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Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain

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ABSTRACT

Soil deterioration and the accompanying decline in crop yields are the main factors limiting the further development of agriculture in North China Plain. The long-term effects of no tillage (NT) and conventional tillage (CT) on soil properties and crop yields were investigated in annual double cropping system of winter wheat–summer maize in the Gaocheng in Hebei, North China Plain over a 11-year period (1998–2009). Long-term NT significantly ($P < 0.05$) increased soil organic matter, available N and P in the top 10 cm by 16.1%, 31.0% and 29.6% as compared to CT treatment. Mean percentage of macro-aggregates (>0.25 mm, +8.1%) and macroporosity (>60 μm, +43.3%) was also enhanced statistically ($P < 0.05$) in the 0–30 cm soil layer. Winter wheat and summer maize yields tended to be 3.5% and 1.4% higher under NT than under CT, particularly in the dry years, suggesting that the change in soil physical properties, soil fertility and moisture has provided a better environment for crop development. These improvements in soil properties and yields are of considerable importance for the degraded soils in semiarid North China Plain, as well as for food security, sustainable agriculture and carbon storage in the annual double cropping areas of China.

1. Introduction

Food security for China's large population can only be sustained with intensified cropping practices, more efficient use of resources and protection of the soil resource. The North China Plain, which includes Beijing, Tianjing, Hebei, Shandong, Henan, and has about 18 Mha of farmland, is the main agricultural production base (represents 20% of total Chinese food production) in China (Sun et al., 2007). Since the 1980s, the cropping system on the North China Plain has changed from a single to a double-cropping system (Liu, 2004). Double cropping winter wheat and summer maize is the main cropping system practiced in these areas. In this system, maize is seeded in early June, immediately after the winter wheat harvest and harvested in mid-September; winter wheat is then seeded in early October and harvested in the following June. In current cropping system, all the crop residues are burned or removed after harvest before mouldboard ploughing. These methods are generally believed to produce favorable seedbeds, conserve water, increase root growth and development, and maintain crop yields (Gao et al., 1999). However, in the long term, this conventional tillage tends to increase soil bulk density, reduce both macroporosity and macro-aggregates, resulting in less water and nutrient availability (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 deterioration in North China Plain also has negative effects on crop production and environment, such as dust storms.

More sustainable farming practices, using conservation tillage to improve residue cover with minimum or no-till, have been demonstrated in many environments. Such systems will be essential for the conservation of soil, water and production cost, and the sustainable development of agriculture in North China Plain.

Numerous researchers have demonstrated that conservation tillage is effective in improving soil physical and chemical properties (Peixoto et al., 2006; Thomas et al., 2007; Madejon et al., 2009), and crop yields (De Vita et al., 2007; Naudin et al., 2010) and reducing energy required and production cost (Tullberg et al., 2007). In China, several long-term experiments (e.g. Li et al., 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 annual double cropping areas of

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North China Plain, Zhou et al. (2007) demonstrated that no-tillage increased the aggregation and stability of soil aggregates in the upper layer (0–10 cm) compared to rotary tillage and conventional tillage after 4 years in Luancheng, Hebei province. He et al. (2009b) conducted a 2-year no-tillage experiment and established that no-tillage increased crop yields by 6.7–8.9% and water use efficiency by over 6.0% compared to conventional ploughing in Dingxing, Hebei province. Results from other studies also reported that no-tillage systems were effective in improving soil moisture and increasing crops yields in North China Plain (Zhou et al., 2001; Jin et al., 2008). The application of conservation tillage was also shown to reduce production costs and increase farm income (Liu, 2004) but these were all short term studies. Little is known about the long-term effects of conservation tillage practices on soil properties and yields in North China Plain.

The objective of this study was to improve our understanding of the long-term effects of conservation tillage in North China Plain, in particular to collect sufficient data to enable a quantitative assessment of the potential benefits on soil properties and crop yields. The long-term comparison also examined the combined effects of changing tillage practice and straw management. The experiments were conducted over a period of 11 years (1998–2009) and included comparing no tillage treatment with conventional ploughing after residue burned.

