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Spring wheat performance and water use efficiency on permanent raised beds in arid northwest China

Jin He[A], *Hongwen Li*[A,E], *A. D. McHugh*[B], *Zhongmin Ma*[C], *Xinhui Cao*[D], *Qingjie Wang*[A], *Xuemin Zhang*[A], *and Xirui Zhang*[A]

[A]Department of Agricultural Engineering, China Agricultural University, PO Box 46, Beijing 100083, China.
[B]National Centre for Engineering in Agriculture, University of Southern Queensland, Z2 West Street, Toowoomba, Qld 4350, Australia.
[C]Gansu Academy of Agricultural Sciences, Lanzhou, China.
[D]Gansu Agricultural Mechanization Bureau, Lanzhou, China.
[E]Corresponding author. Email: lhwen@cau.edu.cn

Abstract. Permanent raised beds have been proposed as a more productive and water-efficient alternative to the conventional system of flat, flood-irrigated bays for planting narrow-spaced crops in arid north-west China. Data from a field experiment (2005–2007) conducted in the Hexi Corridor at Zhangye, Gansu Province, China, were used to compared the effects of traditional tillage (TT), zero tillage (ZT), and permanent raised beds (PRB) on crop growth, yield, and water use in a spring wheat monoculture. The results show that PRB significantly ($P < 0.05$) increased soil water content to 0.30 m depth by 7.2–10.7% and soil temperature to 0.05 m depth by 0.2–0.9°C during the wheat-growing period relative to TT and ZT treatments. Bulk density in 0–0.10 m soil layer under PRB was also 5.8% less than for flat planting treatments. Mean wheat yields over 3 years on PRB plots were slightly greater and furrow irrigation in permanent beds was particularly effective in increasing irrigation water use efficiency (~18%), compared with TT and ZT treatments. This increase in water use efficiency is of considerable importance for these arid areas where irrigation water resources are scarce.

Additional keywords: bed planting, yield, water content, soil temperature, irrigation, arid areas.

Introduction

Water shortage is one of the major constraints to the production of agricultural crops in arid north-west China where average precipitation varies from 40 to 200 mm (Xie *et al*. 2005). Annual potential evaporation in this region exceeds 1500 mm and water requirement for one season of spring wheat, the most popular cereal crop in north-west China, is >600 mm. Crop production is largely dependent on irrigation, so maintaining or improving water use efficiency (WUE) is extremely important, particularly when glaciers supplying the rivers are in rapid retreat and groundwater supplies are decreasing (Kang *et al*. 2000*a*). Current cropping systems in this region rely on conventional mouldboard ploughing and traditional flood irrigation but these have resulted in poor soil structure and water storage capacity (Li *et al*. 2005), and soil temperatures (Huang *et al*. 2006) that have slowed crop development and reduced yields and WUE (Wu 2005).

More sustainable cropping systems, using permanent raised beds (PRB) to improve productivity and reduce water requirements, have been demonstrated in Mexico, Australia, and the Indo-Gangetic plains. All heavy equipment wheels are confined to permanent furrows in the PRB system, which could be an effective way to improve water management, promote crop growth, and increase crop yields when it is combined with bed planting, furrow irrigation, and no tillage (Sayre and Moreno 1997; Singh 2003). Connor *et al*. (2003) and Choudhury *et al*. (2007) found that PRB were effective in increasing soil water content, reducing irrigation water requirement, and improving WUE in the rice–wheat cropping system of the Indo-Gangetic Plains. Limon-Ortega *et al*. (2002) and Govaerts *et al*. (2006) reported that compared with conventionally tilled beds, long-term permanent beds with retained residue significantly increased soil biological and physical properties, thereby promoting crop performance in coarse, sandy clay soils of north-west Mexico. In Australia, Bakker *et al*. (2005) and Holland *et al*. (2007) have demonstrated that raised beds could significantly increase grain yield due to improved air-filled porosity and plant-available water capacity, and reduced waterlogging. Beecher *et al*. (2006), however, indicated that rice yield was approximately 25% lower on permanent beds than on flat land in New South Wales.

