CSIRO PUBLISHING
www.publish.csiro.au/journals/ajsr *Australian Journal of Soil Research*, 2007, **45**, 344–350

Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China

Hongwen Li[A,B], *Huanwen Gao*[A], *Hongdan Wu*[A], *Wenying Li*[A], *Xiaoyan Wang*[A], *and Jin He*[A]

[A]Department of Agricultural Engineering, China Agricultural University, PO Box 46, Beijing 100083, China.
[B]Corresponding author. Email: lhwen@cau.edu.cn

Abstract. An understanding of long-term tillage and straw management impact on soil structure and productivity is necessary for the further development of conservation tillage practice in dryland farming areas. Data from a 15-year field experiment conducted in Shanxi, on the loess plateau of northern China, were used to compare the long-term effects of no-till and residue cover (NTSC) with conventional tillage (CT) in a winter wheat (*Triticum aestivum* L.) monoculture.

Long-term CT and straw removal resulted in poor soil structure and low productivity. Mean soil bulk density in NTSC was 1.5% less than in CT and capillary porosity (<60 μm) 3.2% greater. Water stability of macro-aggregates >2 mm was much greater for NTSC in the 0–0.20 m profile. Soil organic matter and total N and P were 27.9%, 25.6%, and 4.4% greater in NTSC, respectively, and earthworms (19/m^2) were found only in the no tillage treatment.

Crop yield and water use efficiency tended to be higher under NTSC than under CT, especially in the years of low rainfall, suggesting that the change in soil structure has provided a better environment for crop development. Our 15-year experimental data indicate that NTSC is a more sustainable farming system, which can improve soil structure, and increase productivity with positive environmental impacts in the rainfed dryland farming areas of northern China.

Additional keywords: conservation tillage, dryland farming, wheat, aggregate stability, soil porosity, soil fertility, yield, water use efficiency.

Introduction

China is one of the world's major dryland farming countries. Rainfed land (crop production without irrigation) is largely located in the 16 provinces of northern China, where 33 Mha of arid and semi-arid land represents 52.5% of the total national land area (Zhai and Deng 2000). These dryland farming areas have little rainfall (<750 mm/year), low winter temperatures, a short frost-free period (<150 days), and high evaporation (>1500 mm/year). Current cropping systems rely on conventional mouldboard plough tillage but suffer from soil structural degradation, and poor fertility, resulting in low water use efficiency and decreased crop yields (Gao *et al*. 1999; Liu 2004).

Conventional tillage aggravates the problems of erosion by wind and water (Wang *et al*. 2000, 2001), which have serious impacts on the wider community via pollution, dust storms, and desertification (Rong *et al*. 2004; Li *et al*. 2005). Soil erosion has also been shown to deposit 456 Mt/year of sediments, including 5.08 Mt of organic matter and 0.3 Mt of N and P, into the Yellow River in Shanxi province alone. The loss of nutrients is equivalent to 25% of the total chemical fertiliser useage in Shanxi province (Zang and Gao 2003). The average desertification rate is approximately 2000 km^2 per year, and a total of 1.74 Mkm^2 land has already been lost, with desert accounting for about 18.1% of the total land area of China in 2004 (CSFA 2005). Zhang *et al.* (2004) reported that about 30 Mha of farming lands in northern China were seriously affected by the dust storms between March and May 2002.

More sustainable cropping systems, 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 sustainable development of dryland farming in China.

Research in China has generally confirmed the improvements in productivity and sustainability achieved by conservation tillage. Mou *et al*. (1999) and Roldan *et al*. (2005) demonstrated that compared with conventional tillage, conservation tillage led to greater aggregate stability, more small soil pores, and fewer large pores. The effectiveness of no-tillage systems in controlling wind and water erosion, reducing soil loss, and increasing soil organic matter has been reported by Zang *et al*. (2003) and Zhou and Lu (2004). Conservation tillage also has been shown to increase crop yield and water use efficiency (Liao *et al*. 2002; Xue *et al*. 2005).

Most of these reports have been based on short-term experiments. More long-term systematic appraisals of conservation tillage systems in northern China are clearly required (Gao *et al*. 2003). This paper reports the outcomes of a conservation tillage project funded by the Australian Centre for International Agricultural Research (ACIAR) and the Chinese Ministry of Agriculture since 1992 in Shanxi province, northern China. This 15-year project has systematically compared the impact of long-term conservation tillage (i.e. no-tillage, full residue retention) with that of conventional tillage (mouldboard plough, all residue removed), in terms of soil bulk density, soil aggregation, porosity, soil

 10.1071/SR07003 0004-9573/07/050344

fertility, soil available water, winter wheat yield, and water use efficiency.