2. Materials and methods

2.1. Site description

Field experiments were conducted in Gaocheng (37°51′–38°18′N, 114°38′–114°58′E, 50 m a.s.l.), situated in southwest Hebei province, North China Plain from 1998 to 2009. Gaocheng is located in a warm and semi-humid region and has a continental climate. Average annual temperature is 12.5 °C with 190 frost-free days. Average annual rainfall is 494 mm, and more than 56% of the rainfall occurs during July–August. The soils are defined as silt loam according to the USDA texture classification system. Soil chemical and physical property conditions in the experimental site in 1998 are reported in Table 1.

2.2. Experimental design

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. The experiment was designed as a randomized block with three replications. Each plot was 10 m wide and 50 m long. Two tillage/residue treatments were used: no tillage with all residues retained (NT) and conventional tillage with residues burned (CT). NT normally consisted of no-till seeding (to 5 cm depth) and fertilizing (to 10 cm depth) through the previous plant residues. CT included burning of all plant residues, spreading of fertilizer, mouldboard ploughing (to 15 cm depth) and seeding (to 5 cm depth).

The summer maize and winter wheat varieties used in the experiment were Jidan 26 and Jimai 38, respectively, which are the two most widely seeded commercial varieties. During the experimental years of 1998–2009, the seeding time of maize and wheat for CT was 2–3 days later than for NT treatment due to excessive tillage (ploughing, harrowing, leveling, etc.) for seedbed preparation. In Gaocheng, seed and fertilizer are commonly applied at very high rates by farmers to maximize the chance of good yields. In this study, winter wheat was seeded at 5 cm depth with a seedling density of 500 plants/m^2. Urea ($CO[NH_2]_2$), $(NH_4)_2HPO_4$ and KCl (K_2O content: 60%) fertilizers placed by seeder at 10 cm depth in seeding row were applied to provide 95 kg N/ha, 75 kg P/ha and 40 kg K/ha as the basal fertilizer at seeding time. An additional 50 kg N/ha was applied at first-node stage for winter wheat. Summer maize seeding density was 7 plants/m^2 and a complete fertilizer ($N–P_2O_5–K_2O$) was applied at the rate of 85 kg N/ha, 45 kg P/ha, and 40 kg K/ha at seeding. Roundup (glyphosate, 10%) was used for weed control during summer maize growing season.

Fig. 1. The 2BMFS-6/12 (known as strip-shallow-rotary before 2002) no-tillage wheat–maize seeder.

The 2BMFS-6/12 (known as strip-shallow-rotary before 2002) no-tillage wheat–maize seeder (Fig. 1), matched with a 37 kW class tractor, was used for no-tillage seeding of both wheat and maize. The no-till seeder cleans strips (width: 5 cm) by residue chopping and rotary hoeing in front of knife type tine openers, and the seeder can sow wheat immediately after maize harvest. Metal press wheels are used to firm the seed and fertilizer at depths of 5 and 10 cm, respectively. The machine can be operated for seeding 12 rows of wheat or 6 rows of maize. For wheat, the seed openers were set to 20 cm row space to provide maximum residue coverage. For maize, they were set to the 50 cm row space commonly used by local farmers. In CT treatment, wheat and maize were seeded with the same room space as NT using the local 12-row and 4-row seed drill.

2.3. Measured parameters

2.3.1. Rainfall

Rainfall was monitored throughout the experiment by a solar-powered automatic weather station, and data were recorded automatically by data loggers.

Table 1
Soil chemical and physical properties at the experimental site in 1998.

Soil depth (cm)	pH	SOM (g/kg)	Available N (mg/kg)	Available P (mg/kg)	Bulk density (g/cm^3)
0–10	7.9	15.8	69.32	17.28	1.33
10–20	8.1	13.3	69.18	16.32	1.43
20–30	8.2	10.2	54.36	13.20	1.39

Table 2
SOM (g/kg), available N (mg/kg) and P (mg/kg) for NT and CT treatments in 0–30 cm soil depth in 2009.

	SOM		Available N		Available P	
	NT	CT	NT	CT	NT	CT
Depth 1 (0–10 cm)	16.6 (13.8)	14.3 (14.0)	79.72 (64.67)	60.85 (62.92)	20.43 (16.67)	15.76 (16.35)
Depth 2 (10–20 cm)	13.9 (14.5)	13.2 (14.2)	65.83 (66.89)	62.49 (67.65)	14.32 (16.53)	17.69 (16.89)
Depth 3 (20–30 cm)	10.2 (11.5)	10.3 (11.0)	53.09 (59.21)	52.55 (58.69)	13.15 (14.45)	13.97 (14.38)
l.s.d. $(0.05)_{treatment}$		1.56		7.75		2.21
l.s.d. $(0.05)_{depth}$		1.91		9.48		2.72
l.s.d. $(0.05)_{treatment \times depth}$		2.71		13.41		3.86

(): the SOM, available N and P values in 1998. These data were tested at the beginning of experiment (after the ploughing to 40 cm depth, but before wheat seeding) in 1998. The data in 2009 were tested after maize harvest and before wheat seeding in October.

