Effects of Permanent Raised Beds on Soil Chemical Properties in a Wheat-Maize Cropping System

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Abstract: Traditional tillage (TT) in the North China Plain has maintained grain productivity in the past 50 years. Nonetheless, it has also been a major contributor to global greenhouse gas emissions, biodiversity and soil fertility loss, soil degradation, and even desertification. Permanent raised beds (PRB) have been proposed as a viable solution to achieve sustainable farming in this plain. The effects on soil chemical properties of the PRB treatment and two other treatments, namely, no-tillage and TT treatments, were measured between 2005 and 2011 in the annual double cropping regions of the North China Plain. The soil properties significantly ($P < 0.05$) affected by the different treatments. Stratification ratios of soil organic carbon, total nitrogen, available N, available phosphorus, and available potassium under PRB (>1.35) were significantly ($P < 0.05$) higher than those under no-tillage and TT. In the cropping zone of PRB, the bulk density was significantly reduced by 14.4%, whereas soil organic carbon, total nitrogen, phosphorus, and potassium and available nitrogen, phosphorus, and potassium in the 0- to 10-cm soil layer were significantly increased by 24.8%, 78.8%, 121.9%, 81.8%, 46.2%, 7.0%, 2.9%, respectively, in comparison with those of TT treatments. Winter wheat and summer maize yields in PRB also underwent a slight increase. Permanent raised beds seem to be an improvement on current farming systems in the North China Plain and valuable for the sustainability of farming in this region.

Key words: Permanent raised beds, soil chemical properties, soil organic carbon, total nitrogen, double cropping system.

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China needs to feed 22% of the world's population with only 10% of the world's arable area and has recently become the world's largest emitter of CO_2, overtaking the United States (Minx et al., 2011). According to the statistics of the National Bureau of Statistics of China (2011), the North China Plain, with an annual wheat (*Triticum aestivum* L.)-maize (*Zea mays* L.) double cropping system, accounted for more than 30% of the overall grain production in China, therefore playing an important role in alleviating a potential food crisis. Traditional tillage (TT) (using moldboard plowing) has maintained grain productivity in the North China Plain in the past 50 years. Nonetheless, it has also been a major contributor to global greenhouse gas emissions, biodiversity and soil fertility loss, soil degradation, and even desertification (He et al., 2011). Because production largely depends on soil fertility, a change of the nutrient and carbon (C) status in the soil, caused by the excessive tillage of traditional cultivation, leads to soil fertility deficiencies affecting the growth of annual double crops. In the long-term, TT resulted in reduced soil C stocks by as much as 20% to 50% (López-Fando and Pardo, 2011). Therefore, more sustainable agricultural systems are urgently needed in this area to ameliorate soil and ecosystem conditions, which are the key parameters for sustaining China's food quantity and quality.

As a type of conservation tillage, permanent raised beds (PRB) have been shown to be effective in increasing the accumulation rate of soil organic carbon (SOC) and maintaining soil nutrients (Moreno et al., 2006). Compared with traditional tilled raised beds (TT with new bed formation before sowing and residue removal), PRB increase the dynamics of soil C and nitrogen (N) and decrease greenhouse gas emissions (Verachtert et al., 2009). Carbon sequestration was higher in the PRB system in comparison with those in no-tillage (NT) and conventional tillage systems (Oicha et al., 2010). Singh et al. (2010) concluded that pigeonpea (*Cajanus cajan* (L.) Millsp) planted on PRB had greater N and phosphorus (P) recycling than that planted on conventional flat beds in pigeonpea-wheat double cropping regions. Positive effects of PRB included improved crop yield and reduced water requirements as well as runoff. Choudhury et al. (2007) claimed that PRB reduced the water inputs by 32% to 42% compared with traditional flooded rice system in the rice-wheat double cropping regions of the Indo-Gangetic Plain. Talukder et al. (2011) also concluded that PRB resulted in higher average grain yields, water utilization efficiency, and soil conservation in Bangladesh and northern Ethiopia. Hulugalle et al. (2010) showed that the PRB system reduced drainage water losses and increased soil water storage in New South Wales and Queensland with a cotton (*Gossypium hirsutum* L.)-wheat rotation cropping system. Infiltration rates also increased in PRB in southern Spain in a maize-cotton cropping system compared with those in conventionally tilled beds (Boulal et al., 2010). Moreover, PRB can also enhance the ecological environment through reducing waterlogging, soil salinity, and energy savings. Bakker et al. (2010) stated that the raised beds had a great effect on reducing waterlogging, improving productivity, and reducing salinity in Western Australia with a Mediterranean climate. Hussain et al. (2010) found that conventional farming used 6% more energy inputs than raised bed farming.

