Soil & Tillage Research 104 (2009) 192–197

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Controlled traffic farming with no tillage for improved fallow water storage and crop yield on the Chinese Loess Plateau

Wang Qingjie [a], Chen Hao [a], Li Hongwen [a,*], Li Wenying [a], Wang Xiaoyan [a], A.D. McHugh [b], He Jin [a], Gao Huanwen [a]

[a] Department of Agricultural Engineering, China Agricultural University, P.O. Box 46, Beijing 100083, China
[b] University of Queensland, Gatton, Queensland, Australia

ARTICLE INFO

Article history:
Accepted 11 October 2008

Keywords:
Controlled traffic
Zero tillage
Fallow water storage
Yields
Loess Plateau

ABSTRACT

On the semi-arid Loess Plateau of northern China, water is typically the biggest constraint to rainfed wheat production. Controlled traffic, combined with zero tillage and residue cover has been proposed to improve soil water, crop yield and water use efficiency. From 1998 to 2005, we conducted a field experiment comparing the water storage and wheat productivity of controlled traffic farming and conventional tillage farming. Three treatments were studied: controlled traffic with no tillage and full residue cover (NTCN), controlled traffic with shallow tillage and full residue cover (STCN) and random traffic with traditional tillage and partial residue cover (CT). Compared to CT, the controlled traffic treatments significantly reduced soil bulk density in 10–20 cm soil layer, significantly increased soil water content in the 0–150 cm soil profile at sowing, 9.3% for NTCN, 9.6% for STCN. These effects were greater in dry seasons, thus reducing the yearly variation in water conservation. Consequently, mean wheat yield of NTCN, STCN and CT were 3.25, 3.27 and 3.05 t ha^{-1}, respectively, in which controlled traffic treatments increased by 6.9% with less yearly variation, compared to traditional tillage. Furthermore, controlled traffic had greater economic benefits than conventional tillage. Within controlled traffic treatments, NTCN showed better overall performance. In conclusion, controlled traffic farming has a better performance with respect to conserving water, improves yields and increases economic benefits. No tillage controlled traffic farming appears to be a solution to the water problem facing farmers on the Loess Plateau of China.

1. Introduction

In the semi-arid Loess Plateau of northern China, dryland farming is applied on about 80% of all cultivated land. This region receives less than 600 mm of annual rainfall on which farmers rely heavily (Shan, 1993). About 56% of the arable land is used for monoculture winter wheat (Zhu, 1989). Winter wheat (*Triticum aestivum*) is sown in mid-September and harvested in early June the following year, while more than 60% of annual rainfall occurs in the July–September period (Li et al., 2001a; Kang et al., 2001), which indicates that growing seasons are not synchronized with the main rainy period. Consequently on the Loess Plateau, winter wheat yield and water use efficiency depend strongly on soil available water for dryland farming (Yang et al., 1999; Yan and Wang, 2001). A study by Li and Shu (1991) indicated that, on average, 47% of the wheat yield is dependent upon the stored soil water at planting. Studies by Shangguan et al. (2002) on the northern China Loess Plateau and Musick et al. (1994) on the Southern Great Plains of the USA demonstrated the importance of storing soil water during fallow periods for increasing wheat yield and water use efficiency.

However, Chinese farmers traditionally till the soil after harvest with moldboard ploughs, and leave the fields fallow without soil cover during the rainy season (July–September) (Huang et al., 2003b). This traditional farming system results in considerable loss of soil moisture stored during the rainy season (Wang et al., 1999), leads to a poor soil physical condition and negatively influences the chemical properties of the soil profile (Zha and Tang, 2003). Shangguan et al. (2002) attributed the low available water to high potential evaporation under bare fallowing and to over-tillage. They concluded that fallow rainfall storage efficiency was only 35–40% under traditional tillage on the Loess Plateau. Li and Shao (2003) and Tang (2004) showed that in years of low rainfall on the Loess Plateau, crop yield and water use efficiency tended to be low

* Corresponding author. Tel.: +86 10 62737631; fax: +86 10 62737300.
E-mail address: lhwen@cau.edu.cn (L. Hongwen).

