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Traffic and tillage effects on wheat production on the Loess Plateau of China: 1. Crop yield and SOM

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Abstract. Challenges for dryland farming on the Loess Plateau of China are continuous nutrient loss, low soil organic matter and crop yield, and soil degradation. Controlled traffic, combined with zero or minimum tillage and residue cover, has been proposed to improve soil structure and crop yield. From 1998 to 2006, we conducted a field experiment comparing soil organic matter and wheat productivity between controlled traffic and conventional tillage farming systems. The field experiment was conducted using 2 controlled traffic treatments (zero tillage with residue cover and no compaction, shallow tillage with residue cover and no compaction) and a conventional tillage treatment. Results showed that controlled traffic treatments significantly increased soil organic matter and microbial biomass in the 0–0.30 m soil profile. Controlled traffic with zero tillage significantly increased total N in the 0–0.05 m soil profile. The mean yield over 8 years of controlled traffic treatments was >10% greater than that of conventional tillage. Controlled traffic farming appears to be a solution to the cropping problems faced on the Loess Plateau of China.

Additional keywords: controlled traffic, soil organic matter, wheat yield.

Introduction

Maintenance of soil fertility is essential to sustain crop yields, and soil organic matter (SOM) management is an important component because of its direct and indirect effects on various chemical, physical, and biological soil properties (Haynes and Naidu 1998; Edmeades 2003). High SOM content is often advantageous for crop production (Arriaga and Lowery 2003), and its importance for successful farming is recognised in most areas (Merckx *et al*. 2001; Vanlauwe *et al*. 2001; Zhang and He 2004). SOM levels are strongly influenced by tillage and residue management practices (Campbell *et al*. 1996; Piovanelli *et al*. 2006).

Previous research has shown that compaction due to machinery traffic can negatively affect soil nitrogen and carbon cycling and other biochemical qualities. A study conducted by Brevik *et al*. (2002) showed reductions in soil organic carbon in compacted soil in the 0–0.20 m layer. DeNeve and Hofman (2000) reported that microbial biomass was affected and carbon mineralisation and nitrification were restricted when soil bulk density was >1.6 g/cm^3; nitrate-N decreased by 8–16%, and C : N ratio increased 3 weeks after compaction. Soil compaction can also increase N_2O emission, thus decreasing N content in the soil (Barken *et al*. 1987), and Atwell (1990) reported 12–14% reduction in N and K content in the root-zone of simulated traffic-compacted soil. Similar results were reported by Nadian *et al*. (1996).

Low SOM and poor soil water conservation are 2 of the major causes of poor yield on the Loess Plateau of China (Zhu 1984; Zhang *et al*. 1998; Gao *et al*. 1999). Intensive ploughing has contributed to an increase in soil compaction, SOM depletion by exposure of organic matter and organisms to oxidation, declining stability of soil structure and organic nitrogen supplies in soil, and thus reduced soil fertility (Cai *et al*. 1995). SOM content in the surface layer is generally low (around 6–12 g/kg), due to a long history of intensive soil cultivation on the Loess Plateau (Wang *et al*. 2007). Wei and Shao (2007) measured soil organic carbon in the 0–0.20 m soil layer at 8.6 g/kg, attributing this to straw removal and low quality manure inputs. Similar results have been demonstrated by Xing *et al*. (2001) and Ma *et al*. (2006). In addition, severe soil erosion on the Loess Plateau has resulted in large losses of soil and nutrients, including SOC, as reported by Wang *et al*. (2001).

Soil organic matter is an important aspect of soil fertility, nutrient cycling, and soil structure. Improved SOM will be a significant step towards arresting soil degradation and the decline in chemical and physical fertility, as well as improving the sustainability of agriculture in this region.

