doi:10.2489/jswc.70.1.54

Permanent raised beds improved crop performance and water use on the North China Plain

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Abstract: Conservation Agriculture (CA) has been shown to improve cropping system performance around the world. However, there is limited research on this practice in the annual double cropping areas of the North China Plain and consequently limited uptake of the technology by the farming community. Data from a field experiment (2005 to 2011) conducted in Daxing, Beijing, China, were used to compare the effects of tillage practices, namely permanent raised beds (PRB), no-tillage (NT), and traditional tillage (TT) on growth, yield, and water use of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.). Results demonstrated that PRB increased soil water content (0 to 0.3 m [0 to 0.98 ft] depth; >8%) and reduced bulk density by 5.1%. Permanent raised bed soil temperatures were stabilized during winter wheat and summer maize production, compared to NT and TT treatments. Over the six years, PRB yields increased by >3% and gross production water use index (GPWUI) improved by >2.5% compared to TT, due to improved soil properties and crop performance. However, the impact of the changed management practices was not realized until the final two seasons, when yields improved by >6%. Accordingly, differences in farming profits, when viewed over the six years were intangible, but improved significantly by >20% in the final two seasons. These improvements in soil properties, yield, and water use are of considerable importance for food security and sustainable agriculture in the North China Plain; however, limited understanding of the farming system and extended timeframes required before realizing beneficial returns continue to limit widespread adoption.

Key words: conservation agriculture—loess—maize—water use-adoption—wheat

The North China Plain (NCP) was formed by the Yellow River flood plain and is an important agricultural production base. The plain, which includes the regions of Hebei, Henan, Shandong, Shanxi, Anhui, Jiangsu, Beijing, and Tianjin, has about 18,000,000 ha (44,500,000 ac) of farmland (18.3% of the national total) and represents 20% of the total food production in China (Sun et al. 2007). Food security for the large Chinese population is one of the country's highest priorities, but with only 7% of the global arable land and 22% of the world's population (NBSC 2005), increased inputs at the expense of natural resources appear to be the common solution for maintaining yields. Under traditional farming, single blade moldboard plowing is followed by numerous soil workings to produce fine tilth seedbeds. Thus repeated intensive tillage over time has had detrimental effects on soil structure (e.g., the formation of surface crusts and/or compaction). Structural degradation can have several additional consequences on these fragile loess soils, such as increased susceptibility to wind and water erosion (FAO 2001; He et al. 2004; Gao 2006), accelerated top soil loss, and lowered soil water storage capacity, resulting in stagnating yields and reduced water use efficiency (He et al. 2009). In the NCP, average precipitation is low (500 to 600 mm [19.7 to 23.6 in]), with annual potential evaporation exceeding 1,700 mm (66.9 in). Water remains a major constraint to production, generally because groundwater supplies are decreasing rapidly (Word Bank 2005). The total annual yield of irrigated winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) is about 15,000 kg ha^{-1} (13,399 lb ac^{-1}) (He et al. 2011).

In response to worldwide problems associated with traditional tillage, conservation agriculture (CA) has gradually emerged and its adoption is becoming so widespread that it is being hailed as a revolution. Somewhat surprisingly, given China's relatively strong track record in adopting new cropping technologies, there is little evidence in the literature on CA adoption in China (Wang et al. 2010). Currently CA adoption in China is less than 3% of the cropping area (FAO 2013), however, it could be that the area which is claimed to be using CA technology may in fact be counting practices that do not meet international standards for CA implementation (Wang et al. 2010). In recent years permanent raised beds (PRB) combined with the principles of CA, have been shown to improve soil productivity and reduce water requirements in Mexico, Australia, and the Indo-Gangetic Plains (Agustin et al. 2006; Tullberg et al. 2007). Permanent raised beds consist of furrow irrigation, planting crops on the top of raised-beds with low soil disturbance (<15% of the surface area), maximum soil cover with organic residues, and crop rotations (Govaerts et al. 2007). Furthermore, all equipment wheels are confined to furrows in PRB cropping systems (Singh 2009). The positive effects of PRB cropping systems on crop performance, yield, and water use have been demonstrated globally. For example,

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McHugh et al. (2009) (Australia) and Verhulst et al. (2011) (Mexico) indicated that planting on permanent beds increased soil available water capacity, improved water infiltration, and aggregate stability, when compared with conventional tilled crops without beds. Kukal et al. (2005) also determined that PRB were effective in increasing soil water content, reducing irrigation water requirement, and improving water use efficiency in rice (*Oryza sativa* L.)/wheat cropping systems on the Indo-Gangetic Plains. Holland et al. (2007) and Singh et al. (2010) on Loess soils in the Indian Punjab, also demonstrated that PRB were effective in increasing grain yield due to improved soil properties and reduced water logging. Beecher et al. (2006) on the other hand, found rice yield reductions of approximately 25% with permanent beds, compared with rice grown "on the flat" in New South Wales, Australia.

In China, studies have generally confirmed that PRB improve water use and increase soil water content, but with variable yield results in maize and wheat (Wang et al. 2004; He 2007; Wang et al. 2007; Luo et al. 2005; Zhang et al. 2011; Li et al. 2013). Despite the potential benefits, China's adoption of CA technology has only increased by 1.5% to 3% in recent years (FAO 2013). According to Wang et al. (2010), the reasons for the low adoption of conservation farming technologies are not straightforward; these include and are not restricted to, opportunity costs, land scarcity, policies, subsidies, etc. The authors concluded that the absence of locally based information on conservation technology and access to extension were key elements in affecting adoption rates. The research reported here addresses the gap in local knowledge and understanding of the temporal impact and magnitude of changed soil and plant residue management on sustainable cropping.