In China, the raised bed planting system has been used where irrigation systems were developed to save irrigation water and enhance grain yields and water use efficiency (Wang et al., 2004), but it involved considerable tillage operations. Permanent raised beds (combining raised beds with NT) have been recently proposed to increase the sustainability of grain production in China (He et al., 2008). Jiang and Xie (2009) found

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that the method of combining ridge with NT improved soil physical properties, soil total N, total P, total potassium (K), and soil organic matter significantly in southwestern China with a rice-based lowland cropping system. He et al. (2007) designed three kinds of soil-loosening knives to solve the poor lateral water infiltration problems associated with permanently raised beds. He et al. (2008; 2010) showed the effects of PRB on promoting crop performance, water use efficiency, and soil temperature in the arid Northwest China and Northeast China.

Because the PRB treatment represents a sustainable and productive cultivation method, it is essential to investigate its positive influence on soil properties and soil structure in the North China Plain in consideration of the deficiencies of soil nutrient and C status. The available documents about PRB in China in recent years have mainly focused on machine and crop performances in one crop a year regions. Few studies have addressed the problem of the effects of PRB on soil fertility and nutrient changes of crop growth in the North China Plain with annual double cropping systems. The objective of this study was to investigate the effects of PRB on soil chemical properties and stratifications as indicators of management-induced changes in the soil quality in the annual double cropping region of the North China Plain.

MATERIALS AND METHODS

Site and Climatic Conditions

The experiment was conducted from 2005 to 2011 at Daxing region (39°7′N, 116°4′E) in south Beijing. This area is characterized by a semihumid climate and is located at 45 m above sea level. During the experimental period, the average annual temperature was 11.9°C (with 186 frost-free days), and the annual rainfall was 526 mm (>70% of the rainfall occurring from June to September). The rainfall and temperature for each month of the year in Daxing during the experimental period were close to the long-term average values (Fig. 1); although some deviations occurred, these were not closely linked to the patterns found in the experimental data. Double cropping of winter wheat and summer maize is the main cropping system practiced in this region. Summer maize is sown in early June and harvested in the middle of September; winter wheat is sown in early October and harvested the following June. The soil texture of this region is silt loam according to the USDA texture classification system, and the soil type is Fluvents of Entisols under the *USDA Soil Taxonomy* (USDA, 1978). The key soil physical and chemical properties of the 0- to 30-cm soil layer determined in October 2005 after havesting the maize at the start of the present study are listed in Table 1.

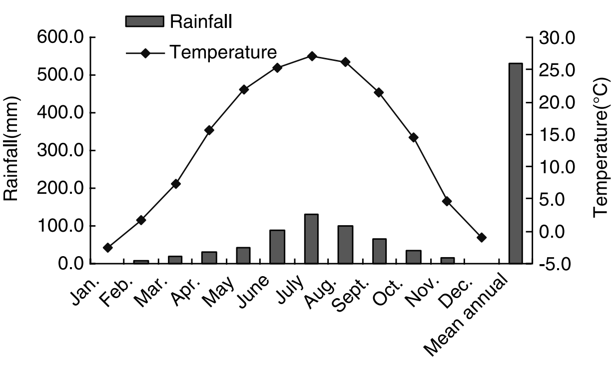

FIG. 1. Mean annual rainfall (7 years) and distribution of mean monthly rainfall and temperature at Daxing during the experimental years from 2005 to 2011.

TABLE 1. Soil Characteristics of the Experimental Field at 0- to 30-cm Depth in 2005

Soil Depth, cm	pH	SOC, g kg^{-1}	Available N, mg kg^{-1}	Available P, mg kg^{-1}	Bulk Density, g cm^{-3}
0–10	8.04	9.28	64.51	17.13	1.32
10–20	8.21	8.37	58.47	15.21	1.41
20–30	8.18	6.93	52.29	11.23	1.36

Experimental Design

The experiment was designed as a randomized block with three replications. Each plot was 9 m wide and 90 m long and was ploughed to a depth of 30 cm to mix soil thoroughly to ensure uniform soil conditions in each of them at the beginning of the experiment in 2005. Three treatments were compared: PRB, NT, and TT. Permanent raised beds implemented NT with bed planting, furrow irrigation, and controlled traffic. In both PRB and NT treatments, the crop was planted through the previous plant residues, leaving a 20-cm high standing stubble and approximately 3.2 t ha^{-1} of wheat straw or approximately 6.0 t ha^{-1} of maize straw cover. In TT, all crop residues were manually removed from the soil surface before the moldboard ploughing to a 20-cm depth. The operation schedules of the three treatments are shown in Table 2. During the experimental years, maize was planted 2 to 3 days later in TT than in PRB and NT treatments because of excessive tillage (plowing, harrowing, leveling, etc.) necessary for seedbed preparation. The same