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Controlled traffic farming has been shown to reduce soil compaction and improve soil health in Australia (Tullberg *et al.* 2003), resulting in greater plant-available water. All heavy equipment wheels are confined to permanent traffic lanes in the controlled traffic system, which should be an effective way to reduce soil erosion when combined with minimum or zero tillage and residue retention. Its effectiveness in arid environments has also been demonstrated by Wang *et al.* (2005) and Hamza and Anderson (2005). There is still, however, no direct evidence of its impact on soil fertility and productivity on the Loess Plateau of China.

This paper reports the outcome of 8 years of continuous experimentation started as part of an ACIAR-funded partnership between China Agricultural University and the University of Queensland. The objective was to determine the effect of controlled traffic and conventional tillage systems on soil fertility and productivity (organic carbon, total N, microbial biomass carbon, soil pH, and winter wheat yield) on the Loess Plateau of China.

Material and methods

Sites

The experiment was conducted in Chenghuang village near Linfen city in the single annual cropping region of Shanxi province (Fig. 1). The altitude ranges from 360 m to 500 m above sea level. The site has a semiarid, warm-temperate climate with frequent dry periods in spring and summer. The annual rainfall is approximately 500 mm, but highly variable and usually occurring largely between June and September. Annual pan evaporation is 1800 mm. Figure 2 shows the mean monthly rainfall and temperature at the experimental site from 1998 to 2006. The cropping system is a winter wheat monoculture with fallow from the middle of June to the middle of September. Because >60% of annual rainfall occurs in July–September, the growing seasons are not synchronised with the main rainy period. Fallow rainfall storage efficiency is only 35–40% under traditional tillage on the Loess Plateau (Shangguan *et al.* 2002).Winter wheat yield and water use efficiency depend strongly on soil available water for dryland farming (Yan and Wang 2001). On average, 47% of the wheat yield is dependent upon the stored soil-water at planting.

The soil is Cinnamon Loess soil, which is low in organic matter (<1%) and slightly alkaline (pH 7.7). Under the USDA Texture Classification System, the soils are defined as silt loam (sand 18.81%, silt 77.45%, and clay 3.71%) and according to the FAO-UNESCO Soil Map (FAO-UNESCO 1974) the soil type is a Chromic Cambisol. It has been intensively cultivated for many centuries. The soils of the Loess Plateau are generally described as porous and homogenous to considerable depth with limited variance across fields (He *et al.* 2007).

The effect of controlled traffic with and without surface tillage was compared with traditional tillage production of winter wheat from 1998 to 2005. Before the treatments were arranged, the experimental area was ploughed (0.30 m depth) to provide uniform soil conditions. For every crop, fertiliser was applied at a rate (per ha) of 150 kg N, 140 kg P, and 62 kg K, and the seeding rate was 225 kg/ha. Wheat was planted in the last 10 days of September and harvested in the first 10 days of June.

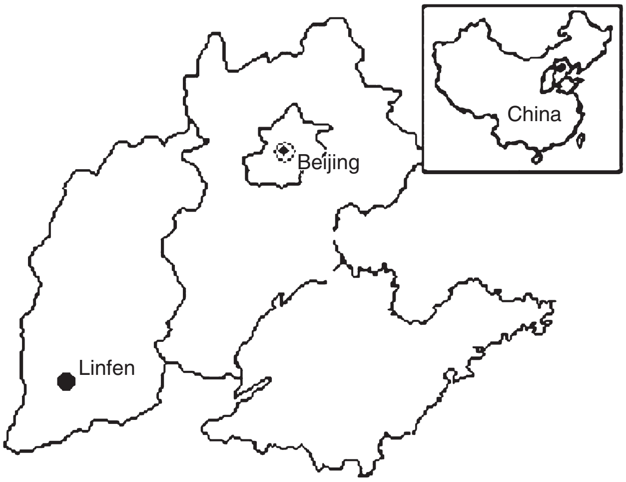

Fig. 1. Location of Linfen experimental site.