Materials and Methods

Site and Climatic Conditions. The field experiment was conducted from 2005 to 2011 in the Daxing (39°7' N, 116°4' E) district of Beijing on the NCP. The NCP has a semiarid climate, with the average annual rainfall of 526 mm (20.7 in), which is largely concentrated between June and September. Average annual temperature is 11.9°C (53.4°F) with 186 frost-free days. The dominant soil type, developed mainly from the Yellow River sediments, was an Entisol (subgroup Fluvents) (USDA 1978) with a silt-loam soil texture. Soil analysis of the top 0.10 m (0.33 ft) soil layer in 2005, determined bulk density was 1,320 kg m^{-3} (82.4 lb ft^{-3}); organic matter was 17.8 g kg^{-1} (1.78%); available N was 64.5 mg kg^{-1} (64.5 ppm); available P was 17.1 mg kg^{-1} (17.1 ppm); and pH was 8.2.

Experimental Design. For decades prior to 2005 the site had been farmed traditionally, which included total plant residue removal following harvest, moldboard plowing to a depth of 0.2 m (0.66 ft), repeated secondary tillage, and rolling and smoothing for seedbed preparation. Following the summer maize harvest in 2005, the entire site was ploughed to a depth of 0.3 m (0.98 ft) with a moldboard plow to remove any existing plow layers. The three treatments, PRB, no-tillage (NT), and traditional tillage (TT), were applied to 9 m (29.5 ft) wide by 90 m (295.2 ft) long field sections in a randomized block, with three replications. During the planting process, soil disturbance was low (~25% of the field area) under PRB and NT treatments, but under TT annual soil disturbance was >100% due to intensive plowing. Under the PRB treatment, there was >100% soil disturbance in the first year due to bed formation. In subsequent years, soil disturbance on the planting surface was ~25%, plus furrow and bed shoulder renovation. The agronomic schedule for the three treatments is shown in table 1.

Beds were formed with an overall width of 1.6 m (5.3 ft) (furrow center to center), which was suited to the local tractor axel width. All wheels of the tractor and implements were confined to the furrows during subsequent seasons. Furrow depth was 0.15 m (0.49 ft), and the bed surface width was 1.1 m (3.6 ft), which allowed for seven rows of wheat at 0.17 m (0.56 ft) spacing and two rows of maize at 0.6 m (1.97 ft) spacing on the bed surface. A no-tillage planter was used to sow the PRB and NT treatments throughout the experiment. Seeds were placed at a depth of approximately 0.05 m (0.16 ft) by using narrow-point openers fitted with press wheels. No-tillage and TT treatments were sown with the same planter, which solidly planted wheat in 0.20 m (0.66 ft) rows and maize in 0.60 m (1.97 ft) wide rows. All plant residue was retained in the field as standing stubble for PRB and NT treatments, whereas in the TT treatment it was manually removed.

Winter wheat (Jing-9428) was planted at a rate of 300 kg ha^{-1} (268 lb ac^{-1}), and summer maize (Huaiyan-10) at a rate of 30 kg ha^{-1} (26.8 lb ac^{-1}) in accordance with local customs. Nitrogen (N) fertilizer as urea ($CO[NH_2]_2$), $(NH_4)_2HPO_4$ and potassium chloride (KCl) (potassium oxide [K_2O] content: 60%) were applied during wheat planting, which provided 95 kg N ha^{-1} (84.9 lb N ac^{-1}), 75 kg phosphorus (P) ha^{-1} (67 lb P ac^{-1}), and 40 kg potassium (K) ha^{-1} (35.7 lb K ac^{-1}). Winter wheat received a further application of 50 kg N ha^{-1} (44.7 lb N ac^{-1}) at the first-node stage. A complete fertilizer

Table 1
Annual agronomic schedules for permanent raised beds (PRB), no-tillage (NT), and traditional tillage (TT) treatments.

Month	PRB	NT	TT
October	Forming beds and furrows, no-tillage wheat planting	No-tillage wheat planting	Manually removing all maize residues, plowing, wheat planting
Late November	Furrow irrigation	Sprinkle irrigation	Sprinkle irrigation
Late March	Furrow irrigation	Sprinkle irrigation	Sprinkle irrigation
Mid-May	Furrow irrigation	Sprinkle irrigation	Sprinkle irrigation
Early June	Wheat harvest	Wheat harvest	Wheat harvest
Mid-June	Bed and furrow renovation and no-tillage maize planting	No-tillage maize planting	Plowing, harrowing, leveling, maize planting
Late June	Weed controlling	Weed controlling	Weed controlling
July	Furrow irrigation	Sprinkle irrigation	Sprinkle irrigation
Late September	Maize harvest	Maize harvest	Maize harvest

($N-P_2O_5-K_2O$) was applied at the rate of 85 kg N ha^{-1} (75.9 lb N ac^{-1}), 45 kg P ha^{-1} (40.2 lb P ac^{-1}), and 40 kg K ha^{-1} (35.7 lb K ac^{-1}) during planting of summer maize. Roundup (glyphosate 10%) was used for weed control during the summer maize growing season.