Materials and methods

Site description

The experiment was conducted in Chenghuang village (37°32′–38°6′N, 112°4′–113°26′E), near the city of Linfen, situated in south-central Shanxi province from 1992 to 2006. Linfen is located in a semi-arid and semi-humid region, 360–500 m above sea level on the loess plateau. Average annual temperature is 10–12°C with 130 frost-free days. Annual rainfall, concentrated from June to September, is about 500 mm and annual evaporation is 1800 mm. Figure 1 shows the annual mean monthly rainfall and temperature during the study from 1992 to 2006. According to the FAO soil classification system, the soil at the experimental site is Chromic Cambisol (FAO/UNESCO 1993), and according to the USDA texture classification system, the soil type is defined as silt loam (sand 23.1%, silt 43.3%, clay 33.6%) derived from loess soils, low in organic matter (0.9%) in the 0–400 mm depth and slightly alkaline (pH 7.9). The soil is deep (the maximum depth amounts to 100 m) and well developed (Li and Gong 2002), with a saturated hydraulic conductivity of 19 mm/h and a field water holding capacity of 26% (gravimetric).

Winter wheat monoculture is common practice, providing an average yield of 2.05 t/ha before 1992 (Li *et al.* 1997), with sowing in September and harvesting in June.

Experimental design

Two tillage/straw treatments were evaluated: no tillage with all residue retained and standing stubble (NTSC); conventional tillage with complete residue removal (CT). NTSC normally consisted of no-till planting and fertilising in the last 10 days of September, spraying herbicide and insecticide in April, and harvest by combine harvester in the first 10 days of June (leaving 0.15–0.25-m-high standing wheat straw stubble). Chemical weed control was applied when necessary in the fallow period.

In the CT treatment all wheat straw was removed for fodder before ploughing to 0.20 m depth at the beginning of the fallow period, followed by tine tillage for seedbed preparation and manual broadcast of fertiliser before planting, normally in the last 10 days of September. Herbicide and insecticide spraying occurred in April, and harvest by combine harvester in the first 10 days of June.

The experiment was designed as a randomised block with 3 replications. Each plot was 9 m wide and 78 m long. Crop management followed local best practice using wheat variety Linfen 225 at a seeding rate of 225 kg/ha, and fertiliser applied to provide 150 kg N, 140 kg P, and 62 kg K (per ha in each case).

The 2BMF-11 no-till wheat planter developed by China Agricultural University (Fig. 2) was used with a 40 kW class tractor throughout the experiment. This machine used narrow-point openers and presswheels to place and firm seed and fertiliser at depths of 50 and 100 mm, respectively. Residue clearance was maximised by mounting 5 openers on the front and 6 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, so operating width was 1.76 m.

Measurements

Rainfall

Rainfall was monitored throughout the experiment by a solar-powered automatic weather station (WeatherMaster® 2000-Environdata Pty Ltd, Qld, Australia).

Soil sampling and preparation

In August 2006, soil samples were collected from the plots of the 2 tillage/straw treatments. In each plot, one soil sample formed by 3 subsamples for aggregate stability and one soil sample consisting of 3 subsamples for organic matter, total N, and P determination were collected at 0–0.10 and 0.10–0.20 m depths, and one composite soil sample of 0–0.10 and 0.10–0.20 m depths, which was formed by 3 subsamples, was taken for soil porosity. Samples were taken using a trowel inserted into the soil at the lower level of each sampling depth to minimise compression and to obtain a representative sample of the soil.

Each soil sample was first passed through an 8-mm sieve by gently breaking apart the soil. Clods and aggregates > 8 mm were discarded, and the samples air-dried for 24 h in the laboratory before analysis.

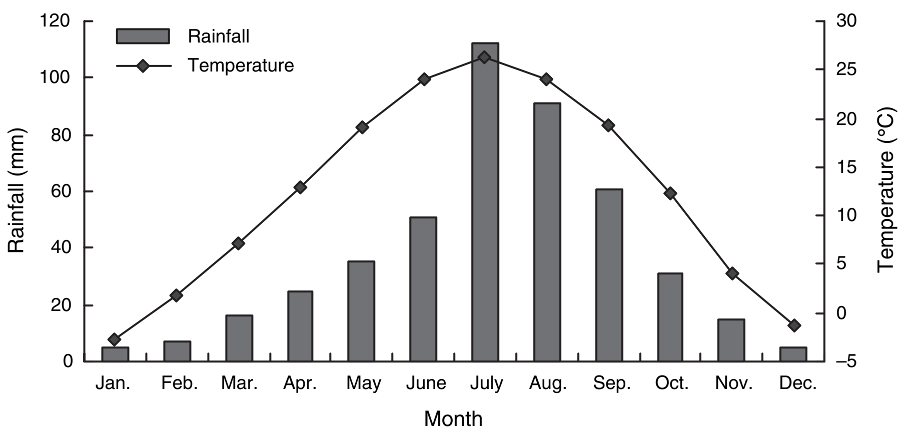

Fig. 1. Distribution of mean monthly rainfall and temperature at the experimental site during the 15 years (1992–2006).

