Permanent Raised Beds Improved Soil Physical Properties in an Annual Double-Cropping System

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ABSTRACT

As a typical semi-humid area with a wheat (*Triticum aestivum* L.)–maize (*Zea mays* L.) annual double-cropping system, Beijing has the lowest food production per capita and is suffering from severe soil degradation and low seedbed temperature in winter. This study evaluated the permanent raised bed (PRB) system in Beijing from 2005 to 2011 to investigate the effects of combining no tillage, residue cover, and controlled traffic with raised beds for improving soil properties. We found that the overall soil bulk density (0–30 cm) in PRB plots was significantly ($P < 0.05$) lower (by 12.4%) than that in traditional tillage (TT) plots, while the penetration resistance in the 10- to 20- and 20- to 30-cm soil layers of PRB plots was 18.2 and 26.1% lower ($P < 0.05$), respectively, than that of TT. The percentage of water-stable soil macroaggregates (>0.25 mm) in the PRB plots was 89.8% ($P < 0.05$) higher than in the TT plots, while the soil temperature was approximately 1.3 and 1.0°C higher under TT at the 5- and 15-cm depths, respectively, in winter. With these improvements, yields of PRBs appeared to have an increasing trend compared with no-till and TT treatments.

China has 9% of the world's arable area and 6% of the world's freshwater resources but has to feed 21% of the world's population (Chen, 2009). Recently, the Chinese central government has suggested that the country should produce another 50 million Mg of grain per year by 2020 due to the expected increase in the population (Peng, 2011). The land used for cropping has decreased from 0.18 ha per capita in the 1950s to <0.1 ha per capita today. Apparently, improvement of yield or land productivity is the major contributor to the increase in food production per capita (Zhang, 2011). As the capital of China, Beijing has the lowest food production per capita due to the highest population density but medium production quantity (Fig. 1). The agricultural production in Beijing is largely dependent on fertile soils, natural climate conditions, and management. Soil structural degradation, however, is a widespread phenomenon in this region (Wang et al., 2006). Some research on no-till management have shown that it can restore deteriorated soil structure (Li et al., 2007; Zhang et al., 2009; Yao et al., 2009). The mulch cover in this system definitely reduces not only sand erosion in Beijing (He, 2007; Zhou, 2001) but also the impact of solar radiation by acting as a physical barrier, which results in lower soil temperatures than the bare soil. Beijing is located in the northern part of China, with an annual mean temperature of 11.0 to 12.0°C, and growing degree days are limited during the year. Increasing the soil temperature of the seedbed is beneficial for the winter plants the region of Beijing, where a wheat–maize annual double-cropping system is practiced. Raised beds have the effect of restoring the soil temperature. To make use of the advantages of no-till and raised beds, adoption of permanent raised beds is essential (Hari Ram et al., 2011).

Combining no-till, permanent bed planting, and furrow irrigation with controlled traffic, the PRB system has proven itself to be an effective method to improve soil properties. The developments of PRB technology in different areas are summarized below.

In arid and semiarid areas, Verhulst et al. (2011) evaluated the effects of tillage and residue management in an arid, irrigated bed planting system with a wheat–maize rotation in an annual double-cropping system and stated that PRB seemed to be the most sustainable option. Devkota et al. (2013) compared permanent beds and residue retention with conventional tillage combined with different levels of residue cover and N fertilization in irrigated arid lands under a cotton (*Gossypium hirsutum* L.)–wheat–maize rotation system and found that the former can increase water productivity in wheat by 27% and in maize by 84% while increasing yields of wheat by 12% and maize by 42%. A PRB system also significantly increased soil water content, soil temperature, water use efficiency, soil structure, and spring wheat yield in arid northwestern China under a spring wheat–maize rotation system compared with TT and no-till (He et al., 2008, 2012). In another study, the PRB planting system reduced operational costs up to 40% and enhanced physical and biological soil quality parameters (compared with traditional ridge beds) in the coarse, sandy clay soils

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Abbreviations: NT, no-till; PRB, permanent raised bed; TT, traditional tillage.

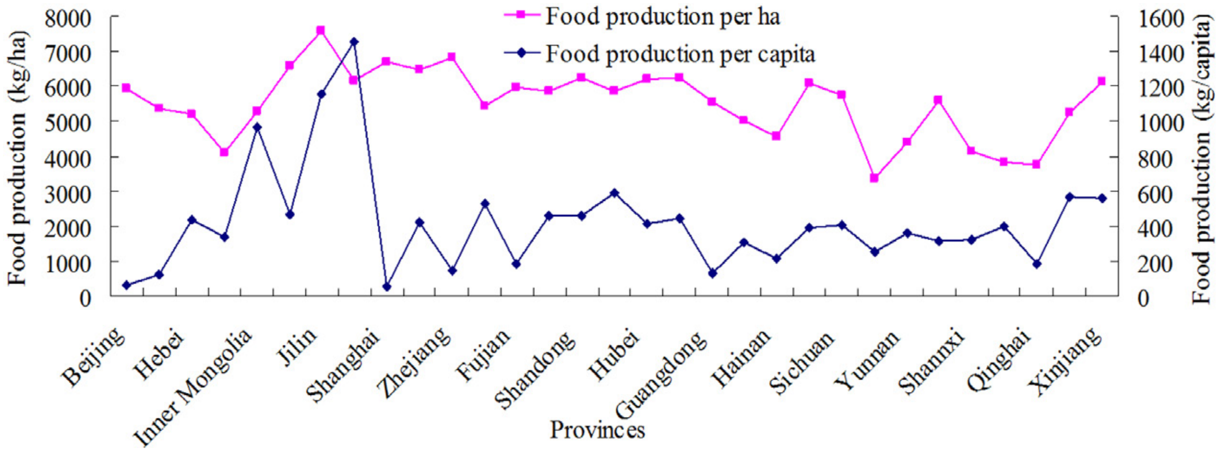

Fig. 1. Distributions of food production per capita and per hectare in different provinces (data from the National Bureau of Statistics of China).