TABLE 2. Operation Schedules for PRB, NT, and TT Treatments in Daxing During the Experimental Years From 2005 to 2011

Treatment	Schedule
PRB	Harvesting maize (early October) (leaving all maize straw cover (~6.0 t ha^{-1})); no-till planting wheat on the beds (early October); furrow irrigating (late November, late March, mid April, mid May); harvesting wheat (early June) (leaving 0.20-m-high standing stubble and all wheat straw cover (~3.2 t ha^{-1})); no-till planting maize on the beds (mid June); furrow irrigating (mid July); harvesting maize (early October) (leaving all maize straw cover (~6.0 t ha^{-1}))
NT	Harvesting maize (early October) (leaving all maize straw cover (~6.0 t ha^{-1})); no-till planting wheat (early October); mechanized spray irrigation (late November, late March, mid April, mid May); harvesting wheat (early June) (leaving 0.20-m-high standing stubble and all wheat straw cover (~3.2 t ha^{-1})); no-till planting maize (mid June); mechanized spray irrigation (mid July); harvesting maize (early October) (leaving all maize straw cover (~6.0 t ha^{-1}))
TT	Harvesting maize (early October); manually removing all maize residues; ploughing; planting wheat (early October); mechanized spray irrigation (late November, late March, mid April, mid May); harvesting wheat (early June); manually removing all wheat residues; ploughing; planting maize (mid June); mechanized spray irrigation (mid July); harvesting maize (early October)

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amount of irrigation water was applied at the same time across the three treatments. Each year, about 210 to 220 mm and 50 to 60 mm of irrigation water was used for winter wheat and summer maize, respectively, in each treatment.

In the PRB system, beds were formed in 2005 with an overall (furrow-center) width of 160 cm to suit the wheel track width of the tractor and harvester. The depth and width of each furrow were 15 and 40 cm, respectively. Bed surface was the zone for crop growing in PRB, allowing eight rows of wheat at a 17-cm spacing and three rows of maize at a 60-cm spacing, and the furrow in PRB was used as a transit zone for the wheel track as well as for the irrigation system, so the land use efficiency in the PRB system was 75%. In NT and TT treatments, the wheat and maize were uniformly planted in each plot with a spacing of 20 and 60 cm respectively, and the land use efficiency was 100% in both cases.

The same seed variety and the same type of fertilizer were applied in equal quantities in the PRB, NT, and TT treatments with the same seed and fertilizer placing depth of approximately 5 cm and approximately 10 cm, respectively. Winter wheat (var. Jing-9428) was planted at 300 kg ha^{-1} and summer maize (var. Huaiyan-10) at 30 kg ha^{-1}. Fertilizers were applied at the following rates: 95 kg N ha^{-1}, 75 kg P ha^{-1}, and 40 kg K ha^{-1} for winter wheat using urea ($CO(NH_2)_2$), $(NH_4)_2HPO_4$, and KCl (K_2O content, 60%) and 85 kg N ha^{-1}, 45 kg P ha^{-1}, and 40 kg K ha^{-1} for summer maize using complete fertilizer (N-P_2O_5-K_2O). An additional 60 kg N ha^{-1} was applied at the first node stage for winter wheat.

Measurements

Soil Sampling and Preparation

Soil samples were collected from the cropping zones in each plot of the treatments and from the unplanted furrows of PRB immediately after wheat harvest and before maize sowing in early June 2011. Undisturbed 36 core samples ((three tillage treatments + PRB furrow) × three depths × three replicates) were collected from randomly located points in all nine plots to measure the bulk density. The 50.4-mm diameter and 50-mm long cores were taken with a manual stainless steel core sampler. Another 36 samples ((three tillage treatments + PRB furrow) × three depths × three replicates) were also randomly taken using a narrow spade from each plot at three depths (0–10, 10–20, and 20–30 cm). These soil samples from each depth of each treatment were then bulked to form 12 composite samples for each treatment at each depth. Each composite soil sample was first passed through an 8-mm sieve by gently breaking soil clods. Pebbles and stable clods larger than 8 mm were discarded (He et al. 2008). Before the analyses, the composite soil samples were air-dried for 24 h in the laboratory.