Fig. 2. The 2BMF-11 no-till wheat planter.

Soil water stable aggregation

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 water. Proportions of wet stable aggregates >2 mm, 2–1 mm, 1–0.25 mm, and <0.25 mm were calculated, and micro-aggregates taken as those <0.25 mm (Oades and Waters 1991). All the measurements were replicated 3 times.

Soil porosity

The mean pore effective diameter size was estimated at different moisture potentials based on a model of parallel cylindrical tubes using the equation:

$$d = \frac{30}{\psi_m} \quad (1)$$

where d the equivalent pore diameter, is expressed in μm, and ψ_m is the absolute value of matric potential expressed in m of water. Hence, matric potential of –50 cm corresponds to pores of diameter 60 μm. Soil porosity was classified as capillary porosity (<60 μm) and aeration porosity (>60 μm). Total porosity (TP) was calculated from bulk density and measured particle density (i.e. 2.6 mg/m^3) (Sasal *et al*. 2006). All the measurements were replicated 3 times.

Soil organic matter, total N, and P

Organic matter (SOM) of air-dried soil samples was determined by dry combustion. Total N and P were determined using the Kjeldahl digestion method and $HClO_4$–H_2SO_4 digestion methods, respectively. All the measurements were replicated 3 times.

Earthworms

In August 1992, 1998, and 2006, one sample was taken from each of the plots by excavating a block of soil (1 m^2 by 0.3 m deep) and fine hand-sieving to observe and count earthworms.

Bulk density

In each plot, 3 random soil samples were taken using a 54-mm-diameter steel core sampling tube, manually driven into 0.20 m depth. The soil cores were divided into 2 depths: 0–0.10 and 0.10–0.20 m, then weighed wet, dried at 105°C for 48 h, and weighed again to determine bulk density.

Yield and water use efficiency

Winter wheat yields were determined by manual harvesting, threshing, and air-drying grain from three 1-m^2 areas taken at random in each plot.

Evapotranspiration (ET) is usually calculated using the formula:

$$\mathrm{ET} = (\mathrm{P} + \mathrm{I} + \mathrm{S_g}) - \mathrm{D} - \mathrm{R_f} - \Delta \mathrm{W} \quad (2)$$

where P is growing seasonal rainfall (mm), I is irrigation (mm), S_g is groundwater contribution to plant-available water (mm), D is downward drainage out of the root-zone (mm), R_f is surface runoff (mm), and ΔW is change of soil water content (mm).

In this experiment, I, S_g, and D were ignored because there was no irrigation, the groundwater contribution from a watertable 50 m below the surface was negligible, and drainage out of the root-zone need not be considered in this area (Huang *et al*. 2005). Surface water runoff (R_f) is normally small under the conditions of this experiment (Kang *et al*. 2000), but might reasonably be regarded as a treatment effect. ΔW was taken as the difference between the initial and final water content of the 1.00 m soil profile during the growing period.

Water use efficiency (WUE) was calculated as the winter wheat yield (kg/ha) divided by the growing-season evapotranspiration (mm):

$$\mathrm{WUE} = \mathrm{Yield}/\mathrm{ET} \quad (3)$$

Statistical analysis

The SPSS analytical software package was used for all statistical analyses. Mean values were calculated for each of the measurements, and ANOVA was used to assess the effects of conservation tillage on the measured variables. When this indicated a significant F-value ($P < 0.05$), multiple comparisons of annual mean values were made on the basis of the least significant difference (l.s.d.).

Results and discussions

Bulk density

Soil bulk density is a first approximation of potential changes in soil structure with improved management (Arshad *et al*. 1999).

Bulk density to 0.20 m depth under both NTSC and CT was approximately 1.24 Mg/m^3 at the start of the experiment after harvesting in 1992, and mean treatment values found between then and 2006 are illustrated in Fig. 3.

