Soil Structure and Crop Performance After 10 Years of Controlled Traffic and Traditional Tillage Cropping in the Dryland Loess Plateau in China

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Abstract: Soil degradation and the accompanying decline in crop yields are the main limiting factors for the further development of agriculture on the Chinese Loess Plateau. A 10-year experiment was conducted in Linfen on the Loess Plateau to assess the potential benefits of controlled traffic on agricultural production. In this region, long-term traditional ploughing with straw removal has resulted in a decline of soil productivity and poor soil structure. Several treatments were compared: controlled traffic with no-tillage and straw cover (NTSC), controlled traffic with shallow tillage and straw cover, and traditional tillage (TT) in a winter wheat (*Triticum aestivum* L.) monoculture. Results show clear benefits of controlled traffic farming. Winter wheat growth in ploughed plots was much slower than in controlled traffic plots. Mean yield from 1998 to 2007 was 11.2% lower for traditional tillage than for controlled traffic plots. The best results were achieved by a no-tillage straw cover and controlled traffic system (NTSC), which resulted in the greatest benefits to soil structure after 10 years. The NTSC significantly improved soil organic matter content in the top 30 cm by 27.2%, total N by 10.8%, and available P (top 10 cm) by 92.3% compared with TT. Aeration (>60 μm) and capillary porosity (2–60 μm) were 155.0% and 16.1% greater, respectively, in NTSC plots than in TT plots. Consequently, for NTSC, final water infiltration rates were 67.4% greater than for TT, whereas water content in the top 130 cm was 14.9% higher than in TT, respectively. We conclude therefore that controlled traffic combined with no-tillage and straw cover is a valuable system for restoring soil productivity and quality of seriously degraded soils on the Loess Plateau for the sustainable development of agriculture in dryland China.

Key words: Controlled traffic, dry land farming, soil fertility, infiltration, crop performance

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Agriculture began in the Paleolithic period along the valley of the Yellow River and its tributaries on the semiarid Loess Plateau of China. The Loess Plateau covers 56,000 km^2 (Wu et al., 2004). Sustainable agriculture in the region is vital for regional, national, and international food supply. However, soil degradation and the subsequent decline of crop yields are serious agricultural and economic problems in this region (He et al., 2007). Soil degradation occurs both as nutrient depletion and structural deterioration because of reduced soil organic matter (SOM) and nutrient content as well as increased bulk density, poor water infiltration, and erosion (Li, 2000; Wang et al., 2007). Current cropping systems on the Loess Plateau are based on traditional ploughing and straw removal. These practices induce surface sealing and soil compaction, which reduce infiltration rate and promote erosion and an overall decrease in soil fertility (Li et al., 2007). The extent and impact of soil degradation on crop production pose a risk to national food security and, in addition, have a negative impact on the environment, most notably, on water quality and increased flood risk. Therefore, many techniques have been developed to restore and sustain soil productivity. One of the proposed innovations to reduce soil compaction, improve soil structure, and increase crop yield is the use of controlled traffic farming inspired by the success of the system in other parts of the world (e.g., Reicosky et al., 1999; Tullberg et al., 2007). Controlled traffic systems, combined with minimum or zero tillage and straw cover, are effective in increasing SOM and total N and P (Tullberg et al., 2003). Physically, controlled traffic reduces soil compaction and improves porosity and pore size distribution (Casau and Carvalho, 2001; Chamen, 2006). The application of controlled traffic in arid regions also reduces water evaporation and, by improving water availability, increases crop yields (Tullberg et al., 2001; Gicheru et al., 2004).

Research in arid areas of China has generally confirmed that controlled traffic practices effectively reduce water erosion, save energy, and increase soil water storage and crop productivity. Du et al. (1997) and Wang et al. (2004) reported initial results of experimental trials for a single maize cropping system on the Central Loess Plateau. In their tests, runoff from controlled traffic was 20% lower than from conventional tillage plots, and soil erosion declined by 16%. Zhang (2002) found that random field traffic increases fuel consumption by 26% to 30% compared with controlled traffic practices. Li et al. (2000) compared no-tillage with controlled field traffic and ploughing with random field traffic in southern Shanxi, China. Results over a 2-year period showed that soil under no-tillage and controlled traffic stored 5.2% more water in the top 50-cm soil layer because of improved water infiltration and decreased bulk density. Moreover, crop yields increased by 2.4% compared with conventional ploughing, which compacted the soil. In the more arid Northwest China, Deng et al. (2005) studied tillage and straw effects on crop yield in controlled traffic systems. They demonstrated that spring wheat yield in no-tillage and straw cover plots were about 16.7% higher than on plots that were ploughed after straw removal. In most of these reports, the changes of soil properties under controlled traffic farming were not recorded. It is also unclear whether long-term controlled traffic practice had significant positive effects on soil moisture and water infiltration. Furthermore, most of these reports about crop yield have been based on short-term experiments. Since 1997, a long-term

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systematic trial has been conducted in Linfen on the Loess Plateau of China with the objective of investigating the effects of controlled traffic on the soil and cropping processes previously discussed. This article reports on controlled traffic effects on soil properties, water infiltration, and crop performance after 10 years. We also discuss suggestions for further research to take the development of controlled traffic farming to other arid areas of China. Treatment effects on soil microbial biomass, soil water retention curves, and saturated hydraulic conductivity are discussed in the accompanying articles by Bai et al. (2008) and Chen et al. (2008).