Soil Bulk Density and Soil pH

Bulk density was measured by using undisturbed soil cores. In the measurement, the soil cores were weighed wet, dried at 105°C for 48 h, and then weighed again to determine bulk density. Soil pH was measured on the subsamples of the 12 composite samples, which were dried at 40°C and ground to a size less than 2 mm, then measured in a 1:5 soil-water suspension (Thomas et al., 2007). All measurements were conducted in triplicate.

Soil Total N, P, and K and Available N, P, and K

The total soil N concentration was determined using the Kjeldahl digestion method. Total P was extracted by means of microwave digestion in sulfuric acid and H_2O_2 (Olsen and Sommers, 1982). Total K was measured using the sodium hydroxide melting method. Available N was extracted using a 5-mL H_2SO_4 solution. Available P was extracted with 0.5 *M* $NaHCO_3$ solution adjusted to a pH 8.5. Available K was determined by 1 M neutral ammonium acetate-flame photometric method. All measurements were conducted in triplicates.

SOC Content

Presently, SOC has been recognized both as an indicator of soil quality and a broader indicator of ecosystem response to environmental changes (Périé and Ouimet, 2008). Soil organic C was determined using the Walkley and Black method (Walkley and Black, 1934) on the subsamples from the 12 composite samples, which were taken and ground to pass through a 0.5-mm sieve first. All measurements were conducted in triplicates.

Yield

Wheat and maize yields were determined by manually harvesting five areas of 1.6 m^2 (1 m long × 1.6 m wide) 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.

Statistical Analysis

Mean values were calculated for each of the measured variables, and analysis of variance was used to assess the statistical effects of conservation tillage on the measured values. The one-way analysis of variance test was carried out separately for each depth using treatment tillage as a factor and also for each tillage system using depth as a factor. Treatment means were separated by the least significant difference test. All significant differences were reported at the 5% level. The SPSS 17.0 analytical software package was used for all statistical analyses.

RESULTS AND DISCUSSION

Soil Bulk Density

Soil compaction can be a severe limiting factor altering chemical movements in the soil and resulting in environmental problems (Hamza and Anderson, 2005). Soil bulk density is an essential indicator of soil compaction. Figure 2 shows that, in the cropping zone, the mean soil bulk density (0- to 30-cm soil layer) of the PRB beds was 5.9% and 12.4% lower ($P < 0.05$)

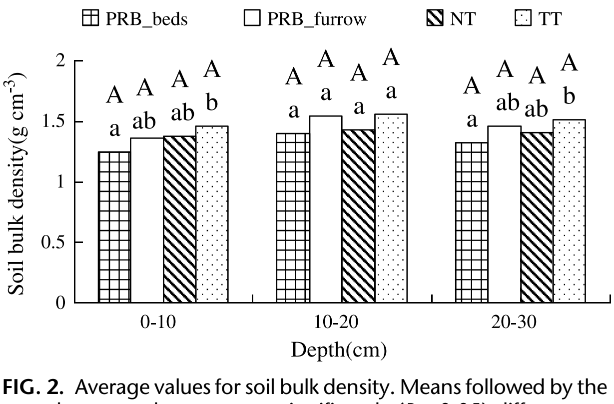

FIG. 2. Average values for soil bulk density. Means followed by the same lowercase letter are not significantly ($P > 0.05$) different between tillage treatments at the same depth; means followed by the same uppercase letter are not significantly ($P > 0.05$) different between depths for the same treatment. PRB_bed, cropping zone of the permanent raised beds; PRB_furrow, track and irrigation ditch of the permanent raised beds.

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TABLE 3. Treatment Effects on SOC for 0- to 30-cm Soil Depth

Soil Depths, cm	PRB		NT	TT
	PRB_bed	PRB_furrow		
0–10	13.81^{aA}	9.05^{bA}	10.06^{bA}	8.71^{bA}
10–20	8.65^{aB}	7.69^{aB}	8.27^{aB}	7.60^{aA}
20–30	7.91^{aB}	5.86^{bC}	6.82^{aC}	5.95^{bB}

Values within a row followed by the same lowercase letter are not significantly ($P > 0.05$) different between tillage treatments at the same depth; whereas, values within a column followed by the same uppercase letter are not significantly ($P > 0.05$) different between depths for the same treatment. The data in 2011 were tested after winter wheat harvest.

