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Permanent raised beds improved soil structure and yield of spring wheat in arid north-western China

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Abstract

In arid north-western China, soil degradation, limited water and subsequent yield decline, largely as a result of excessive tillage and residue removal practices, are the main factors limiting further development of local agriculture. The effects of permanent raised beds (PRB), no-till (NT) and traditional tillage (TT) on soil structure and yield were investigated in a wheat (*Triticum aestivum* L.) – maize (*Zea mays* L.) cropping system from 2004 to 2009 in the Hexi Corridor of Gansu Province, China. PRB and NT had more macro-aggregates (>0.25 mm, +2.7%), a better distribution of pore size classes and improved hydraulic conductivity, whereas TT soils were dominated by micro-aggregates and micro-porosity. In PRB, soil bulk density decreased significantly by 6.3 and 7.0% for the 0- to 10-cm and 20- to 30-cm depths relative to TT. The PRB mean crop yields increased by 4.2% and water use efficiency improved by 21.3% compared with TT because of greater soil moisture and improved soil physical and chemical status. These improvements in soil properties, yield and water use are of considerable importance for soil regeneration, food security and sustainable agriculture in arid regions, such as north-western China.

Keywords: Permanent raised beds, soil fertility, aggregate stability, soil porosity, yield

Introduction

In arid north-western China annual rainfall ranges from 40 to 200 mm, whereas potential evaporation exceeds 1500 mm, therefore water shortage is one of the major constraints to the production of agricultural crops (Xie *et al*., 2005). Agriculture is largely dependent on irrigation, thus water use efficiency (WUE) has become extremely important in this region. In traditional flood irrigation cropping systems, farmers use the mouldboard plough followed by numerous soil workings to produce good seedbeds. In the longer term, this traditional tillage (TT) tends to reduce soil moisture, increase soil bulk density (D_b) by reducing macro-porosity and macro-aggregates, resulting in less plant available water and reducing nutrient availability (He *et al*., 2007). Consequently, in this degraded loess soil, crop yields and WUE have declined, particularly in dry years.

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Owing to significant overall benefits, a farming system using permanent raised beds (PRB) has been proposed for irrigated wheat and maize production for sustainable development of agriculture in this region of China (Wang *et al*., 2009). This farming system consists of furrow irrigation, planting crops on raised beds with medium soil disturbance and maximum residue cover (Govaerts *et al*., 2007). Furthermore, all equipment wheels are confined to permanent furrows in the PRB system.

The positive effects of PRB cropping system on soil properties and crop yields have been demonstrated globally. For example, in north-western Mexico Govaerts *et al*. (2007) reported that long-term permanent beds developed in coarse sandy soils, significantly improved soil chemical and biological properties, compared with conventionally tilled beds. McHugh *et al*. (2009) and Verhulst *et al*. (2011) indicated that planting on permanent beds increased soil available water capacity and improved aggregate stability compared with conventional tillage without beds. Holland *et al*. (2007) and Singh *et al*. (2010) demonstrated that PRB was effective in increasing grain yield because of improved soil properties and reduced waterlogging on Loess soils in the Indian Punjab. In China, studies have generally confirmed the positive effects of bed planting and furrow irrigation systems on crop development and water use. Wang *et al*. (2009) showed that raised bed systems reduced irrigation water use by 30% and improved WUE by 20%, compared with conventional flat planting in Shandong Province. He *et al*. (2007) demonstrated that bed planting increased soil moisture to 1.0 m depth by over 3% relative to the flat planting system in north-western China, and Zhang *et al*. (2011) reported yield improvements of over 6% for spring wheat grown on raised beds compared with flat planting. However, most Chinese grain production on raised bed systems still involves substantial tillage operations to form the beds and plant the crop each year. Consequently, information and experience with irrigated PRB is limited for north-western China.

In 2004, a unique experiment began in Hexi Corridor, Gansu Province, north-western China to assess the potential benefits of PRB, which prompted parallel research in related issues. This study reports that the outcome of this continuing experiment with the objective of improving understanding of the longer-term (6 yr) impacts of PRB, in particular to enable a quantitative assessment of the potential benefits on soil structure and crop yields in the arid conditions of north-western China.