In the well-developed agricultural areas of the North China Plain, i.e. Beijing and Tianjin, overhead sprinkler irrigation is common; therefore, sprinkler irrigated NT and TT treatments were compared with furrow irrigated PRB treatment. Three in-season irrigations were applied during winter wheat dormancy, jointing, and grain filling stages, which generally coincided with the soil water content in the 1 m (3.3 ft) soil profile reaching a deficit of 60%. Summer maize was irrigated at the jointing stage, when the soil water content in 0.8 m (2.62 ft) soil profile approached a deficit of 60%.

Soil Sampling. Soil samples were collected at the start of the experiment in 2005 and for each subsequent season until 2011. A soil core sampler, 0.15 m (0.49 ft) long and 0.054 m (0.177 ft) in diameter was used to sample at 0 to 0.15 m (0 to 0.49 ft) and 0.15 to 0.3 m (0.49 ft to 0.98 ft) soil depths. Three soil cores were randomly collected from the cropping zones of each replicated treatment to determine soil water content and bulk density.

Soil Bulk Density and Water Content. Average soil bulk density and gravimetric soil water content were determined from three 0.054 m (0.177 ft) diameter soil cores, which were initially weighed and oven dried at 105°C (221°F) for 48 hours. The soil samples were taken in 2005 and 2011 after summer maize harvesting and before winter wheat planting, which were essentially final and starting soil water contents for each cropping cycle. Volumetric water content was determined from the equation:

$$\theta_v = \theta_m \times (\rho_b \div \rho_w), \quad (1)$$

where θ_v is the volumetric water content, θ_m is the gravimetric water content, ρ_b is the soil bulk density, and ρ_w is the density of water.

Available Water Content. Available water content (AWC) was determined by pressure plate extraction (Klute 1986) by utilizing subsamples of the soil cores collected in 2011. The difference between the volumetric soil water content at the −30 and −1,500 kPa (−4.4 and −217.6 psi) was used to determine AWC.

Soil Temperature. Soil temperature was recorded at 0.05 and 0.10 m (0.16 and 0.33 ft) soil depths for three times per day at 08:00 ($T_{08:00}$), 14:00 ($T_{14:00}$), and 20:00 ($T_{20:00}$) on a daily basis. Mean daily soil temperature (T) was determined from equation 2 following the procedure described by Mao et al. (1998):

$$T = (2 \times T_{08:00} + T_{14:00} + T_{20:00}) \div 4. \quad (2)$$

Above and Below Ground Biomass. Aboveground biomass and root samples were taken from three 1 m^2 (10.8 ft^2) areas per treatment at jointing and filling stages for winter wheat and jointing and maturation stages for summer maize. Root samples were collected to a depth of 0.40 m (1.31 ft) (He et al. 2009). All samples were oven-dried at 65°C (149°F) to a constant weight to determine aboveground biomass and root dry weights.

Crop Yield and Gross Production Water Use Index. Three crop rows of 3 m (9.8 ft) in length were selected randomly from each treatment to determine maize and wheat yields. Grain yields were determined at 12% moisture content and over the total treatment area. In other words, nonplanted areas, i.e., the furrows in PRB, were included in the calculation.

Gross production water use index (GPWUI) is the gross amount of crop produced per unit volume of total water input. The total water input included irrigation, rainfall, and total soil moisture used. Although effective rainfall is typically used in water use efficiency and indices calculations, in this case total rainfall was used.

Total water applied (TWA) was calculated from a simplified water balance equation:

$$TWA = P + I - \Delta W, \quad (3)$$

where P is the total in-season rainfall, I is the applied irrigation, and ΔW is the change in stored soil water content in the soil profile (0 to 1 m [0 to 3.3 ft] depth) from seeding to harvesting. Irrigation water losses, such as, drainage below the root zone and evaporative losses are not included in the calculation of total water applied.

Gross production water use index was the ratio of grain yield to seasonal water applied:

$$GPWUI = \text{Total yield} \div \text{Total water applied}. \quad (4)$$

The cost of all operations and inputs (water, fuel, labour, materials, etc.) were recorded throughout the field trial, together with the value of the outputs per unit of yield.

Statistical Analysis. The Statistical Product and Service Solutions (SPSS) analytical software package was used for all of the statistical

Figure 1

Mean available soil water content to the depth of 0.30 m for permanent raised beds (PRB), no-tillage (NT), and traditional tillage (TT) treatments in 2011. Means within same soil depth followed by the same letter are not significant (p = 0.05).

