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Soil physical properties and infiltration after long-term no-tillage and ploughing on the Chinese Loess Plateau

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Abstract Water is the most limiting factor for crop production in dryland farming. A better understanding of the long-term impact of tillage and residue management systems on soil structure and water infiltration is necessary for the further development of conservation tillage practice to improve water use efficiency. The objectives of this study were to assess the influence of no-till with residue retention (NT) and conventional (plough) tillage with residue removal (CT) on soil properties and soil water transmission characteristics in a winter wheat (*Triticum aestivum*) monoculture system in Shanxi, on the Chinese Loess Plateau. Soil physical parameter measurements were made in the top 30 cm depth in September 2007 after 16 years under the two tillage treatments. Compared with CT treatment, NT significantly ($P < 0.05$) reduced soil bulk density (7.1%) in the 20–30 cm soil layer, and increased macroporosity (>60 µm, 17.0%) and saturated hydraulic conductivity (249%) in the 15–30 cm soil layer. There were no significant differences in these soil physical properties between tillage systems in the 0–15 cm layer. In addition, plant available water and water infiltration rate were greater in the NT treatment. The improved soil quality parameters and water infiltration from this long-term experiment indicate that no-tillage with residue retention is a promising farming system for the dryland farming areas of northern China.

Keywords conservation tillage; soil water retention characteristics; saturated hydraulic conductivity; soil aggregates; soil porosity; infiltration

INTRODUCTION

Non-irrigated "dryland" agriculture is practiced on c. 40% of the world's land, most of it (60%) in developing countries (UNEP 1997). China is one of the major dryland farming countries in the world. The arid and semi-arid areas, mainly located in the 16 provinces of northern China, account for 52.5% of the total national land area with 33 Mha

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of rainfed land (Zhai & Deng 2000). The main crop in dryland farming regions, particularly on the Loess Plateau, is winter wheat (*Triticum aestivum* L.). The crop is conventionally planted in autumn and harvested in June, followed by 3 months of summer fallow before autumn planting. During the fallow period, rainfall is stored in the soil for the following wheat crop. Over the past 20 years, however, wheat yields have been increased by fertiliser application, thus increasing water consumption, so soil water is often not fully replenished during the fallow period (Huang & Zhong 2003). Crop yield varies strongly with rainfall (Li 2001), and the greatest threat to winter wheat production is water shortage.

Conventional tillage practices based on mouldboard ploughing and preparing fine seedbeds with residue removed or buried have resulted in poor soil fertility and degraded soil structure as indicated by soil surface sealing, low mesoporosity (pores of diameter <60 μm), unstable soil aggregates, and low soil organic matter content, all of which affect water infiltration and soil water retention (Elliott 1986; Fabrizzi et al. 2005). One of the most common characteristics of dryland farming is sub-optimal precipitation unevenly distributed during the cropping season, resulting in low or variable yields and poor water use efficiency (WUE). WUE can also be improved by appropriate management strategies such as no-tillage or mulching and conservation tillage (Unger 1978; Du et al. 2005).

Conservation tillage (e.g., no-tillage with standing stubble and residue retention) has been shown to improve soil properties, therefore enhancing water transmission, water retention, and crop yield in many parts of the world. In central Texas, United States, a period of 20 years of no-tillage in a wheat cropping system increased mean soil organic matter by 28% and total nitrogen (N) by 33% in the 0–105 cm soil layer (Wright et al. 2007). In NSW, Australia, no-till cultivation has been shown to reduce soil bulk density to 50 cm depth by 6.7% compared with conventional cultivation after 14 years (So et al. 2004). Benjamin (1993) and Baumhart & Lescano (1996) indicated that soils under no-tillage treatment have greater infiltration rates and water storage capacities than tilled soils. Conservation tillage was also shown to improve soil water content and crop yields in many environments (Radford et al. 1995; Hemmat & Eskandari 2004; Munoz et al. 2007), but Wilhelm et al. (1987) and Hammel (1995) observed negative effects of no-tillage on crop yields in arid areas of the United States.