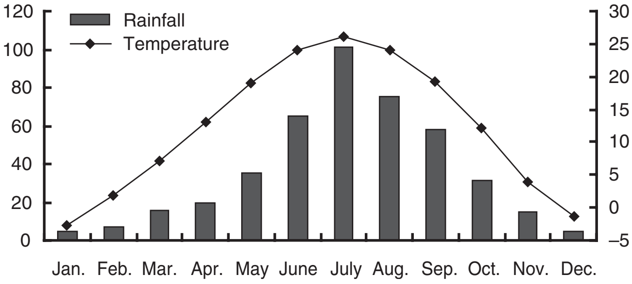

Fig. 2. Distribution of mean monthly rainfall and temperature at the experimental site from 1998 to 2006.

Experimental design

The experimental design used 3 treatments in 5 randomised blocks. The treatments included 2 controlled traffic treatments with full straw cover—zero tillage (NTCN) and shallow tillage (STCN)—and 1 conventional tillage treatment (CT), representing traditional practice in that area.

In the NTCN treatment, 0.30-m-high wheat stubble was left at harvest, and all wheat straw was returned to the plots after threshing. This was a zero till treatment, so herbicide weed control was used in the fallow period, and wheat planted with a no-till planter in September.

The STCN also left 0.30-m-high stubble at harvest, and all wheat straw was returned to the plots after threshing. Herbicide weed control was used throughout the fallow period, but a shallow (50–80 mm) sweep tillage was carried out before planting with the same machine as used for the NTCN treatment.

The CT treatment represented conventional district practice; wheat stubble was left 50–60 mm high at harvest, but the wheat straw was not returned to the plots. The soil was ploughed to 0.20 m after the first summer rain, and weeds controlled with light tillage in the fallow period. The plot was ploughed again to 0.20 m by mouldboard plough, then harrowed and dragged before planting with a conventional planting.

The layout of crop rows and permanent traffic lanes of controlled traffic treatments are shown in Fig. 3, designed according to the characteristics of the local tractors and planters. Six rows of winter wheat (*Triticum aestivum* Linfen 225) at 0.20 m row spacing were planted in beds 1.5 m wide between wheel track centre lines. The width of each wheel track was 0.30 m, occupying 20% of land area. The plots were 4.5 m wide and 30 m long (Fig. 4). In the CT treatment, there was no track, with each plot 4.5 m wide and 30 m long. The row space was 0.20 m.

Measurements

Soil sampling and preparation

Soil was sampled in the plots grown with winter wheat in December 2006. Three sampling points approximately 3 m apart were chosen in each subplot. Samples of the topsoil zones were collected at depths of 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m. Soil bulk density was collected at depths of 0–0.10, 0.10–0.20, 0.20–0.30, and 0.30–0.40 m. The spatially replicated samples were individually analysed for each treatment.

Soil samples for SOC, total N, and soil pH 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 had 3 replications. 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.

Soil samples for microbial biomass C were immediately stored at 4°C after collection, air-dried, and plant and animal residues were removed. Each soil sample was then passed through a 2-mm sieve.

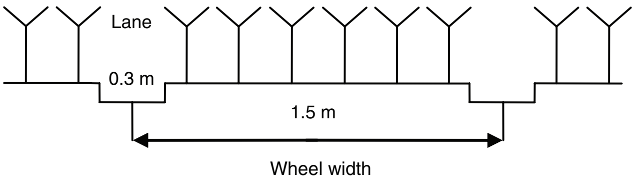

Fig. 3. Traffic lanes and crop row layout for winter wheat.

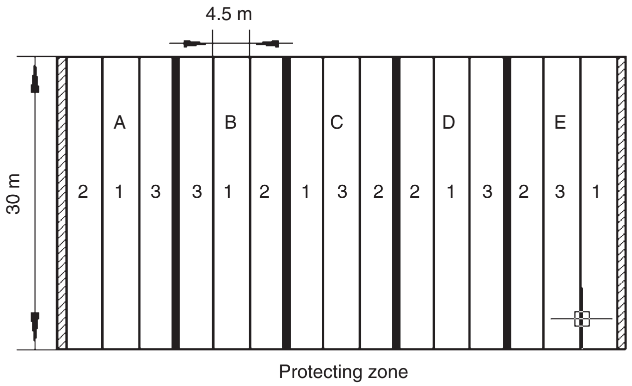

Fig. 4. Layout of treatments in experiment field. 1, NTCN; 2, STCN; 3, CT.