Research in China has generally confirmed the improvements in soil moisture, crop development, and WUE using bed planting systems with furrow irrigation. Wang *et al*. (2004*a*, 2004*b*), for instance, compared conventional flat planting, flood irrigation with bed planting, furrow irrigation farming systems on light loam soils for winter wheat in Shandong province of northern China. The results of 4 years of testing showed that raised bed systems required approximately 30% less irrigation water than conventional flat planting, increasing WUE by 20%. In more

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arid north-west China, He *et al*. (2007*a*) demonstrated that bed planting increased soil water content to 1.0 m depth relative to the flat planting system by 3–8%. Ma and Wang (2005) reported yield improvements of up to 6.3% for spring wheat grown on raised beds compared with flat planting. He (2007), however, found no mean (2 years) yield advantage for spring wheat in a raised bed system (5800 kg/ha) compared with conventional flat system (5789 kg/ha). In most research to date, however, raised-bed systems have still involved substantial tillage operations to form the beds before planting for each crop production, so it is important to assess the effects of permanent raised beds (bed planting, furrow irrigation, no-tillage, straw cover, standing stubble, etc.) on crop performance and yield in arid north-west China. It is also unclear whether the irrigation water saving and increased soil water content was an outcome of irrigation management, tillage, or crop residue in permanent raised bed system.

This paper reports the results of an ongoing investigation of spring wheat production on permanent raised beds in the Hexi Corridor, north-west China. The objective of this study is to identify the effects of permanent raised beds on crop performance and WUE in arid areas of China, and we also present suggestions for further research to enhance the development of permanent raised bed systems in China.

Materials and methods

Site description

The experiment was started in 2005 at the GAAS (Gansu Academy of Agricultural Sciences) water-saving research station (38°50′N, 100°10′E), at Zhangye in the Hexi Corridor of north-west China. Zhangye is located in the warm-temperate arid region, 1200–1700 m above sea level. Average annual temperature is about 7.3°C with 169 frost-free days. The average annual rainfall is 146 mm and rainfall events were of low intensity (85% of rainfall <1mm/h), short duration, and infrequent occurrence during the experimental years reported here (2005–2007). The annual pan-evaporation is around 2390 mm. A spring wheat monoculture is common, with sowing in March and harvesting in July. The soil at the station was a sandy-loam (sand 49%, silt 34%, clay 17%) with a bulk density of 1.35 Mg/m^3, organic matter 7.2 g/kg, total N 0.48 g/kg, and pH 8.0 in the top 0.60 m soil layer. Soil water content at field capacity and wilting point was 32% and 9.5% by volume, respectively.

Experimental design

The experimental design was a randomised block with 3 replications. Each plot was 8 m wide and 20 m long. Three spring wheat production treatments were compared: traditional tillage (TT), zero tillage (ZT), and PRB.

The TT system included manually broadcasting of fertiliser, ploughing to 0.20 depth and tillage for seedbed preparation, planting (to 0.05 m depth) on a flat field at the end of March, flood irrigation in the middle of April, May, and June, and mechanical harvesting at the end of July. While the majority of straw was removed, a small amount of standing stubble of 0.08–0.10 m height (~0.6 t/ha) remained after the spring wheat was harvested. The soil was ploughed to 0.20 m depth again in the fallow period (end July to middle March).

The ZT treatment consisted of no tillage planting (to 0.05 m depth) and fertilising (to 0.10 m depth) on a flat field at the end of March, flood irrigation in the middle of April, May, and June, and mechanical harvesting at the end of July. Standing stubble of 0.20 m in height was retained with all spring wheat straw left as mulch cover (~3.2 t/ha). A fallow period followed harvest until middle March.

