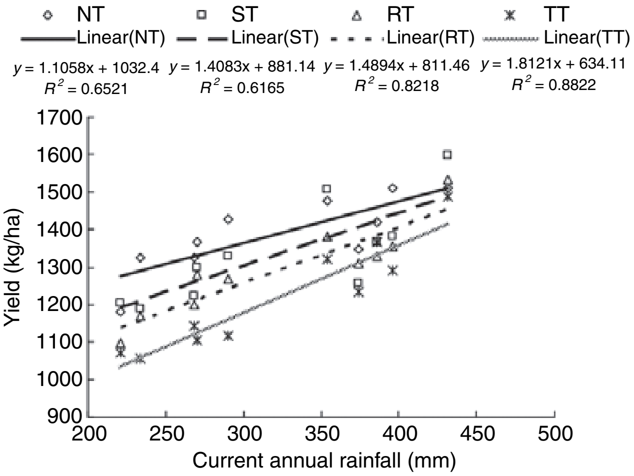

Figure 5 Relationship between grain yield and rainfall from 1998 to 2007 at Wuchuan. NT, no-tillage with straw cover; ST, subsoiling with straw cover; RT, rototilling with straw cover; TT, traditional ploughing.

This long-term study demonstrates that conservation tillage, particularly no-tillage with complete straw retention, offers a potentially significant improvement over the current farming systems in farming–pastoral transition zone of northern China. The improvements in soil properties, water use and crop yields are generally similar to those reported for similar treatments in other semiarid areas, but the positive effects are more significant than those in short-term studies. From the perspective of sustainable development, more information on the potential benefits of conservation tillage on greenhouse gas emissions is required. However, at the farm level the issue becomes economic due to an overall change in farm incomes caused by retaining all the straw residues in the field rather than using it as an animal fodder.

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