2.3.2. Soil sampling and preparation

In October 2009, soil samples were collected after maize harvest and before wheat seeding. In each plot, one composite soil sample formed by 5 sub-samples was obtained at 0–10, 10–20 and 20–30 cm soil depths to determine aggregate stability, soil organic matter (SOM), available N and P. Each soil sample was first passed through an 8 mm sieve by gently breaking apart the soil. Clods, pebbles and aggregates larger than 8 mm were discarded. For porosity tests, five un-disturbed soil cores were taken from the same three depths in each plot. All the soil samples were air-dried for 24 h in the laboratory before analysis.

2.3.3. SOM, available N and P

Total organic carbon was measured by dry combustion using a Leco Carbon Analyzer (Nelson and Sommers, 1982). Nitrate was extracted with 1 M KCl and analyzed by the cadmium reduction method (Dorich and Nelson, 1984). Plant available P was extracted with 0.5 M $NaHCO_3$ (Hedley and Stewart, 1982).

2.3.4. Soil water-stable aggregates

Soil water-stable aggregate distribution was determined by placing the soil sample on a nest of sieves, immersing directly in water, and agitating the sieves up and down 35 mm at 30 cycles/min for 15 min in a water bath. Proportions of wet stable aggregates >2, 2–1, 1–0.25, and <0.25 mm were calculated, and micro-aggregates taken as those <0.25 mm (Oades and Waters, 1991). All the measurements were replicated 5 times.

2.3.5. Soil porosity

Soil porosity was classified as macroporosity (consisting of pores with equivalent diameter > 60 μm), mesoporosity (0.2–60 μm), and microporosity (<0.2 μm). 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. All the measurements were replicated 5 times.

2.3.6. Bulk density and soil moisture

In each plot, 5 random soil samples were taken using a 54-mm diameter steel core sampling tube, manually driven into a 30 cm depth. The soil cores were split into three sections: 0–10, 10–20 and 20–30 cm from the soil surface. These moisture samples were then weighed wet, dried at 105 °C for 48 h, and weighed again to determine bulk density and gravimetric soil moisture. Gravimetric water content was multiplied by soil bulk density to obtain volumetric water content.

2.3.7. Yield

Wheat and maize yields were determined at 12% moisture content by manually harvesting three 3 m length of rows taken randomly in each plot.

2.4. Statistical analysis

Mean values were calculated for each of the variables, and ANOVA was used to assess the effects of NT and CT on the measured soil parameters and crop yields. Significance of the *F*-value was determined from ANOVA tables. Multiple comparisons of annual mean values were performed by the least-significant-difference method (l.s.d.). In all analyses, a probability of error smaller than 5% ($P < 0.05$) was considered significant. The SPSS 13.0 analytical software package was used for all the statistical analyses.

3. Results

3.1. Soil organic matter, available N and P

Soil organic matter, available N and P results are presented in Table 2. Treatment, depth, and treatment × depth interaction significantly affected soil fertility. In the 0–10 and 10–20 cm soil depths, SOM, available N and P were higher than in deeper (20–30 cm) soil depth. For the different treatments, at the beginning of the experiment in 1998, the differences between NT and CT were not significant, but pronounced treatment effects on SOM could be observed after long-term different tillage management in 2009. SOM to 30 cm soil depth for NT in 2009 was 0.3 g/kg greater than that in 1998, while CT reduced SOM by 0.5 g/kg in 2009 relative to 1998. Consequently, SOM in 0–30 cm for NT was approximately 7.7% higher than for CT after 11 years. In the surface soil layer (0–10 cm), the mean SOM was 16.6 g/kg for no-till plot, which is significantly ($P < 0.05$) greater than the 14.3 g/kg observed on the conventional tillage plot. In the deeper (10–20 and 20–30 cm) soil layer, however, no significant differences were observed between NT and CT treatments. Soil available N showed the same trend as SOM in relation to tillage treatments. Compared to 1998, mean available N in 0–30 cm soil depth improved by 4.1% on NT while it reduced by 7.1% on CT. In the 0–10 cm soil depth, available N under NT soils was 31.0% significantly ($P < 0.05$) higher than that under CT soils, while in the 10–20 and 20–30 cm soil layers, the available N differences were non-significant. The quantity of available P in both treatments was very similar in 1998, but significant differences developed across the soil profile during the 11-year experiment. In 2009, the available P under NT was 29.6% higher than under CT in the 0–10 cm soil layer, significant at $P < 0.05$, while in the 10–20 cm layer, the P content was 19.1% statistically ($P < 0.05$) lower under NT than under CT. In the 20–30 cm layer the difference was not significant.