Research in China has generally confirmed the improvements in productivity and sustainability achieved by conservation tillage in other parts of the world. In northern China, no-tillage with mulch has been reported to increase 4.3% of soil organic matter and 5.5% of total porosity in the 0–20 cm soil layer, respectively, compared with traditional tillage after 4 years of treatment (Zhu et al. 1999). Wang et al. (2000) showed that conservation tillage could delay run-off by 12–16 min in heavy rainfall events and improve final infiltration rate by 60.9% in comparison with conventional mouldboard ploughing in Shanxi province. In addition, improvements of crop yields have been documented where conservation tillage was used (Yan et al. 2005; Wu et al. 2006). Ma & Tong (2007) indicated that the winter wheat yields for conservation tillage were 10–20% higher than for conventional tillage in Shandong, northern China. Mean wheat yield improvement with no-tillage was estimated to be 4.3% between 2003 and 2004 in the more arid Hexi Corridor area of north-west China (Zhang et al. 2007).

Most of these reports about the effect of tillage on soil structure have been based on short-term experiments. There is a need to assess the long-term impact of conservation tillage systems on soil bulk density, pore size distribution, and aggregate stability on the Loess Plateau in arid areas of northern China. Furthermore, few studies have investigated the long-term effects of conservation tillage practices on soil water transport properties (Huang et al. 2003). This paper reports the results of a long-term winter wheat study under conservation tillage at the Linfen site, located on the Loess Plateau and documents the impact of two contrasting tillage systems on soil properties and water infiltration after 16 years.

MATERIALS AND METHODS

Site description

The study was conducted as part of a long-term tillage experiment (1992–2007) located in the village of Chenghuang near Linfen city (38°6′N, 113°E, 456 m a.s.l.), on the Loess Plateau in the south-central Shanxi province, China. The area is described as a semi-arid, warm temperate zone, and has a continental climate with c. 180 frost-free days. The mean annual temperature is 10.7°C (range –14 to 31°C) and precipitation is c. 555 mm, but highly variable between years. About 65% of the annual precipitation occurs as rainfall during the summer season (June–September). The soil type is a Chromic Cambisol (sand 23.1%, silt 43.3%, clay 33.6%, pH 8.1) according to the FAO/UNESCO soil classification. Winter wheat is planted in autumn and harvested in June, which leaves a 3-month fallow period before autumn planting in September.

Experimental design

At the beginning of the experiment, the entire field was ploughed to a depth of 30 cm to mix soil thoroughly and improve uniformity. The experiment was designed as a randomised block with two tillage systems and three replications. Each plot was 9 m wide and 78 m long. The two tillage systems, no-till with residue retention (NT) and conventional tillage with residue removal (CT), were applied annually to the experimental plots from 1992 to 2007. The NT system consisted of no-tillage planting and fertilising between 20 and 30 September, herbicide (2,4-D butylate) and insecticide (40% dimethoate) spray application in April, and crop harvesting with a combine between 1 and 10 June. Standing stubble 15–25 cm high was retained with full wheat residues left as mulch. Herbicides were applied with a sprayer, when necessary for weed control, during the fallow period from harvest to mid September. The CT system included fertiliser broadcast on the soil surface, mouldboard ploughing, harrowing, and levelling for seedbed preparation and planting between 20 and 30 September, herbicide (2,4-D butylate) and insecticide (40% dimethoate) spraying in April, and manual harvesting between 1 and 10 June. Although the majority of residue was removed, a small amount of standing stubble 8–15 cm high remained after the winter wheat harvest, and was mixed in soil. During the experimental period from 1992 to 2007, for each crop cycle, 2,4-D butylate and 40% dimethoate were applied to both tillage treatments at the rate of 0.9 and 0.3 kg (a.i.) ha^{-1} using a knapsack sprayer with a flat fan nozzle. The winter wheat variety was Linfen 225 with a seeding rate of 225 kg ha^{-1}. Fertilisers ($CO(NH_2)_2$, $(NH_4)_2HPO_4$ and KCl (K_2O content: 60%)) were applied to provide 150 kg N ha^{-1}, 140 kg P_2O_5 ha^{-1}, and 62 kg K_2O ha^{-1}.