Mean soil bulk density from 1993 to 2006 for NTSC and CT was 1.36 and 1.31 Mg/m^3, respectively, and NTSC showed slightly higher soil bulk density. During the first 6 years of this experiment (1993–1998), soil bulk density to 0.20 m depth was significantly less in the CT treatment ($P < 0.05$), demonstrating the increase in bulk density which occurred in the no-till treatments, probably caused by wheel traffic. From 1999 to 2004, however, mean soil bulk densities of NTSC and CT were similar (1.37 and 1.36 Mg/m^3), and in 2005 and 2006, bulk density in NTSC was slightly less than that in CT. Bulk density of soil under NTSC, while initially greater than that of soil under CT, became similar after about 8 years, suggesting that the traffic effect on bulk density has been negated by other changes in soil condition, such as improved soil organic carbon, increased biotic activity, and improved structure (Karlen *et al*. 1994).

Water stable aggregates

Soil aggregation is an important variable influencing soil structure and soil erosion (Eldridge and Leys 2003). Table 1 illustrates treatment effects on aggregate wet stability in 2 size classes and for 2 treatments at 0–0.10 and 0.10–0.20 m depths.

Significant ($P < 0.05$) treatment differences can be seen in the size distribution of water-stable soil aggregates. In long-term no-till soil, the percentage of water-stable aggregates of the largest size class (>2 mm) was approximately twice that in ploughed soil in both 0–0.10 and 0.10–0.20 m depths. Similarly, the percentage of water-stable aggregates of the smallest size class (<0.25) was greater in ploughed soil. Macro-aggregates constituted 58.6% and 53.5% of 0–0.10 and 0.10–0.20 m depths, respectively, of no-till soil, compared with 45.1% and 47.4% for ploughed soil.

These data are consistent with the increase in aggregation occurring as a result of greater biological activity in no-till soil, demonstrated by Tisdall and Oades (1982), and with a reduction in breakdown of surface soil aggregates as a result of residue protection of the soil surface and the absence of tillage (Oyedele *et al*. 1999). These findings are similar to the results of Peixoto *et al*. (2006).

Soil porosity

Tillage usually increases total porosity (Roseberg and McCoy 1992), but there were no significant differences between the porosity of no-tillage and conventional ploughed plots after 15 years of continuous treatment. Mean aeration porosity was slightly greater in the ploughed treatment, and mean capillary porosity (Table 2) was slightly greater in the no-till treatment.

Soil organic matter, total N, and P

Soil organic matter, total N, and P were significantly ($P < 0.05$) different between treatments after 15 years (Table 3). Improvements in mean soil organic matter and fertility levels of both soil layers of no-till were the range 10–30%, with the exception of phosphates in the 0.10–0.20 m depth, which declined. Effects were larger in the upper soil layer. The results show that over the longer term, no-tillage with all residues retained is effective in improved soil organic matter, total N

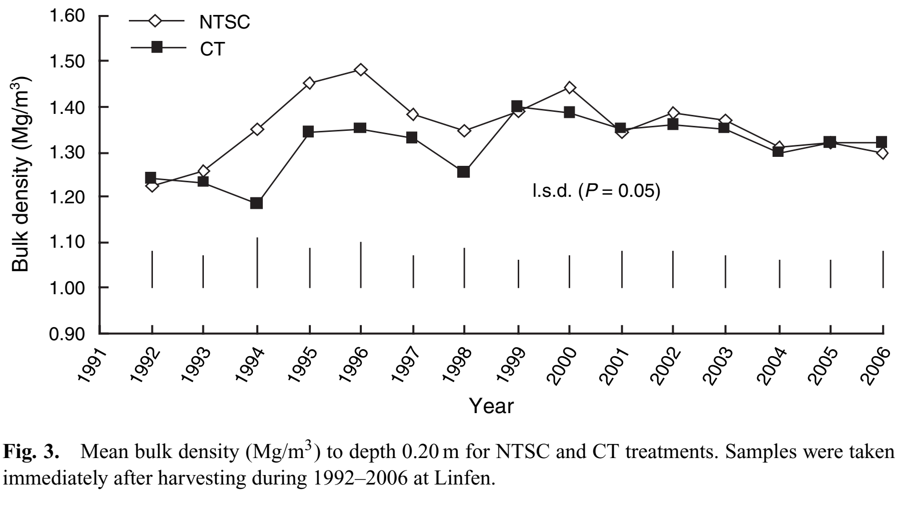

Fig. 3. Mean bulk density (Mg/m^3) to depth 0.20 m for NTSC and CT treatments. Samples were taken immediately after harvesting during 1992–2006 at Linfen.