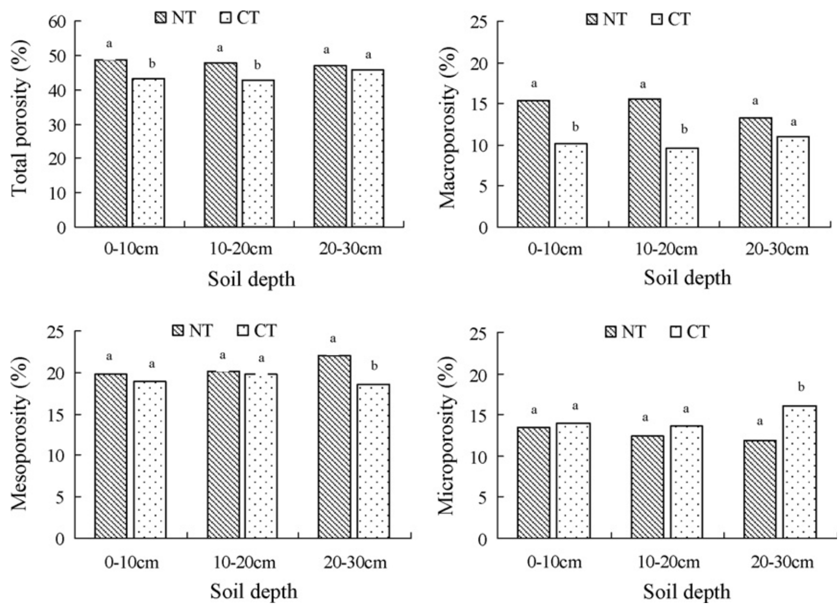

Fig. 2. Mean soil porosity for NT and CT treatments in 0–30 cm soil depth in 2009. Means in the same soil depth followed by same letters are not significant ($P > 0.05$).

3.2. Soil porosity

In general, macro and mesoporosity were greater in no-till soils but microporosity was less than that in ploughing soils (Fig. 2). In the 0–10 cm soil depth, macroporosity and mesoporosity on NT plots were 51.2% (significant at $P < 0.05$ level) and 4.6% greater, but microporosity was 3.8% less than on CT plots. In deeper soil layers, NT treatment also had 61.6% statistically ($P < 0.05$) higher macroporosity in the 10–20 cm soil layer, and significantly ($P < 0.05$) greater (17.8%) mesoporosity in the 20–30 cm soil layer, but mean microporosity in the 10–30 cm soil layer was 18.3% less. Consequently, mean total porosity was 9.0% greater in NT (47.9%) than that in CT (43.9%) largely due to an increase in macroporosity and mesoporosity on the NT plots.

3.3. Water-stable aggregates

The size distribution of water-stable aggregates is shown in Table 3. The percentages of water-stable aggregates of the largest size class (>2 mm) in 0–10, 10–20 and 20–30 cm soil layers for NT were 46.7%, 33.2% and 27.3% significantly ($P < 0.05$) greater than for CT, respectively. Furthermore, no tillage was also associated with a significant improvement in water-stable aggregates of the large size class (2–1 mm) as compared to conventional tillage in the top 2 soil layers (0–10 and 10–20 cm). In contrast, with the exception of 20–30 cm soil depth, the percentages of water-stable aggregates of the smallest size class (<0.25 mm) in 0–10 and 10–20 cm soil depths in NT plots were 19.3% and 24.3% statistically ($P < 0.05$) lower than that in CT plots.