The PRB treatment applied the no tillage planting (to 0.05 m depth) and fertilising (to 0.10 m depth) on the bed at the end of March, furrow irrigation in the middle of April, May, and June, and harvest by combine harvester at the end of July, leaving 0.20-m-high standing stubble and all spring wheat straw cover (~3.2 t/ha). The fallow period was from the end of July to the middle of March.

In the Hexi Corridor, seed and fertiliser are commonly applied at very high rates by farmers to maximise the chance of good yields. In this study, spring wheat (*T. aestivum* L. ‘Longfu 2’) was planted on 25 March 2005, 28 March 2006, and 28 March 2007, with the district-recommended rate of 450 kg/ha. The wheat was harvested on 24 July 2005, 26 July 2006, and 28 July 2007. The $CO(NH_2)_2$ and $(NH_4)_2HPO_4$ fertilisers were applied to provide 225 kg N and 180 kg P/ha at planting.

Three irrigations during the growing season were applied to all treatments. Irrigation was applied at different intervals according to the soil water content measurements. During the seedling, heading, and filling stages, all the plots were irrigated when the soil water content in the upper 0.8, 1.0, and 1.2 m soil profiles reached 80% of field capacity, respectively. The water was supplied from the surface river by channel, and the 120° V-notch weirs installed at the plot inlets were used to measure the amount of water applied. The water for flood and furrow irrigation was irrigated at the rate of 2100 and 900 m^3/ha.h according to local practices used by farmers.

Beds were formed in 2005 with an overall (furrow centre) width of 1.0 m for the PRB treatment to fit the wheel track width of the tractor and harvester. Furrow depth was 0.15 m, and the bed surface width was 0.70 m, allowing 5 rows of wheat at 0.13 m spacing. This is slightly less than the conventional 0.18-m row spacing used in the TT and ZT treatments, where a 1.0-m width accommodated almost 6 rows.

Measurements

The impact of permanent raised beds was assessed by changes in soil water content, bulk density, soil temperature, plant growth characteristics, yield, and water use. Volumetric soil water content to a depth of 1.0 m for the 3 treatments was measured during the whole growing season, and only the value at 0–0.30 m soil depth was analysed in the paper. Measurements for PRB treatment were taken at the centre of the bed and 0.25 m from the centre. For soil moisture and bulk density, 3 soil samples were taken using a 54-mm-diameter steel core sampling tube (length 1.0 m), manually driven into 1.0 m depth. The soil cores were weighed wet, dried in a fan-aided oven at 105°C for 48 h, and weighed again to determine soil water content and bulk density.

Soil temperature was recorded at 0.05, 0.15, and 0.25 m soil depths at 08 : 00 ($T_{08:00}$), 14 : 00 ($T_{14:00}$), and 20 : 00 ($T_{20:00}$) hours. Mean daily soil temperature (T) for 10 days after planting was estimated following the procedure described by Mao *et al*. (1998):

$$T = (2 \times T_{08:00} + T_{14:00} + T_{20:00})/4 \tag{1}$$

Wheat yields for TT, ZT, and PRB (including furrows and beds) treatments were determined by manual harvesting, threshing, and air-drying grain from three 1-m^2 areas of each plot. Wheat yield components (grains per spike, kernel weight, and harvest index) were also measured.

Water use efficiency values reported here are the ratio of grain yield to seasonal evapotranspiration (ET) according to the studies of Kang *et al*. (2000*b*) and Zhang *et al*. (2007) in the similar climate and cropping system areas:

$$\mathrm{WUE} = \mathrm{Yield}/\mathrm{ET} \tag{2}$$

ET was calculated using the general water balance equation:

$$\mathrm{ET} = P + I + Sg - D - Rf - \Delta W \tag{3}$$

where P is rainfall (mm), I is irrigation (mm), Sg is groundwater contribution to plant-available water (mm), D is deep drainage into groundwater (mm), Rf is surface runoff (mm), and ΔW is change in soil water content (mm).