Table 1. Soil wet stable aggregate size classes (mm) at 0–0.10 and 0.10–0.20 m depths (%)
Values within a column in the same depth followed by the same letters are not significantly different ($P < 0.05$)

Soil depth (m)	Treatment	Aggregate size classes >2	2–1	1–0.25	<0.25	Macro-aggregates >0.25	Micro-aggregates <0.25
0–0.10	NTSC	16.0a	25.0a	17.6a	41.4a	58.6	41.4
	CT	8.0b	21.0a	16.1a	54.9b	45.1	54.9
0.10–0.20	NTSC	20.8a	27.0a	5.7a	46.5a	53.5	46.5
	CT	9.5b	23.0a	14.9b	52.6a	47.4	52.6

(Roldan *et al*. 2005), and P (Rhoton 2000) in the upper soil layer, compared with the plough and residue removed.

Soil health

Earthworm numbers are often regarded as an index of soil biological activity and health, and the soil biota are particularly important in no-till systems because of their ability to modify the soil physical environment and assist in nutrient cycling (Chan 2001). Mean data in Table 4 show that there were no earthworms in the experimental plots to the depth of 0.30 m at the start of the experiment (in 1992). Six years later, there were 5 earthworms/m^2 in no-till treatments, and by 2006 the mean population was 19 earthworms/m^2, while there were still none in the ploughed plots. This improvement in earthworm population under no till has been commented on by many authors (e.g. Mele and Carter 1999; Chan and Heenan 2006; Reeleder *et al*. 2006), and could be explained by more natural soil surface conditions (residue) and reduced soil disturbance.

Soil water storage

Table 5 shows the soil water storage (0–0.20 m) at the time of winter wheat planting for different tillage/straw treatments. The mean soil water storage (0–0.20 m) in CT plots from 1993 to 2006 was 35.9 mm, while in NTSC plots it was higher, approximately 38.9 mm. In the dry years of 1998, 2000, and 2005, particularly, soil water storages in NTSC were 47.2, 38.0, and 28.5 mm, and in CT plots were 40.2, 29.6, and 24.4 mm, respectively, representing a mean improvement of 20.9% in the no-till treatment.

Table 2. Soil porosity (cm^3/100 cm^3) at 0–0.20 m depth under NTSC and CT treatments

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

Treatment	Total porosity	Aeration porosity (>60 μm)	Capillary porosity (<60 μm)
NTSC	43.02a	34.31a	8.71a
CT	44.89a	36.45a	8.44a

Table 3. Soil organic matter (%), total N (g/kg), and P (g/kg) under NTSC and CT treatments at 0–0.10 m and 0.10–0.20 m depths

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

Soil depth (m)	Treatment	Soil organic matter	Total N	Total P
0–0.10	NTSC	1.822a	0.668a	0.738a
	CT	1.356b	0.553b	0.645b
0.10–0.20	NTSC	1.202a	0.541a	0.608a
	CT	0.991b	0.415b	0.644b

Table 4. Mean earthworm population (number/m^2) under NTSC and CT treatments to the depth of 0.30 m

Treatment	1992	1998	2006
NTSC	0	5	19
CT	0	0	0

Winter wheat yield

Winter wheat yields in 2 tillage/straw treatments fluctuated widely from year to year (Table 6). Mean yield for no-till management was generally greater than that for conventional ploughing treatment, and yield differences between treatments were significant in 6 out of 14 years ($P < 0.05$). It is interesting to note that the mean yield advantage of no till was relatively small (9.2%) in the first 5 years of the experiment, but this increased to a mean value of 24.5% in the subsequent 9 years.

Regression analysis of yield and rainfall for each treatment demonstrated significant correlations (De Vita *et al*. 2007). This is illustrated in Fig. 4, which demonstrates the relatively small difference between treatments in the 4 wet years (rainfall >500 mm), and much greater difference in the 10 dry years (rainfall <500 mm). Considering these dry 10 years on their own, the mean yield of no-till winter wheat was 24.5% greater

Table 5. Soil water storage (mm) at winter wheat planting time of NTSC and CT at 0–0.20 m soil depth

Values within a column followed by the same letters are not significantly different ($P < 0.05$). Samples were taken before planting during 1993 to 2006 at Linfen. IR, Increasing ratio of NTSC to CT

Treatment	1993	1994	1995	1996	1997	1998	1999
NTSC	30.0a	36.0a	28.3a	48.9a	52.0a	47.2a	38.6a
CT	27.6a	37.2a	28.0a	49.2a	50.0a	40.2b	35.8a
IR (%)	8.7	–3.2	1.1	–0.6	4.0	17.4	7.8
	2000	2001	2002	2003	2004	2005	2006
NTSC	38.0a	40.0a	36.0a	37.6a	56.2a	28.5a	27.5a
CT	29.6b	34.6b	34.2a	35.4a	52.4a	24.4b	24.3b
IR (%)	28.4	15.6	5.3	6.2	7.3	16.8	13.1