Microbial biomass C

Microbial biomass C was estimated by fumigation extraction (Vance *et al.* 1987). A moist soil sample was divided into 2 portions equivalent to 25 g oven-dried soil. One portion was fumigated for 24 h at 25°C with ethanol-free $CHCl_3$. Following fumigant removal, the soil was extracted with 100 mL 0.01 M $CaCl_2$ by 45 min horizontal shaking at 200 r.p.m. and filtered through a folded paper filter. The non-fumigated portion was extracted similarly at the time fumigation commenced. Organic C in the extracts was measured as CO_2 by infrared absorption after combustion at 800°C using a Maihak Tocor 2 automatic analyser; 10 mL of the $CaCl_2$ extracts was adjusted to pH 3 ± 3.5 with HCl and fed into the C analyser. Microbial biomass C was calculated as follows: microbial biomass $C = EC/k_{EC}$, where EC = (organic C extracted from fumigated soils) – (organic C extracted from non-fumigated soils) and $k_{EC} = 0.45$ (Joergensen 1995). The measurement was replicated 3 times.

Soil organic C, total N, and soil pH

Soil organic C was measured using modified Mebius method (Nelson and Sommers 1982). Briefly, 0.5 g soil was digested with 5 mL 1.0 N K_2CrO_7 and 10 mL H_2SO_4 at 150°C for 30 min, followed by titration with standardised $FeSO_4$. Total N concentration was determined by the Kjeltec autosystem. Soil pH was measured by using standard methods. All measurements were replicated 3 times.

Yield

A small-size combine harvester attached on the rear of tractor (4GL–130 Qinfeng Wheat Harvester) was used for harvesting. The harvesting width was 1.3 m, which matched crop area width of 1.2 m. The wheels were aligned as per controlled traffic layout. Yield samples were dried, cleaned with combinations of sieves and wind, and weighed. Yield of controlled traffic treatments was calculated on the basis of whole-plot (including wheel tracks and crop zones).

Statistical analysis

Mean values and standard deviations (s.d.) were calculated for each of the measurements. All data were subjected to analysis of variance (ANOVA) to assess the effects of traffic management and tillage on the measured variables. When ANOVA indicated a significant *F*-value, multiple comparisons of annual mean values were performed by the least significant difference (l.s.d.) method. The SPSS (2003) analytical software package was used for all statistical analyses.

Results and discussion

Soil bulk density

Soil bulk density is a useful indicator of soil structural change and water retention capability. Significant difference was observed in 0.10–0.20 m layer between controlled traffic treatments and CT treatment ($P < 0.05$); CT induced a compacted hard layer caused by repeated wheel track (Table 1). In the 0–0.10 m layer, expected difference was not observed between controlled traffic treatments and CT, probably due to the effect of root growth in the topsoil layer at sampling time. STCN showed significantly lower bulk density than

Table 1. Mean soil bulk density (g/cm^3) of the 3 treatments in 0–0.40 m soil profile

Within rows, means followed by the same letter are not significantly different at $P = 0.05$. s.d., Standard deviation; s.e., standard error

Depth (m)	NTCN	STCN	CT	s.d. (total)	s.e. (total)
0–0.10	1.37b	1.20a	1.27ab	0.08	0.03
0.10–0.20	1.31a	1.36a	1.54b	0.13	0.04
0.20–0.30	1.36a	1.41a	1.41a	0.05	0.02
0.30–0.40	1.44a	1.44a	1.45a	0.03	0.01

NTCN, due to effect of the shallow tillage. In the 0.20–0.40 m soil layer, the difference in bulk density between CT and controlled traffic treatments was not significant.