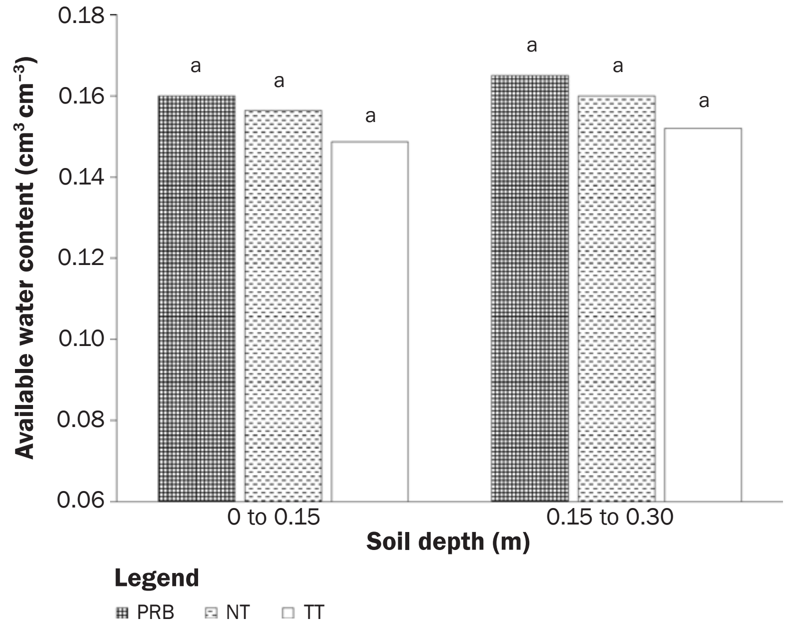
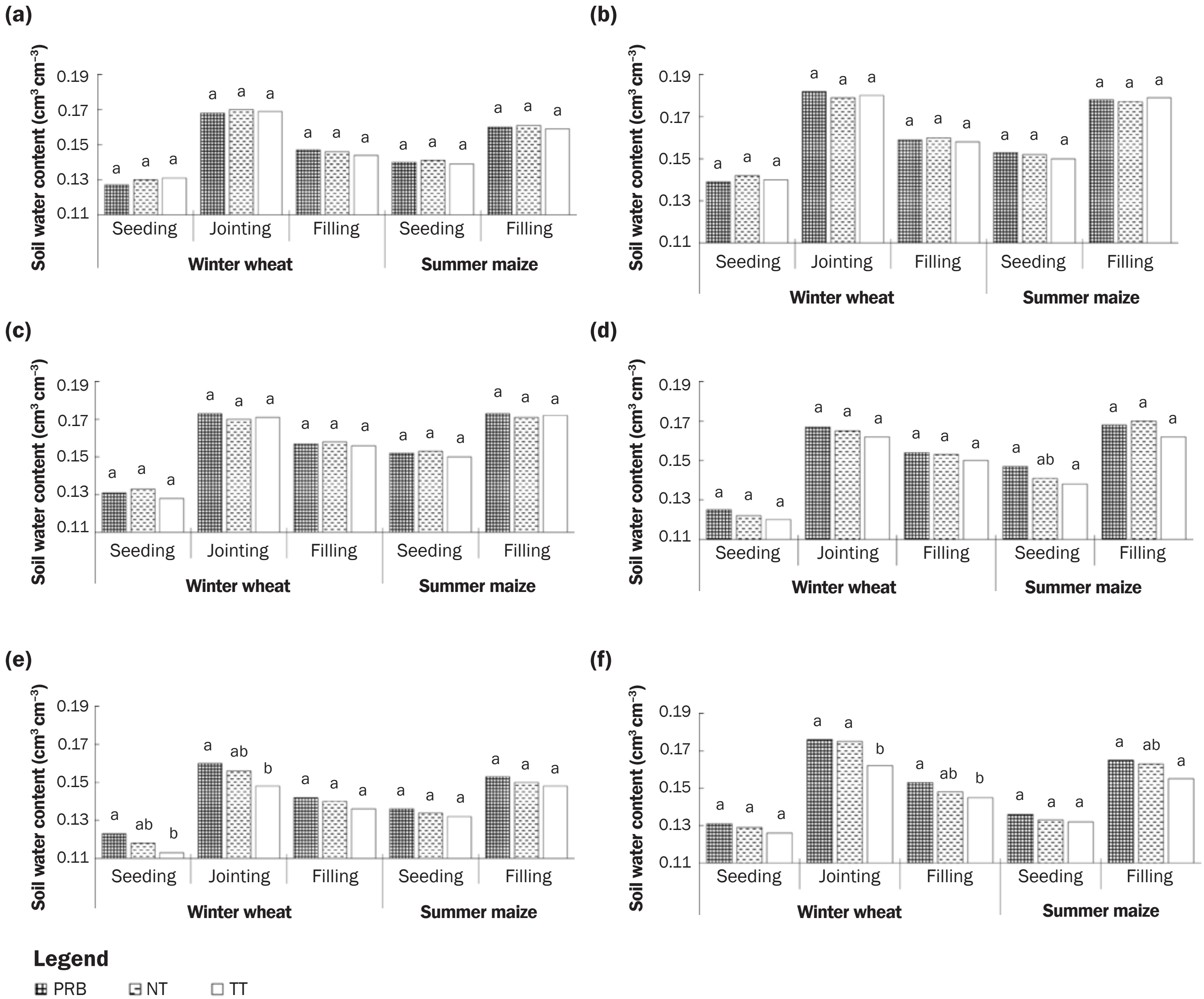


Figure 2

Mean soil volumetric water content to the depth of 0.3 m for permanent raised beds (PRB), no-tillage (NT), and traditional tillage (TT) treatments in key growing stages of winter wheat and summer maize from (a) 2005 to 2006, (b) 2006 to 2007, (c) 2007 to 2008, (d) 2008 to 2009, (e) 2009 to 2010, and (f) 2010 to 2011. Means within same key growing stage in the same year followed by the same letter are not significantly different (p = 0.05).



analyses. Mean values were calculated for each of the measurements, and analysis of variance (ANOVA) was applied to the data sets 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 (LSD).