Materials and methods

Site and climatic conditions

The experiment was conducted at the Gansu Academy of Agricultural Sciences water-saving research station (38°50′N, 100°10′E), near Zhangye City in the Black River valley of north-western China from 2004 to 2009. The station is located in this arid region at 1200–1700 m above sea level. The annual mean air temperature was 7.3 °C, and the accumulated temperature was about 3088 °C (daily mean temperature ≥10 °C over 150 days). Average annual rainfall was 146 mm, and potential pan-evaporation was 2390 mm. The soil at the station was a Loess derived sandy-loam (sand 49%, silt 34%, clay 17%). According to the FAO-UNESCO soil map, the soil type is a Cambisol, with a pH of 8.0 (water) in 0- to 60-cm layer. Soil water content at field capacity and wilting point was 32 and 9.5% by volume, respectively. In the surrounding irrigated area, spring wheat and spring maize rotation (one crop per year) were the main crops. Cropping operations summarized in Table 1 are typical of those for the irrigated farming areas in north-western China.

Experimental design

Following harvest of spring-sown maize in 2004, the entire site was tilled to a depth of 30 cm to remove any plough pan. Treatment plots were applied as a randomized block with three replications. Each plot was 8 m wide and 20 m long consisting of three farming system treatments: PRB, no-till (NT) and TT:

Table 1 The operation schedules for spring wheat and spring maize at the experimental site and district surrounding Zhangye City in north-western China

Crops	Schedules
Spring wheat	Seeding (late March) – irrigation (mid-April, May and June) – harvesting (late July) – winter fallow (late July to late March, of the following year)
Spring maize	Seeding (mid-April) – irrigation (mid-May, June, July and August) – harvesting (late September) – winter fallow (late September to mid-April, of the following year)

The PRB system included NT seeding and fertilizer application on the bed (<25% of the bed surface was disturbed), furrow irrigation and combine harvesting. Standing stubble, 20 cm in length, remained on the field, and ca. 3.2 Mg/ha of straw from harvesting was chopped and spread uniformly across the plots, providing >100% ground cover. The NT system consisted of NT seeding (<25% field surface was disturbed) and fertilizer application on a flat field, flood irrigation and combine harvesting. Standing stubble and ground cover were the same as PRB treatment. The TT system included manual broadcasting of fertilizer, on a flat field, mouldboard ploughing to 20-cm depth, harrowing and smoothing for seedbed preparation and flood irrigation. The majority of wheat straw was removed, except for 8 cm of standing stubble (ca. 0.6 Mg/ha), which was incorporated during ploughing prior to the winter fallow period.

After maize under TT, the stalks were manually removed and burnt. In the PRB and NT treatments, wheat rows were seeded either side of the undisturbed stalks.

The spring wheat variety, *Triticum aestvum* L. cv. Longfu 2, was seeded in 2005, 2006, 2007 and 2009, and maize (*Zea mays* L. cv Jinkai 1) was seeded in 2008. In Zhangye seed and fertilizer are commonly applied at very high rates by farmers to maximize the chance of good yields. In this study, wheat was seeded at the district-recommended rate of 450 kg/ha, and $CO(NH_2)_2$ and $(NH_4)_2$ HPO_4 fertilizers were applied to provide 225 kg N/ha and 180 kg P/ha. Maize was seeded at a rate of 60 kg/ha and fertilized with 205 kg N/ha and 102.5 kg P/ha.

In-season irrigation was applied three times for wheat and four times for maize. For wheat, irrigation was applied at seedling, heading and grain-filling stages, when the soil water content in the upper 0.8, 1.0 and 1.2 m depths of soil reached 60% of field capacity, respectively. For maize, irrigation was applied at seedling, jointing, heading and grain-filling stages when the soil moisture in top 0.4, 0.8, 1.0 and 1.2 m depths reached 60% of field capacity, respectively.

In PRB plots, the overall (furrow centre to centre) bed width was 1.0 m to fit the wheel track width of the tractor and harvester. Furrow depth was 15 cm, and the bed surface width was 70 cm, allowing for five rows of wheat at 13 cm spacing or two rows of maize at 55 cm spacing, wheel tracks and furrows were not seeded. In NT and TT plots, wheat and maize were seeded with the row space of 18 and 55 cm, respectively.