Soil organic C and total N

Soil organic C concentration decreased with soil depth under both controlled traffic and CT systems. Organic C content was significantly ($P < 0.05$) greater in the 0–0.30 m soil layer of both controlled traffic treatments than CT (Table 2). Organic C levels of controlled traffic treatments in the 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m soil layers were 25.2, 14.2, 37.0, and 41.0%, respectively, greater than those in CT.

The increase in soil organic C in the 0–0.05 and 0.05–0.10 m layers was related directly to the residue retained and straw returned in the field. Previous studies have indicated that residue retention can result in significant increases in soil organic C in dryland farming areas, especially for annual cropping systems with high residue crops such as wheat (Fan *et al.* 2005). Furthermore, wheat residue may reduce biological oxidation of organic C to CO_2 in controlled traffic plots, confirmed by Nyakatawa *et al.* (2001), Brevik *et al.* (2002), and Thomas *et al.* (2007). Another reason was probably related to the lower intensity of tillage associated with the controlled traffic zero (or very minimal) tillage system. Conventional tillage breaks aggregates, and aerates the soil, processes which would enhance biochemical oxidation of soil organic C (Cambardella and Elliot 1993; Islam and Weil 2000).

Soil organic C decreased more sharply in CT in the layer below 0.10 m, probably associated with severe compaction in the 0.10–0.20 m soil layer (Table 1). Brevik *et al.* (2002) reported a significant decrease of soil organic C below the compacted soil layer. The hard layer causes a decline in roots and root mass with depth, which is the source of soil organic C. Compaction may also decrease microbial activity, which is important for soil organic C transformation, confirmed by DeNeve and Hofman (2000). Furthermore, this hard layer may have a negative effect on soil water movement, which would restrict nutrient movement in the soil layer. In controlled traffic systems, soil structure improved in the absence of major tillage and traffic compaction in the root-zone, enhancing root growth and nutrient movement in the soil layers, as well as microbial activity. All of these factors might have contributed to the significant soil organic C increase.

Table 2. Mean soil organic carbon and total N (mg/kg) in control traffic and conventional treatments in the 0–0.30 m soil profile

Within rows, means followed by the same letter are not significantly different at $P = 0.05$

Depth (m)	C			N		
	NTCN	STCN	CT	NTCN	STCN	CT
0–0.05	11.08a	9.98b	8.41c	0.82a	0.88a	0.74b
0.05–0.10	8.24a	8.18a	7.19b	0.74a	0.72a	0.71a
0.10–0.20	6.09a	6.79a	4.70b	0.55a	0.49a	0.53a
0.20–0.30	3.54a	3.48a	2.49b	0.42a	0.41a	0.47a

Some of the same factors would contribute to the marked soil organic C difference between the shallow-tilled STCN and zero till NTCN, which occurred only in the top 0.05 m. An additional factor might be the greater proportion of stable aggregates in the top 0.05 m layer in NTCN, which could incorporate greater concentrations of soil organic C (Beare *et al.* 1994*b*). There were no major differences between the 2 controlled traffic systems, indicating that a light tillage did not impact greatly on the C balance.

The concentration of N declined significantly with increasing soil depth in both controlled traffic and CT systems. The amount of total N in the 0–0.05 m soil layer was significantly greater in NTCN and STCN than CT, on average 14.9% higher ($P < 0.05$). This was probably due to the greater quantity of residue returning to the soil in controlled traffic treatments, as suggested by Thomas *et al.* (2007), who observed greater total N in no-till and residue-retained treatments. In other soil profiles, there was no significant difference between controlled traffic and CT systems. In controlled traffic systems, no major difference was observed.

Microbial biomass C

Although microbial biomass C is a small proportion of total soil C, microbial biomass C is quite sensitive to changes in land use and soil management, and varies with soil depth (Alvarez and Alvarez 2000). Microbial biomass C showed a similar trend to soil organic C, i.e. a decrease with increase in soil depth (Fig. 5). At all soil depths, controlled traffic treatments showed a significantly higher level of microbial biomass C than CT.