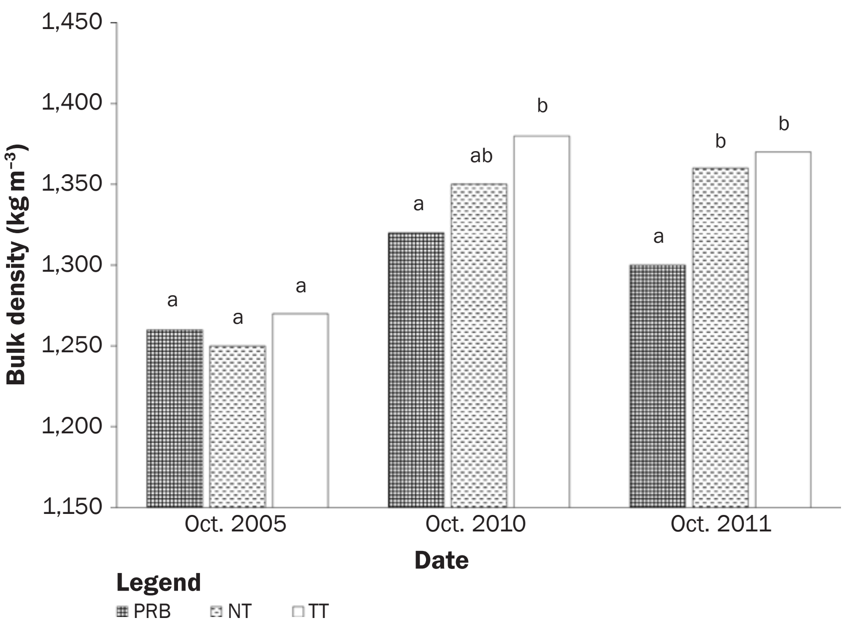
Results and Discussion

Available Water Content and Soil Water Content. Mean AWC to 0.3 m (0.98 ft) soil depth of PRB was not significantly different from the other treatments in 2011 (figure 1). However, there appeared to be a trend of improvement in AWC between the treatments in the range of 1.2% to 1.7%. Although the difference in AWC between PRB and TT treatments was marginal, an overall improvement of 7.3% was generally observed in the 0 to 0.15 m (0 to 0.49 ft) soil profile.

Mean volumetric soil water content at key growth stages for each crop was highly variable across the seasons from 2005 to 2011. At the onset of the experiment, soil water content to 0.3 m (0.98 ft) soil depth in the PRB treatment was slightly less than that of TT, probably due to moisture losses during bed-forming (figure 2). However, there was a consistent trend in soil water content improvement between treatments from 2005, which became increasingly obvious in the latter years. Although not significantly different in the first four seasons, the mean volumetric soil water content in the 0 to 0.3 m (0 to 0.98 ft) soil profile of PRB appeared the greatest. In the fifth season, soil water content in PRB treatment at seeding and jointing stages of winter wheat was significantly greater by 8.8% for NT and by 8.1% for TT ($p = 0.05$). Similar effects were found in 2010 to 2011,

Figure 3

Mean soil bulk density to the depth of 0.30 m for permanent raised beds (PRB), no-tillage (NT), and traditional tillage (TT) treatments in 2005, 2010 and 2011. The data were measured after summer maize harvesting and before winter wheat planting. Means in the same year followed by the same letter are not significantly different ($p = 0.05$).



when PRB in comparison to TT had significantly ($p = 0.05$) greater soil water content in the jointing and filling stages of winter wheat and filling stage of summer maize. Generally, the PRB treatment tended to have the greatest soil water content during the whole experimental period, while NT and TT treatments had intermediate and the least water contents, respectively.

Soil Bulk Density. After site preparation and bed formation, average soil bulk density in the 0 to 0.3 m (0 to 0.98 ft) profile was similar across all treatments at 1,260 kg m^{-3} (78.7 lb ft^{-3}) for PRB, 1,250 kg m^{-3} (78 lb ft^{-3}) for NT, and 1,270 kg m^{-3} (79.3 lb ft^{-3}) for TT (figure 3). However, after five seasons, bulk density between PRB and TT treatments was significantly different ($p = 0.05$) due to greater densification in TT. In 2010 (after summer maize harvesting) PRB average bulk density was 1,320 kg m^{-3} (82.4 lb ft^{-3}), 1,350 kg m^{-3} (84.3 lb ft^{-3}) for NT, and 1,380 kg m^{-3} (86.2 lb ft^{-3}) for TT. Permanent raised bed bulk density values were 2.2% less than NT and 4.3% less than TT treatment. In 2011, bulk density values in PRB treatment had continued to show less densification at 1,300 kg m^{-3} (81.2 lb ft^{-3}). By comparison this value was 4.4% less than NT and 5.1% less than TT values, as the bulk density in these treatments remained relatively similar to 2010 values.

Soil Temperature. In general, soil temperatures in PRB and NT treatments were marginally greater than that in TT treatment during winter wheat planting (October). However, these differences were not significant ($p = 0.05$) (results not shown). Soil temperature in relation to tillage practices in summer maize's seeding stage (June) showed an opposite trend to the results in October; again, treatments were not statistically different. Permanent raised bed temperatures appeared to fluctuate less in both cold and warm weather conditions.

Seedling Emergence. As indicated in table 2 during all years, seedling emergence of winter wheat from the two flat planting systems (NT and TT) was generally better than PRB treatment. However, this was inconsistent and largely rectified in later years. Generally, average seedling emergence for NT was 6.3% and for TT 5.3% greater than PRB throughout the experiment. Overall, the NT plots produced the greatest emergence for winter wheat seedlings.

Crop Growth. In the final year of the experiment winter wheat biomass in PRB and NT treatments was significantly improved on than that of TT. Permanent raised bed and NT treatments increased in mean shoot biomass by 5.8% and 4.6% during the jointing stage of 2005 to 2011, and by 5% and 4.1% during the filling stages of 2005 to 2011, respectively. More interestingly, by 2010 PRB root dry weight was significantly greater than TT at jointing by 11% and by 6.4% at grain filling.