MATERIALS AND METHODS

Site and Climatic Conditions

The experiment was conducted from 1997 to 2007 in the village of Chenghuang (36° 02′ N, 111° 38′ E), near the city of Linfen on the Loess Plateau. The site is located in a semiarid region at 554 m above sea level. Average annual temperature is 12 °C with 130 frost-free days. Average annual rainfall, concentrated between June and September, is 500 mm, whereas pan-evaporation is around 1800 mm per year. The soil in the experimental plots is a silt loam (sand, 18.8%; silt, 77.5%; clay, 3.7%) derived from loess parent material. The soils are low in organic matter content (0.9%; 0- to 400-mm depth) and slightly alkaline (pH 7.9).

Experimental Design

Two controlled traffic treatments were compared with one traditional tillage treatment in a winter wheat monoculture system: controlled traffic with no-tillage and straw cover (NTSC), controlled traffic with shallow tillage and straw cover (STSC), and traditional tillage (TT). The NTSC consists of no-till planting and fertilizer application in the last 10 days of September, herbicide and insecticide application in April, and harvest with a combine harvester in the first 10 days of June. The 30-cm-high stubble and all of the straw were left on the field. Chemical weed control was applied in the fallow period between harvest in early June and planting in late September. The STSC included shallow (5–8 cm) sweep tillage, followed by planting and fertilizer application in the last 10 days of September, herbicide and insecticide application in April, and harvest by combine harvester in the first 10 days of June. Similar to NTSC, the 30-cm-high wheat stubble and all of the wheat straw were left on the field. Chemical weed control was also applied during the fallow period. In the TT treatment, all wheat straw was removed during the June harvest for fodder, followed immediately by ploughing to a depth of 20 cm. In the last 10 days of September, fertilizer was spread manually before moldboard ploughing, followed by harrowing for seedbed preparation and planting. Herbicide and insecticide were sprayed in April. Harvest with a combine harvester occurred in the first 10 days of June. Only 5- to 6-cm-high wheat stubble remained on the field.

The experiment was designed as a randomized block with five replications. Each plot was 4.5 m wide and 30 m long. Before the treatments were applied in 1997, the entire experimental area was ploughed (30-cm depth) to provide uniform soil conditions. Crop management followed local best practice. Linfen 225 winter wheat was planted in all plots at a seeding rate of 225 kg ha^{-1}, and fertilizer was applied to provide 150 kg N ha^{-1}, 140 kg P_2O_5 ha^{-1}, and 62 kg K_2O ha^{-1} in all the treatments. In controlled traffic treatments, the bed width was 150 cm from wheel center to wheel center. Six rows of winter wheat were planted in a 120-cm-wide cropping zone, and the space between each row was 20 cm, which is common practice in Linfen.

Measurements

Soil Sampling and Preparation

In June 2007, soil samples were collected from the plots of the three treatments. For each plot, one soil sample was split into three subsamples for organic matter, total N, and plant-available P analysis. Samples were collected at 0- to 5-, 5- to 10-, 10- to 20-, and 20- to 30-cm depth. First, each soil sample was gently broken apart and passed through an 8-mm sieve. Clods and aggregates larger than 8 mm were discarded. Before further analysis, the samples were air dried for 24 h in the laboratory. For porosity tests, three undisturbed soil samples were collected at 0- to 15-, 15- to 40-, and 40- to 60-cm depths in each plot.

SOM, Total N, and Available P

Soil organic carbon was determined using the Walkley-Black wet oxidation method (Nelson and Sommers, 1982). Total N concentration was calculated by the Kjeldahl digestion method. The available phosphorous (Olsen P) for plants was extracted with 0.5 *M* $NaHCO_3$ solution adjusted to a pH of 8.5. Extractable P was determined following the modified Murphy-Riley ascorbic acid procedure (Olsen and Sommers, 1982). The measurements were replicated five times.