Soil sampling and preparation

In July 2009, five undisturbed soil core (50.4 mm diameter × 50 mm) samples from 0- to 10-cm, 10-to 20-cm and 20- to 30-cm soil layers were randomly collected from the cropped areas of each treatment to determine soil porosity and bulk density, and from 0- to 15-cm and 15- to 30-cm soil layers for saturated hydraulic conductivity (K_s). Five disturbed soil samples were collected at each of the 0- to 10-cm, 10- to 20-cm and 20- to 30-cm layers in the cropping zones of each plot and mixed to form a single composite sample for each depth band for soil organic matter (SOM), available N and P, and aggregate stability measurements. Before the analyses, soil samples were air-dried for 24 h in the laboratory.

SOM, available N and P

Soil organic matter was determined by dry combustion using a Leco Carbon Analyser (Nelson & Sommers, 1982). Nitrate was extracted with 1 M KCl and analysed by the cadmium reduction method (Dorich & Nelson, 1984). Available P was extracted with 0.5 M $NaHCO_3$ solution adjusted to pH 8.5 (Olsen & Sommers, 1982).

Water-stable aggregates

Water-stable aggregates were determined by placing the soil sample on a nest of sieves, immersing directly in water, and agitating the sieves up and down by 3.5 cm at a frequency of 30 cycles per minute for 15 min. Proportions of stable aggregates >2, 2–1, 1–0.25 and <0.25 mm were calculated, and micro-aggregates taken as those <0.25 mm (Oades & Waters, 1991).

Soil porosity and saturated hydraulic conductivity

Soil porosity, determined using a laboratory pressure plate extractor with undisturbed soil cores, was classified as aeration porosity (pores with equivalent radius >60 μm), capillary porosity (0.2–60 μm) and microporosity (<0.2 μm). Aeration porosity and capillary porosity were determined from volumetric water content at suctions between 0 to −5 kPa and −5 to −1500 kPa matric potential. Microporosity was determined from the volumetric water content at −1500 kPa matric potential. K_s was determined on undisturbed soil cores by the constant-head method for repacked soil cores (Klute & Dirksen, 1986).

Bulk density

Bulk density was determined from undisturbed soil cores on a soil oven-dry mass basis. Soil cores were weighed wet, dried at 105 °C for 48 h and weighed again to determine bulk density.

Yield and water use efficiency

Yields were determined by manual harvesting, threshing and air-drying grain from five 1 m^2 quadrates taken randomly from each plot.

Apparent evapotranspiration (AET) was calculated using the formula:

$$\mathrm{AET} = P + I - \Delta W \tag{1}$$

where P is growing season rainfall (mm), I is irrigation (mm), and ΔW is the change in stored soil water (mm) of the soil profile (0- to 100-cm depth) from seeding to harvesting.

Water use efficiency was estimated as the grain yield (kg/ha) divided by the growing season evapotranspiration (mm):

$$\mathrm{WUE} = \mathrm{Yield}/\mathrm{AET}. \tag{2}$$

Statistical analysis

Mean values were calculated for each of the measured variables, and ANOVA was used to assess the treatment effects. When ANOVA indicated a significant F-value, multiple comparisons of annual mean values were performed by the least significant difference method (*l.s.d.*). Statistical analyses were conducted with SPSS 13.0.

Results

Soil organic matter, available N and P

The SOM in the 0- to 30-cm layer of all three treatments was similar at the commencement of the experiment in 2004, and values in 2009 showed no significant differences (results not shown). Soil available N showed the same trend as SOM. Although there was some variation between treatments, no treatment was statistically different from any other. Available P also showed no significant treatment effects.

Bulk density (D_b)

The mean D_b for PRB, NT and TT in 0- to 30-cm soil layer were 1.18, 1.17 and 1.18 Mg/m^3 following ploughing in 2004.

After 3 yr in 2007, mean D_b was not significant different between treatments ($P > 0.05$) (Table 2). However, by 2009, after 5 yr of <25% surface soil disturbance under PRB, D_b was significantly ($P < 0.05$) smaller in the 0- to 10-cm and 20- to 30-cm layers compared with TT. D_b for the NT treatment was not significantly different from either of other treatments.