PRB_bed, cropping zone of permanent raised beds; PRB_furrow, track and irrigation ditch of permanent raised beds.

than that of NT and TT, respectively. In the 0- to 10- and 20- to 30-cm soil layers, a 14.4% and 12.6% significantly ($P < 0.05$) lower bulk density was observed under PRB beds in comparison with the values respectively found in TT, indicating that ploughing resulted in the formation of a very compact layer. As to the wheel tracks, PRB furrows of the PRB treatment were found to have similar soil bulk density to TT. The soil bulk density in each treatment increased indistinctively in the top 0- to 20-cm soil layers, in accordance to the results achieved by Singh et al. (2010). The effects of PRB in reducing soil bulk density are consistent with those of He et al. (2008), showing that the significant difference among PRB and TT existed in the 0- to 10-cm soil depth. Similar results have also been obtained by Bai et al. (2008) and Wang et al. (2008), who observed that the mean bulk density of soils with controlled traffic was 11.2% lower ($P < 0.05$) than that of traditionally tilled soils, but the value in wheel tracks was 10.2% greater in the 0- to 15-cm soil layer.

At the end, bulk density of the PRB treatment decreased, whereas it increased slightly in the NT treatment and considerably in the TT treatment compared with the initial mean bulk density (1.36 g cm^{-3}) in October 2005. The result is in conformity with that of McHugh et al. (2009), showing that the bulk density of PRB was reduced significantly in the cropping zone using controlled traffic. These results demonstrate that the highest compaction in TT was mainly caused by the excessive tillage practices and by the repeated wheel traffic. Compaction was significant in the subsoil layer (10–30 cm) but less pronounced in the topsoil layer (0–10 cm).

SOC Content

Soil organic C decreased gradually with soil depth. Soil organic C contents for the three different treatments were 21.2% and 36.2% significantly ($P < 0.05$) higher in the 0- to 10-cm soil layer than those in the 10- to 20-cm and 20- to 30-cm soil layers, respectively. In the cropping zones in 2011, mean SOC (0–30 cm) in PRB beds and NT was increased by 23.6% and 2.4%, whereas SOC in TT decreased by 9.4% compared with the initial levels in 2005 (Table 3). Soil organic C concentrations significantly ($P < 0.05$) differed in the 0- to 10-cm soil layer in conservation tillage (PRB beds and NT) treatments. In the 0- to 10- and 20- to 30-cm soil layers, SOC contents were 24.8% and 36.9% significantly ($P < 0.05$) higher in PRB beds than those in TT. No-tillage also showed an increasing trend in SOC content compared with that in TT. Especially in the 20- to 30-cm soil layer, SOC content was 14.6% higher ($P < 0.05$) in NT than in TT. The trend of the SOC changes coincided with the results of Oicha et al. (2010), who showed that SOC in the PRB system significantly increased in the topsoil profile (0–5 cm) but not in the 5- to 20-cm soil layer. A similar tendency was also observed in NT in comparison with TT. These results are also in agreement with studies by López-Fando and Pardo (2011). The increased SOC in the planting systems are crucial for stabilizing soil structure against erosive forces and reducing greenhouse gas emission to sustain grain yield and ecosystem security (Shukla et al., 2006).

As shown in Fig. 3, SOC correlated negatively with the bulk density. Zibilske et al. (2002) noted that the physical environment constitutes a great challenge to the achievement of an increase in soil organic matter. The significantly higher SOC in PRB and NT soils were attributed to a greater C input from residue retention and to a reduced biological oxidation of SOC to CO_2 (Chan et al., 2002). Controlled traffic in the PRB treatment was closely related to a reduction in soil bulk density, which resulted in a higher SOC in the PRB cropping zones, alongside to a lower SOC in the wheel furrows. On the other hand, excessive tillage and removal of crop residues in TT did result in a significant SOC reduction.

Soil Total N, P, and K and Available N, P, and K

Total N, P, and K and available N, P, and K are major soil nutrients, which affects crop growth and yields. In the 0- to 30-cm soil layer, the mean contents of total N, total P, total K, available N, available P, and available K in the cropping zones of the three treatments generally followed the order of PRB > NT > TT. As shown in Table 4, the orders of variation of the values varied in each individual sampled depth (0–10, 10–20, and 20–30 cm) between PRB cropping zones and NT, but all the values were negative in the PRB furrows.