In this experiment, ΔW was the change in total soil water content of the 1.0 m profile during the growing period. The capillary contribution from groundwater to the crop root-zone (Sg) was negligible because the ground water table is >5 m below the bed. Surface water runoff (Rf) was very small as irrigation water was protected by 0.2-m-high bunds. Deep drainage, D, was measured using the method developed by Grimes *et al*. (1992).

Input (seeds, fertiliser, water, labour, etc.) quantities and direct cost of all mechanical operations were recorded throughout the field trial, together with the value of outputs (crop yield × value), on a common basis (US$/ha).

Equipment description

Bed former

The mouldboard bed former used with the 20 kW tractor has 2 opposing mouldboards to plough soil from the furrows into 1-m-wide beds, where a levelling blade and roller completed the work of forming and pressing beds (Fig. 1, left). The relative horizontal position of tractor and bed former was adjusted by a centre position-adjusting unit, and different heights of beds could be achieved by use of the depth-control wheel.

Planter

A no-tillage planter developed by China Agricultural University (Fig. 1, right) was used for the planting of PRB and ZT treatments throughout the experiment. The planter was fitted with reshaping mouldboards to push soil and trash from the furrow to the bed. Narrow-point openers were used to place seed at a depth of approximately 0.05 m, where it was firmed by nylon press wheels. Residue clearance was maximised by mounting 3 openers on the front and 2 on the rear bar of the machine. This machine could complete bed-renovating, no-tillage planting and firming of the raised bed in one operation with a 20 kW tractor. The same planter could also complete no-tillage planting in flat fields by removing the reshaping mouldboards, lowering the openers, and increasing opener spacing. In traditional tillage treatment, spring wheat was planted in ploughed fields by a local 6-row seed drill.

Statistical analysis

The SPSS analytical software package (2003) was used for all of the statistical analyses. Mean values were calculated for each of the measurements, and ANOVA was used to assess the treatment effects on the measured variables. When ANOVA indicated a significant F-value, multiple comparisons of annual mean values were made on the basis of the least significant difference (l.s.d.).

Results

Water content

Soil volumetric water content to a depth of 0.30 m for each treatment is illustrated in Fig. 2 for the wheat growing periods from 2005 to 2007. In all cases, soil moisture gradually decreased with crop water use during the growing period. At the beginning of the experiment (March, 2005), soil water content in the top 0.30 m depth in the PRB treatment was about 18%, and significantly ($P < 0.05$) less than in TT probably due to moisture losses during bed-forming. However, the PRB treatment still had the greatest soil water

Fig. 1. Mouldboard bed former (left) and no-tillage planter (right).