Water-stable aggregates

The percentage of water-stable soil aggregates of the largest size class (>2 mm) in 0- to 10-cm, 10- to 20-cm and 20- to 30-cm soil layers for PRB was significantly ($P < 0.05$) larger than for TT by 2.7, 2.2 and 3.0%, respectively (Table 3). NT values were not significantly different from those for PRB or TT except that at the 20- to 30-cm depth, the value was greater than that for TT, otherwise values generally fell between the other two treatments. There was no effect of treatment in water-stable aggregates of the size class 2–1 mm, and in the 1–0.25 mm size class, the only treatment effect was at the 20- to 30-cm depth, where the value for TT was significantly greater than that for the other treatments by 3%. Similarly, TT water-stable micro-aggregates (<0.25 mm) were ca. 3% greater than for PRB.

Soil porosity

The soil porosity size class distributions for PRB and NT in 2009 were broadly similar and generally greater than for TT. Mean total porosity in 0- to 30-cm layer in PRB, NT and TT were 46.7, 44.9 and 43.3% (Table 4), and PRB mean porosity was significantly larger at all depths when compared with TT. In all three layers, PRB aeration porosity was significantly ($P < 0.05$) greater than TT by 14.3, 54.9 and 70.8%, respectively. In the uppermost soil layer of PRB capillary porosity, which generally reflects plant available water, was significantly greater than TT treatment, by 24.3%. TT had a significantly ($P < 0.05$) greater percentage of microporosity than PRB at 0- to 10-cm and 20- to 30-cm at 11.6 and 12.8%, respectively. There was no significant effect in the 10-to 20-cm layer. In general, the data in Table 4 indicated that the nontillage treatments (PRB and NT) had a broader pore size class distribution than TT, whereas TT had a

Table 2 Treatment effects on soil bulk density (Mg/m^3) for 0–10, 10–20 and 20–30 cm depths

	2007			2009		
Soil depths (cm)	PRB	NT	TT	PRB	NT	TT
0–10	1.21^{a}	1.24^{a}	1.26^{a}	1.20^{a}	1.25^{ab}	1.28^{b}
10–20	1.32^{a}	1.33^{a}	1.34^{a}	1.31^{a}	1.34^{a}	1.35^{a}
20–30	1.34^{a}	1.35^{a}	1.38^{a}	1.32^{a}	1.34^{ab}	1.42^{b}

NT, no-till; PRB, permanent raised beds; TT, traditional tillage. Values within a year for the same depth followed by the same letters are not significantly different ($P > 0.05$). The data were measured after spring wheat harvest in 2007 and 2009.

Table 3 Treatment effects on soil stable aggregate size classes (%) for 0–10, 10–20 and 20–30 cm depths

		Macro-aggregates (>0.25 mm)			Micro-aggregates (<0.25 mm)
Soil depth (cm)	Treatment	>2 mm	2–1 mm	1–0.25 mm	<0.25 mm
0–10	PRB	12.3^{a}	10.3^{a}	62.2^{a}	15.2^{a}
	NT	11.1^{ab}	9.3^{a}	63.1^{a}	16.5^{ab}
	TT	9.6^{b}	8.4^{a}	63.9^{a}	18.1^{b}
10–20	PRB	14.2^{a}	12.6^{a}	58.4^{a}	14.8^{a}
	NT	13.1^{ab}	13.8^{a}	58.1^{a}	15.0^{a}
	TT	12.0^{b}	12.2^{a}	58.1^{a}	17.7^{b}
20–30	PRB	18.2^{a}	22.0^{a}	43.7^{a}	16.1^{a}
	NT	17.4^{a}	21.8^{a}	44.3^{a}	16.5^{a}
	TT	15.2^{b}	19.8^{a}	47.1^{b}	17.9^{a}

NT, no-till; PRB, permanent raised beds; TT, traditional tillage. Values within a column in the same depth followed by the same letters are not significantly different ($P > 0.05$). The data were measured after spring wheat harvest in 2009.