Available N

Plant-available N, P, and K can provide the crop with proper nutrients for a quick recovery while improving crop yield. In 2011, the overall available N (0–30 cm) improved by 42.4% on PRB beds, 21.6% in NT and 4.8% in PRB furrows, whereas it decreased by 5.4% in TT compared with the initial status. In the 0- to 10-cm soil layer, PRB beds had 16.8% and 78.8% higher ($P < 0.05$) available N compared with NT and TT, respectively. Moreover, in the 20- to 30-cm soil layer, available N in PRB was 33.4% and 49.1% significantly ($P < 0.05$) greater than that in NT and TT, respectively. Permanent raised bed

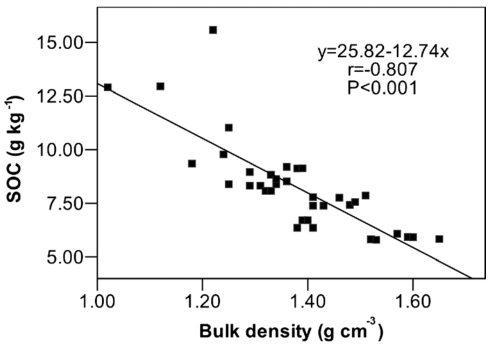

FIG. 3. Relationship between soil organic C (in grams per kilogram) and soil bulk density (in grams per cubic centimeter) in the 0- to 30-cm depth using every value of all the treatments, including PRB (bed and furrow), NT, and TT. x, the value of bulk density; y, soil organic carbon; *r*, correlation coefficient.

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TABLE 4. Treatment Effects on Total N, P, and K and Available N, P, and K in 0- to 30-cm Soil Depth

Depth, cm	Treatment	Total N, g	Total P, g	Total K, g	Available N, mg	Available P, mg	Available K, mg
		kg^{-1}					
0–10	PRB_bed	1.74^{aA}	0.87^{aA}	18.70^{abA}	100.73^{aA}	30.33^{aA}	232.03^{aA}
	PRB_furrow	1.21^{bcA}	0.73^{cA}	16.96^{cA}	64.53^{cA}	14.67^{cA}	139.63^{cA}
	NT	1.28^{bA}	0.81^{bA}	18.91^{aA}	86.23^{bA}	20.00^{bA}	153.53^{bA}
	TT	1.19^{cA}	0.81^{bA}	18.17^{bA}	56.33^{dA}	13.67^{cA}	127.63^{dA}
10–20	PRB_bed	1.26^{aB}	0.82^{aB}	18.80^{aA}	70.70^{bB}	18.50^{aB}	129.93^{bB}
	PRB_furrow	1.05^{cB}	0.75^{bB}	18.76^{abB}	53.97^{cB}	11.50^{cB}	126.23^{bB}
	NT	1.16^{bB}	0.90^{cB}	18.20^{bB}	68.20^{bB}	13.67^{bB}	128.73^{bB}
	TT	1.16^{bA}	0.80^{dB}	17.55^{cB}	74.93^{aB}	14.67^{bA}	154.74^{aB}
20–30	PRB_bed	1.10^{aC}	0.83^{aC}	19.03^{aA}	78.13^{aC}	11.50^{aC}	131.73^{aC}
	PRB_furrow	0.78^{bC}	0.67^{bC}	18.50^{aB}	47.27^{dC}	9.50^{abC}	128.93^{aC}
	NT	1.10^{abC}	0.80^{cC}	18.81^{aA}	58.57^{bC}	10.00^{abC}	129.63^{aC}
	TT	1.08^{abB}	0.70^{dC}	17.87^{bAB}	52.40^{cA}	9.00^{bB}	118.04^{bC}

For the same variable, values within a column at the same depth followed by the same lowercase letter are not significantly ($P > 0.05$) different between tillage treatments, and values in the column under the same treatment followed by the same uppercase letter are not significantly ($P > 0.05$) different between depths.

PRB_bed, cropping zone of permanent raised beds; PRB_furrow, track and irrigation ditch of permanent raised beds.

furrows also had 14.6% higher ($P < 0.05$) available N than TT did in 0 to 10 cm. This is consistent with the results of a 10-year experiment conducted in Kentucky, which showed significantly higher organic N in the top 0- to 5-cm layer with NT compared with a plow tillage treatment (Blevins et al., 1983). Surprisingly, the available N contents in PRB and NT treatments were both highest in 0- to 10-cm soil layer, whereas in TT, it was highest in the 10- to 20-cm layer. These results are in agreement with those of Bauer et al. (2002), who reported that N tended to accumulate near the surface in conservation tillage, whereas the removal of crop residues would decrease the N mineralization rate in the soil and finally decline of available N in TT.