Soil Porosity

Soil porosity was classified as aeration porosity (consisting of pores with equivalent radii >60 μm), capillary porosity (0.2–60 μm), and microporosity (<0.2 μm). Aeration porosity was calculated as the volumetric water content difference between 0 kPa and -5 kPa matric potential. Capillary porosity was calculated as the volumetric water content difference between -5 kPa and -1500 kPa matric potential. Microporosity was determined by the volumetric water content at -1500 kPa matric potential. The measurements were replicated five times.

Infiltration

The infiltration of water into the soil was determined by the double ring infiltrometer method (Bouwer, 1986), with a 30-cm inner diameter and 60-cm outer diameter cylinder. The infiltrometer was inserted for 10 cm into the soil on the experimental field (five replicates for each treatment). A constant water head of 20 mm was maintained in both rings, and the rate of infiltration was measured using discharge from a calibrated Mariotte bottle.

Bulk Density and Soil Moisture

In each plot, three random soil samples were taken using a 54-mm-diameter steel core sampling tube, manually driven into a 60-cm depth. The soil cores were split into three sections: 0– to 15–, 15– to 40–, and 40– to 60–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. Volumetric water content was determined by multiplying gravimetric moisture content with soil bulk density.

Plant Growth Characteristics

Cores for root length density were collected using a core sampler at the jointing, booting, and filling stage of the winter wheat at depths of 0– to 15– and 15– to 40–cm. The soil cores were immersed in a sodium haxametaphosphate (10%) solution for 4 h to disperse the soil. Roots were then separated from the dispersed soil by washing. A Delta-T root scanner and image analysis system (Delta-T Devices Ltd, Burwell, Cambridge, England) was used to estimate root lengths of individual samples. The plant samples taken at the booting and filling stages of winter wheat were oven dried at 65 °C to constant weight and weighed to calculate plant dry weight.

Yield

Winter wheat yields were determined at 12% moisture content by manually harvesting, threshing, and air drying grain from three 1-m^2 areas taken randomly in each plot. In addition, grains per spike and kernel weight were also measured separately.

Statistical Analysis

For each of the measurements, mean values were calculated from the replicate samples. Analysis of variance was then used to assess the effects of controlled traffic on the soil and plant properties. When analysis of variance indicated a significant F value, multiple comparisons of the mean values were performed by the least significant difference (l.s.d.) method. The SPSS analytical software package was used for all the statistical analyses.

RESULTS

SOM, Total N, and Available P

Soil organic matter, N, and P differed between the treatments after 10 years (Table 1). The mean SOM of the 0- to 5-cm layer in the controlled traffic treatments (NTSC and STSC) was 18.2 g kg^{-1} compared with 14.5 g kg^{-1} for the TT treatment. The 25% improvement in SOM in the controlled traffic treatments was significant (P = 0.05). In the 5- to 10-cm layer, SOM was still 14% higher (significant at P = 0.05) in controlled traffic treatments. A significant increase of 38.3% was also achieved between 10 and 30 cm. A similar result was found in total N in the 0- to 5-cm soil layer, where total N content was 15% higher (significant at P = 0.05) in controlled traffic treatments than in the traditional tillage treatment. However, there was no significant difference between controlled traffic and traditional system at greater depths. The amount of available P was 84.2% higher under controlled traffic than under traditional tillage in the 0- to 5-cm layer (significant at P = 0.05). Below 5 cm, this pattern seems to be reversed, where TT contained 12.7% to 54.7% more plant-available P than controlled traffic.

TABLE 1. SOM, Total N, and Available P for Three Treatments at the 0- to 5-, 5- to 10-, 10- to 20-, and 20- to 30-cm Soil Depths

	Soil Depths, cm	Treatments		
		NTSC	STSC	TT
SOM, g kg^{-1}	0–5	19.1^a	17.2^b	14.5^c
	5–10	14.2^a	14.1^a	12.4^b
	10–20	10.5^a	11.7^a	8.1^b
	20–30	6.1^a	6.0^a	4.3^b
Total N, g kg^{-1}	0–5	0.82^a	0.88^a	0.74^b
	5–10	0.74^a	0.72^a	0.72^a
	10–20	0.55^a	0.49^a	0.53^a
	20–30	0.42^a	0.41^a	0.47^a
Available P, mg kg^{-1}	0–5	42.17^a	38.63^a	21.93^b
	5–10	23.96^a	23.62^a	32.05^b
	10–20	10.47^a	10.80^a	23.45^b
	20–30	5.24^a	6.76^a	6.76^a

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

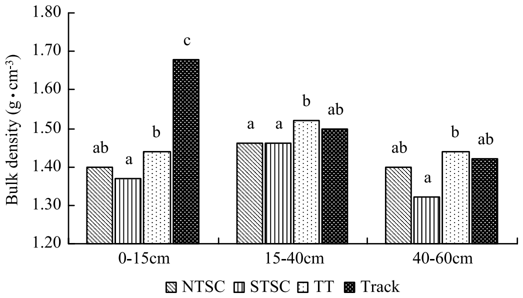

FIG. 1. Mean bulk density of the three treatments and wheel track in the 0- to 15-, 15- to 40-, and 40- to 60-cm depths. Samples were taken immediately after harvesting in 2007 at Linfen. Means within each depth followed by the same letter were not significantly different (P = 0.05).