Table 4 Treatment effects on soil porosity ($cm^3/100\ cm^3$) for 0–10, 10–20 and 20–30 cm depths

Soil depth (cm)	Treatment	Total porosity	Aeration porosity (> 60 μm)	Capillary porosity (0.2–60 μm)	Microporosity (< 0.2 μm)
0–10	PRB	49.5[a]	11.2[a]	23.0[a]	15.3[a]
	NT	47.8[ab]	10.5[a]	20.4[b]	16.9[ab]
	TT	45.6[b]	9.8[a]	18.5[b]	17.3[b]
10–20	PRB	46.4[a]	12.7[a]	16.2[a]	17.5[a]
	NT	44.1[ab]	11.4[a]	14.4[a]	18.3[a]
	TT	43.0[b]	8.2[b]	15.9[a]	18.9[a]
20–30	PRB	44.3[a]	12.3[a]	14.9[a]	17.1[a]
	NT	42.8[ab]	11.0[a]	14.2[a]	17.6[a]
	TT	41.2[b]	7.2[b]	14.4[a]	19.6[b]

NT, no-till; PRB, permanent raised beds; TT, traditional tillage. Values within a column in the same depth followed by the same letters are not significantly different ($P > 0.05$). The data were measured after spring wheat harvest in 2009.

greater percentage of micropores than macropores, except in the surface layer.

Saturated hydraulic conductivity

Values for K_s in 2009 for 0- to 15-cm soil layer of PRB was 32.1% greater ($P < 0.05$) than that of TT (Figure 1). K_s value for PRB and NT in 15- to 30-cm soil layer were significantly ($P < 0.05$) greater than that for TT.

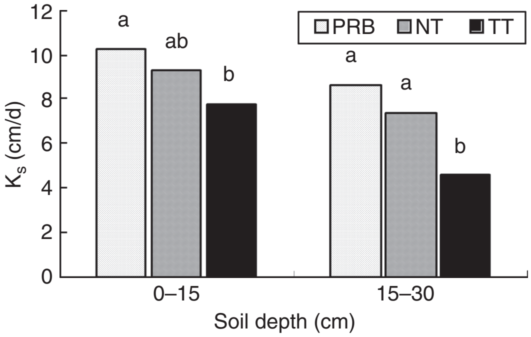

Figure 1 Soil saturated hydraulic conductivity (K_s) of 0 to 15 cm and 15 to 30 cm layers under permanent raised beds (PRB), no-till (NT) and traditional tillage (TT) treatments. Means in the same soil profile followed by same letters are not significant ($P > 0.05$). The data were determined immediately after spring wheat harvest in 2009.

Soil water storage

At the commencement of the experiment in 2005, soil water storage (0–30 cm) was similar in all three treatments (Figure 2). However, differences between tillage treatments emerged in 2008 and persisted in 2009. In those 2 yr, soil water storage was significantly enhanced in PRB ($P < 0.05$) by 6.5% (68.5 mm) and 13.9% (54.8 mm) compared with TT at 64.3 and 48.1 mm, respectively. Overall mean soil water storage in the 0- to 30-cm layer was over 3.0% higher in PRB and NT treatments than in TT treatment. There was a consistent trend in soil structural improvement from 2006 in PRB treatment reflected in improved plant available water capacity (Figure 2), which became increasingly obvious in the latter years.

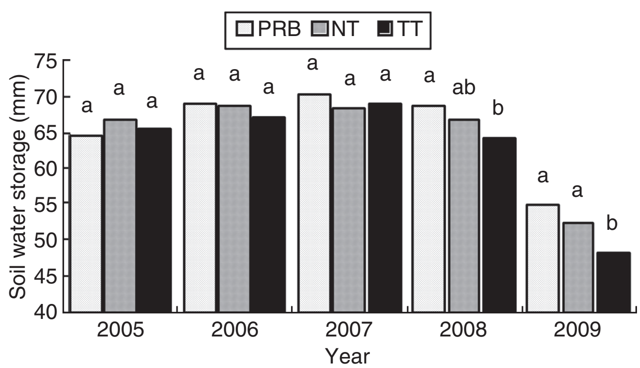

Figure 2 Soil water storage of 0- to 30-cm layer under permanent raised beds (PRB), no-till (NT) and traditional tillage (TT) treatments at time of seeding spring wheat and maize. Means in the same year followed by same letters are not significant ($P > 0.05$).