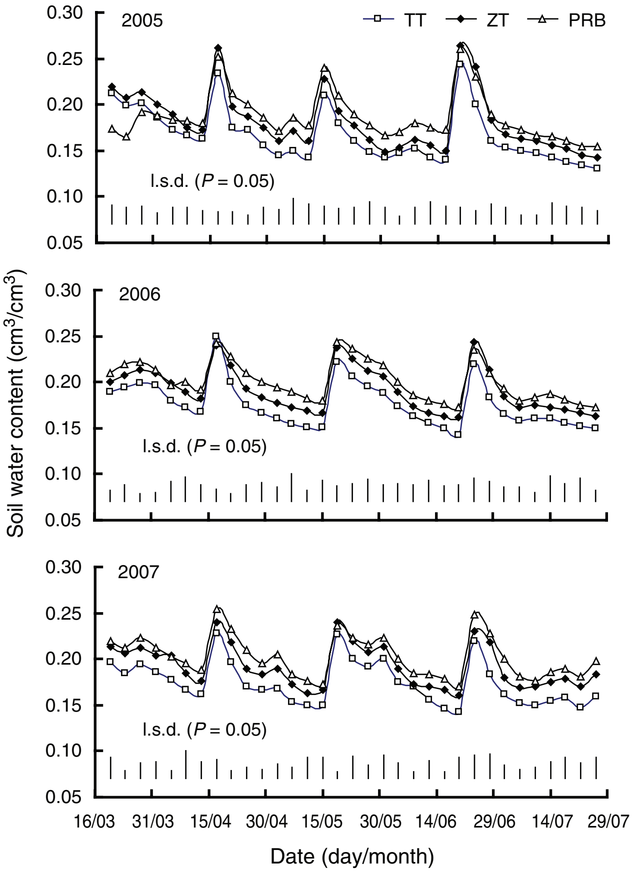

Fig. 2. Mean soil volumetric water content to the depth of 0.30 m for 3 treatments (TT, traditional tillage; ZT, zero tillage; PRB, permanent raised beds) in the wheat growing period from 2005 to 2007.

content during the wheat growing period, while ZT and TT treatments had intermediate and the least water contents, respectively. In 2005, the mean volumetric water contents in the 0–0.30 m soil profile of TT, ZT, and PRB were 0.167, 0.182, and 0.187 cm^3/cm^3, respectively, so the mean soil moisture content of ZT and PRB treatments was significantly ($P < 0.05$) greater by about 9% and 12.0%, respectively, than TT. In 2006, the mean volumetric water contents for 0–0.30 m depth in ZT and PRB were 8.7% and 14.2% higher than in TT, which was significant ($P < 0.05$) at most of the wheat growing stages. Similar effects were found in 2007, indicating that PRB might provide more water for the growth of wheat by maintaining greater soil water content than TT.

Soil bulk density

The mean soil bulk density in the 0–0.30 m profile for TT, ZT, and PRB treatments was 1.29, 1.30, and 1.28 Mg/m^3, respectively, after wheat harvesting in 2005 (Table 1). These differences were not significant in 2005, but there were some significant ($P < 0.05$) differences in 2006 and 2007. In 0–0.10 m soil depth, soil bulk density in PRB was 8.6% and 10.9% lower ($P < 0.05$) than in ZT in 2006 and 2007, respectively, but there were no significant bulk density advantages of PRB compared with TT treatments in both years. Similar trends could be discerned in the means for the 0.10–0.20 and 0.20–0.30 m soil layers, but none of these approached significance.

Table 1. Treatment effects on soil bulk density (Mg/m^3) for 0–0.30 m depth

TT, Traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Means within a row followed by the same letter are not significantly different ($P > 0.05$). Soil samples were taken after harvesting in August

Soil depth	2005			2006			2007		
(m)	TT	ZT	PRB	TT	ZT	PRB	TT	ZT	PRB
0–0.10	1.23a	1.24a	1.20a	1.21ab	1.28a	1.17b	1.22ab	1.29a	1.15b
0.10–0.20	1.28a	1.31a	1.30a	1.33a	1.37a	1.32a	1.31a	1.36a	1.32a
0.20–0.30	1.36a	1.34a	1.33a	1.38a	1.39a	1.39a	1.37a	1.38a	1.36a

Soil temperature

Temperature differences and their significance followed a pattern similar to that of soil bulk density (Table 2). At 0.05 m soil depth, mean soil temperature in the PRB treatment was greater by up to 0.3°C in 2005 than in TT and ZT. These mean surface soil temperature differences increased in 2006 and again in 2007, when some became significant ($P < 0.05$). ZT with straw cover consistently had the lowest soil temperature, and PRB the highest. Temperature differences further down the soil profile were smaller and never significant.

Seedling emergence

Seedling emergence from flat planting systems (TT and ZT) in 2005, 2006, and 2007 was greater ($P < 0.05$, except for TT in 2005) than the PRB treatment (Fig. 3). Mean seedling emergence in ZT and TT plots was 15.2% and 11.6% greater ($P < 0.05$) than in PRB over the 3 years of the experiment.