Differences in summer maize root and shoot biomass followed a similar pattern (table 3). Compared with TT, PRB and NT demonstrated increased shoot biomass at the jointing stage by 1.7% and 2.8% and at maturation by 3.9% and 1.9% (2005 to 2011). Improvement for PRB and NT root dry weight was 6.6% and 2.7% in jointing stage and 4.1% and 2.7% at maturation, respectively, in comparison to TT treatment.

Crop Yield and Gross Production Water Use Index. Winter wheat and summer maize yields in the three treatments fluc-

Table 2

Winter wheat seedling emergence (plant m^{-2}) for three treatments during the experimental years. Data were measured 15 days after planting. In permanent raised beds (PRB) treatment, the m^2 in unit (plant m^{-2}) refers to the area of bed and furrow combined. Means within a column in the same year followed by the same letters are not significantly different ($p = 0.05$).

Treatments	Oct. 2005	Oct. 2006	Oct. 2007	Oct. 2008	Oct. 2009	Oct. 2010
PRB	483a	525a	495a	516a	493a	536a
NT	518b	545ab	537b	550b	521a	561a
TT	516b	558b	527ab	537ab	508a	550a

Notes: NT = no-tillage. TT = traditional tillage.

Table 3

Shoot biomass (kg ha^{-1}) and root dry weight (kg ha^{-1}) of winter wheat and summer maize for three treatments in key growing stages during the experimental years. Means within a column in the same year followed by the same letters are not significantly different (p =0.05). PBR = permanent raised beds. NT = no-tillage. TT = traditional tillage.

		Winter wheat				Summer maize			
		Jointing stage (Mar.)		Filling stage (May)		Jointing stage (July)		Maturing stage (Oct.)	
Years	Treatment identifiers	Shoot biomass	Root dry weight	Shoot biomass	Root dry weight	Shoot biomass	Root dry weight	Shoot biomass	Root dry weight
2005 to	PRB	3,900a	1,180a	14,900a	3,110a	12,400a	136a	6,670a	2,858a
2006	NT	4,400a	1,200a	15,500a	3,250a	12,800a	133a	6,880a	2,893a
	TT	4,200a	1,250a	15,000a	3,190a	12,700a	140a	6,740a	2,831a
2006 to	PRB	4,800a	1,410a	16,600a	3,150a	13,100a	169a	6,890a	3,105a
2007	NT	4,200a	1,350a	16,000a	3,120a	12,900a	163a	6,990a	3,279a
	TT	4,600a	1,470a	16,800a	3,220a	13,700a	158a	7,030a	3,186a
2007 to	PRB	5,000a	1,630a	18,200a	3,950a	13,900a	153a	8,090a	3,356a
2008	NT	4,800a	1,590a	18,500a	3,920a	14,200a	150a	7,760a	3,267a
	TT	5,300a	1,560a	17,700a	3,880a	13,300a	141a	7,830a	3,125a
2008 to	PRB	4,700a	1,530a	17,900a	3,860a	12,000a	135a	6,990a	2,689a
2009	NT	4,900a	1,480a	17,000ab	3,790a	12,500a	128ab	6,790a	2,573a
	TT	4,100a	1,400a	16,300b	3,580b	11,500a	120b	6,540a	2,496a
2009 to	PRB	4,300a	1,460a	16,300a	3,120a	12,200a	130a	5,990a	2,356a
2010	NT	3,900a	1,390ab	16,600a	3,060ab	11,900a	123ab	5,700ab	2,267a
	TT	3,600a	1,300b	14,300b	2,920b	11,500a	113b	5,430b	2,125a
2010 to	PRB	4,800a	1,530a	19,100a	4,040a	15,000a	148a	8,320a	3,588a
2011	NT	5,000a	1,480a	18,500ab	3,950a	15,200a	142a	7,980ab	3,436a
	TT	4,200a	1,420a	18,000b	3,780a	14,600a	145a	7,760b	3,485a

Notes: PBR = permanent raised beds. NT = no-tillage. TT = traditional tillage.

tuated widely from year to year (table 4). Within years the average winter wheat yields for PRB and NT were 3% greater than that of TT. However, significant yield advantage of PRB over TT treatment only appeared in the fourth and fifth cropping seasons (2008 to 2010). Similar results occurred for the summer maize production. Over the first three seasons average annual yield for PRB was 5,956 kg ha^{-1} (5,320 lb ac^{-1}), 5,820 kg ha^{-1} (5,199 lb ac^{-1}) for NT, and 5,665 kg ha^{-1} (5,060 lb ac^{-1}) for TT, which was 5.1% improvement by PRB over TT treatment yields. During the fourth and fifth seasons, PRB maize yields were significantly improved by 8% when compared to TT treatment. In the final sixth season the trend continued, but the treatments differences were not significant. Overall PRB maize yield tended to be the greatest in five out of six years, whereas winter wheat tended to have the greatest yields in three out of six years.

Gross production water use index was not significantly different for any year, generally because the difference in TWA between furrow irrigated treatment (PRB) and the sprinkler irrigated basin treatments was less than 10 mm (0.39 in) and yield differences were marginal for most seasons. Overall, mean GPWUI of PRB winter wheat was 2.5% greater than that in TT treatment, and the NT treatment was 4.2% greater than TT (table 4). Summer maize GPWUI improved by 4.9% for PRB and 3.7% for NT treatment in comparison to TT. Furthermore, in 2009 to 2010 cropping season, where yield differences were significant, GPWUI for wheat and maize was improved by 6.1% and 10.4%, respectively.