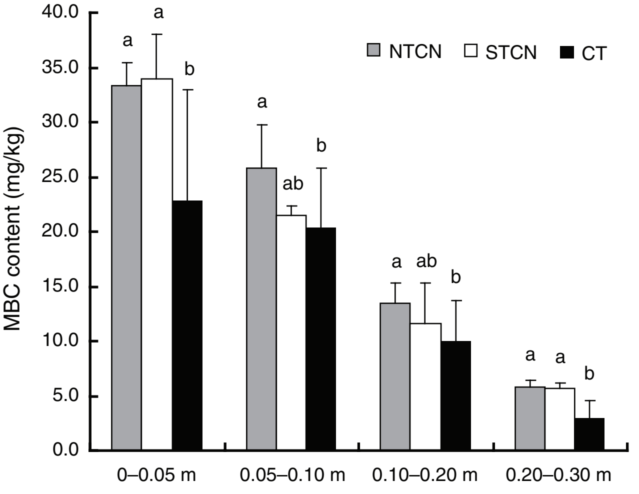

Fig. 5. Mean microbial biomass carbon (MBC) after 8 years. Error bars represent the standard error of means. Means in the same soil profile followed by same letters are not significant at $P = 0.05$.

Compared to CT, the increment of microbial biomass C for 0–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.30 m soil layers in controlled traffic treatments were 47.6, 15.3, 23.8, and 90%, respectively.

The increase in microbial biomass C in the surface layer was associated with the retention of residue and soil structural improvement induced by removing soil compaction in controlled traffic treatments (Powlson *et al.* 1987). The greatest increase was observed in the 0.20–0.30 m layer, even with quite small quantities, where microbial biomass C almost doubled under controlled traffic systems. This was associated with the removal of soil compaction, especially the removal of the hard pan in the 0.10–0.20 m soil layer. Hard pan induced by repeated wheel track in CT reduced root mass, porosity, and biomass activity below the layer (DeNeve and Hofman 2000), while in controlled traffic systems, better condition for root growth with depth and biomass activity may increase the quantity of microbial biomass C.

No significant difference was observed between controlled traffic treatments. STCN showed a slightly higher level of microbial biomass C than NTCN in the 0–0.05 m depth, but in other layers, NTCN showed a higher level of microbial biomass C than STCN, especially in the 0.05–0.10 and 0.10–0.20 m soil layers, perhaps on account of the greater level of stable aggregates in NTCN (DeNeve and Hofman 2000).

Soil pH

Soil pH ranged from 7.98 to 8.17 at depths of 0–0.05 and 0.20–0.30 m, respectively (Table 3). The only significant difference occurred between NTCN and CT in the 0–0.05 m profile, which was probably associated with surface retention of crop residue and lack of soil mixing in NTCN (Blevins *et al.* 1985; Mrabet *et al.* 2001). Higher soil organic C may have induced a slight pH reduction in controlled traffic treatments, especially in the zero tillage treatment. Regression analysis yielded significant, negative correlation between pH and organic C concentration—estimated equation: pH = 8.224–0.0178 soil organic C, ($R^2 = 0.6562$, $P < 0.0001$). There was no major difference in pH, however, indicating that tillage and traffic did not impact greatly on soil pH, and controlled traffic has not influenced soil chemical quality.