The 2BMF-11 no-till wheat planter was matched with a 40 kW class tractor for no-tillage planting of winter wheat for NT treatment throughout the experiment. This machine used narrow-point openers and presswheels to place and firm seed and fertiliser at depths of 5 and 10 cm, respectively. Residue clearance was maximised by mounting five openers on the front and six 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 and an operating width of 1.76 m. In the CT treatment, winter wheat was planted into ploughed fields by a local 6-row seed drill set to the same row space (16 cm) as the no-till planter used for NT treatment.

Measurements

Soil sampling and preparation

Soil sampling for soil property measurements was carried out in September 2007 immediately before planting winter wheat. Undisturbed core samples were collected from randomly located points in all six plots (two tillage treatments × three replicates) for bulk density, soil water content, saturated hydraulic conductivity (*Ks*), soil water retention characteristics, and soil porosity measurements. The 50.4 mm diameter × 50 mm long cores were taken with a manual stainless steel core sampler. Three disturbed soil samples were collected at each of the 0–5, 5–10, 10–20, and 20–30 cm soil depths in each plot and mixed to form a single composite sample for each depth band for aggregate stability measurements. Each composite soil sample was gently broken apart and passed through an 8 mm sieve. Clods and aggregates >8 mm were discarded. After sieving, each composite soil sample was divided into three subsamples and air dried for 24 h in the laboratory before analysis.

Bulk density and soil water content

Bulk density and soil water content measurements were made on three undisturbed soil cores from each of the 0–5, 5–10, 10–20, and 20–30 cm soil layers in each plot. The cores were weighed wet, oven dried at 105°C for 48 h, and weighed again.

Saturated hydraulic conductivity

Ks was determined by the constant-head method (Klute & Dirksen 1986). Undisturbed saturated soil cores were fixed within a permeameter and supplied with water at the top, using a Marriotte to maintain a stable hydraulic head of 3 cm. The *Ks* was measured for three soil cores from each of the 0–15 and 15–30 cm depth bands from each plot.

Soil water retention

Soil water retention was determined following the procedure of Klute & Dirksen (1986). Soil cores were wetted to saturation by capillary action in a sand and kaolin box and then placed on a laboratory pressure plate extractor to drain them to matric potentials of 0, –5, –10, –30, –50, –80, –100, –300, and –500 kPa. Finally, they were oven dried at 105°C for 24 h. The weight of each sample was recorded after reaching equilibrium at each matric potential and after oven drying. Soil water retention measurements were made on three undisturbed cores from each of the 0–15 and 15–30 cm depth bands for each plot.

Pore size distribution

Soil pores were classified as macro-pores (consisting of pores with equivalent radius >60 μm) and meso-pores (<60 μm). Macroporosity and mesoporosity were taken as the volumetric water content difference between 0 and –5 kPa and between –5 and –1500 kPa matric potential, respectively.

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^{-1} for 15 min. Samples remaining on each sieve were dried and proportions of wet stable aggregates >2, 2–1, 1–0.25, and <0.25 mm were calculated. The fraction of micro-aggregates was taken as those <0.25 mm (Oades & Waters 1991).

Infiltration

Infiltration of water into the soil was determined in the experimental field using a double ring infiltrometer (Bouwer 1986), with a 30 cm inner diameter and 60 cm outer diameter cylinder inserted 10 cm into the soil at the experiment field. Water entering the soil was measured with a calibrated Marriot bottle. A constant water head of 20 mm was maintained in both rings. Infiltration measurements were made at three separate randomly selected points in each plot.

Statistical analysis

Mean values were calculated for each parameter from the multiple within-plot measurements, and ANOVA was used to assess the effects of different tillage modes on the measured variables. When ANOVA indicated a significant *F*-value, multiple comparison of mean values was performed by the least significant difference method (LSD). The SPSS analytical software package (SPSS 2003) was used for all of the statistical analyses.