of semiarid northwestern Mexico under a wheat–maize annual double-cropping system (Limon-Ortega et al., 2002, 2006). A PRB system also reduced waterlogging and increased grain yields in monoculture systems of Western Australia (Bakker et al., 2010a, 2010b). Limon-Ortega and Sayre (2012) confirmed the effects of rainfall on wheat yields in a PRB wheat–maize rotation system in the highlands of Mexico and pointed out that wheat grain yield was mostly determined by the amount and distribution of rainfall during the cropping season. Panettieri et al. (2013) investigated the effect of permanent bed planting combined with controlled traffic on soil chemical and biochemical properties under irrigated semiarid Mediterranean conditions with a maize–cotton rotation system. Ortega (2011) evaluated the effects of using permanent raised beds with different furrow diking treatments and N fertilizer application timing in a wheat–maize rotation. In the cold and semiarid Northeast China with a spring maize cropping system, He et al. (2010) showed that a PRB system increased the mean soil temperature and water use efficiency compared with traditional plowing and no-till.

In semihumid and humid areas, Hari Ram et al. (2011) compared no-till, mulched, raised beds with seven other treatments in an irrigated maize–wheat system in northwestern India, showing the advantages of the raised bed system in increasing soil temperature, water use efficiency, and other characteristics. Naresh et al. (2012) tested the effects of PRBs and tilled raised beds with different residue management under irrigated conditions in western Uttar Pradesh under an alternative wheat production system and found higher crop yield and aggregate stability with the PRB system. The adoption of PRBs for a pigeon-pea [*Cajanus cajan* (L.) Huth]–wheat annual double-cropping system in the humid Indo-Gangetic Plain showed higher wheat–pigeon-pea productivity, irrigation application efficiency, and water use efficiency compared with traditional flat beds (Singh et al., 2010). A PRB system also increased the soil water content and water use efficiency in a rice (*Oryza sativa* L.)–wheat cropping system in the Indo-Gangetic Plain (Connor et al., 2003; Kukal et al., 2005; Choudhury et al., 2007). The positive effects of using bed planting systems with furrow irrigation have also been confirmed in Shandong province of China for winter wheat in semihumid areas with a wheat–maize rotation annual double-cropping system (Wang et al., 2004).

Currently, a PRB system is mainly used in arid and semiarid areas under monoculture cropping systems or in humid and semihumid areas with abundant water resources. Beijing, as a semihumid region, does not have abundant water to irrigate its wheat–maize annual double-cropping system (Zhou, 2001). Therefore, in this study, we investigated the effects of a PRB system on soil physical properties in semihumid areas under a wheat–maize annual double-cropping system. No-till (NT) and TT were also introduced for comparison.

MATERIALS AND METHODS

Site Description

The experiment was conducted in the Daxing District (39°7′ N, 116°4′ E, 45 m asl) in the southern part of Beijing from 2005 to 2011. The average annual temperature in this area is 11.9°C, with 186 frost-free days per year. During the experiment, the mean annual rainfall was 518 mm (Fig. 2a), and >70% of the rainfall occurred from June to September. The distribution of the mean monthly rainfall from 2005 to 2011 was close to the overall mean values (Fig. 2b). The winter wheat and summer maize double-cropping system is the most common cropping system in this region. The soil in the experimental plots was classified as a Fluvent under the U.S. soil taxonomy (Soil Survey Staff, 1978) and had a bulk density of 1.33 g/cm^3 and a pH of 8.0 in the upper 30-cm layer (as measured in 2005 before plowing the entire experimental plot).

Experimental Design

The experiment was designed as three randomized blocks. Each block consisted of three plots, one for each treatment. Each plot was 9 m wide by 90 m long. In 2005, at the beginning of the experiment, each plot was plowed to a depth of 30 cm using moldboard plow followed by rotary tillage, harrowing, and leveling to thoroughly mix the soil, thus ensuring uniform soil conditions. Three treatments, i.e., TT, NT, and PRB, were applied simultaneously.

The TT treatment combined removing residues, tillage, random traffic, and a flat field. All the crop residues after harvesting the crop were manually removed. The seedbed was prepared by traditional plowing to a depth of 20 cm and conventional tillage practices. The fertilizer was incorporated into the soil of the flat field to a 10-cm depth. Wheat was sowed in early October and maize sowed in mid-June (at a 5-cm depth) and were mechanically harvested in early June and early October, respectively.