Bulk Density

The mean soil bulk density for all the treatments was 1.33 g cm^{-3} before planting in 1997. After 10 years of different tillage treatments, soil bulk density on the controlled traffic plots had declined compared with traditional tillage (Fig. 1). In the 0- to 15-cm soil layer, the mean bulk density on controlled traffic treatments was 3.8% lower than on traditional tillage. In the 15- to 40-cm soil layer, the two controlled traffic treatments, NTSC and STSC, significantly (P = 0.05) reduced bulk density by 5.2% and 4.0%, respectively, compared with TT. A similar trend was observed at the 40- to 60-cm soil depth, but only the difference between STSC and TT was significant at the P = 0.05 level. In wheel tracks, soil bulk density values decreased with soil depth after 10 years. Compared with traditional tillage, the wheel track increased soil bulk density by 16.7% in the top 15-cm soil layer, but the differences in the 15- to 40- and the 40- to 60-cm soil layers were negligible.

Soil Pore Size Distribution

Pore size distribution also showed a significant improvement on controlled traffic plots between 1997 and 2007 (Table 2). Total porosity in each of the three sampled layers on the controlled traffic treatments increased by approximately 5 (36–41) cm^3 · 100 cm^{-3} compared with traditional tillage, representing a mean improvement of 14%. The changes were most pronounced for macropores in the top soil layer. In the 0- to 15-cm soil layer, aeration porosity was 200% higher on controlled traffic compared with traditional tillage. Similar trends but lower improvements of aeration porosity were found in the deeper soil layers. Consequently, microporosity was greater in the traditional tillage at all depths.

Infiltration

Treatment effects on soil infiltration were evaluated by comparing infiltration rates during the 120-min test with the cumulative infiltration rates at the end of the test (Fig. 2). Initial infiltration rates (at 20 min) for controlled traffic and traditional tillage treatments were similar, but the final infiltration rates in NTSC and STSC plots (15.9 and 24.8 cm h^{-1}) were about twice the rate measured in TT plots (9.5 cm h^{-1}). Cumulative infiltration after 120 min for controlled traffic plots was 47.3 cm,

TABLE 2. Soil Pore Size Distribution for Three Treatments at the 0- to 15-, 15- to 40-, and 40- to 60-cm Soil Depths

Soil Depths, cm	Treatments	Soil Pore Size Distribution, $cm^3 \cdot 100\ cm^{-3}$			
		Total Porosity	Aeration Porosity (>60 μm)	Capillary Porosity (0.2–60 μm)	Microporosity (<0.2 μm)
0–15	NTSC	40.4[ab]	6.6[ab]	18.9[a]	14.9[a]
	STSC	42.8[a]	11.7[a]	18.9[a]	12.2[b]
	TT	35.6[b]	3.0[b]	16.9[a]	15.7[a]
15–40	NTSC	40.9[a]	8.4[a]	19.3[a]	13.2[a]
	STSC	39.5[a]	5.6[a]	20.5[a]	13.4[a]
	TT	34.8[b]	1.1[b]	17.6[b]	16.1[b]
40–60	NTSC	40.6[a]	6.0[a]	21.0[a]	13.6[a]
	STSC	41.2[a]	8.8[b]	20.1[a]	12.3[b]
	TT	37.3[b]	4.1[a]	16.5[b]	16.7[c]

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

which is significantly higher than the 32.7 cm observed on the TT plots.

Soil Water Content in the Fallow Period

The soil water content in the fallow period is indicative of the plant-available water after planting in September. The NTSC treatment plots generally experienced the largest soil volumetric water content in the fallow period, whereas STSC and TT treatments had intermediate and lowest soil moistures, respectively (Fig. 3). The volumetric moisture in the 0- to 30-cm soil layer for NTSC and STSC were 20.5% and 13.8% greater than for TT, respectively. Similar improvements were found in the 30- to 130-cm soil layer. Clearly, controlled traffic provided more water, particularly in the 60- to 130-cm soil depth, for winter wheat compared with traditional tillage at the planting time.