Crop yield

On average, crop yields in PRB and NT were greater than those in TT (Table 5). In the 4-yr (2005, 2006, 2007, 2009), mean wheat yields for PRB, NT and TT were 6.1, 6.0 and 5.9 Mg/ha, respectively, an improvement in yield of 3.3 and 1.7% for PRB and NT as compared with TT. For the maize crop grown in 2008, no differences between treatments were significant.

Water use efficiency

Applied annual irrigation water was highly variable (Table 5); nevertheless, it resulted in a relative saving of 11.4–18.1% and 17.5–28.0% in applied water for PRB compared with NT and TT, respectively. Coupled with the modest yield increases in PRB, average WUE in this treatment was 2–3 kg/ha/mm

Table 5 Crop yields and water use efficiencies (WUE) from 2005 to 2009

Year	P (mm)	ΔW (mm)			I (mm)			Yield (kg/ha)			WUE (kg/ha/mm)		
		PRB	NT	TT	PRB	NT	TT	PRB	NT	TT	PRB	NT	TT
2005	95	−56.4	−54.7	−40.5	311	373	403	5576^{a}	5420^{a}	5621^{a}	12.1^{a}	10.4^{b}	10.4^{b}
2006	73	−53.4	−58.4	−36.5	280	342	389	6314^{a}	6128^{ab}	5981^{b}	15.5^{a}	12.9^{b}	12.0^{b}
2007	84	−55.6	−52.6	−43.2	306	357	377	6297^{a}	6354^{a}	6154^{a}	14.1^{a}	12.9^{b}	12.2^{b}
2008	96	−73.5	−79.6	−60.3	462	530	589	12021^{a}	11796^{a}	11356^{a}	19.0^{a}	16.7^{b}	15.2^{b}
2009	49	−68.6	−62.1	−54.6	326	368	395	6188^{a}	6082^{ab}	5830^{b}	13.9^{a}	12.7^{ab}	11.7^{b}

NT, no-till; PRB, permanent raised beds; TT, traditional tillage. Values within a row in the same year followed by the same letters are not significantly different ($P > 0.05$). Spring wheat was seeded in 2005, 2006, 2007 and 2009. Spring maize was seeded in 2008 as a rotation crop. P, growing season rainfall; I, irrigation; ΔW, change in stored soil water of the soil profile (0–100 cm depth) from seeding to harvesting.

greater than that of TT, an increase of between 15.6 and 29.2%, and was 9.3–20.2% greater than that under NT. Importantly, PRB WUE in PRB was at least 1 kg/ha/mm greater in the two dryer years of 2006 and 2009 than in the years with larger rainfall and in the latter year the WUE under NT was not different to that for the PRB treatment.

Discussion

The experiment conducted from 2004 to 2009 clearly demonstrated that PRB farming in north-western China was associated with improvements in soil structure and crop yield. Although the increase in SOM in PRB soils was nonsignificant, retained residue and the removal of soil disturbance reduced oxidation and loss of SOM. This result is expected in low rainfall, single-cropping regions over a 6-yr cropping period; however, it is an encouraging step towards soil regeneration. Other studies have demonstrated that straw cover can result in significant increases in SOC (Li *et al*., 2007; Chen *et al*., 2008). Similar results were obtained in a study in north-western China study by McHugh *et al*. (2010), where SOC increased by 10.3% in the 0- to 10-cm layer. Furthermore, residues may reduce biological oxidation of organic C to CO_2 in NT soils (He *et al*., 2011), while frequent and excessive tillage and residue removal in TT plots had the opposite effect. Improved aggregate stability under PRB was also a consequence of increased SOM and reduced disturbance (Zhang *et al*., 2007). Tillage-induced changes in soil organic N are also directly related to changes in soil organic C (Zibilske *et al*., 2002). In TT, soil aggregates were broken down inhibiting O_2 diffusion, stimulating denitrification (Verachtert *et al*., 2009) and inducing waterlogging and increasing the incidence of denitrification. PRB was furrow irrigated and thus was not generally waterlogged for any period. Coupled with increased aeration and capillary porosity in PRB, the period of any denitrification episodes would be expected to be of short duration.