The NT treatment included residue cover, no tillage, little random traffic, and a flat field. Wheat was planted in early October

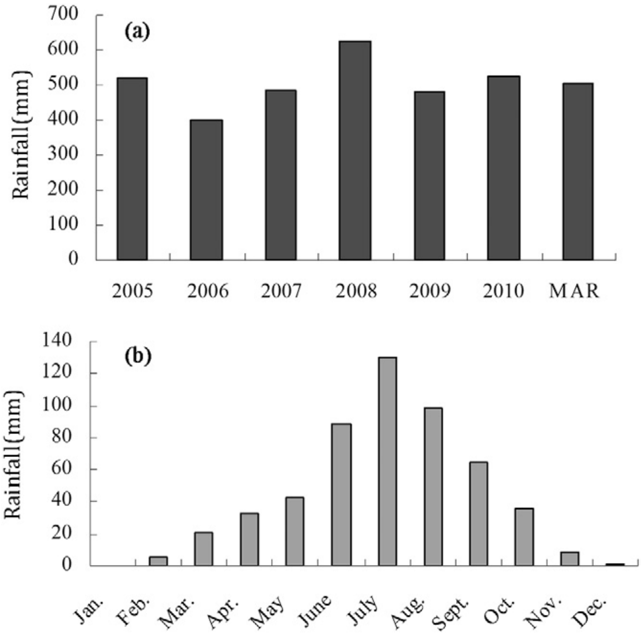

Fig. 2. Annual rainfall and distribution of mean monthly rainfall at Daxing during the experiments: (a) annual rainfall and mean annual rainfall (MAR); and (b) distribution of mean monthly rainfall.

and maize in mid-June on a flat field. Winter wheat and summer maize were mechanically harvested in early June and early October, respectively. Approximately 20-cm-high standing stubble together with all the wheat or maize straw chopped by the harvester were left on the field surface to serve as a mulch cover.

The PRB treatment consisted of PRB furrows and PRB beds. The PRB beds consisted of residue cover, no tillage, controlled traffic, and raised beds. Wheat was planted in early October and maize in mid-June on the beds and harvested by combine harvester in early June and early October, respectively. All the chopped wheat and maize straw was randomly left on the field surface together with the high standing stubble.

In the NT and PRB treatments, planting and fertilization were performed simultaneously through the previous plant residue. Each year, maize and wheat were planted 2 to 3 d later in the TT than the NT and PRB treatments due to the additional tillage operations needed for the seedbed preparation. The planting beds of the PRB treatment were formed in 2005 with a furrow-to-center width of 160 cm to fit the tractor as well as the harvester wheels; the furrow depth was 15 cm, while the width of the bed surface was 120 cm. Consequently, the land use efficiency was 75%. Eight rows of wheat and three rows of maize were planted at 17- and 60-cm spacing, respectively, on the PRB beds. In the NT and TT treatments, the wheat and maize were uniformly planted in each plot with spacing of 20 and 60 cm, respectively, with a land use efficiency of 100%.

In Beijing, farmland holders just own small-scale lands. High seeding and fertilizer rates were regularly used to obtain higher yields. The winter wheat (Jing-9428) and summer maize (Huaiyan-10) were planted at seeding rates of 300 and 30 kg/ha, respectively. The recommended N rates for wheat is 160 to 180 kg/ha and 150 kg/ha for short-duration maize on small-scale lands (Ministry of Agriculture and Water Resources, 2000). All treatments included an equal amount of fertilizer for each treatment as the basal N, P, K fertilizer at planting time: 145 kg/ha of N, 75 kg/ha of P, and 30 kg/ha of K for winter wheat; 80 kg/ha of N, 45 kg/ha of P, and 40 kg/ha of K for summer maize. An additional 60 kg/ha of N was applied at the first-node stage for winter wheat. Glyphosate [10%, *N*-(phosphonomethyl)glycine] was used for weed control during the summer maize growing season.

Irrigation was essential for all three treatments. To use the water efficiently, sprinkler irrigation was used in the TT and NT flat planting systems. Furrow irrigation was used in the PRB planting system. In each of the three treatments, every plot was irrigated four times during the growth period of winter wheat and only once during the growth period of summer maize. In other words, wheat was irrigated in late November, late March, mid-April, and mid-May, while maize was irrigated in mid-July. The same amount of irrigation water was applied each time for the three treatments: 60 cm in late November and late March, 80 cm in mid-April, 100 cm in mid-May, and 80 cm in mid-July.

Measurements

Soil Sampling and Preparation

Soil sampling was performed for the TT, NT, and PRB treatments in 2011 immediately after wheat harvest and before maize seeding in early June. In the TT and NT treatments, undisturbed core samples were randomly collected in triplicate from the plots. For the PRB treatment, undisturbed core samples were also randomly collected in triplicate from the beds of PRB plots. All undisturbed core samples consisted of three subsamples taken at the 0- to 10-, 10- to 20-, and 20- to 30-cm depths and were used to measure the soil bulk density and water content. A set of three subsamples taken at the same depth and representing each one of the three treatments was used as a single composite sample to measure the soil water-stable aggregation. Undisturbed core samples were also collected from the 0- to 100-cm soil depth in three plots of the TT, NT, and PRB treatments during the crop growth period at the beginning of the experiment (2005–2006) to detect changes in the soil bulk density and water content. The sampling was conducted before irrigation at each key stage of crop growth. All the undisturbed core samples were taken by using a manual stainless steel core sampler (50.4-mm diameter by 120-mm length) and then stored in aluminum boxes (100 cm^3).

Soil Bulk Density and Water Content

Each soil core sample, sealed in the aluminum box, was weighed wet, then dried in an oven at 105°C for 48 h, and finally weighed again to determine the bulk density (Blake, 1965). The gravimetric water content was multiplied by the soil bulk density to obtain the volumetric water content. All measurements were conducted in triplicate.