Plant Growth Characteristics

Seedling emergence for NTSC was 4.1% higher than for the TT (4.83 vs. 4.64 million plants ha^{-1}), whereas the advantages in STSC treatment were not significant (Table 3). Winter wheat growth on controlled traffic was markedly faster than on traditional tillage possibly because of the improved soil moisture and soil fertility and the effects of more favorable soil physical structure. Plant growth conditions also seemed to improve on controlled traffic plots, especially in the root zone, where the effects of NTSC and STSC on root length density (RLD) were pronounced, increasing between 17% and 78% compared with TT. The RLD improved similarly in the lower soil layers.

Yield

The accompanying article (Chen et al., 2008) showed that mean yield for the measurement period of 1998 to 2006 in

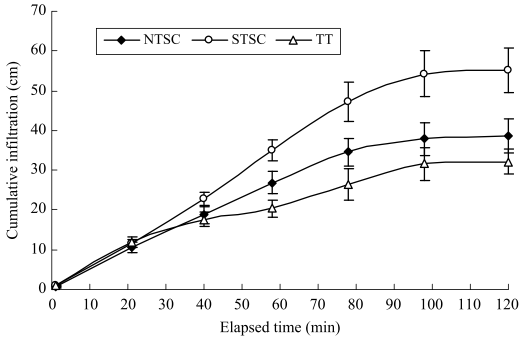

FIG. 2. Changes in cumulative infiltration during 120 min under NTSC, STSC, and TT treatments. Tests were conducted in June 2007. Error bars represent SE.

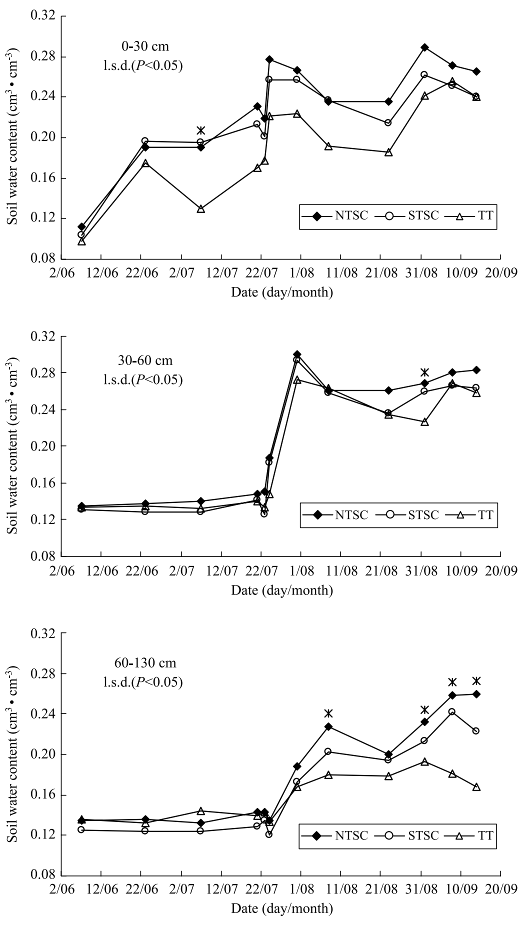

FIG. 3. Mean soil volumetric water content to the depth of 130 cm for NTSC, STSC, and TT treatments in the fallow period in 2007. *Significant difference at $P = 0.05$ level among treatments.

TABLE 3. Winter Wheat Performance for Three Treatments During 2006–2007

Seedling Emergence	Seedling Emergence Million Plants ha^{-1}
STSC	4.83^{a}
NTSC	4.58^{a}
TT	4.64^{a}

Plant

	Jointing Stage	Booting Stage		Filling Stage	
Treatments	Plant Height, cm	Plant Height, cm	Plant Dry Weight, g per 10 Plants	Plant Height, cm	Plant Dry Weight, g per 10 Plants
NTSC	38.6^{a}	69.5^{a}	14.7^{a}	78.7^{a}	21.2^{a}
STSC	40.5^{a}	68.6^{a}	13.0^{a}	81.8^{b}	20.3^{ab}
TT	38.8^{a}	67.2^{a}	13.5^{a}	78.2^{a}	18.0^{b}

Root

		Jointing Stage	Booting Stage	Filling Stage
Soil Depth, cm	Treatments	RLD, $cm{\cdot}cm^{-3}$		
0–15	NTSC	6.96^{a}	10.20^{a}	6.99^{a}
	STSC	5.35^{ab}	8.91^{a}	7.38^{a}
	TT	4.01^{b}	6.67^{b}	5.59^{a}
15–40	NTSC	0.58^{a}	1.75^{a}	1.46^{a}
	STSC	0.27^{b}	1.44^{a}	0.76^{b}
	TT	0.45^{ab}	1.49^{a}	0.82^{b}

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

controlled traffic (3.44 t ha^{-1}) was 9.8% greater than that in traditional tillage (3.11 t ha^{-1}), and the yield improvements on controlled traffic plots were significant (P = 0.05) in 3 out of 8 years. A similar trend of crop yield continued in 2006/2007 crop cycle (Table 4). The winter wheat yields in NTSC, STSC, and TT plots were 4.76, 5.03, and 3.96 t ha^{-1}, respectively, showing a mean improvement of 23.6% on controlled traffic plots. Plant maturity was also affected by the tillage system. Grains per spike and kernel weight were enhanced by 12.5% and 9.1%, respectively, on controlled traffic treatments.