Growth

Jointing to heading stage

Wheat growth on PRB was faster than that in TT (Table 3), and crop performance was better, particularly when assessed by leaf area and plant dry weight in 2005 and 2006. Root dry weight and leaf area were greater by approximately 6% and 7%, respectively, in PRB than TT. Within flat planting

Table 2. Soil temperature (°C) measured over 3 treatments at 0.05, 0.15, and 0.25 m soil depths

TT, traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Means within a row followed by the same letter are not significantly different ($P > 0.05$)

Soil depth	2005			2006			2007		
(m)	TT	ZT	PRB	TT	ZT	PRB	TT	ZT	PRB
0.05	15.1a	15.2a	15.5a	16.5a	16.2a	16.7a	17.0ab	16.6a	17.5b
0.15	13.6a	13.3a	13.5a	14.4a	14.3a	14.6a	15.5a	15.4a	15.8a
0.25	12.9a	12.9a	13.0a	13.4a	13.4a	13.3a	14.3a	14.5a	14.2a

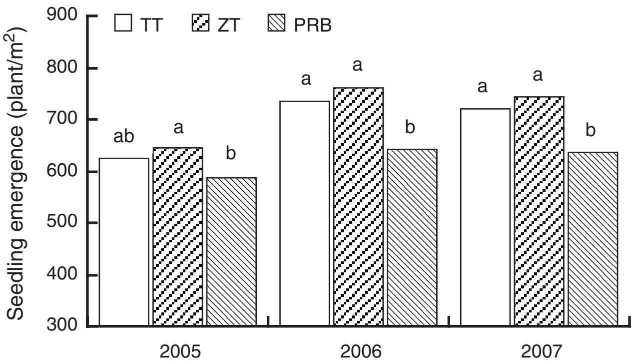

Fig. 3. Seedling emergence of wheat in 2005, 2006, and 2007. TT, Traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Data were measured 15 days after planting. In PRB treatment, the m^2 in unit ($plant/m^2$) refers to the area of bed and furrow combined. Means within seeding emergence in the same year followed by the same letter are not significantly different ($P > 0.05$).

systems, plant condition tended to be better in ZT than TT, although significant differences ($P < 0.05$) were rare.

Maturing stage

Wheat yield was not significantly affected by different treatments in the first growing season, but pronounced yield advantages were found in PRB plots in 2006 (Table 4). The mean wheat yields for TT, ZT, and PRB treatments were 5981, 6128, and 6314 kg/ha, indicating a significant ($P < 0.05$) yield improvement of 5.6% for PRB compared with TT treatment. A similar trend continued in 2007, but yield advantages of PRB were not significant ($P > 0.05$). Other aspects of crop growth were also sometimes significantly ($P < 0.05$) affected by the planting system, including spike length, grains per spike, and kernel weight.

Table 3. Leaf area (cm^2/plant), plant height (cm), plant dry weight (g/plant), and root dry weight (g/100 plants) at 0–0.20 m depth of wheat for 3 treatments from joint to heading stage in 2005, 2006, and 2007

TT, traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Data measured on 21 May 2005, 24 May 2006, and 29 May 2007. Means within a column in the same year followed by the same letter are not significantly different ($P < 0.05$)

Treatment	Leaf area	Plant height	Plant dry wt	Root dry wt
		2005		
TT	55.8a	75.1a	34.1a	753a
ZT	56.5a	72.6a	36.5b	723b
PRB	56.6a	74.3a	36.7b	765c
		2006		
TT	65.3a	63.4a	28.4a	736a
ZT	70.6b	70.3b	29.8ab	773b
PRB	76.3c	68.7b	31.6b	850c
		2007		
TT	63.7a	64.2a	34.7a	757a
ZT	68.8b	66.8a	32.6a	743a
PRB	65.3ab	67.9a	33.5a	776a

Table 4. Treatment effects on yield and yield components of wheat in maturing stage in 2005, 2006, and 2007

TT, Traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Means within a column in the same year followed by the same letter are not significantly different ($P > 0.05$)