Frequent and excessive ploughing in TT led to the formation of plough pan in the lower soil profile after several years. Continuous PRB practice can result in a smaller soil bulk density by increasing organic C and aggregate stability and improving root growth (Karlen *et al*., 1994). This effect was apparent at the 20- to 30-cm soil depth in the last year of the experiment and supports the observation by He *et al*. (2007) that PRB reduced bulk density by 3.5% on silt loam soils.

Permanent raised beds had positive effects on pore size distribution and pore connectivity. Mean aeration porosity and improved K_s, particularly in 10- to 20-cm and 20- to 30-cm soil depths, improved significantly as compared with TT. This generally means that PRB soils will drain more readily after irrigation, thus as discussed previously will reduce waterlogging, episodes of denitrification and ultimately crop stress. The effects on capillary porosity were consistently positive, and even these marginal changes over the soil profile can increase plant available water and the ability of the plant to forage broadly and thus explains improved WUE and nutrient consumption. The shift in pore geometry towards macro size classes for PRB soils and the opposite trend towards microporosity of TT plots agrees with McHugh *et al*. (2009). These results are also consistent with those of Bai *et al*. (2008) and He *et al*. (2009) who demonstrated the negative effects of long-term TT on porosity and D_b. Compared with NT treatment, PRB produced more aeration porosity and less microporosity in 0- to 30-cm layer, and this improvement in soil pore size distribution in PRB treatment is consistent with bulk density results.

Permanent raised beds practice was effective in improving soil Ks, which is of considerable importance for the weakly structured, easily erodible soils of north-western China. The significant increase of K_s in PRB could be attributed to the increased water-stable aggregates and the number and continuity of aeration pores in nonwheeled and nontilled soils (McHugh *et al*., 2009). The reduction in TT K_s at 15- to 30-cm is indicative of a hard pan common under long-term TT.

In the flood irrigated plots, ca. 2100 m^3/ha h of water was used to ensure the complete area was flooded. However, under PRB, ca. 900 m^3/ha h was required to fill the narrow furrows. This reduced free water surface and evaporation losses. In addition, improved soil structure, as evidenced by aggregate stability, pore size distributions, K_s and porosity/bulk density results through PRB is an effective way to improve plant available water. The 5-yr mean soil water storage in 0- to 30-cm soil profile of PRB was 4.2% greater than on TT and consistently had the highest soil moisture at seeding. In combination with all of the above with soil cover, PRB had improved internal drainage and readily available water and reduced soil moisture loss. Thus, in arid north-western China improved soil properties and water content from PRB farming is of particular importance to sustainable production. Mean wheat yield was improved overall and was significant ($P < 0.05$) in 2 of 4 yr. Similar improvements in crop yields on PRB were reported by He *et al.* (2007) in China and Singh *et al.* (2009, 2010) in India. The significant improvement in WUE by 15.6–29.2% over TT at ca. 14 kg/ha/mm exceeded the well-watered nonplastic mulched results of Xie *et al.* (2005) at the same research station by 1–2 kg/ha/mm. However, Ma *et al.* (2005) and McHugh *et al.* (2010) demonstrated in the same area that 14–18 kg/ha/mm was achievable under raised bed farming, which shows that cropping potential for this study was equivalent to previous studies, but there was some room to advance the efficiency frontier. According to French & Schultz (1984), WUE for wheat was often below the potential of 20 kg/ha/mm because of the presence of pests, diseases and nutritional disorders. Therefore, further investigation of the constraints, other than those mentioned by French & Schultz (1984), to higher wheat productivity in this region is warranted.

Conclusions

Permanent raised beds farming in arid north-western China led to improvements in soil structure and crop yields. The benefits included significantly increased macro-aggregate stability, aeration and capillary porosity, and soil moisture. Consequently, PRB yields and WUE were improved by up to 4.0 and 21.0%, respectively, as compared with TT. However, PRB wheat production still did not achieve expected water-limited potential for the region. This study demonstrated that PRB farming is potentially a significant improvement over the current farming system in arid north-western China. From the perspective of sustainable development, continued study of the potential benefits of PRB on resource conservation is required for arid north-western China.

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