DISCUSSION

The results of the long-term test on the effects of controlled traffic on winter wheat performance and soil quality in Linfen on the Loess Plateau clearly demonstrate that a significant improvement can be achieved. All relevant soil properties (SOM, N and P content, bulk density, porosity, infiltration) improved and, consequently, led to higher yields. Overall, the benefits of controlled traffic were more pronounced on no-tillage plots than on shallow-tillage treatments.

The significant increase of SOM on controlled traffic plots is attributed to both increased carbon input from residue retention and reduced biological oxidation of soil organic C to carbon dioxide, resulting from decreased soil disturbance and wheel traffic (Brevik et al., 2002; Chan et al., 2002). Tillage-induced changes in soil organic N are often directly related to changes in soil organic C. Controlled traffic treatments resulted in significantly (P = 0.05) higher concentrations of total N in the surface layer, whereas lower layers were not affected. Plant-available P was also improved, but mostly close to the surface (0–5 cm). This confirms the findings of Weil et al. (1988) and Rhoton (2000) who attributed the topsoil accumulation to the concentration of fertilizers and crop residues, the limited vertical movement of particle-bound P under no-tillage, and the upward movement of nutrients from deeper layers by root uptake (Urioste et al., 2006). In the 0- to 30-cm soil depth, NTSC increased mean SOM by 1.8%, total N by 1.2%, and available P by 2.5% in 2007 relative to STSC, which indicated that no-tillage offered marked benefits to soil fertility in comparison with shallow tillage in controlled traffic farming.

Random traffic from field operations and annual ploughing in traditional tillage leads to soil compaction and the formation of a plough pan in the lower soil profile (Kukal and Aggarwal, 2003). In the controlled traffic systems, soil compaction can be avoided by permanently separating crop areas and traffic lanes, providing optimal conditions for crop growth in the nontrafficked zones between the traffic lanes and traction in the compacted traffic lanes. At the beginning of the experiment in 1997, the bulk density differences between treatments were slight because of the initial deep ploughing (30-cm depth) that loosened the preexisting soil compaction. However, after 10 years, the mean bulk density in the top 60 cm on NTSC and STSC plots

TABLE 4. Grains Per Spike, Kernel Weight, and Yield of Winter Wheat for Three Treatments in 2007

Treatments	Grains per Spike	Kernel Weight, g	Yield, t ha^{-1}
NTSC	27.7^{a}	40.5^{a}	4.76^{a}
STSC	28.8^{a}	40.7^{a}	5.03^{a}
TT	25.1^{b}	37.2^{b}	3.96^{b}

Means within a column followed by the same letters are not significantly different (P = 0.05).

was significantly lower than on the TT plots, especially below the ploughing depth of the TT treatment. This result is consistent with the results of Horn et al. (1998), who demonstrated that repetitive wheeling on conventionally ploughed soils increases soil bulk density. The relatively small increase of bulk density in wheel tracks indicates that the relatively light tractors (<3 t) used on the Loess Plateau seem to have little impact at greater soil depth. This is important to limit runoff and erosion in wheel tracks. Similar effects have been observed by McHugh (2003), who speculated that the surface compaction in a wheel track might have provided some protection to deeper layers.

The changes of soil porosity in the 0- to 60-cm layer are consistent with the bulk density changes observed in this test. After 10 years of controlled traffic, the mean aeration porosity was up to 200% greater than on traditional tillage. Final infiltration rate and cumulative infiltration consequently improved on controlled traffic plots, especially for shallow tillage and straw cover. The latter result is of considerable importance for the weakly structured Loess Plateau soils, which are prone to water erosion. Our results on water infiltration are consistent with a 5-year controlled traffic experiment conducted in south-eastern Queensland, Australia (Li et al., 2001). This test demonstrated that the steady infiltration rate in controlled traffic plots was four to five times larger than in traditional tillage plots.