Economic Benefit. Annual input costs averaged US$1,034 ha^{-1} (US$418.50 ac^{-1}) for PRB, US$1,083 ha^{-1} (US$438.30 ac^{-1}) for NT, and US$1,270 ha^{-1} (US$514 ac^{-1}) for TT. The reduction in PRB and NT input costs was due to reduced mechanical operations and labor requirements (table 5). When these savings were aggregated over the six years PRB was 20.4% and NT was 13.9% more profitable than TT treatment. However, in the years 2008 to 2010, when yields were significantly different, income was US$2,214 ha^{-1} (US$896 ac^{-1}) for PRB, US$2,068 ha^{-1} (US$836.50 ac^{-1}) for NT, and US$1,707 ha^{-1} (US$690.80 ac^{-1}) for TT, which for PRB was a 23% improvement in profit for these particular years.

On the North China Plain, after winter wheat planting in October, maintenance of soil temperature is important for wheat growth, while in contrast, lower soil temperature is helpful for the growth of summer maize during high summer temperatures (He et al. 2009). In this study, PRB and NT treatments tended to increase average soil temperature by 0.3°C and 0.2°C (32.5°F and 32.4°F) following winter wheat planting, and decreased soil temperature by 0.4°C and 0.5°C (32.7°F and 32.9°F) after summer maize planting, which indicated that CA practices, particularly PRB farming, may have a positive effect on crop production compared with traditional farming methods. Our results were consistent with Wang et al. (2001) who also demonstrated positive temperature gains under CA practices on the North China Plain.

Soil bulk density is often used as an indicator of change in soil properties under different tillage practices (Kukal and Aggarwal 2003). Following six years of frequent and excessive plowing, soil compaction and the formation of a plow pan in traditional farming resulted in up to 5% higher bulk density than PRB treatment, even though PRB itself remained quite dense. Over a much longer timeframe than the length of this experiment, soil densification in PRB farming is

Table 4
Gross production water use index of winter wheat and summer maize for three treatments during the experimental years. Means within a column in the same year followed by the same letters are not significantly different ($p = 0.05$).

		Winter wheat				Summer maize			
Years	Treatment identifiers	I (mm)	TWA (mm)	Yield (kg ha^{-1})	GPWUI (kg ha^{-1} mm^{-1})	I (mm)	TWA (mm)	Yield (kg ha^{-1})	GPWUI (kg ha^{-1} mm^{-1})
2005 to	PRB	222	352.4	4,294a	12.2a	58	450.3	5,621a	12.5a
2006	NT	215	351.5	4,549a	12.9a	55	445.4	5,500a	12.3a
	TT	219	359.3	4,356a	12.1a	53	442.1	5,402a	12.2a
2006 to	PRB	189	368.0	4,986a	13.5a	38	475.8	6,097a	12.8a
2007	NT	180	360.6	5,015a	13.9a	33	470.0	6,100a	13.0a
	TT	177	359.0	5,036a	14.0a	36	476.7	6,145a	12.9a
2007 to	PRB	201	373.2	5,035a	13.5a	44	473.0	6,230a	13.2a
2008	NT	189	363.8	5,126a	14.1a	34	461.9	6,176a	13.4a
	TT	193	368.9	4,897a	13.3a	38	470.5	6,005a	12.8a
2008 to	PRB	242	377.0	4,357a	11.6a	67	426.8	5,889a	13.8a
2009	NT	240	375.2	4,289a	11.4a	60	422.3	5,687ab	13.5a
	TT	248	382.9	4,158a	10.9a	66	429.9	5,546b	12.9a
2009 to	PRB	247	379.2	4,412a	11.6a	70	422.8	5,700a	13.5a
2010	NT	240	374.2	4,287ab	11.5a	67	422.4	5,521a	13.1a
	TT	245	381.5	4,156b	10.9a	69	423.8	5,116b	12.1a
2010 to	PRB	231	393.6	5,056a	12.8a	68	446.9	6,197a	13.9a
2011	NT	214	382.6	4,876a	12.7a	62	439.7	5,934a	13.5a
	TT	220	387.0	4,711a	12.2a	66	441.7	5,775a	13.1a

Notes: I = applied irrigation. TWA = total water applied. GPWUI = gross production water use index. PRB = permanent raised bed. NT = no-tillage. TT = traditional tillage.

generally offset by increases in soil organic carbon (C), greater aggregate stability, and improved and varied root growth (Li et al. 2013). However, with limited crops in rotation, as in this case, this will be difficult to achieve. Our data agree with that of He et al. (2008), who demonstrated that PRB reduced mean bulk density by 5.8% on similar soils, also with limited crops in rotations, in Western China. In PRB farming wheel traffic effects are eliminated from the cropping zone, whereas NT field traffic can still be random across the field as in traditional farming systems. This could explain the differences in bulk density between the two conservation type treatments PRB and NT. Lower soil bulk density infers improvement in soil porosity, for oxygen and water storage, thereby encouraging root foraging and enhanced AWC. However, the soil amelioration process, according to McHugh et al. (2009) takes considerable time to become apparent, as was evidenced in this study as the increase in root biomass only occurring in the latter years of the experiment.