Treatment	Spike length (cm)	Grains per spike	Kernel wt (g)	Yield (kg/ha)
		2005		
TT	8.3a	32a	39.5a	5621a
ZT	8.4a	29a	39.0a	5420a
PRB	8.2a	31a	40.1a	5576a
		2006		
TT	8.1a	35a	40.7a	5981a
ZT	8.5ab	37ab	41.8a	6128ab
PRB	8.9b	40b	48.1b	6314b
		2007		
TT	8.6a	38a	38.7a	6154a
ZT	8.9a	36a	43.2b	6354a
PRB	8.8a	38a	42.8b	6297a

Water use efficiency

The mean annual irrigation water applied between 2005 and 2007 varied from 377 to 403 mm under TT, from 342 to 373 mm under ZT, and from 280 to 311 mm under PRB (Table 5). This resulted in a relative saving of 18.9–28.0% and 14.3–18.1% in annual irrigated water quantity for PRB compared with TT and ZT, respectively. Wheat yield was also greater in PRB than in TT and ZT treatments, so the mean WUE for PRB treatments was 11–29% greater than TT and ZT for all 3 years of the experiment ($P < 0.05$). Within flat-planting systems, the mean WUEs in ZT were measured 4.3% higher than that in TT, but these differences were not significant.

Economic benefit

Mean annual input costs for these treatments varied from US $586/ha in ZT to US$718/ha in TT (per season of wheat

Table 5. Mean water use efficiencies (kg/ha.mm) for 3 treatments in 2005, 2006, and 2007

TT, traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Means within a column in the same year followed by the same letter are not significantly different ($P > 0.05$)

Treatment	Rainfall (mm)	Total irrigation (mm)	ΔW (mm)	D (mm)	WUE (kg/ha.mm)
		2005			
TT	95	403	40.5	42.1	11.3a
ZT	95	373	54.7	40.2	11.2a
PRB	95	311	56.4	37.8	13.1b
		2006			
TT	73	389	36.5	33.2	12.9a
ZT	73	342	58.4	34.2	14.0a
PRB	73	280	53.4	29.2	16.7b
		2007			
TT	84	377	43.2	34.2	13.1a
ZT	84	357	52.6	30.9	13.7a
PRB	84	306	55.6	31.2	15.2b

production) (Table 6). ZT and PRB treatments cost less with reduced mechanical operation costs, water, and labour. Mean wheat yields of ZT and PRB were also greater than TT, so the farmer profits of ZT and PRB treatments were 30.3% and 32.0% greater, respectively, than TT. Compared with ZT, PRB increased mechanical inputs due to the cost of bed-forming in the first experimental year, but reduced water cost and enhanced yield, so the economic benefits in ZT (US$607/ha) and PRB (US$615/ha) treatments were similar overall.

Discussion

Field experimental results reported here demonstrate that PRB production was associated with a substantial and significant improvement in WUE in all 3 years compared with TT or ZT practice, and an increase (significant in 1 year only) in the mean yield of wheat compared with TT. ZT was associated with a non-significant trend to improvement in mean WUE and yield. This accords with the findings of He *et al.* (2007*b*) and Li *et al.* (2007), and might well be explained by improved soil physical properties in permanent bed systems demonstrated by Mele and Carter (1999) and by Sotomayor-Ramirez *et al.* (2006), and improved soil moisture characteristics (Su *et al.* 2007).

The PRB practice was associated with higher soil temperatures than TT and ZT, which might be of considerable importance in the cold weather of these arid areas (Li *et al.* 1999). Mean maximum soil temperatures reported here for PRB systems were 0.3–0.7°C greater than for flat systems (TT and ZT) in the first 10 days after planting during the 3 experimental years, an increase similar to that found by Yang *et al.* (2005) at 0.05 m soil depth under an 0.80 m bed compared with flat tillage in March in arid northern China. This improvement in soil temperature might well be due to the bed configuration, which increased the area available to absorb solar energy, together with more porous soils as indicated by lower bulk density in PRB, which tended to retain greater heat energy and warm more quickly in the spring.