Penetration Resistance

Soil penetration resistance was measured in 2011 in early June using an SC900 Field Scout soil compaction meter (Spectrum Technologies) (He et al., 2012). Three points were randomly chosen in three plots of each flat field of TT and NT. The points in the PRB treatment were chosen on the PRB beds. The instrument was manually inserted to the 30-cm depth with a velocity of ~6 cm/min and kept vertical to the field surface at the selected points. The data were recorded at every 2.5-cm interval. The measurements were not corrected for soil moisture content because real field conditions were considered.

Soil Water-Stable Aggregation

Each composite sample was air dried for 24 h in the laboratory, then gently broken apart and passed through an 8-mm sieve. Clods and aggregates >8 mm were discarded. Each composite sample was divided into four parts to repeatedly test the aggregate stability. The distribution of water-stable aggregates was then determined by placing the soil samples on a nest of sieves (Tisdall and Oades, 1979). The soil was weighed first to record the total weight. The sieves containing the soil samples were immersed directly in water and moved up and down 35 mm slowly and steadily at 30 cycles/min for 6 h without mixing the soil. The percentage of water-stable aggregates >2, 2 to 1, 1 to 0.5, 0.5 to 0.25, 0.25 to 0.106 and <0.106 mm were calculated by drying and weighing the soil aggregates remaining on each sieve. The proportions of different aggregate sizes were calculated by dividing by the total weight (Oades and Waters 1991). Macroaggregates were taken as those aggregates >0.25 mm, while microaggregates as those <0.25 mm.

Soil Temperature

The soil temperature was measured using Model 125 WatchDog dataloggers with external soil temperature thermocouples. The thermocouples have the ability to record soil temperatures with an accuracy of ±0.2°C. Soil temperatures were recorded every 3 d at the 5- and 15-cm soil depths at 0800 h from 10 Oct. to 9 Nov. 2010 during the growing season of winter wheat. In each plot, nine thermocouples were placed in the row at the 5- and 15-cm soil depths (three for each soil depth) for all planting areas of the treatments. The dataloggers were mounted on fiberglass poles 1 m above the ground.

Yield

Wheat and maize yields were determined by manually harvesting five areas of 1.6 by 1 m taken randomly from the plots representing each of the three treatments; the moisture level at harvest time was 12%. The grains were then threshed and air dried.

Equipment

Bed Former

The beds of the PRB system were formed at the beginning of the experiment by using a 1QL-70 moldboard bed former designed by the China Agricultural University attached to a 65-horsepower tractor with two opposing moldboards; a leveling blade and a roller completed the work of forming and pressing the beds. The relative horizontal position of the tractor and bed former was adjusted by a center-position adjusting unit, and different bed heights could be achieved by using the depth-control wheel.

Seeder

Maize and wheat under the PRB treatment were sown using a PRB no-till wheat–maize seeder developed by the China Agricultural University (Fig. 3a and 3c) matched with a 65-horsepower tractor. This seeder could successfully pass through the residues due to its high frame as well as its double beam, which prevented the openers from blockage. The seeder could plant seven rows of wheat at 17-cm spacing and two rows of maize at 60-cm spacing. Seed and fertilizer were placed at a depth of ~5 and ~10 cm respectively, and were firmed by metal press wheels. This machine could also complete bed renovation and bed planting and firming in one single operation.

The strip-chop no-till wheat–maize seeder developed by China Agricultural University (Fig. 3b and 3d) attached to a 65-horsepower tractor was used for the planting of both wheat (12 rows) and maize (four rows) in the NT treatment (Yao et al., 2009). Two flail blades rotating at 1200 to 1400 revolutions/min were placed beside each opener to chop the residues without disturbing the soil. The metal press wheels were used to firm seeds and fertilizer at a depth of 5 and 10 cm, respectively. In the TT treatment, wheat and maize were planted using the local 12-row and four-row seed drill after plowing the field with a moldboard plow.

Data Analysis

Mean values were calculated for each of the variables, and ANOVA was used to assess the treatment effects on the measured variables. When ANOVA indicated a significant F value, multiple comparisons of mean annual values were performed by the LSD method. In all analyses, a probability of error <5% ($P < 0.05$) was considered statistically significant. The SPSS analytical software package (version 13.0) was used for all statistical analyses.

RESULTS

Soil Bulk Density

In 2006, the soil bulk density in the top layers (0–10 and 10–20 cm) of the PRB treatment was 6.1 to 7.7% lower (significant at $P < 0.05$) than that of TT treatment (Table 1). By 2011, the mean soil bulk density in the 0- to 30-cm soil layer of the PRB and NT plots was 12.4 and 6.8% lower, respectively ($P < 0.05$), than the TT plots. In addition, the PRB treatment had significantly ($P < 0.05$) lower soil bulk density in the 0- to 10- and 20- to 30-cm soil layers than TT by 14.3 and 12.8%, respectively. The significant difference between treatments appears largely to stem from an increase in bulk density under TT not necessarily an improvement under PRB. No tillage, controlled traffic, mulch, and raised beds have significant effects in reducing the soil bulk density.