Table 1 Treatment effects on soil bulk density (Mg m^{-3}) for the 0–30 cm soil layer. Values within a row in the same soil layer followed by different letters are significantly different ($P < 0.05$). (CT, conventional tillage; NT, no tillage.)

Depth (cm)	CT	NT	SD (total)	SE (total)
0–5	1.28^{a}	1.31^{a}	0.07	0.02
5–10	1.36^{a}	1.39^{a}	0.05	0.01
10–20	1.45^{a}	1.47^{a}	0.07	0.02
20–30	1.54^{a}	1.43^{b}	0.10	0.03

RESULTS AND DISCUSSION

Bulk density

Soil bulk density can be a significant indicator of the change of soil structure and water retention capacity under different tillage modes (He et al. 2007). Mean bulk density in the 0–30 cm soil layer under NT and CT treatments was 1.40 and 1.41 Mg m^{-3}, respectively, and the difference was negligible. However, after 16 years of no-tillage management, soil bulk density in the 20–30 cm soil layer was 6.7%, significantly ($P < 0.05$) less than that in conventional tillage (Table 1). The greater bulk density in this layer of the conventional treatment indicates the development of a compacted "hard pan" beneath tillage depth, caused by the traffic associated with tillage. The changes of soil bulk density are consistent with the findings of Mou et al. (1999) who showed that soil bulk density in 20–30 cm soil depth in northern China was 5.4% lower for no-tillage than for conventional tillage after 5 years. On the Chinese Loess Plateau, crop stubble retention under no-tillage and controlled traffic has been reported to increase soil organic matter and biotic activity, thereby reducing bulk density in the surface soil layer (Chen et al. 2008). However, in our study the soil bulk density in top 15 cm layer in NT was similar to that of CT after 16 years. This was probably owing to the soil compaction caused by random traffic counteracting the positive effect of long-term residue retention on bulk density in NT plots.

Pore size distribution

Many studies have indicated that tillage systems significantly affect soil pore size distribution (Roseberg & McCoy 1992; Lipiec et al. 2006). Total porosity, macroporosity and mesoporosity in the 0–15 cm layer were similar under both treatments (Table 2). However, significant ($P < 0.05$) differences were found in the 15–30 cm soil depth (Table 2). Compared with CT, NT increased mesoporosity by 18%, which coincided with the changes in soil bulk density at that depth. Our results were similar to the findings of Zhang & Song (2004) who demonstrated

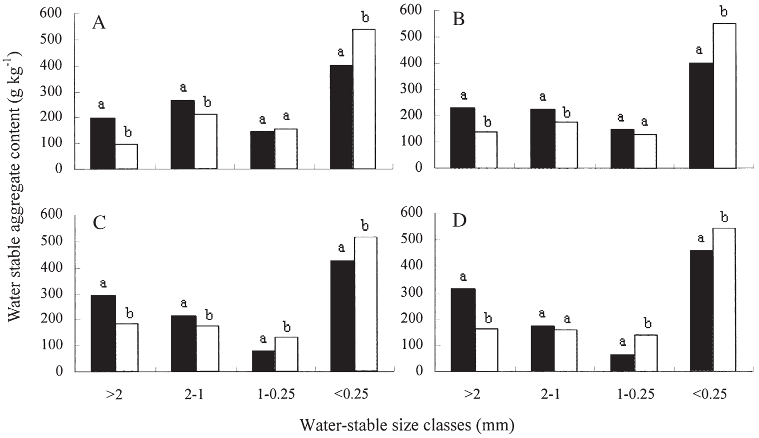

Fig. 1 Effects of no-tillage (closed bars) and conventional tillage (open bars) on water-stable size classes (mm) at **A**, 0–5; **B**, 5–10; **C**, 10–20; and **D**, 20–30 cm soil layers. Bars within the same depth and having different letters are significantly different at $P < 0.05$.

Table 2 Soil porosity (cm^3 100 cm^{-3}) of the 0–15 and 15–30 cm soil layers under no-tillage (NT) and conventional tillage (CT) treatments. Values within a column followed by different letters are significantly different ($P < 0.05$).