0167-1987/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2008.10.012

under traditional tillage, especially in the years of low rainfall, because of poor soil structure and limited available soil water. Furthermore, water extraction by crops can progressively lower the amount of water stored in the soil. Huang et al. (2003a) indicated that wheat monoculture leads to a steady decrease in soil water (−12.6 mm per year) during the growing season.

The concept of controlled traffic may offer a feasible system to ameliorate soil structure and increase soil available water and water use efficiency. Controlled traffic farming separates crop areas and traffic lanes permanently, providing optimal conditions for crop growth (no traffic) and traction (compacted) (Li et al., 2001b). The system has proven its value in Australia (Radford et al., 2000; Tullberg et al., 2001) and can also be used in temperate European conditions (Chamen, 2000). The combination of this traffic system with reduced or zero tillage, which retains residue at the soil surface, has shown merit in arid and semi-arid regions (Wang et al., 2005). Li et al. (2001b) reported that plant-available water capacity in controlled traffic plots increased by 11.5% in the 0–500 mm profile and mean grain yields increased by 9.4% compared to wheeled plots.

In China, so far, only short-term studies have been done to evaluate the effects of controlled traffic on soil water storage, crop yield and water use efficiency. Based on a 2-year controlled traffic experiment in Shanxi, northern China, Li et al. (2000a) reported that controlled traffic increased water storage in the 0–50 cm soil profile, compared with conventional tillage. Even though 20% of the field was occupied by wheel tracks without planting, no yield decrease was observed in controlled traffic treatment when compared with conventional tillage. Power requirements and fuel consumption were lower in controlled traffic. Comparable results were reported by Wang et al. (2005). Apart from these studies, little is known about the long-term effects of controlled traffic on water conservation, crop yield and water use efficiency on the semi-arid Loess Plateau of northern China.

The experiments reported here evaluated, over a period of 7 years, the effects of controlled traffic and conventional systems on water-storage efficiency during fallow periods, winter wheat yield, crop water use efficiency and economic returns.

2. Materials and methods

2.1. Site

The experiment was conducted in Chenghuang village (37°32′–38°6′N, 112°4′–113°26′E), near the city of Linfen, located in south-central Shanxi province. Linfen is located in a semi-arid and semi-humid region, 360–500 m above sea level on the Loess Plateau. Average annual temperature is 10–12 °C with 130 frost-free days. Annual rainfall with high annual variation, concentrated in the period June–September, is about 500 mm and annual evaporation is 1800 mm. The fallow period is from the middle 10 days of June to the middle 10 days of September. The erosion index is less than 400 t km^{-2} year^{-1} (Wang et al., 2008).

The soil is a Cinnamon Loess, low in organic matter (<1%) and slightly alkaline (pH 7.7). Under the USDA texture classification system, the soils are defined as silt loam 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 effects of controlled traffic and traditional tillage on winter wheat were studied from 1998 to 2005. Before the treatments were applied, the experimental area was ploughed (30 cm depth) to provide uniform soil conditions. To make the treatments comparable, the same rates of fertilizer and seed were used each year. Every season, fertilizer was applied at the rate of 150 kg N ha^{-1}, 140 kg P ha^{-1} and 62 kg K ha^{-1} and the seeding rate was 225 kg ha^{-1}. Wheat was sown in the last 10 days of September and harvested in the first 10 days of June.

2.2. Experimental design

The field experiment had a randomized block design with three treatments in five replications. The treatments consisted of two controlled traffic treatments with full straw cover, no tillage (NTCN) and shallow tillage (STCN), and one conventional tillage treatment (CT).

NTCN: a controlled traffic treatment, no tillage, residue cover and none compaction in crop zone. In this treatment, 30 cm high wheat stubble was left at harvest, and all wheat straw was returned to the plots after being threshed. In the fallow period, there was no tillage—weeds controlled by herbicides only. Wheat was sown with a no-till planter in September.

STCN: another controlled traffic treatment, shallow tillage, residue cover and none compaction in crop zone. In this treatment, 30 cm high wheat stubble was left at harvest, and all wheat straw was returned to the plots after being threshed. In the fallow period, there was no tillage. Shallow tillage was done before sowing with a two-shovel sweep at a depth of 5–8 cm, and then wheat was sown in September using the same sowing machine used for NTCN.