Penetration Resistance

The three treatments had similar trends in penetration resistance. Their values increased rapidly in the 0- to 20-cm soil layer but changed only slightly in the 20- to 30-cm layer. The PRB treatment showed a significantly ($P < 0.05$) lower level of penetration resistance than TT in the 17.5- to 30.0-cm soil layer, while NT had a significant ($P < 0.05$) lower level only in the 22.5- to 25.0-cm soil layer compared with TT. More precisely, resistance to penetration in the PRB plots was found to be 18.2 and 26.1% lower ($P < 0.05$) than under TT in the 10- to 20- and 20- to 30-cm soil layers, respectively (Fig. 4). The ANOVA of the results showed that no tillage and a mulch covering appeared to have nonsignificant effects on reducing penetration resistance.

Soil Water-Stable Aggregates

The mean percentage of macroaggregates (>0.25 mm) in the 0- to 30-cm soil layer of the PRB and NT treatments was 89.8 and 71.1% higher ($P < 0.05$), respectively, than in the same layer of the TT treatment (Table 2). The percentage of water-stable aggregates of the largest size class (>2 mm) in PRB plots at depth of 0 to 10, 10 to 20, and 20 to 30 cm was approximately twice the percentage under TT but significant only below the 10-cm soil layer. The comparison between NT and TT did not produce significant results until a depth of 20 cm. In contrast, the soil in all layers of the

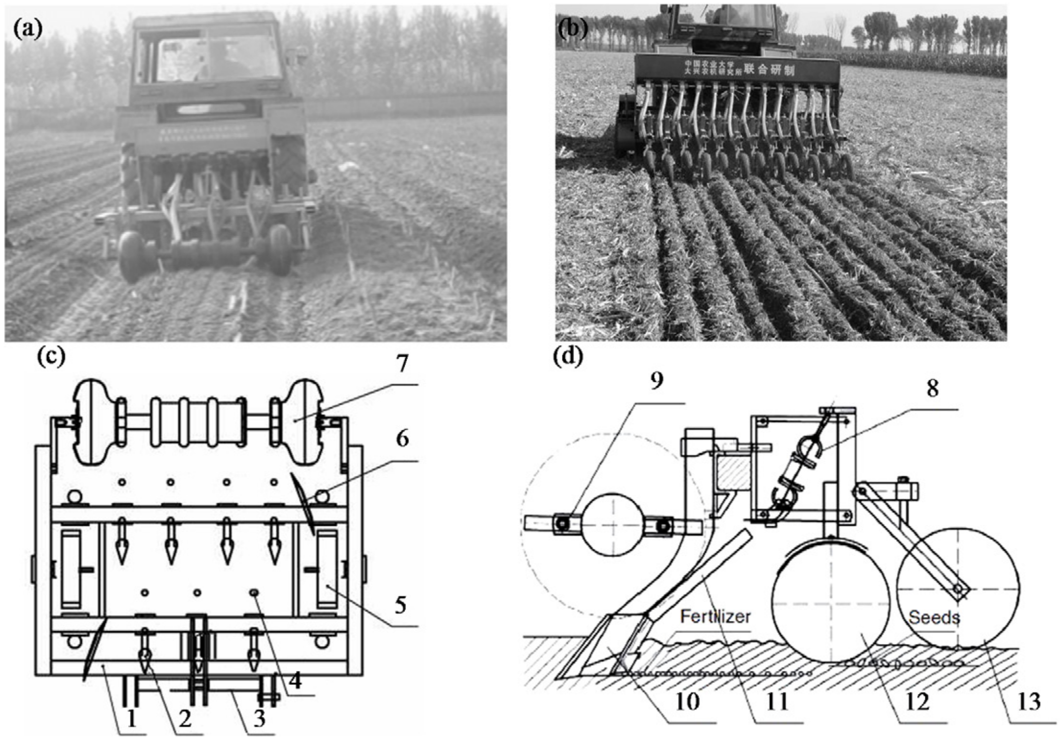

Fig. 3. (a) Permanent raised bed (PRB) no-till wheat–maize seeder, (b) strip-chop no-till wheat–maize seeder, (c) schematic of the PRB no-till seeder, and (d) schematic of the strip-chop seeder: 1. frame; 2. opener; 3. three-point hanging bracket; 4. seed pipe; 5. travel wheel; 6. bed-renovating device; 7. combined press device; 8. floating unit support; 9. strip-chopping rotary coulter unit; 10. tine opener; 11. fertilizer tube; 12. double-disk opener; 13. press wheel.

TT treatment had the highest percentage of water-stable aggregates of the smallest size class (<0.106 mm) compared with both the PRB and NT treatments. In this experiment, no tillage, mulch covering, controlled traffic, and raised beds showed nonsignificant effects on aggregation.

Soil Water Content

The advantages of PRB and NT in saving water were unobservable or even negative at the beginning of the experiment (November 2005–May 2006) (Table 3). Only half a year later, however, some positive results began to show up in the PRB and NT treatments. During the growing period of summer maize, the mean soil moisture in the 0- to 100-cm soil layer of the PRB and NT plots appeared to increase on average compared with the soil moisture in the TT plots. During the maturing season of summer maize (September 2006), the PRB plots had significantly higher ($P < 0.05$) soil water contents in the 30- to 60- and 60- to 100-cm soil layers.

By June 2011, the final effects of the PRB and NT treatments on water saving showed up in the 0- to 30-cm soil layer as well (Fig. 5). The mean soil volumetric moisture content (0–30 cm) in the PRB and NT plots was 59.3 and 56.4% higher, respectively, than the TT plots ($P < 0.05$). In the 0- to 10-cm layer, the PRB and NT plots showed 90.7 and 95.4% higher values (significant at $P < 0.05$) of soil volumetric water content. No tillage, residue covering, and raised beds probably had nonsignificant effects on increasing the soil water content.