Table 6. Winter wheat yields (kg/ha) and water use efficiencies (kg/ha.mm) under NTSC and CT treatments from 1993 to 2006

Values within a row followed by the same letters are not significantly different ($P < 0.05$)

Year	P (mm)	ΔW (mm)		Yield		WUE	
		NTSC	CK	NTSC	CK	NTSC	CK
1993	192.4	–74.1	–78.7	2985a	2548a	11.2a	9.4b
1994	199.4	–43.8	–44.7	3162a	3002a	13.0a	12.3a
1995	198.3	–58.1	–59.1	2513a	2342a	9.8a	9.1a
1996	137.4	–32.1	–43.5	3865a	3455a	22.8a	19.1b
1997	175.1	–79.0	–80.3	4142a	3908a	16.3a	15.3a
1998	209.3	–56.8	–35.3	3060a	2495b	11.5a	10.2a
1999	67.6	–77.7	–70.1	2644a	2148b	18.2a	15.6b
2000	76.1	–56.8	–43.6	2578a	1652b	19.4a	13.8b
2001	169.2	–56.5	–48.5	3814a	2917b	16.9a	13.4b
2002	137.3	–45.8	–37.1	4230a	3000b	23.1a	17.2b
2003	162.9	–39.9	–42.0	3975a	3360a	19.6a	16.4b
2004	269.5	–51.9	–50.3	5175a	4605a	16.1a	14.4b
2005	100.9	–86.4	–51.4	3765a	2650b	20.1a	17.4b
2006	207.1	–48.1	–44.9	4696a	4410a	18.4a	17.5a
Mean	164.5	–57.6	–52.1	3614	3035	16.9	14.4

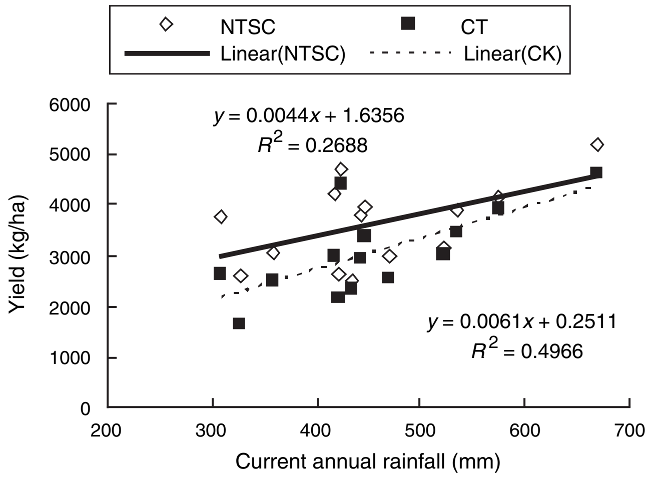

Fig. 4. Correlation between grain yield and rainfall during winter wheat cycle at Linfen.

than that from ploughed plots and the maximum difference of 56.1% occurred in 2000 (328 mm annual rainfall).

The positive effect on crop yield of conservation tillage found in this study is consistent with the results of Radford *et al*. (1995) and Basamba *et al*. (2006). The significant contribution under conservation tillage management can be attributed to increased soil water storage, combined with the changes in soil bulk density, water stability of aggregates, capillary porosity, and fertility.

Water use efficiency

The WUE of no-till and conventional tillage ranged from 9.8 and 9.1 kg/ha.mm to 23.1 and 19.1 kg/ha.mm, respectively, and the WUE in no tillage was significantly higher than that in conventional tillage in 9 out of 14 years (at $P = 0.05$). The maximum difference of 5.9 kg/ha.mm (23.1 *v.* 17.2 kg/ha.mm) occurred in the dry year of 2002 (417 mm annual rainfall).

These results demonstrated that, during the experimental period from 1993 to 2006, especially in the dry years, conservation tillage was considerably more efficient in converting available water into crop yield, whereas in ploughed plots, the poor soil structure caused by excessive tillage decreased soil water storage and winter wheat yield, thereby resulting in low water use efficiency.

Conclusions

Continuous long-term (15 years) conservation tillage practice in northern China provided evidence consistent with an improvement in soil structure and biological activity resulting from no tillage. This included significantly increased aggregate stability in the larger size classes, and greater capillary porosity (pores of diameter <60 μm). There was no evidence of change in long-term bulk density (compared with traditional tillage) but improvements in the mean values of soil nutrients and soil water storage at 0–0.20 m soil depth. Crop yield and WUE were 19.1% and 17.6% significantly greater for no-till than for ploughing practice, respectively. Our data demonstrated that conservation tillage was a significant improvement for current farming in dryland farming areas, and more long-term research on the relationships between conservation tillage, soil structure, productivity, and environment conditions is required in northern China.