The water content on controlled traffic systems was higher than on traditional tillage, and the differences were particularly evident in the 60- to 130-cm soil layer in the fallow period. This can be explained by improved water retention capacity (Bai et al., 2008) caused by greater capillary pores in controlled traffic plots. And also the higher soil water infiltration in controlled traffic systems was responsible for the greater soil water content in the deep soil layer (60–130 cm). The benefits of shallow tillage on infiltration do not translate into improved water availability, indicating that shallow tillage increases moisture loss compared with no-tillage. The apparently greater loss of water might be caused by a greater surface area for evaporation, higher soil temperatures, or a greater gas permeability of the shallow tilled layer. On the Loess Plateau, with frequent droughts and seriously degraded soils, a good understanding of the effects of tillage and traffic treatments on soil water content are of particular importance for better crop performance. Mean (1998–2007) crop yields for the controlled traffic treatments were significantly higher than on traditional tillage plots, especially for shallow tillage. Improved seedling emergence and plant condition (e.g., plant dry weight, root length density) were also achieved on controlled traffic, particularly for the NTSC treatment. Similar improvements of crop growth and yields have been reported from controlled traffic experiment conducted by Deng et al. (2006) in northern China.

CONCLUSIONS

A continuous 10-year controlled traffic experiment on the Loess Plateau of China provided evidence that reduction of wheel traffic, soil disturbance, and the increase of residue input can lead to a significant improvement of soil quality and crop performance. Soil bulk density, pore size distribution, water content and infiltration, as well as SOM content and nutrient status changed toward a more desirable condition on the controlled traffic plots. The enhanced soil conditions led to an increase in crop yields. These results demonstrate that confining traffic to permanent traffic lanes can provide a significant improvement over the current farming system on the semiarid Loess Plateau. Overall, soil quality improvements were more pronounced when controlled traffic was combined with no-tillage and straw cover. However, yields improved slightly more on the plots with shallow tillage after harvest. This raises the question how soil quality improvements and yields are exactly related to each other on the experimental plots. More research on the relationships between controlled traffic, soil structure, and productivity is required to fully assess the possibilities of extrapolating the results collected in this study throughout the drylands of northern China. Apart from on-site improvement of soil properties and yields, further benefits to the environment, such as the reduction of runoff and erosion and the storage of carbon in the soil, should be considered.

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REFERENCES

Bai, Y. H., F. Chen, H. W. Li, H. Chen, J. He, Q. J. Wang, J. N. Tullberg, and Y. S. Gong. 2008. Traffic and tillage effects in wheat production on the Loess Plateau of China: II. Soil physical properties. Aust. J. Soil Res. 46:652–658.

Bouwer, H. 1986. Intake rate: Cylinder infiltrometer. *In* Methods of Soil Analysis, Part I-Physical and Mineralogical Methods, No. 5, 2nd Ed. A.Klute (ed.). Soil Science Society of America Book Series, Madison, WI, pp. 825–844.

Brevik, E., T. Fenton, and L. Moran. 2002. Effect of soil compaction on organic carbon amounts and distribution, South-central Iowa. Environ. Pollut. 116:137–141.

Casau, F., and M. Carvalho. 2001. Soil tillage with controlled traffic. Effects on soil structure and on corn production in Vale do Mondego. Revista de Ciencias Agrarias. 24:377–385.

Chamen, T. 2006. Controlled-traffic farming as a complementary practice to no-tillage. *In* No-tillage Seeding in Conservation Agriculture. C. J. Baker, K. E. Saxton, W. R. Ritchie, T. Chamen, D. C. Reicosky, S. Ribeiro, S. E. Justice, and P. R. Hobbs (eds.). CABI, Wallingford, UK, pp. 236–256.

Chan, K. Y., D. P. Heenan, and A. Oates. 2002. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. Soil Till. Res. 63:133–139.

Chen, H., Y. H. Bai, Q. J. Wang, F. Chen, H. W. Gao, J. N. Tullberg, J. R. Murray, H. W. Li, and Y. S. Gong. 2008. Traffic and tillage effects in wheat production on the Loess Plateau of China: 1. Crop yield and SOM. Aust. J. Soil Res. 46:1–7.

Deng, Z., G. B. Huang, F. Wu, Y. S. Fan, C. Zhao, Z. Z. Luo, and P. Xin. 2006. Study on the yield effects and soil water dynamic change of ridge culture spring wheat [In Chinese]. Water Saving Irrig. 6:4–6.

Deng, Z., G. B. Huang, C. Zhao, and P. Xin. 2005. Effects of controlled traffic tillage irrigation on soil water and yield of film-mulched spring wheat [In Chinese]. J. Gansu Agric. Univ. 40:334–339.

Du, B., Z. X. Liao, J. Deng, and J. Zhang. 1997. Effects of conservation tillage and tractor wheel compaction on water conservation for winter wheat under simulated rainfall [In Chinese]. J. China Agric. Univ. 1:65–69.

Gicheru, P., C. Gachene, J. Mbuvi, and E. Mare. 2004. Effects of soil management practices and tillage systems on surface soil water conservation and crust formation on a sandy loam in semi-arid Kenya. Soil Till. Res. 75:173–184.