CT: the conventional tillage treatment. In this treatment, random wheel traffic was used. 5–6 cm high wheat stubble was left at harvest, but the wheat straw was not returned to the plots. The soil was ploughed to a depth of 20 cm after the first summer rain, and mechanical weed control was used in the fallow period. Before sowing, the plot was plowed again to 20 cm by mouldboard plough, then harrowed and dragged before wheat was sown with a conventional planter in September.

The layout of crop rows and permanent traffic lanes was designed according to the characteristics of the local tractors and planters. Six rows of winter wheat (*T. aestivum*: Linfen 225) at 20 cm row spacing were sown in beds 1.5 m wide between the wheel tracks. The wheel tracks were 30 cm wide and occupied 20% of the land area. The plots were 4.5 m wide (three beds) and 30 m long.

2.3. Measurements

In order to assess the effect of the treatments, the following data were collected: rainfall, soil moisture content, bulk density, crop yields.

Rainfall data were recorded manually from an on-site rainfall collector after each fall of rain. Gravimetric soil water content was measured by taking soil cores in 10 cm increments to a depth of 150 cm at sowing and harvest for each growing season.

The fallow rainfall storage efficiency (RSE) was calculated as the difference in soil water content between the beginning and the end of the summer fallow period, using the following equation:

$$\mathrm{RSE} = \frac{\mathrm{SWP} - \mathrm{SWH}}{R_{\mathrm{F}}} \times 100\% \quad (1)$$

SWP is the amount of soil water at sowing, SWH is the amount of soil water at harvest, and R_{F} is the total rainfall during the fallow period.

Evapotranspiration (ET) is usually calculated using the formula:

$$\mathrm{ET} = (P + I + S_{\mathrm{G}}) - D - R_{\mathrm{OFF}} - \Delta W \quad (2)$$

where P is growing seasonal precipitation (mm), I is irrigation (mm), S_{G} is groundwater contribution to plant-available water (mm), D is downward drainage out of the root-zone (mm), R_{OFF} is surface runoff (mm), and ΔW is the soil water change between sowing and harvesting. In this experiment, there was no irrigation (I), the groundwater contribution (S_G) from a water table 50 m below the surface was negligible, and drainage out of the root-zone (D) need not be considered in this area (Huang et al., 2005). Since the field was flat and terraced, and located in the semi-arid Loess Plateau, the surface runoff was zero (Huang et al., 2005).

Winter wheat yields were determined by manual harvesting, threshing, and air-drying grain from three 1 m^2 areas taken at random in each plot. Water use efficiency (WUE) was calculated as grain yield (t ha^{-1}) divided by the growing season evapotranspiration (ET) (mm).

The economic benefit of different tillage modes was also assessed. Costs for inputs and labor were derived from local market information and common sources of farming inputs. Common labor charges from this region were used to assess further input costs.

2.4. Statistical analysis

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

3. Results

3.1. Rainfall

Fig. 1 illustrates the intra-annual rainfall and summer fallow rainfall during the study period. Both annual rainfall (435 mm, S.D. 118 mm) and fallow rainfall (277 mm, S.D. 62 mm) during the experimental period were lower than the long-term average in all years except 2003.

3.2. Soil bulk density

A significantly higher bulk density was observed in the 10–20 cm soil layer in conventional tillage compared to the controlled traffic treatments, indicating that a hard layer was formed by random traffic (Table 1). In other soil layers, there was no significant difference between controlled traffic treatments and conventional tillage treatment. In controlled traffic treatments, STCN showed significantly lower bulk densities than NTCN in the 0–10 cm soil layer.

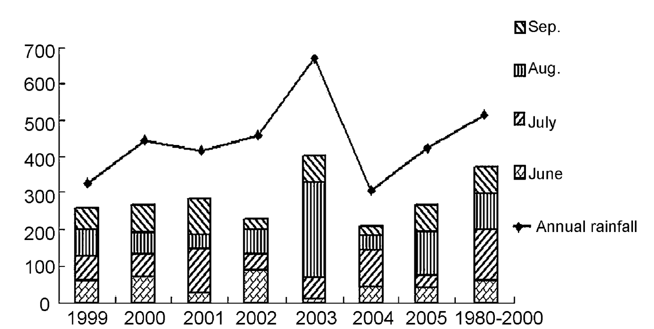

Fig. 1. Annual and fallow rainfall (mm) at the study site. Rainfall from 1981 to 2005 was measured at the Linfen City weather station.