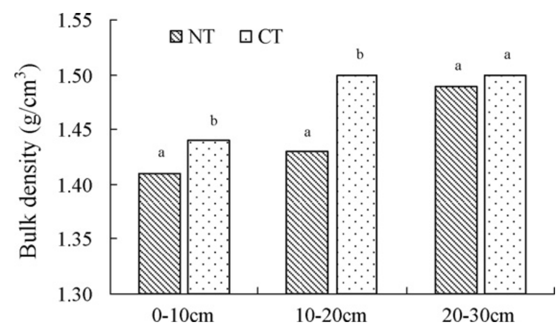

Fig. 3. Mean bulk density of NT and CT treatments in 0–10, 10–20 and 20–30 cm depths in 2009. Samples were taken immediately after wheat harvest (before ploughing CT plots) in June 2009. Means within each depth followed by the same letter were not significantly different ($P > 0.05$).

3.4. Bulk density

The mean soil bulk density for NT and CT treatments in 0–30 cm soil depth was 1.38 g/cm^3 after ploughing and before wheat seeding in 1998. After 11 years of different tillage treatments, soil bulk density in the no tillage plots had declined compared with conventional tillage (Fig. 3). In 0–10 and 10–20 cm soil layers, the mean bulk density in NT treatment was 2.1% and 4.7% significantly ($P < 0.05$) lower than in conventional tillage. A similar trend was

Table 3
Soil stable aggregate size classes (%) for NT and CT treatments in 0–30 cm soil depth in 2009.

Soil depth (cm)	Treatment	Macro-aggregates (>0.25 mm)			Micro-aggregates (<0.25 mm)
		>2 mm	2–1 mm	1–0.25 mm	<0.25 mm
0–10	NT	17.8^a	19.3^a	34.9^a	28.0^a
	CT	12.1^b	16.7^b	36.4^a	34.7^b
10–20	NT	20.3^a	19.9^a	30.9^a	28.9^a
	CT	15.2^b	17.5^b	29.1^a	38.2^b
20–30	NT	22.0^a	21.6^a	30.3^a	26.1^a
	CT	17.3^b	23.8^a	32.6^a	26.3^a

Values within a column in the same depth followed by the same letters are not significantly different ($P > 0.05$). The data were tested after maize harvest and before wheat seeding in October 2009.

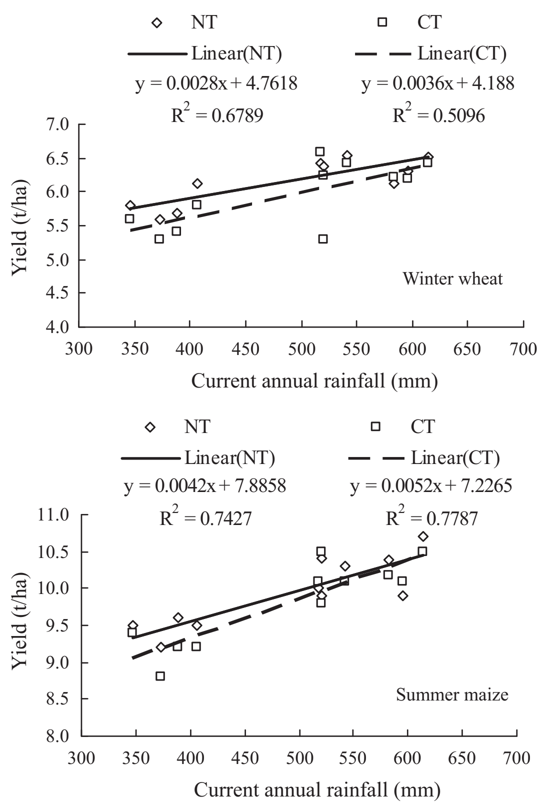

Fig. 4. Correlation between grain yield and rainfall from 1998 to 2009.

observed at the 20–30 cm soil depth, but the difference between NT and CT was negligible.

3.5. Soil water storage

Table 4 shows the soil water storage (0–30 cm) at the time of winter wheat seeding for different tillage treatments. The mean soil water storage (0–30 cm) in conventional ploughed soils from 1999 to 2009 was 55.8 mm, while in no tillage soils it was higher, approximately 60.0 mm. In the dry years of 2001 (annual rainfall: 347 mm), 2004 (annual rainfall: 373 mm), 2006 (annual rainfall: 400 mm) and 2009 (annual rainfall: 389 mm), particularly, soil water storages in NT treatment were 49.9, 48.5, 48.1 and 45.9 mm, and in CT plots were 40.3, 41.1, 40.2 and 34.3 mm, representing a mean improvement of 19.3% in no-till treatment.