He, J., H. W. Li, X. Y. Wang, A. D. McHugh, W. Y. Li, H. W. Gao, and N. J. Kuhn. 2007. The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. Soil Till. Res. 94:493–502.

Horn, R., H. Kretschmer, T. Baumgartl, K. Bohne, A. Neupert, and A. R. Dexter. 1998. Soil mechanical properties of a partly reloosened (split plough system) and a conventionally tilled over consolidated gleyic luvisol derived from glacial till. Int. Agrophys. 12:143–154.

Kukal, S. S., and G. C. Aggarwal. 2003. Puddling depth and intensity effects in rice-wheat system on a sandy loam soil. I. Development of subsurface compaction. Soil Till. Res. 72:1–8.

Li, G. L.. 2000. Study on soil degeneration on southern Plateau [In Chinese]. Yunnan Environ. Sci. 19:89–92.

Li, H. W., H. W. Gao, J. D. Chen, W. Y. Li, and R. X. Li. 2000. Study on controlled traffic with conservation tillage [In Chinese]. Trans. C. S. A. E. 16:73–77.

Li, H. W., H. W. Gao, H. D. Wu, W. Y. Li, X. Y. Wang, and J. He. 2007. Effects of 15 years of conservation tillage on soil structure and productivity of wheat cultivation in northern China. Aust. J. Soil Res. 15:344–350.

Li, Y., J. N. Tullberg, and D. M. Freebairn. 2001. Traffic and residue cover effects on infiltration. Aust. J. Soil Res. 39:239–247.

McHugh, A. D. 2003. Field traffic effects on the soil environment. PhD dissertation. University of Queensland, Brisbane, Australia.

Nelson, D. W., and L. E. Sommers. 1982. Total carbon, organic carbon, and organic matter. *In* Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, Agron. Monograph No. 9, 2nd Ed. A. L. Page (ed.). ASSA and SSSA, Madison, WI, pp. 539–579.

Olsen, S. R., and L. E. Sommers. 1982. Phosphorous. *In* Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties, Agron. Monograph. No. 9, 2nd Ed.A. L. Page (ed.). ASSA and SSSA, Madison, WI, pp. 403–430.

Reicosky, D. C., D. W. Reeves, S. A. Prior, G. B. Runion, H. H. Rogers, and R. L. Raper. 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil Till. Res. 52:153–165.

Rhoton, F. E. 2000. Influence of time on soil responses to no-till practices. Soil Sci. Soc. Am. J. 64:700–709.

Tullberg, J. N., D. F. Yule, and A. D. McGarry. 2007. Controlled traffic farming—From research to adoption in Australia. Soil Till. Res. 97:272–281.

Tullberg, J. N. , D. F. Yule, and A. D. McGarry. 2003. "On Track" for Sustainable Cropping in Australia. International Soil Tillage Research Organisation Conference (Invited plenary paper). ISTRO Proceedings CD, University of Queensland, Queensland, Australia.

Tullberg, J. N., P. J. Ziebarth, and Y. X. Li. 2001. Tillage and traffic effects on runoff. Aust. J. Soil Res. 39:249–257.

Urioste, A. M., G. G. Hevia, E. N. Hepper, L. E. Anton, A. A. Bono, and D. E. Buschiazzo. 2006. Cultivation effects on the distribution of organic carbon, total nitrogen and phosphorous in soils of the semiarid region of Argentinian Pampas. Geoderma. 136:621–630.

Wang, L., Q. Zhang, X. W. Niu, Z. P. Yang, and J. J. Zhang. 2007. Effects of different land uses on soil physical and chemical properties in the Loess Plateau of Shanxi Province [In Chinese]. Chinese J. Ecol. Agric. 15:53–56.

Wang, X. Y., H. W. Gao, H. W. Li, Y. Zang, and J. F. Rong. 2004. Tillage, traffic and residue impacts on soil and water loss from dryland in China. *In* Conservation Tillage & Sustainable Farming. Z. C. Wang, H. W. Gao (eds.). China Agricultural Science and Technology Press, Beijing, China, pp. 481–490.

Weil, R. R., P. W. Benedetto, L. J. Sikora, and V. A. Bandel. 1988. Influence of tillage practices on phosphorous distribution and forms in three Ultisols. Agron. J. 80:503–509.

Wu, T. Y., J. J. Schoenau, F. M. Li, P. Y. Qian, S. S. Malhi, Y. C. Shi, and F. L. Xu. 2004. Influence of cultivation and fertilization on total organic carbon and carbon fractions in soils from the Loess Plateau of China. Soil Till. Res. 77:59–68.

Zhang, J. 2002. Experimental study on controlled traffic farming [In Chinese]. Shanxi Agric. Machinery. 16:22–25.