Table 1. Mean soil bulk density in 0–30 cm soil depth after the summer maize harvest in 2006 (a) and winter wheat harvest in 2011 (b).

	Soil bulk density					
	2006			2011		
Depth	TT	NT	PRB	TT	NT	PRB
cm	g/cm^3					
0–10	1.33 a†	1.27 ab	1.22 b	1.46 a	1.38 ab	1.25 b
10–20	1.43 a	1.32 ab	1.28 b	1.56 a	1.43 a	1.40 a
20–30	1.45 a	1.44 a	1.42 a	1.51 a	1.41 ab	1.32 b
Mean	1.40 a	1.34 a	1.31 a	1.51 a	1.41 b	1.32 b

† Means for the same soil depth followed by the same letter are not significantly different ($P > 0.05$).

Soil Temperature

The soil temperature for the 5- and 15-cm soil depths from 10 October to 9 November for the TT, NT, and PRB treatments in 2010 is presented in Fig. 6. The 30-d mean soil temperatures at the 5- and 15-cm depths were 7.9 and 8.5°C under PRB, 7.6 and 8.4°C under NT, and 6.6 and 7.5°C under TT. After winter wheat planting, the mean soil temperature in the soils under PRB and NT was approximately 1.3 and 0.9°C greater than under TT at the

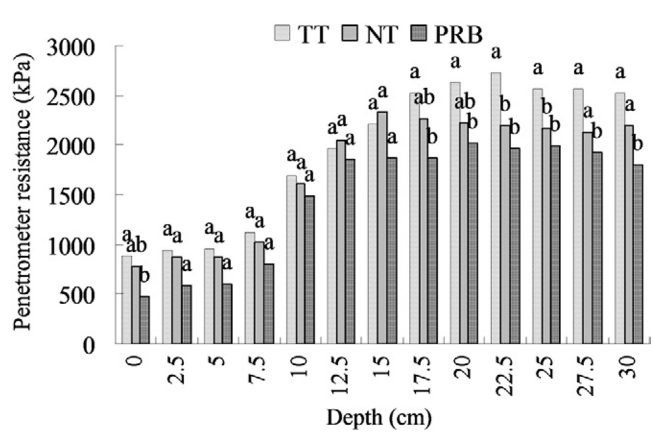

Fig. 4. Penetration resistance in the 0- to 30-cm soil depth for three treatments in 2011: traditional tillage (TT), no-till (NT), and permanent raised beds (PRB).

Table 2. Soil stable aggregate size classes for traditional tillage (TT), no-till (NT), and permanent raised bed (PRB) treatments in the 0- to 30-cm soil depth in 2011.

Depth	Treatment	Aggregate size distribution >2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	0.25–0.106 mm	<0.106 mm	Macroaggregates (>0.25 mm)	Microaggregates (<0.25 mm)
cm		%							
0–10	TT	2.13 a†	6.06 a	5.59 a	5.33 a	13.08 a	66.91 a	19.01 a	79.99 a
	NT	5.34 b	4.29 a	5.67 a	17.60 a	35.45 b	31.66 b	32.89 a	67.11 a
	PRB	6.60 b	9.79 b	8.09 a	8.95 a	12.83 a	53.73 a	33.44 a	66.57 a
10–20	TT	2.90 a	3.57 a	4.17 a	5.53 a	12.34 a	72.08 a	15.59 a	84.42 a
	NT	4.44 ab	5.68 a	5.22 a	20.23 b	36.90 b	27.55 b	35.56 b	64.44 b
	PRB	6.71 b	5.72 a	4.05 a	14.98 ab	11.07 a	57.47 a	31.46 b	68.54 b
20–30	TT	3.56 a	4.07 a	3.09 a	4.10 a	11.90 a	76.86 a	13.81 a	88.76 a
	NT	4.70 a	4.19 a	3.52 a	4.70 a	21.06 b	61.84 ab	17.10 a	82.90 a
	PRB	7.93 a	8.58 b	8.43 b	13.96 b	17.56 ab	43.55 b	38.89 b	61.11 b
0–30	TT	3.20 a	4.24 a	4.25 a	4.79 a	12.44 a	71.95 a	16.47 a	84.39 a
	NT	4.49 ab	4.72 a	4.80 a	14.17 b	31.47 b	40.35 b	28.18 b	71.82 b
	PRB	6.41 b	8.03 b	7.52 b	9.30 ab	13.82 a	54.92 b	31.26 b	68.74 b

† Means within a column for the same depth followed by the same letter are not significantly different ($P > 0.05$).

Table 3. Soil volumetric water content to the depth of 100 cm for three treatments, traditional tillage (TT), no-till (NT), and permanent raised beds (PRB), in the winter wheat–summer maize growing period from 2005 to 2006.