Table 1
Mean soil bulk density of the three treatments in 0–40 cm soil profile. All values in g cm^{-3}.

Treatment	Soil depth			
	0–10 cm	10–20 cm	20–30 cm	30–40 cm
NTCN	1.37^b	1.31^a	1.36^a	1.44^a
STCN	1.20^a	1.36^a	1.41^a	1.44^a
CT	1.27^{ab}	1.54^b	1.41^a	1.45^a
S.D.	0.08	0.13	0.05	0.03
S.E.	0.03	0.04	0.02	0.01

NTCN: controlled traffic with no tillage and full residue cover. STCN: controlled traffic with shallow tillage and full residue cover. CT: random traffic with traditional tillage and partial residue cover. Means within the same column in the same soil profile followed by the same letter are not significantly different at $P < 0.05$. S.D.: standard deviation; S.E.: standard error.

3.3. Soil water storage during the fallow period

Soil water storage in 0–150 cm soil layer over the fallow periods is given in Table 2. Both controlled traffic treatments increased the fallow soil water storage averaged from 1999 to 2005, averagely 14.2%, when compared to CT. In three relatively dry fallow years (1999, 2002 and 2004), the difference of fallow water storage was significant at $P < 0.05$ level. Within the controlled traffic treatments, NTCN and STCN showed similar capacity to store water during fallows.

3.4. Soil water at wheat sowing

The controlled traffic treatments had significantly ($P < 0.05$) higher mean soil water storage in 0–150 cm soil layer at sowing than conventional tillage from 1998 to 2005 (Table 3). Compared to CT, mean soil water content at sowing was 9.3% and 9.6% higher. Besides the first year of the experiment, water storage in the two controlled traffic treatments was always higher than that in conventional tillage treatment during experiment period, with significant difference in relatively dry years, 1999, 2002 and 2004. NTCN conserved significantly higher water, compared with CT. The two controlled traffic systems (NTCN and STCN) differed little in all years.

Table 3 also shows that soil water in controlled traffic treatments was less variable over the years than in conventional tillage. This was a result of higher rainfall storage during the fallow in the controlled traffic treatments, especially in the low rainfall years (Table 2).

3.5. Yield

Wheat grain yield averaged over the experimental period was 6.9% higher for controlled traffic than CT, and in 3 out of 7 years, these differences were significant ($P < 0.05$) (Table 4). Furthermore, in two relatively dry growing seasons (2000 and 2005), the mean yield of controlled traffic was 54.4% higher than that of

Table 2
Fallow rainfall storage for the three treatments during the study period (1999–2005) (mm).

Treatments	1999	2000	2001	2002	2003	2004	2005	Mean
NTCN	145.2^a	76.1^a	1223.6^a	99.5^{ab}	256.3^a	83.2^a	159.9^a	149.1^a
STCN	155.9^a	71.3^a	218.3^{ab}	108.5^a	262.7^a	85.5^a	143.9^{ab}	149.4^a
CT	128.7^b	77.5^a	205.8^b	70.2^b	241.7^a	58.6^b	132.2^b	130.7^b

NTCN: controlled traffic with no tillage and full residue cover. STCN: controlled traffic with shallow tillage and full residue cover. CT: random traffic with traditional tillage and partial residue cover. Water storage means followed by the same letter, within the same year, are not significantly different at $P < 0.05$.

Table 3
Soil water (mm) at wheat planting time of three tillage systems from 1998 to 2005 at depth of 0–150 cm.

Treatments	1998	1999	2000	2001	2002	2003	2004	2005	Mean	S.D.
NTCN	336.3[a]	332.6[a]	287.6[a]	362.8[a]	336.0[a]	403.9[a]	338.8[a]	355.8[ab]	344.2[a]	32.8
STCN	334.3[a]	337.3[a]	284.4[a]	366.2[a]	347.8[a]	402.8[a]	330.1[a]	358.1[a]	345.1[a]	33.9
CT	337.3[a]	251.8[b]	282.2[a]	350.8[a]	283.6[b]	283.6[b]	285.3[b]	342.7[b]	314.8[b]	42.3

NTCN: controlled traffic with no tillage and full residue cover. STCN: controlled traffic with shallow tillage and full residue cover. CT: random traffic with traditional tillage and partial residue cover. Means within a column in the same year followed by the same letter are not significantly different at $P < 0.05$. S.D.: standard deviation.