Soil depth (cm)	Treatment	Total porosity	Macroporosity >60 µm	Mesoporosity <60 µm
0–15	NT	44.16^{a}	34.23^{a}	9.93^{a}
	CT	46.02^{a}	37.09^{a}	8.93^{a}
	SD (total)	2.13	3.19	1.10
	SE (total)	0.50	0.75	0.24
15–30	NT	41.98^{a}	32.91^{a}	9.07^{a}
	CT	35.80^{b}	28.12^{b}	7.68^{b}
	SD (total)	3.36	2.13	0.95
	SE (total)	0.74	0.47	0.18

that no-tillage increased mesoporosity (<60 µm) by 12.5% in 15–30 cm soil layer compared with ploughing tillage, and resulted in no significant difference in the surface layer.

Although not demonstrated in this study, it was assumed that levels of compaction would be greater in CT than NT owing to the number of passes of wheels during the field preparation phases. Zhang (2005) showed that the volume of macropores (>60 µm) were influenced by the level of compaction. As compaction increases, soil water retention decreases, as those large pores which are strongly affected by structure at low suctions (0–100 kPa) are reduced. As shown in Table 2, macroporosity in NT was significantly ($P < 0.05$) higher than that in CT, demonstrating the agronomic benefit of NT in terms of increased air exchange, root development, and an increased water retention capacity. Reduced macroporosity of the deep layer (15–30 cm) is further evidence of the formation of hard pan below tillage depth in CT plots after 16 years of conventional ploughing. Generally, tillage systems that incorporate random wheel traffic and intensive ploughing resulted in a decrease of the proportion of meso- and macropores, respectively (Gupta et al. 1989). In the NT treatment in a controlled traffic experiment where the wheel traffic was absent in the cropped area, the soil pore size distribution changed from one dominated by micropores to one that had more uniform distribution of pores in the micro-, meso-, and macro-size ranges (McHugh 2003).

Soil water-stable aggregates

Significant ($P < 0.05$) treatment differences can be seen in the size distribution of soil water-stable aggregates. In long-term NT soils, the percentages of >2 mm water-stable aggregates was significantly ($P < 0.05$) higher than that in CT plots in all soil layers (Fig. 1), whereas soil in the CT treatment had a greater proportion of micro-aggregates (<0.25 mm) in all the layers. In 0–30 cm soil layer of the CT plots the proportion of micro-aggregates

(<0.25 mm) ranged from 51% to 55% in 0–30 cm depth, compared with 32–43% in NT plots. Greater proportions of large water-stable aggregates under NT are considered beneficial to improving water infiltration and reducing run-off (Yang et al. 1999). The increased proportion of large water-stable aggregates under NT may be a result of greater biological activity in no-tillage soils (Tisdall & Oades 1982), and the decreased breakdown of surface and deep soil aggregates owing to residue protection and minimum tillage (Oyedele et al. 1999).

Soil water content

Table 3 shows the mean soil volumetric water content within the 0–30 cm profile under NT and CT management before planting in 2007. In 0–20 cm soil layer, NT treatment improved mean soil water content by 6.3% compared with CT treatment. In the deeper soil layer (20–30 cm), soil moisture in NT was 10.9% significantly ($P < 0.05$) greater than that of CT. This improvement, particularly at 20–30 cm which is below the ploughing depth, could be attributed to the lower soil bulk density and higher mesoporosity of NT treatment (Yang & Wander 1998). This suggests that no-tillage with residue retention is effective in improving soil water store capacity, which is of particular importance for the growth of winter wheat in arid Loess Plateau of China.

Saturated hydraulic conductivity

Ks of soil in 0–15cm soil layer for NT (9.39 cm day^{-1}) was 7.6% higher than for CT (8.73 cm day^{-1}), but this difference was not significant. In the 15–30 cm soil layer, however, the mean *Ks* value for NT was 249% greater than CT, and this treatment difference was significant ($P < 0.05$) (Fig. 2). Our findings are similar to the results of Zhang (2005) who demonstrated that hydraulic conductivity in conventionally tilled and compacted soil was 28–36% of that in non-compacted loess soil in Shaanxi province. The decrease of *Ks* in CT could be attributed to the destruction of water-stable aggregates and reduction of the number and continuity of macropores in ploughed soils (Singh et al. 2002). Reduced hydraulic conductivity at 15–30 cm is another symptom of the soil degradation immediately below ploughing depth produced by conventional tillage.