The PRB treatments were also associated with greater soil water content in the top 0.30 m depth during the entire wheat growing period, compared with flat planting systems (TT and ZT). These improvements were pronounced, particularly immediately after irrigation, when mean soil water content to 0.30 m depth was about 8.7% greater ($P < 0.05$) in PRB plots than that in flat planting plots. Our data demonstrate that more water was available for germination and growth for wheat grown on permanent beds then flat fields, in each cropping season. These positive effects on soil moisture were consistent with the results of Yuan *et al.* (2005), who found that soil water content in 0.80-m-wide beds was 5.3% higher than that in traditional flat fields after 2 years in the Ningxia region of north-west China.

Table 6. Output and input (US$/ha) of wheat under 3 treatments
TT, traditional tillage; ZT, zero tillage; PRB, permanent raised beds. Data for water, mechanical operation cost, and yield are the mean values from 2005 to 2007

	TT	ZT	PRB
Inputs			
Seed	163	163	163
Fertiliser	202	202	202
Water	76	69	58
Labour	51	37	37
Mechanical operation cost	226	115	137
Total	718	586	597
Outputs			
Yield	5919	5967	6062
Price (US$/kg)	0.2	0.2	0.2
Income	1184	1193	1212
Farmer income	466	607	615

In this study, flood irrigation was applied to the whole surface area in flat planted systems, requiring 2100 m^3/ha.h in TT and ZT plots, to ensure the complete area was flooded. For PRB, however, only about 900 m^3/ha.h was needed to fill the narrow furrows between neighbouring beds, where the smaller free water surface area (compared with flat systems) might be expected to decrease evaporation losses (Lei *et al.* 2004). Permanent beds with furrow irrigation could be an effective way to reduce water delivery rate requirements as well as reducing total water requirements and improving WUE, compared with flood-irrigated TT and ZT. Similar outcomes have been demonstrated in irrigated wheat–rice and wheat–maize areas by Sayre and Hobbs (2004) and Meisner *et al.* (2005).

In the PRB treatment, the cropping zone accounted for only about 70% of total experimental plot area because wheat was planted only on the beds. Furthermore, the frame-based planter depth control used in the experiment was less effective in raised beds with non-uniform residue distribution, particularly when bed/furrow profile varied. This influenced planter performance, particularly its ability to place and firm seed and fertiliser at the proper depth, and probably accounted for the 10–15% reduction in seedling numbers of PRB, compared with flat treatments. Compared with flat planting systems, PRB generally had a positive effect on leaf area, plant dry weight, and root dry weight due to improved moisture conditions (7.2–10.7% greater) and faster topsoil warming (0.3–0.7°C higher), compensating for the shortfall in plant density. This faster growth rate was probably responsible for the increased wheat yield (in 2 out of 3 years) grown in the PRB treatment. This outcome is similar to that reported from other experiments on water saving in north-west China (Deng *et al.* 2006; Lian *et al.* 2007).

Conclusions

Results from this research indicate that a PRB system with furrow irrigation is an effective water-saving farming technique in the irrigation farming areas of arid north-west China. Mean data indicate that adoption of PRB systems reduced irrigation water requirement by 18% and increased water use efficiency by 20%, which has profound implications in this environment of greatly decreasing water availability. The improved (2%) mean yield in PRB treatment also indicates that the change from flat planting, flood irrigation systems to permanent bed planting, furrow irrigation systems will not have a negative effect on wheat production. Zero tillage with residue cover also appeared to provide some advantage in yield and water use efficiency, compared with traditional tillage.

Permanent raised bed cropping systems clearly have the potential to make an important contribution to agricultural productivity. The results reported here are encouraging, but ongoing research is needed on several aspects of this cropping system, including the suitability of current wheat varieties and the relationships between tillage and water management practices, productivity and environmental conditions. The absence of suitable no-tillage planter for permanent beds is likely to be a significant constraint to adoption and must be investigated in arid north-west China.

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