Table 4
Mean ET (mm), mean wheat yield (t ha^{-1}) and WUE (kg ha^{-1} mm^{-1}) for the three treatments from 1999 to 2005.

Treatment	1999	2000	2001	2002	2003	2004	2005	Mean
R_G (mm)	67.6	76.1	169.2	137.3	162.9	269.5	100.9	149.1
ET								
NTCN	216.4[a]	197.2[a]	317.6[a]	263.6[a]	351.3[a]	417.9[a]	243.7[a]	286.8[a]
STCN	223.9[a]	200.2[a]	305.7[a]	264.2[a]	370.5[a]	427.8[a]	216.7[b]	287.0[a]
CT	220.1[a]	123.3[a]	306.4[a]	276.8[a]	313.5[a]	407.4[a]	185.6[c]	261.9[a]
Yield								
NTCN	3.27[a]	2.48[a]	3.08[a]	3.68[a]	3.51[a]	4.01[a]	2.71[a]	3.25[a]
STCN	3.45[a]	2.52[a]	3.14[a]	3.90[b]	3.44[a]	4.39[b]	2.73[a]	3.37[a]
CT	3.79[b]	1.46[b]	2.91[a]	3.52[a]	3.64[a]	4.12[a]	1.91[b]	3.05[b]
WUE								
NTCN	15.1[a]	12.6[a]	9.7[a]	14.0[a]	10.5[a]	9.1[a]	11.1[ab]	11.7[a]
STCN	15.4[a]	12.6[a]	10.3[a]	14.8[a]	10.5[a]	10.3[a]	12.6[a]	12.3[a]
CT	17.2[b]	11.8[a]	9.5[a]	10.9[b]	9.7[b]	10.1[a]	10.3[b]	11.4[a]

NTCN: controlled traffic with no tillage and full residue cover. STCN: controlled traffic with shallow tillage and full residue cover. CT: random traffic with traditional tillage and partial residue cover. R_G: growing season rainfall (mm). Means within the same column in the same year followed by the same letters are not significantly different at $P < 0.05$.

conventional tillage, indicating controlled traffic had a greater effect on yield during dry years. NTCN and STCN showed similar performance with respect to yields, because of the aforementioned similar soil available water at planting (Tables 2 and 3).

Table 4 also shows that winter wheat yield from 1999 to 2005 was affected by annual rainfall amount. However, controlled traffic reduced the effects of rainfall amount on yield. The mean yield and standard deviation for NTCN, STCN and CT was 3.25 ± 0.54, 3.27 ± 0.65 and 3.05 ± 1.01 t ha^{-1}, indicating that controlled traffic was less affected by rainfall variations.

3.6. WUE

Averaged over the 7 years, WUE of controlled traffic treatments NTCN and STCN was higher than that of CT, 2.6% and 7.9%, respectively. CT showed a similar trend as yields when related to rainfall and RSE (Table 4). Significantly higher value of WUE was observed in CT than both controlled traffic treatments in the first year ($P < 0.05$). While controlled traffic treatments showed significantly higher value of WUE in 2002 and 2005. No significant differences were found between NTCN and STCN.

3.7. Economic benefits

The agronomic input costs and mechanical operation costs are shown in Table 5. The agronomic costs refer to expenses such as seed, fertilizer and herbicide. The operation costs include fuel, salary, maintenance, depreciation and administration expense. Outputs refer to grain yield in kg ha^{-1} and income received in Chinese monetary units.

The agronomic costs were lower under CT than controlled traffic because mechanical instead of chemical weed control was used, but operational costs were higher due to tillage and labor. The cost of field operations was reduced by 44.4% and 35.6% in NTCN and STCN, respectively, compared to CT. As the 7-year average grain yields for controlled traffic were higher than for CT, the controlled traffic treatments (NTCN and STCN) doubled the profits compared with CT. The results indicate that controlled traffic farming is a vastly superior option than conventional tillage farming with less advantage in STCN compared to NTCN.

Table 5
Economic cost benefit analysis of three traffic and tillage modes.