Acknowledgments

This work was financed by Australian Centre for International Agricultural Research (ACIAR) and Ministry of Agriculture, China. We are grateful to Mr Deng Jing and Zhou Wanrong for managing the field experiment. Also thanks to all the postgraduate students working in Conservation Tillage Research Centre, MOA, who provided their input to this work.

References

Arshad MA, Franzluebbers AJ, Azooz RH (1999) Components of surface soil structure under conventional and no-tillage in northwestern Canada. *Soil & Tillage Research* **53**, 41–47.

Basamba TA, Barrios E, Amezquita E, Rao IM, Singh BR (2006) Tillage effects on maize yield in Colombian savanna oxisol: Soil organic matter and P fractions. *Soil & Tillage Research* **91**, 131–142. doi: 10.1016/j.still.2005.11.010

Chan KY (2001) An overview of some tillage impacts on earthworm population abundance and diversity implications for functioning in soils. *Soil & Tillage Research* **57**, 179–191. doi: 10.1016/S0167-1987(00)00173-2

Chan KY, Heenan DP (2006) Earthworm population dynamics under conservation tillage systems in south-eastern Australia. *Australian Journal of Soil Research* **44**, 425–431. doi: 10.1071/SR05144

CSFA (2005) The bulletin of desertification in China. Chinese State Forestry Administration, pp. 1–6 (in Chinese).

De Vita P, Di Paolo E, Fecondo G, Di Fonzo N, Pisante M (2007) No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. *Soil & Tillage Research* **92**, 69–78. doi: 10.1016/j.still.2006.01.012

Eldridge DJ, Leys JF (2003) Exploring some relationships between biological soil crusts, soil aggregation and wind erosion. *Journal of Arid Environments* **53**, 457–466. doi: 10.1006/jare.2002.1068

FAO/UNESCO (1993) World soil resources. An explanatory note on the FAO world soil resource map at 1 : 25 000 000 scales. Roma, pp. 64.

Gao HW, Li HW, Chen JD (1999) Research on sustainable mechanized dryland farming. *Agricultural Research in the Arid Areas* **1**, 57–62 [in Chinese].

Gao HW, Li WY, Li HW (2003) Conservation tillage technology with Chinese characteristics. *Transactions of the CSAE* **19**, 1–4 [in Chinese].

Huang YL, Chen LD, Fu BJ, Huang ZL, Gong J (2005) The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. *Agricultural Water Management* **72**, 209–222. doi: 10.1016/j.agwat.2004.09.012

Kang SZ, Shi P, Pan YH, Liang ZS, Hu XT, Zhang J (2000) Soil water distribution, uniformity and water-use efficiency under alternate furrow irrigation in arid areas. *Irrigation Science* **19**, 181–190. doi: 10.1007/s002710000019

Karlen DL, Wollenhaupt NC, Erbach DC, Berry EC, Swan JB, Eash NS, Jordahl JL (1994) Long-term tillage effects on soil quality. *Soil & Tillage Research* **32**, 313–327. doi: 10.1016/0167-1987(94)00427-G

Li HW, Chen JD, Gao HW (1997) A comparison of three tillage methods in dryland farming. *Agricultural Research in the Arid Areas* **15**, 7–11 [in Chinese].

Li HW, Gao HW, Feng XJ, Wang XY, Du B (2005) Contribution of farmland wind erosion to sand storms in northern China. In 'Proceedings of SPIE—The International Society for Optical Engineering, v 5884, Remote Sensing and Modeling of Ecosystems for Sustainability II, 2005'. pp. 1–12.

Li XY, Gong JD (2002) Compacted catchment with local earth materials for rainwater harvesting in the semiarid region of China. *Journal of Hydrology* **257**, 134–144. doi: 10.1016/S0022-1694(01)00550-9

Liao YC, Han SM, Wen XX (2002) Soil water content and crop yield effects of mechanized conservative tillage-cultivation system for dryland winter wheat in the loess tableland. *Transactions of the CSAE* **4**, 68–71 [in Chinese].

Liu LJ (2004) Systematic experiments and effect analysis of all year conservation tillage in two crops a year region. PhD dissertation, China Agricultural University, Beijing, China (in Chinese).

Mele PM, Carter MR (1999) Impact of crop management factors in conservation tillage farming on earthworm density, age structure and species abundance in south-eastern Australia. *Soil & Tillage Research* **50**, 1–10. doi: 10.1016/S0167-1987(98)00189-5

Mou SJ, He MH, Zang FY, Ma JX, Huang MQ (1999) Study on the coordinative techniques of no-tillage, mulch, deep loosening and the farming mode. *Journal of Tianjin Agricultural College* **6**, 22–26 [in Chinese].