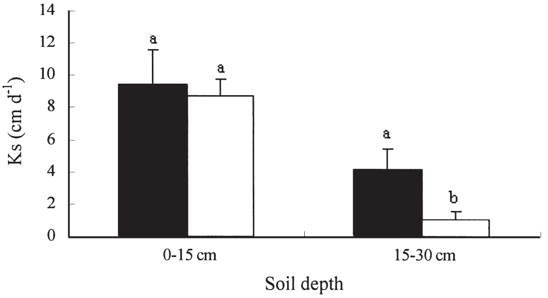

Fig. 2 Soil saturated hydraulic conductivity of **A**, 0–15 and **B**, 15–30 cm layers under no-tillage (closed bars) and conventional tillage (open bars) treatments. Bars within the same depth and having different letters are significantly different at $P < 0.05$.

Table 3 Treatment effects on soil volumetric water content (cm^3 100 cm^{-3}) in the different soil layers before planting. Values within a row in the same soil layer followed by different letters are significantly different ($P < 0.05$). (Samples were taken before planting in September 2007.)

Depth (cm)	CT	NT	SD (total)	SE (total)
0–5	16.1^a	17.3^a	1.33	0.31
5–10	18.6^a	19.6^a	1.82	0.43
10–20	20.6^a	21.9^a	1.91	0.45
20–30	22.0^a	24.4^b	1.40	0.33

Soil water retention characteristics

The differences in soil water content at any given suction were not significant between NT and CT in the 0–15 cm soil layer (Fig. 3), which was consistent with the findings of Hill et al. (1985). This similarity can be attributed to similar mesoporosity values in NT and CT treatments in this layer. As soil depth increased, mesoporosity in conventional tillage reduced, resulting in reduced soil water retention capacity under traditional plough tillage compared with no-tillage treatment. In the 15–30 cm soil layer, for example, at saturation and –30 kPa (drained upper limit), soil water content was 10.4% and 16.4% larger under NT than under CT soil. Increased water retention in this layer continued up to tensions of –500kPa. The result was attributed to a more uniform pore-size distribution, an attribute that is not necessarily reflected in macroscopic values like bulk density (Gupta et al. 1989). The small difference in soil water retention between NT and CT in the upper 15 cm layer indicated that tillage had little effect on pore-size distribution, but was more indicative of the destructive effects of traffic and tillage and the consolidating nature of loess soil on macropores.

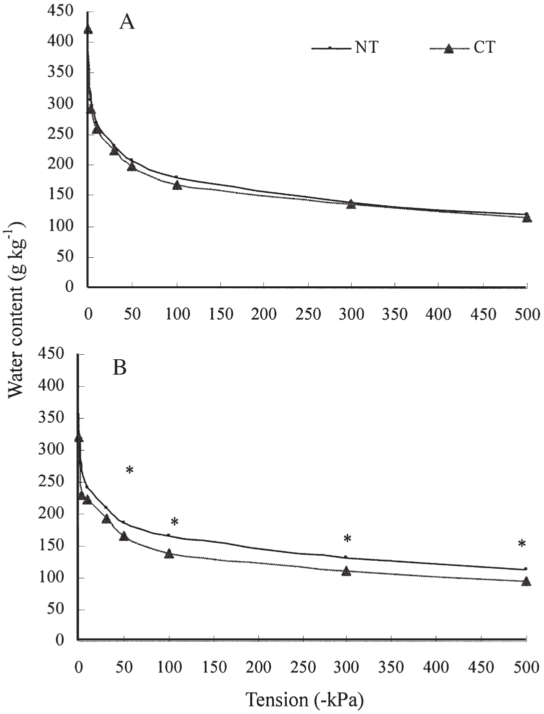

Fig. 3 Changes in soil water retention at different pressure under no tillage (NT) and conventional tillage (CT) treatments at **A**, 0–15 and **B**, 15–30 cm depths. (*, significant difference at $P < 0.05$ level probability between treatments.)