	NTCN	STCN	CT
Inputs			
Seed, fertilizer and herbicides (Yuan)	1455	1455	1215
Operation costs (Yuan)	750	870	1350
Total (Yuan)	2205	2325	2565
Outputs			
Yield (t/ha)	3.25	3.27	3.05
Income (Yuan/ha)	3250	3270	3050
Farmer income (Yuan/ha)	1045	945	458
Incremental improvement on traditional tillage (%)	128.2	106.3	

NTCN: controlled traffic with no tillage and full residue cover. STCN: controlled traffic with shallow tillage and full residue cover. CT: random traffic with traditional tillage and partial residue cover. Yield is the average value from 1998 to 2005. Income = yield × price; grain price = 1 Yuan per kg, the Yuan is the Chinese currency unit.

4. Discussion

Controlled traffic farming practices from 1998 to 2005 in the experimental sites were effective in increasing soil water storage, crop yield and WUE compared to conventional tillage (Tables 3 and 4). These results are consistent with an earlier study of Li et al. (2000a).

The significant water storage differences between controlled traffic and conventional tillage were due to the combination of alternative traffic, tillage and residue management in the fallow period. Tillage decreases soil moisture when a bare soil (without mulch) is left (Richard and Cellier, 1998; Wang et al., 2001; Reicosky et al., 1999). Controlled traffic treatments conserve the natural soil structure by zero tillage and straw cover and therefore reduce evaporation (Liao et al., 2003).

Another reason for the positive effects may be the amelioration of soil structure in controlled traffic treatments. As conventional tillage showed a significantly higher bulk density in the 10–20 cm soil layer compared to the controlled traffic treatments, this compacted layer may retard downward water movement (Wu et al., 1999). Water retained in the topsoil will more easily be lost by evaporation.

Controlled traffic treatments significantly increased pre-sowing soil water storage during the experimental period, showing the highest significance in dry years. This effect reduces annual variation of fallow water storage and keeps the water supply for crop growth more stable over the years, as shown in a study by Rohde and Yule (1998).

The extra soil water stored during fallow in controlled traffic treatments can enhance crop productivity and reduce its annual variation due to rainfall. Correlation analysis showed consistent result, in which significant positive correlation was observed between fallow rainfall and yield, with the correlation coefficient value of 0.6075. Musick et al. (1994) showed that wheat yield under comparable conditions was linearly related to soil water stored at planting and this positive relationship was more significant than the relationship with seasonal water use. Furthermore, the compacted layer in conventional tillage could also impede root growth, thereby contributing to a reduction in yield. The positive effects on crop yield of controlled traffic found in this study were consistent with the experimental results from Chamen et al. (1992), Rohde and Yule (1995) and Li et al. (2007). Results indicated that, in dryland farming on the Loess Plateau, even when 20% of the field was occupied by wheel tracks, wheat yield in controlled traffic treatments was higher than in CT. Annual shallow tillage did not influence yield in controlled traffic treatments.

The average WUE was lower than the 14.8 kg ha^{-1} mm^{-1} reported by Zhu et al. (1994) in a sub-humid region of north China, but higher than the 9.0 kg ha^{-1} mm^{-1} reported by Li et al. (2000b) on the Loess Plateau. Correlation analysis showed WUE was less affected by fallow rainfall than by growing season rainfall, in which the correlation coefficient between growing season rainfall and WUE was 0.6631, while the correlation coefficient between fallow rainfall and WUE was only 0.1002. Therefore, the effect of controlled traffic treatments on WUE was not significant.

Controlled traffic management, with both no tillage and shallow tillage has the additional advantage that it needs fewer farming operations, compared to conventional tillage, hence reducing the total cost of crop production. It also reduces the risk on crop failure in drier years.

5. Conclusions

Seven years of experiments on the Chinese Loess Plateau showed that controlled traffic treatments significantly increased water conservation and crop yields and reduced the annual variation of both.

(1) Compared to conventional tillage, controlled traffic increased mean fallow water storage by 13.9%. This effect was more evident in dry fallow seasons.
(2) Controlled traffic increased mean soil moisture at sowing by 10.5%.
(3) Controlled traffic increased mean winter wheat yield by 6.9%. The increase was greater in dry years, reducing the annual variation in yields.
(4) Controlled traffic with both zero tillage and shallow tillage doubled profit, compared with conventional tillage.