Conservation agriculture has also been associated with greater soil water content in other Australasian and northern Asian studies (Tullberg et al. 2007; He et al. 2011). The improvements shown in this experiment were pronounced, particularly after five or six years. Our data demonstrated that more water was available for germination and growth for winter wheat and summer maize when grown on permanent beds. These positive effects on soil water content are consistent with Yuan et al. (2005), who found that after two years soil water content in 0.8 m (2.62 ft) wide beds was 5.3% greater than that in traditional flat fields in Central China. Clearly, this result highlights the importance of soil and residue management to increase water infiltration and reduce soil degradation in the arid northwest areas as well as the higher rainfall zones of eastern China.

There are a number of aspects which can limit yield on PRB in the early years, such as the size of the cropping zone, which accounts for only about 70% of the total land area, low tilling, and thus limited edge effects. Additionally, nonuniform residue distribution on beds can influence a no-tillage planter's ability to place and firm the wheat seed and fertilizer at the appropriate depth, which in this case resulted in 5% to 6% reduction in seedling emergence under PRB. This problem has largely been solved by improved residue management at harvest and the availability of suitable planters in recent years.

Compared with flat planting systems, PRB generally had a positive effect on shoot biomass and root dry weight, because of increased moisture conditions, stable soil temperature, and improved soil properties, compensating for the shortfall in winter wheat plant density and accelerated crop growth, aspects that improved with time. Increased growth rate was largely responsible for improved crop yields under PRB, which was similar to that reported by Deng et al. (2006) and Lian et al. (2007) in northwest China. This study demonstrated that appropriate residue management was critical in facilitating planting and that retention of residues reduced soil surface exposure and favourably influenced underlying soil conditions.

The results reported here also demonstrated that PRB production was associated with trending GPWUI improvement and as with other parameters, notably appreciated with time, compared with NT and TT practices. The total water volume applied for in-season irrigation was based on a soil water content deficit of 60% over 1 m (3.3 ft) soil depth for winter wheat and 0.8 m (2.62 ft) soil depth for summer maize. Based on the slight improvement in AWC and improved soil moisture conditions under PRB, it would appear that furrow

Table 5
Economic benefit analysis for three treatments. The data for mechanical operation cost, water and yield are the mean values from 2005 to 2011.

Inputs, outputs, and farmer income	PRB Wheat	PRB Maize	NT Wheat	NT Maize	TT Wheat	TT Maize
Inputs						
Seed (US$ ha^{-1})	152	76	152	76	152	76
Fertilizer (US$ ha^{-1})	195	136	195	136	195	136
Herbicide (US$ ha^{-1})*	38		38		38	
Mechanical operation cost (US$ ha^{-1})	150	162	139	162	243	243
Water and labor (US$ ha^{-1})*	125		185		187	
Total (US$ ha^{-1})*	1,034		1,083		1,270	
Outputs						
Yield (kg ha^{-1})	4,837	6,052	4,765	5,866	4,616	5,709
Price (US$ kg^{-1})	0.31	0.33	0.31	0.33	0.31	0.33
Income (US$ ha^{-1})*	3,496		3,413		3,315	
Farmer income (US$ ha^{-1})*	2,462		2,330		2,045	

Notes: PBR = permanent raised beds. NT = no-tillage. TT = traditional tillage.
*Values for the whole treatment.

irrigation was as efficient as sprinkler irrigation, even though furrow irrigation is widely reported as a less efficient irrigation method. Furthermore, the crop yield in PRB was generally higher than that in NT and TT treatments; therefore it is probable that PRB could have produced an equivalent mass of grain with even less water. This would tend to indicate that the soil under PRB was providing enhanced functions that the other treatments could not provide.

In general terms, the loess soil under TT is renowned for low soil organic C, surface crusting, poor infiltration capacity, low water holding capacity, and high internal drainage. Reversing soil degradation through CA requires a considerable amount of time, favourable climatic conditions, and cropping intensification (biomass). The annual results tend to bear this out (PRB > NT > TT) in terms of general appreciation of improvements in soil bulk density (compaction), available soil water, yield, and water utilization. Conservation agriculture through the use of PRB is a suitable cropping system, which improves crop growth and water use on the North China Plain. However, adoption will be constrained because the agronomic benefits (GPWUI, AWC, and yield) are not immediately apparent in the short to medium term. The economic data clearly demonstrated that the annual return between farming methods used on a research site was nonsignificant until five or more seasons had passed; however, this was largely based on only reduced variable costs. McHugh (2010) also demonstrated that after four years of CA on-farm only marginal increases in profit were achievable when accounting for only variable and labor costs over the short term. Fixed and whole of farm business (system) costs need to be included to demonstrate the long-term profitability of CA farming.

Summary and Conclusions

Permanent raised beds farming is an effective farming method and has the potential to make an important contribution to agricultural productivity and sustainability in North China Plain. Although furrow irrigation is generally known to be less efficient, the better integrated positive effects of CA makes PRB irrigation more competitive, particularly in the economically underdeveloped areas of the North China Plain, where sprinkler irrigation could not be widely adopted. This study indicated that at least six years are required to start to realize the agronomic and economic benefits of CA. The results reported here demonstrate that CA is not a "silver bullet" approach, but rather a combination of technologies that must be adapted and managed to have an impact. If widespread adoption is to occur, more knowledge is required on this as a cropping system, which includes longer term trials across the various Chinese agroecological zones.

Acknowledgements

This work was financed by the National Natural Science Foundation of China (Grant No. 51205398) and the Program for Changjiang Scholars and Innovative Research Team in University of China (Grant No. IRT13039). Also, thanks to all the postgraduate students working in Conservation Tillage Research Centre, Ministry Of Agriculture, who provided their input to this study.

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