Table 3. Mean soil pH of the 3 treatments in 0–0.30 m soil profile
Within rows, means followed by the same letter are not significantly different at $P < 0.05$

Depth (m)	NTCN	STCN	CT
0–0.05	7.98a	8.02ab	8.08b
0.05–0.10	8.10a	8.07a	8.18a
0.10–0.20	8.13a	8.13a	8.16a
0.20–0.30	8.17a	8.13a	8.15a

Wheat yield

Table 4 illustrates winter wheat yields over the 8 years of this experiment. Crop yield was influenced by traffic management and tillage, the mean yield of controlled traffic plots being 10.8% greater than that of CT plots. In 3 of 8 years, controlled traffic treatments showed significantly higher yield than CT ($P < 0.05$). In 1999, the yield of controlled traffic was significantly lower than that of CT. As the first year of conservation tillage, it was hard to plant on undisturbed soil, which caused lower emergence in controlled traffic treatments. Also, 20% of the field was occupied by the wheel track in controlled traffic. As years went by, controlled traffic improved its performance on wheat yield, associated with higher SOM and better soil water conservation. The overall mean yield of STCN was 3% greater than NTCN, but this yield difference was significant only in 2002 and 2004.

The increase in SOM in controlled traffic systems stabilised nutrient supply and availability for uptake, and improved water-holding capacity, water and air infiltration, and soil structure, which have positive effects on crop yield (Campbell *et al.* 1996). Besides SOM, water availability is another important factor for crop yield in water-limited dryland cropping systems in the Loess Plateau of China. Previous research conducted at the same site (Li *et al.* 2000; Wang *et al.* 2003, 2005) has shown that controlled traffic reduces runoff and erosion, and increases available soil water content. Bai *et al.* (2008) also demonstrated the positive impact of controlled traffic management (with or without shallow tillage) on porosity, hydraulic conductivity, and water retention capacity.

Together with the improvement in soil structure in controlled traffic systems, greater yield was observed. These data indicate that even with 20% of the field occupied by wheel tracks, controlled traffic still can increase overall crop yield compared with CT in dryland farming on the Loess Plateau. These positive effects of controlled traffic on crop yield are consistent with those demonstrated by Li *et al.* (2000). Furthermore, annual shallow tillage had little effect on increasing yield in controlled traffic systems.

Several authors (Li *et al.* 2000; He *et al.* 2007) have commented on the remarkable uniformity soils of the Chinese Loess Plateau, where these experiments were carried out. Soil within these treatments has also had consistent and uniform management for a period of 8 years. Replication in this experimental design was based on past experience of

Table 4. Mean winter wheat yield (t/ha) for the 3 treatments in 1999–2006
Within columns, means followed by the same letter are not significantly different at $P = 0.05$. s.d., Standard deviation; s.e., standard error

Treatments	1999	2000	2001	2002	2003	2004	2005	2006	Mean
NTCN	3.27a	2.48a	3.08a	3.68a	3.51a	4.01a	2.71a	4.43a	3.40a
STCN	3.45a	2.52a	3.14a	3.90b	3.44a	4.39b	2.73a	4.37a	3.49a
CT	3.79b	1.46b	2.91a	3.52a	3.64a	4.12a	1.91b	3.50b	3.11b
s.d. (total)	0.25	0.53	0.17	0.21	0.15	0.21	0.43	0.26	0.75
s.e. (total)	0.07	0.15	0.05	0.06	0.04	0.09	0.12	0.10	0.15

biological variability within cropping plots. Greater replication is recommended for future research to elucidate the impact of tillage and traffic on soil structure, and its physical and biological properties.

Conclusion

Eight years of data from this experiment show that controlled traffic, zero or minimum tillage systems significantly increased soil organic matter and crop yield in dryland wheat production on the Loess Plateau of northern China. Controlled traffic treatments significantly increased soil organic C and microbial biomass C in the 0–0.30 m soil profile, and with zero tillage it also increased total N in the 0–0.05 m soil profile.

Our data demonstrate that controlled traffic practice was a significant improvement on current farming systems on the Loess Plateau. Combined with other advantages on water conservation, energy saving, and income, controlled traffic could be a useful tool in the development of sustainable agriculture in this region. However, the manufacture of matched machinery may be a big problem for its adoption. More long-term research on the relationships between controlled traffic, tillage, residue, productivity, and environmental conditions is required to demonstrate its effect in the Loess Plateau of China. Greater replication should be used in future assessments of on soil structure, and its physical and biological properties.

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