Our data demonstrate that the practice of controlled traffic is a significant improvement on the current farming system in the Loess Plateau and may enhance the sustainable development of agriculture in this region. Although more long-term research on the relationships between controlled traffic, soil structure, productivity and environmental conditions is needed to adapt the system to local conditions, farmers are encouraged to change to controlled traffic systems.

Acknowledgements

This work was supported by the Australian Centre for International Agricultural Research (ACIAR), under project 96143. Thanks to the Chinese Ministry of Agriculture, and Shanxi Provincial Government, for guiding and funding. Thanks to Dr. Jeff Tullberg and Mr. Ross Murray for their work in implementing the ACIAR project in China. Also thanks to the stuff working in Conservation Tillage Research Center, Ministry of Agriculture, People's Republic of China.

References

Chamen, W.C.T., Watts, C.W., Leede, P.R., Longstaff, D.J., 1992. Assessment of a wide span vehicle (gantry), and soil and cereal crop responses to its use in a zero traffic regime. Soil Tillage Res. 24, 359–380.
Chamen, W.C.T., 2000. New methodology for weed control and crop production: controlled traffic, precision guidance and direct seeding. In: Proceedings of the Fourth European Weed Research Society Workshop on Physical Weed Control, Elspeet, The Netherlands, 20–22 March 2000.
FAO-UNESCO, 1974. Soil Map of the World. UNESCO, Paris.
He, J., Li, H.W., Wang, X.Y., McHugh, A.D., Li, W.Y., Gao, H.W., Kuhn, N.J., 2007. The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. Soil Tillage Res. 94, 493–502.
Huang, M., Dang, T., Gallichand, J., Goulet, M., 2003a. Effect of increased fertilizer application to wheat crop on soil–water depletion in the Loess Plateau, China. Agric. Water Manage. 58, 267–278.
Huang, M.B., Shao, M.A., Zhang, L., 2003b. Water use efficiency and sustainability of different long-term crop rotation systems in the Loess Plateau of China. Soil Tillage Res. 72, 95–104.
Huang, Y.L., Chen, L.D., Fu, B.D., Huang, Z.L., Gong, J., 2005. The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. Agric. Water Manage. 72, 209–222, doi:10.1016/j.agwat.2004.09.012.
Kang, S., Zhang, L., Song, X., Liu, Z., Liang, Y., Zeng, S., 2001. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau. Hydrol. Process. 15, 977–988.
Li, F.M., Song, Q.H., Liu, H.S., Li, F.R., Liu, X.L., 2001a. Effects of pre-plant irrigation and phosphate application on water use and yield of spring wheat under semi-arid conditions. Agric. Water Manage. 45, 32–48.
Li, H.W., Gao, H.W., Chen, J.D., Li, W.Y., Li, R.X., 2000a. Study on controlled traffic with conservative tillage. Trans. Chin. Soc. Agric. Eng. 16, 73–77 (in Chinese).
Li, F., Zhao, S., Geballe, G.T., 2000b. Water use patterns and agronomic performance for some cropping systems with and without fallow crops in a semi-arid environment of northwest China. Agric. Ecosyst. Environ. 79, 129–142.
Li, Y., Shu, S., 1991. A Comprehensive Research on High Efficient Eco-economic System in Wangdonggou Watershed of Changwu County. Sci-Tech Document Press, Beijing, China.
Li, Y.X., Tullberg, J.N., Freebairn, D.M., 2001b. Traffic and residue cover effects on infiltration. Aust. J. Soil Res. 39, 239–247.
Li, Y.X., Tullberg, J.N., Freebairn, D.M., 2007. Traffic and tillage effects on runoff and crop yield. Soil Tillage Res. 97, 282–292.
Li, Y.Y., Shao, M.A., 2003. Impact of tillage on water transformation and runoff-sediment-yielding characteristics on slope land. Trans. CSAE 19 (1), 46–50.
Liao, Y.C., Wen, X.X., Han, S.M., Jia, Z.K., 2003. Effects of mulching of water conservation for dryland winter wheat in the Loess Tableland. Scientia Agric. Sin. 36 (5), 548–552 (in Chinese).
Musick, J.T., Jones, O.R., Stewart, B.A., Dusek, D.A., 1994. Water-yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. 86, 980–986.
Radford, B.J., Bridge, B.J., Davis, R.J., McGarry, D., Pillai, U.P., Richman, J.F., Walsh, P.A., Yule, D.F., 2000. Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. Soil Tillage Res. 54, 155–170.
Reicosky, D.C., Reeves, D.W., Prior, S.A., Runion, G.B., Rogers, H.H., Raper, R.L., 1999. Effects of residue management and controlled traffic on carbon dioxide and water loss. Soil Tillage Res. 52, 153–165.
Richard, G., Cellier, P., 1998. Effect of tillage on bare soil energy balance and thermal regime: an experimental study. Agronomie 161–178.