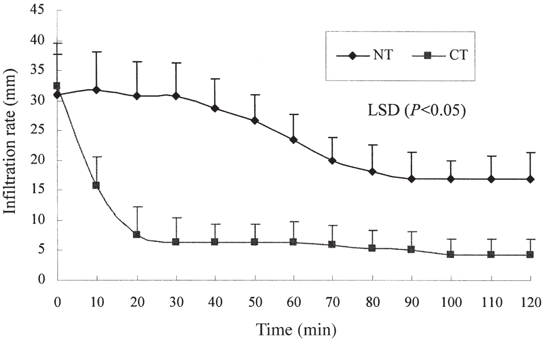

Fig. 4 Changes in soil infiltration rate within 120 min under no tillage (NT) and conventional tillage (CT) treatments.

Bescansa et al. (2006) also reported that retention of water was significantly greater in untilled soils than in tilled soils in the 20–30 cm soil layer.

Infiltration

The dynamics of infiltration was also used to assess tillage effects. Soil water infiltration rate under NT and CT decreased with time (Fig. 4). In the first 3 min of the infiltration test, differences between the infiltration rates of CT and NT plots were negligible, probably due to the similarity of soil physical properties in the upper layer. However, when water infiltrated into deeper soil layers, NT plots showed significantly ($P < 0.05$) higher infiltration rates than the CT plots. Consequently, total infiltration under NT treatment was greater, and final (steady state) infiltration rate for NT plots (17.0 mm min^{-1}) was 4 times that of the CT plots (4.25 mm min^{-1}).

The greater final infiltration rate in the plots under NT was probably owing to residue retention of the surface, less disturbance to the continuity of water conducting pores (Acharya & Sood 1992), and increased large (>2 mm) aggregate stability. In CT soils, the degradation at 20–30 cm depth after 16 years of conventional ploughing significantly reduced both macroporosity and pore continuity, thereby decreasing water infiltration. In addition, reduction of large water-stable aggregates under CT leaves more small soil particles free to move with water, clog soil pores, and reduce infiltration.

These results confirmed those of Wang et al. (2001) who reported that final infiltration rate under no-tillage with residue cover (3 years) was 1.5–1.6 times that of conventional mouldboard plough in northern China. In north-western Canada, Arshad et al. (1999) also demonstrated that steady-state infiltration rate was 60% greater for no-tillage than for conventional tillage after 12 years.

CONCLUSIONS

Comparison of plots after 16 years of continuous tilled and no-till treatments on the Loess Plateau of China have provided evidence that reduced soil disturbance and increased residue retention under no-till have improved soil physical structure, structural stability, and water infiltration. These improvements were more significant deeper in the profile, where degradation of the sub-tillage layer, and development of a hard pan in conventional tillage was not present in non-tilled soil. Adoption of no-till system significantly reduced bulk density by 7.2% and increased large (>2 mm) water-stable aggregates by 93.8% in the 20–30 cm soil layer, and improved macroporosity (pores of diam. >60 µm) by 17.0% in the 15–30 cm soil layer. Mean values of these parameters suggested that no-till with residue retention might also have positive effects on soil physical structure in the surface soil, but the differences were small and not significant. These improvements in soil physical properties and water infiltration under no-till system have profound implications for crop production in the northern provinces of China which are presently experiencing rapid soil degradation and decreasing water availability.

Our data demonstrate that soil management regimes influence soil hydraulic properties. No-tillage with residue retention was an effective method for improving soil structure, increasing rainfall capture, increasing plant available water, and, therefore, should benefit long-term productivity and sustainability. No-till also improved the end-of-fallow (pre-planting) water content and water transport capacity in the 20–30 cm soil layer. More research on the relationships between tillage, residue, and productivity is required. Furthermore, from a sustainable development perspective, more information is needed on the impact of no-tillage with residue retention on accompanying factors such as greenhouse gas emissions.

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