3.6. Yield

Winter wheat and summer maize yields in NT and CT treatments fluctuated widely from year to year (Fig. 4). Mean winter wheat yield for no tillage was 3.5% greater than that for conventional tillage over all in 11 years, and yield differences were significant in 4 years ($P < 0.05$). It is interesting to note that the mean yield advantage of no tillage was slight in the first 5 years of the experiment, but the improvement to a mean value of 6.2% in the subsequent 6 years.

Similar result was found in maize production. As indicated in Table 5, mean (1999–2009) yield for NT plots was 1.4% higher than that for CT plots, and the yield differences were significant ($P < 0.05$) in the years of 2004 and 2009. Again, these yield advantages produced by NT were only evident in the last 6 years of the whole experiment.

4. Discussion

The experiment conducted from 1998 to 2009 clearly demonstrates that no tillage was associated with a substantial and significant improvement in soil properties and nutrient status in annual double cropping areas of North China Plain compared to conventional tillage. All relevant soil properties (SOM, N and P content, bulk density, porosity, aggregate size) improved and led to greater soil moisture and crop yields. In our study, the significantly higher SOM in no tillage soils was attributed to greater carbon input from residue retention and reduced biological oxidation of soil organic C to CO_2 (Chan et al., 2002). On the other hand, frequent and excessive tillage and crop residue burning in conventional tillage did result in significant SOM loss. Tillage-induced changes in soil organic N are often directly related to changes in soil organic C (Zibilske et al., 2002). No tillage had significantly ($P < 0.05$) greater concentrations of available N in the surface soil layer (0–10 cm), while deeper layer (20–30 cm) was not affected. Soil available P in 0–10 cm depth also increased under NT, confirming the finding of Wang et al. (2008). The topsoil accumulation of P in NT can be explained by the limit downward movement of particle bound P in no tillage soils and the upward movement of nutrients from deeper layers through nutrient uptake by roots (Urioste et al., 2006). The lack of soil turnover also explains the lower amount of available P in no tillage treatment below 10 cm depth compared to conventional tillage. In the North China Plain, Zhang et al. (2009) reported that the mean SOM in 0–10 and 10–20 cm layers of no-till soils was 10.5% and 13.6% higher than in the conventional ploughed soils in Daxing, Beijing. Similarly, Huang et al. (2006) also

Table 4
Soil water storage (mm) at winter wheat seeding time of NT and CT at 0–30 cm soil depth from 1999 to 2009.

Treatment	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Annual rainfall (mm)	583	596	347	518	614	373	521	400	521	542	389
NT	60.1[a]	65.0[a]	49.9[a]	58.5[a]	72.5[a]	48.5[a]	58.6[a]	48.1[a]	77.3[a]	76.0[a]	45.9[a]
CT	61.3[a]	62.2[a]	40.3[b]	58.1[a]	70.6[a]	41.1[b]	55.8[a]	40.2[b]	74.9[a]	75.2[a]	34.3[b]

Values within a column followed by the same letters are not significantly different ($P > 0.05$).

Table 5
Winter wheat and summer maize yields (t/ha) of NT and CT treatments from 1999 to 2009.

Crop	Treatment	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Winter wheat	NT	6.1[a]	6.3[a]	5.8[a]	6.4[a]	6.5[a]	5.6[a]	6.4[a]	6.1[a]	6.3[a]	6.5[a]	5.7[a]
	CT	6.2[a]	6.2[a]	5.6[a]	6.6[a]	6.4[a]	5.3[b]	6.2[a]	5.8[b]	5.3[b]	6.4[a]	5.4[b]
Summer maize	NT	10.4[a]	9.9[a]	9.5[a]	10.0[a]	10.7[a]	9.2[a]	9.9[a]	9.5[a]	10.4[a]	10.3[a]	9.6[a]
	CT	10.2[a]	10.1[a]	9.4[a]	10.1[a]	10.5[a]	8.8[b]	9.8[a]	9.2[a]	10.5[a]	10.1[a]	9.2[b]

Values within a column followed by the same letters are not significantly different ($P > 0.05$).

showed a 4% greater organic matter concentration in the top 20 cm compared to conventional tillage in Mengjin, Henan province. The significant increases of available N and P in no tillage were also consistent with the findings of other researchers (e.g. Díaz-Zorita and Grove, 2002; Thomas et al., 2007).