Rohde, K.W., Yule, D.F., 1995. Soil and crop responses to compaction by rubber tyres on a cracking clay in Central Queensland. In: National Controlled Traffic Conference, Queensland, Australia, pp. 82–87.
Rohde, K.W., Yule, D.F., 1998. Controlling runoff, soil loss and soil degradation with controlled traffic and crop rotations. In: 2nd National Controlled Traffic Conference, Queensland, Australia, pp. 108–113.
Shan, L., 1993. The Theory and Practice of Dryland Agriculture in the Loess Plateau of China. Science Press, Beijing, China (In Chinese).
Shangguan, Z.P., Shao, M.A., Lei, T.W., Fan, T.L., 2002. Runoff water management technologies for dryland agriculture on the Loess Plateau of China. Int. J. Sustain. Dev. World Ecol. 9, 341–350.
SPSS, 2003. SPSS Version 12 for Windows. SPSS Inc., Chicago, USA.
Tang, K.L. (Ed.), 2004. Soil Erosion in China. Science and Technology Press, p. 845 (in Chinese).
Tullberg, J.N., Ziebarth, P.J., Li, Y.X., 2001. Tillage and traffic effects on runoff. Aust. J. Soil Res. 39, 249–257.
Wang, J.P., Jiang, J., Ran, Q.F., Jia, Z.K., Zhang, J.C., 1999. Technique of spring wheat cultivation of farmland water micro-collection in semiarid areas of South Ningxia. Agric. Res. Arid Areas 17 (2), 8–13 (in Chinese).
Wang, Q.J., Bai, Y.H., Gao, H.W., He, J., Chen, H., Chesney, R.C., Kuhn, N.J., Li, H.W., 2008. Soil chemical properties and microbial biomass after 10 years of no-tillage farming on the Loess Plateau, China. Geoderma l44 (3–4), 502–508.
Wang, W., Xu, F., Li, X., Li, L., 2001. The soil moisture content affected by mulching methods in Weibei rainfed highland. Acta Agric. Boreali-occident. Sin. 10, 56–58 (in Chinese).
Wang, X.Y., Li, H.W., Gao, H.W., Du, B., He, J., Li, W.Y., 2005. In: Proceedings of SPIE—the International Society for Optical Engineering, v 5884, Remote Sensing and Modeling of Ecosystems for Sustainability II. pp. 1–12.
Wu, L., Chen, W., Baker, J.M., Lamb, J.A., 1999. Evaluation of the root zone water quality model using field-measured data from a sandy soil. Agron. J. 91, 177–182.
Yan, X., Wang, J., 2001. The responses and their physio-ecological bases of spring wheat to limited irrigation in Loess Plateau. Acta Bot. Boreal. Occideng. Sin. 21 (4), 1–795 (in Chinese).
Yang, F.K., Gao, S.M., He, B.L., 1999. Research the rainwater collection and water-saving irrigation in west Loess Plateau of Gansu Province, China. Soil Water Conserve 5, 24–27 (in Chinese).
Zha, X., Tang, K., 2003. Change about soil erosion and soil properties in reclaimed forestland of loess hilly region. Acta Geographica Sinica 58 (3), 464–469.
Zhu, X., 1989. Soil and Agriculture in the Loess Plateau. Agricultural Science Press, Beijing, China (in Chinese).
Zhu, Z., Stewart, B.A., Fu, X., 1994. Double cropping wheat and corn in a sub-humid region of China. Field Crop Res. 36, 175–183.