Available P

In 2011, available P (0–30 cm) increased by 38.5% on PRB beds, whereas it decreased by 14.3% in TT after 6 years. In the 0- to 10-cm soil layer, PRB beds had 51.7% and 121.9% higher ($P < 0.05$) available P compared with NT and TT, respectively. Moreover, in the 10- to 20-cm layer, available P was 35.3% and 26.1% higher ($P < 0.05$) on PRB beds than that in NT and TT, respectively. Even in the 20- to 30-cm soil layer, available P in PRB was 27.8% ($P < 0.05$) greater than that in TT. The decline of available P in TT could have resulted from disruption of soil aggregates by tillage, inhibiting O_2 diffusion and, thereby, stimulating dephosphorization (Verachtert et al., 2009). The controlled traffic that reduced the compaction in PRB beds contributed to the establishment of a better environment for root growth and finally increased nutrients in the soil. Conversely, PRB furrows showed no advantage on maintaining soil-available P; instead, available P decreased by 21.6% ($P <$ 0.05) in the PRB furrows compared with that in TT in the 10- to 20-cm soil layer. This may be caused by the permanent traffic tracks in PRB furrows compared with the random traffic in TT.

As the depth increased, the available P in PRB (including beds or furrows) and NT decreased sharply ($P < 0.05$), whereas it increased slightly in TT from the 0- to 10-cm soil layer to the 10- to 20-cm layer but then decreased significantly ($P < 0.05$) in 20 to 30 cm. The trend of available P in PRB is consistent with the results of Boulal and Gómez-Macpherson (2010), who found that available P decreased with depth. The average available P in the 0- to 5-cm layer was more than three times that in the 20- to 30-cm layer in an irrigated permanent bed system on sloping land. The trend of available P in NT is also in agreement with that in the NT farming on the Loess Plateau (Wang et al., 2008) and the North China Plain (He et al., 2011), whereas the trend in TT is just similar with that in conventional tillage farming (using ploughing) in the North China Plain.

Available K

Available K in PRB beds, PRB furrows, NT, and TT followed the same trends as available P. In the 0- to 10-cm soil layer, PRB beds, PRB furrows, and NT had 81.8%, 9.4%, and 20.3% higher ($P < 0.05$) available K than that in TT, respectively. Moreover, in the 20- to 30-cm soil layer, available K in

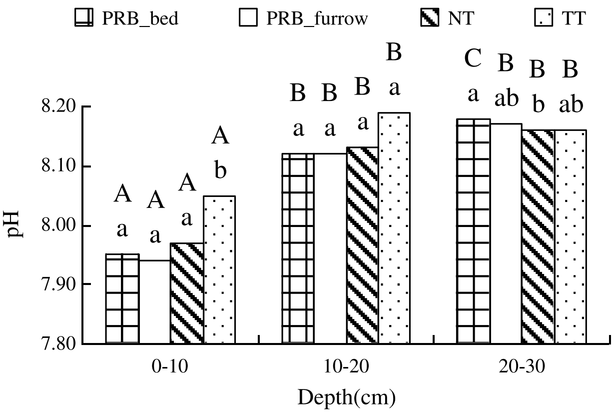

FIG. 4. Soil pH for different treatments at 0- to 10-cm, 10- to 20-cm, and 20- to 30-cm depths at Daxing in 2011. Means followed by the same lowercase letter are not significantly ($P > 0.05$) different between tillage treatments at the same depth; means followed by the same uppercase letter are not significantly ($P > 0.05$) different between depths for the same treatment. PRB_bed, cropping zone of the permanent raised beds; PRB_furrow, track and irrigation ditch of the permanent raised beds.

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TABLE 5. Stratification Ratio* of Soil Chemical Properties for PRB, NT, and TT Treatments in 2011

	PRB			
Component	**PRB_bed**	**PRB_furrow**	**NT**	**TT**
SOC	1.67[a]	1.18[b]	1.22[b]	1.07[b]
Total soil N	1.38[a]	1.56[b]	1.11[c]	1.03[d]
Total soil P	1.06[a]	0.98[b]	0.90[c]	1.01[d]
Total soil K	0.99[a]	0.90[b]	1.04[b]	1.04[c]
Available soil N	1.43[a]	1.20[b]	1.26[c]	0.75[d]
Available soil P	1.64[a]	1.28[ab]	1.46[c]	0.93[b]
Available soil K	1.79[a]	1.11[b]	1.19[c]	0.83[d]

Values within a row followed by the same letter are not significantly ($P > 0.05$) different between tillage treatments.

*Stratification ratios were calculated here from soil chemical properties at a depth of 0 to 10 cm divided by those at a 10- to 20-cm depth.

PRB_bed, cropping zone of permanent raised beds; PRB_furrow, track and irrigation ditch of permanent raised beds.

PRB beds, PRB furrows, and NT was 11.6%, 9.2%, and 9.8% greater ($P < 0.05$) than that in TT. With the same rate of fertilizer application each year, the available K in PRB and NT was greater in the 0- to 10-cm soil layer, whereas in TT, it was greater in the 10- to 20-cm soil layer. Compared with TT, NT favored the surface accumulation of available K.