No tillage practice was associated with a greater percentage of soil in macro-aggregates (>0.25 mm) compared to conventional ploughing. Mean macro-aggregates in 0–20 cm soil layer was approximately 12.7% greater under NT than those under CT. The improved aggregate stability under NT management resulted from greater biological activity in minimum tillage soils, demonstrated by Tisdall and Oades (1982), and with a reduction in breakdown of surface soil aggregates as a result of residue cover of soil surface and the absence of tillage (Zhang et al., 2007). The greater macro aggregation under NT is consistent with the findings of other researchers (e.g. Li et al., 2007; He et al., 2009a) in one crop a year region in China. However, these studies reported a greater increase (29.9–44.2%) of macro-aggregates (>0.25 mm) in topsoil appears to be greater than in our test.

Frequent and excessive ploughing in conventional tillage leads to soil compaction and the formation of a plough pan in the lower soil profile (Kukal and Aggarwal, 2003). In our study, at the beginning of the experiment in 1998, the bulk density differences between NT and CT treatments were slight because of the initial deep ploughing (40 cm depth) that loosened the preexisting soil compaction. However, after 11 years, the mean bulk density in the top 30 cm on NT plots was significantly lower than on the CT plots, especially below the ploughing depth of the CT treatment (Fig. 3). 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). Our data agree with the results Bai et al. (2009) obtained on the Loess Plateau, who showed that no-tillage and straw cover reduced mean bulk density by 0.08 g/cm^3 on silt loam soils.

The changes of soil porosity in the 0–30 cm layer are consistent with the bulk density changes observed in this test. After 11 years of no tillage, mean macroporosity in the top 0–30 cm improved significantly ($P < 0.05$) compared to conventional tillage. The effects on mesoporosity were smaller, but consistently positive. Accordingly, microporosity of no tillage soils is consistently smaller than on CT plots. These results are consistent with those of Benjamin (1993) and demonstrate the negative long-term effects of conventional tillage on macro- and mesopore volumes after the introduction of crop farming on formerly pastoral land. The benefits of no tillage for porosity in our test were more pronounced than those of shorter term experiments conducted in semi-arid China. For example, Zhang et al. (2006) found an increase of mesoporosity in the 0–10 cm soil layer of only 1.6% compared to ploughing during a 3-year test in western Liaoning.

Soil moisture increased as a consequence of the improved soil properties. The 11 years mean soil water storage in the 0–30 cm soil profile of NT was 7.6% greater than on conventional tillage, demonstrating that ploughing resulted in less soil water retention capacity and higher soil moisture loss compared to no tillage. These might be explained by smaller number of macro- and mesopores, the greater surface area for evaporation and greater gas permeability after ploughing. In semiarid North China Plain with frequent droughts and degraded soils, the improvement in soil water combining with increased fertility under no tillage management is of particular importance for stabilizing and improving crop yields. It is interesting to note that the yield increases due to no tillage and residue retained were less in wetter years (annual rainfall > 400 mm) than in drier years (annual rainfall < 400 mm) (Fig. 4). Considering these four dry years (2001, 2004, 2006 and 2009), the mean yields of winter wheat and summer maize for NT were about 4.8% and 2.0% greater than for CT treatment. The positive effects of no tillage and residue cover on grain yields are consistent with other reported results (e.g. Zhang and Lou, 2002; Fang et al., 2003; Zhao et al., 2007). Compared to conventional ploughing systems, no tillage improved grain yields by 10–40% in the similar climatic conditions.

5. Conclusions

Continuous long term (11 years) no tillage and residue cover practice in semiarid North China Plain led to significant positive effects on soil properties. The benefits included significantly greater soil organic matter content and improved nutrient status, increased macro-aggregate stability, higher proportions of macropores and mesopores, and enhanced soil water storage. Consequently, winter wheat and summer maize yields for the NT treatment were improved by 3.5% and 1.4% compared to the soils under conventional ploughing management. Our long-term experiment demonstrates that no-tillage with residues retained offers a potentially significant improvement over the current farming systems in annual double cropping areas of North China Plain. From the perspective of sustainable development, more long-term research on the relationships between conservation tillage, soil structure, crop productivity, and environmental integrity is needed, and more information on the potential benefits of no tillage on greenhouse gas emissions is required in annual double cropping areas in North China Plain.

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