Growth stage	Depth	TT	NT	PRB
	cm	%		
		Winter wheat		
Seedling (6 Nov. 2005)	0–30	13.9 a†	12.3 b	13.6 a
	30–60	18.5 a	17.6 a	17.6 a
	60–100	20.2 a	22.4 b	21.6 b
	Avg.	17.5 a	17.4 a	17.6 a
Jointing (12 Mar. 2006)	0–30	17.4 a	16 b	15.9 b
	30–60	18.5 a	18.7 a	18.9 a
	60–100	22.0 a	24.5 b	22.6 a
	Avg.	19.3 a	19.7 a	19.1 a
Heading (17 Apr. 2006)	0–30	13.9 a	14.9 ab	15.3 b
	30–60	19.3 a	18.6 a	18.7 a
	60–100	21.5 a	21.3 a	21.7 a
	Avg.	18.2 a	18.3 a	18.6 a
Grain filling (14 May 2006)	0–30	12.4 a	14 b	14.3 b
	30–60	18.8 a	17.4 b	17 b
	60–100	20.3 a	20.1 a	19.1 a
	Avg.	17.2 a	17.2 a	16.8 a
		Summer maize		
Jointing (12 July 2006)	0–30	16.2 a	16.3 a	16.0 a
	30–60	16.8 a	18.3 b	17.4 ab
	60–100	19.8 a	21.1 b	20.7 ab
	Avg.	17.6 a	18.6 a	18.0 a
Grain filling (20 Aug. 2006)	0–30	16.5 a	15.4 a	15.7 a
	30–60	17.8 a	17.3 a	17.0 a
	60–100	19.3 a	20.2 a	20.4 a
	Avg.	17.9 a	17.6 a	17.7 a
Maturation (25 Sept. 2006)	0–30	13.7 a	14.5 a	14.7 a
	30–60	15.5 a	16.2 a	18.7 b
	60–100	19.3 a	19.6 a	21.7 b
	Avg.	16.2 a	16.8 a	18.4 b

† Means within a row followed by the same letter are not significantly different ($P > 0.05$).

5-cm depth and 1.0 and 0.9°C greater than under TT at the 15-cm depth. The differences were nonsignificant, however, for most of the 30 d. Our results indicated that raised beds with residue cover and no tillage appears to keep the heat and enhances the oil temperature under cold weather conditions.

Crop Yields

As the soil structure changed across the three different treatments, some differences also appeared in crop yields. As shown in Table 4, the PRB and NT treatments appeared to have increasing yield trends compared with TT. The PRB plots had increased wheat yields by 4.8 to 6.2% ($P > 0.05$) and maize yields by 2.0 to 7.2% ($P > 0.05$) compared with TT. Even though the PRB furrows were kept just as tracks, the yield appeared to increase due to the higher plant density on the PRB beds.

DISCUSSION

As illustrated by this long-term experiment conducted from 2005 to 2011 in the Daxing District of Beijing, the PRB treatment showed substantial and significant improvements in soil physical properties by using no tillage, controlled traffic, residue cover, and raised beds in annual double-cropping areas of Beijing compared with TT and NT treatments.

In this experiment, the soil bulk density changed in different years. No tillage, controlled traffic, mulch cover, and raised beds showed significant effects in reducing the soil bulk density. These results were in accordance with the results of He et al. (2008) in arid northwestern China with a wheat monoculture system. The effect of controlled traffic on bulk density was similar to the research results of Bai et al. (2008). However, Hari Ram et al. (2011) found that the soil bulk density in the 0- to 15-cm layer was significantly affected by tillage and planting systems but insignificantly affected by straw mulch in an irrigated maize–wheat system in northwestern India. A reduced soil bulk density may represent a factor of considerable practical interest in terms of better soil porosity and lower soil compaction associated with NT and residue cover (McHugh et al., 2009).

The increased aggregate stability under the PRB treatment was significantly affected by the combination of no tillage, mulch covering, controlled traffic, and raised beds, not by any of them separately. This result agreed with that of He et al. (2012) in northwestern China under a spring wheat monoculture system. Oyedele et al. (1999), however, demonstrated that the negative effects of wheel traffic and tillage on macroaggregate formation were significant. Furthermore, Naresh et al. (2012) showed significant effects of NT and residue retention on soil aggregate stability in western Uttar Pradesh under an alternative wheat production

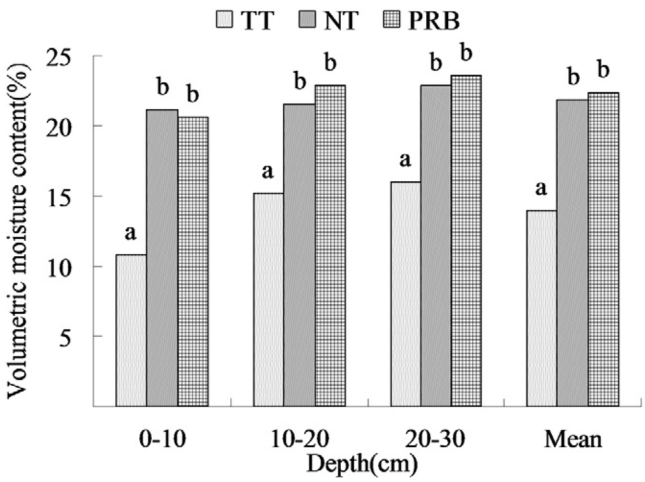

Fig. 5. Soil volumetric moisture content at three soil depths and the mean for three treatments in 2011: traditional tillage (TT), no-till (NT), and permanent raised beds (PRB). Mean values for the same soil depth followed by the same letter were not significant different (P > 0.05).