Oades JM, Waters AG (1991) Aggregate hierarchy in soils. *Australian Journal of Soil Research* **29**, 815–828. doi: 10.1071/SR9910815

Oyedele DJ, Schjonning P, Sibbesen E, Debosz K (1999) Aggregation and organic matter fractions of three Nigerian soils as affected by soil disturbance and incorporation of plant material. *Soil & Tillage Research* **50**, 105–114. doi: 10.1016/S0167-1987(98)00200-1

Peixoto RS, Coutinho HC, Madari B, Machado PA, Rumjanek NG, Van Elsas JD, Seldin L, Rosado AS (2006) Soil aggregation and bacterial community structure as affected by tillage and cover cropping in the Brazilian Cerrados. *Soil & Tillage Research* **90**, 16–28. doi: 10.1016/j.still.2005.08.001

Radford BJ, Key AJ, Robertson LN, Thomas GA (1995) Conservation tillage increases in soil water storage, soil animal populations, grain yield, and response to fertiliser in the semi-arid subtropics. *Australian Journal of Experimental Agriculture* **35**, 223–232. doi: 10.1071/EA9950223

Reeleder RD, Miller JJ, Ball Coelho BR, Roy RC (2006) Impacts of tillage, cover crop, and nitrogen on populations of earthworms, microarthropods, and soil fungi in a cultivated fragile soil. *Applied Soil Ecology* **33**, 243–257. doi: 10.1016/j.apsoil.2005.10.006

Rhoton FE (2000) Influence of time on soil responses to no-till practices. *Soil Science Society of America Journal* **64**, 700–709.

Roldan A, Salinas-Garcia JR, Alguacil MM, Caravaca F (2005) Changes in soil enzyme activity, fertility, aggregation and C sequestration mediated by conservation tillage practices and water regime in a maize field. *Applied Soil Ecology* **30**, 11–20. doi: 10.1016/j.apsoil.2005.01.004

Rong JF, Gao HW, Wang XY (2004) Effects of ridge direction in a field on soil erosion in Hebei Bashang region. *Journal of China Agricultural University* **9**, 13–15 [in Chinese].

Roseberg RJ, McCoy EL (1992) Tillage and traffic-induced changes in macroporosity and macroporosity community: air permeability assessment. *Soil Science Society of America Journal* **56**, 1261–1267.

Sasal MC, Andriulo AE, Taboada MA (2006) Soil porosity characteristics and water movement under zero tillage in silty soils in Argentinian Pampas. *Soil & Tillage Research* **87**, 9–18. doi: 10.1016/j.still.2005.02.025

Tisdall JM, Oades JM (1982) Organic matter and water stable aggregates in soil. *European Journal of Soil Science* **33**, 141–163. doi: 10.1111/j.1365-2389.1982.tb01755.x

Wang XY, Gao HW, Du B (2001) Rainfall infiltration related to different conservation tillage factors. *Journal of China Agricultural University* **6**, 42–47 [in Chinese].

Wang XY, Gao HW, Li HW, Zhou XX (2000) Experimental study on runoff and erosion under conservation tillage. *Transactions of ASAE* **3**, 66–69 [in Chinese].

Xue SP, Yan Q, Zhu RX, Wang HQ, Yao WS (2005) Experimental study on conservation tillage technology of complete corn stalk cover by mechanization and furrow sowing beside film mulching. *Transactions of the CSAE* **7**, 81–83 [in Chinese].

Zang Y, Gao HW (2003) Experimental study on soil wind erosion under different tillage treatments in the dryland. In 'Soil management for sustainability—Proceedings of International Soil Tillage Research Organization. 16th Triennial Conference'. Brisbane, Australia, The University of Queensland, 13–18 July.

Zang Y, Gao HW, Zhou XX (2003) Experimental study on soil erosion by wind under conservation tillage. *Transactions of ASAE* **19**, 56–60 [in Chinese].

Zhai JL, Deng W (2000) Flooding, floodplain development and management in China. In 'Ecosystem Service and Sustainable Watershed Management in Northern China. International Conference'. Beijing, P.R. China, 23–25 August, pp. 184–192.

Zhang GY, Zhao SX, Sun JH (2004) Analysis of climatological characteristics of severe dust storms in recent years in the northern China. *Climatic Environmental Research* **9**, 101–115 [in Chinese].

Zhou JZ, Lu M (2004) Experimental study on preventing soil wind erosion by conservative crop stubble coverage. *Journal of Jilin Agricultural University* **26**, 170–173 [in Chinese].

Manuscript received 9 January 2007, accepted 5 June 2007