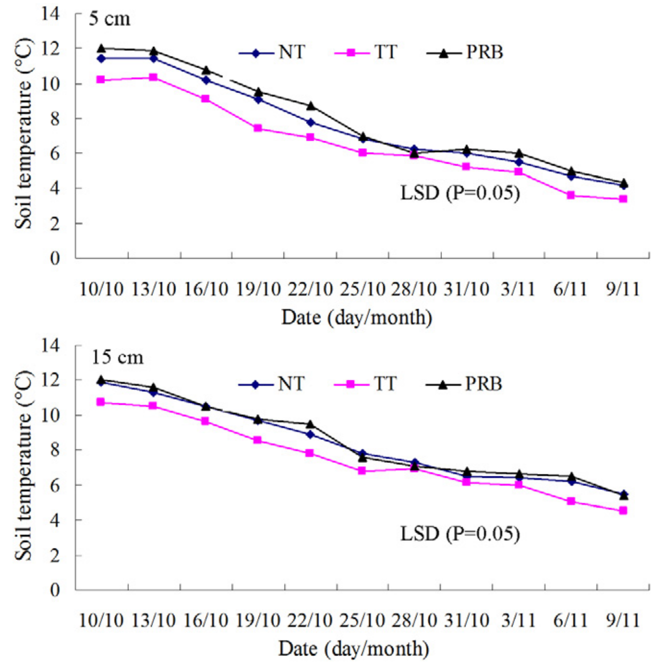

Fig. 6. Soil temperature at the 5- and 15-cm soil depths at 0800 h from 10 Oct. to 9 Nov. 2010 during the growing season of winter wheat as influenced by different treatments: traditional tillage (TT), no-till (NT), and permanent raised beds (PRB).

system. These differences may be attributed to the different planting systems. A reduced presence of macroaggregates (>0.25 mm) under TT was partly due to excessive tillage and heavy traffic, which hindered the soil biological activity (Tisdall and Oades, 1979).

The soil water content initially showed similar patterns across the three treatments. Approximately half a year later (June–October 2006), however, the water stored in the 30- to 100-cm soil layer of the PRB and NT plots began to increase as a result of soil amelioration by conservation tillage. Similar changes were observed by He et al. (2008, 2010) and McHugh et al. (2009) in short-term experiments. They assumed that the initial moisture losses in the shallow soil layer (0–30 cm) of PRB plots were associated with the bed formation. By 2011, the PRB plots achieved significantly (P < 0.05) higher soil water contents. Nevertheless, no tillage, residue covering, and raised beds had nonsignificant effects on increasing soil water content. These results were different from the results of Connolly et al. (1997), who demonstrated that residue covering had a significant effect on increasing soil water content. This may have been caused by the different irrigation method.

In the PRB treatment, the penetration resistance was significantly (P < 0.05) reduced as a result of controlled traffic, especially in topsoil layers (0–20 cm). Soil resistance was significantly (P < 0.05) related to the soil water content. In reference to the penetration resistance in the 12.5- to 15.0-cm soil layer of the NT plots, some data were obtained that were surprisingly inconsistent with the general trend. At this depth, penetration resistance under NT is generally mitigated by little traffic, and these results should therefore be seen as an aberration. Other data were consistent with the results of Rasaily et al. (2012), demonstrating that controlled-traffic conservation tillage could minimize soil compaction, improve soil structure, and increase soil moisture in cropping areas. Verhulst et al. (2011) found that the combination of permanent beds with the burning of straw is not a sustainable management option in arid regions with a wheat–maize irrigated bed planting system.

During the seedling stage of the winter wheat, the soil temperature was significantly increased, which was beneficial for wheat sprouting. This was consistent with the research of He et al. (2008). Moreover, winter wheat and summer maize yields both appeared higher (P > 0.05) in the PRB than the TT treatment. This result was consistent with the findings of Bai et al. (2008) and Li et al. (2007) and might be well explained by means of improved soil physical properties.

CONCLUSIONS

The experiment of TT, NT, and PRB treatments was performed in the Daxing district of Beijing to assess the effects of no tillage, residue covering, controlled traffic, and raised beds. The results

Table 4. Crop yields (winter wheat and summer maize) in three treatments: traditional tillage (TT), no-till (NT), and permanent raised beds (PRB).

Treatment	2005	2006	2007	2008	2009	2010	2011
				Winter wheat			
TT		4800 a†	4912 a	5110 ab	4587 a	4600 a	4639 a
NT		4649 ab	4983 a	4900 b	4785 a	4643 a	4784 a
PRB		4294 b	5097 a	5409 a	4869 a	4630 a	4805 a
				Summer maize			
TT	5711 a	5670 a	6890 a	6098 b	6159 a	7086 b	
NT	5665 a	4500 b	6995 a	6338 ab	6048 a	7430 a	
PRB	5989 a	5700 a	7464 a	6455 a	6282 a	7269 ab	

† Values within a column for the same crop followed by the same letter are not significantly different between tillage treatments (P > 0.05).

demonstrate the same positive influence of PRB treatment in terms of penetration resistance, soil bulk density, soil water content, water-stable aggregation, and soil temperature. As a consequence, the PRB treatment leads to an increasing trend in crop yields.

The PRB system clearly has the potential for a positive contribution when facing severe problems related to agricultural productivity and soil quality. The findings presented throughout this work are encouraging, although further research is required to investigate several aspects of this cropping system, including the suitability of wheat and maize cultivars and seeding rate, the stability of different fertilizer levels in increasing yields, and the correlations between tillage, water management practices, productivity, and environmental conditions.

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