Total N, P, and K

In the 0- to 10-cm soil layer, total N in PRB beds was 46.2% and 36.1% higher ($P < 0.05$) than those in TT and NT, respectively. In the 10- to 20-cm soil layer, it was 8.6% higher ($P < 0.05$) in PRB beds than that in both TT and NT. For PRB furrows, the total N was similar to those in NT and TT in the 0- to 10-cm and 20- to 30-cm soil layers. But in the 10- to 20-cm soil layer, PRB furrows had lower ($P < 0.05$) total N than the other treatments. Total N showed the same trend with SOC in relation to tillage treatments, which is consistent with the data of Guzman et al. (2006) who also observed that N cycling was directly linked to C cycling.

Total P in PRB was 6.6% and 4.7% higher ($P < 0.05$) than in NT in the 0- to 10-cm and 20- to 30-cm soil layers, respectively; furthermore, it was 7.0%, 2.8%, and 19.2% higher ($P < 0.05$) than in TT in the 0- to 10-cm, 10- to 20-cm, and 20- to 30-cm soil layers, respectively. It is interesting to note that total P in NT was 9.7% higher ($P < 0.05$) than that in PRB beds. And the change of the total P in each of the treatments showed no significant trends with soil depth.

Total K in PRB was 2.9%, 7.1%, and 6.5% higher ($P < 0.05$) than that in TT in the 0- to 10-cm, 10- to 20-cm, and 20- to 30-cm soil layers. In the 10- to 20-cm soil layer, PRB had 3.3% higher ($P < 0.05$) total K than in NT. Total K showed nonsignificant relationships with the soil depth in most of the treatments (Table 4).

The distributions of the total N, P, and K agree with the findings of Jiang et al. (2009), who pointed out that total N, P, and K levels in soil improved significantly after PRB had been continuously practiced for 17 years. The results with total N coincide with those of Chen et al. (2009) who found that NT resulted in increased total N in the upper 0- to 15-cm soil layers in comparison with the conventional tillage. There were significant differences in total N, P, and K caused by cultivation duration. Plant residue is very important for the regeneration and maintenance of soil fertility within this cropping system. Similar to SOC, available N, P, and K and total N, P, and K were also affected by the crop residue mulch. Furthermore, significant differences between PRB beds and NT were also related to compaction caused by field traffic.

Soil pH

Decreases in soil pH as a result of continuous application of N fertilizers have been well documented (Blevins et al., 1983). Soil pH in the different treatments decreased by 0.4% to 1.0% in 2011 (Fig. 4) compared with that in 2005. Most of the decreases appeared in the upper 10-cm soil layer. In the 0- to 10-cm soil layer, PRB beds, PRB furrows, and NT reduced the soil pH by 1.2%, 1.4%, 1.0%, significantly ($P < 0.05$) compared with that in TT. These results agree with those of Wang et al. (2008) who showed that soil pH decreased in the upper soil with increasing N rates from surface applications of urea–ammonium nitrate solution. The distribution of the soil pH was also consistent with that suggested by Thomas et al. (2007) who showed that pH of soils under NT was marginally acidic in the 0- to 2.5-cm and 2.5- to 5-cm soil layers but increased in the 10- to 30-cm layer. However, the pH of acidic soils has been shown to decrease with soil depth (Guzman et al., 2006).

Stratification Ratio of Soil Chemical Properties

The type of tillage was expected to alter the distribution of soil properties with depth because of the different soil disturbance (Malhi and Lemke, 2007). The initial stratification ratios of SOC, available N, and available P were 1.15, 1.10, and 1.13, respectively, in 2005. After the winter wheat harvest in 2011, those values decreased under TT treatment whereas they increased under PRB and NT treatments. Stratification ratios of SOC, total N, available N, available P, and available K (Table 5) under PRB beds were more than 1.35 in 2011,

TABLE 6. Crop Yield (Winter Wheat and Summer Maize) in Different Treatments

Treatment	2005	2006	2007	2008	2009	2010	2011
Winter wheat							
TT		4,800[a]	4,912[a]	5,110[ab]	4,587[a]	4,600[a]	4,639[a]
NT		4,649[ab]	4,983[a]	4,900[b]	4,785[a]	4,643[a]	4,784[a]
PRB		4,294[b]	5,097[a]	5,409[a]	4,869[a]	4,630[a]	4,805[a]
Summer maize							
TT	5,711[a]	5,670[a]	6,890[a]	6,098[b]	6,159[a]	7,086[b]	
NT	5,665[a]	4,500[b]	6,995[a]	6,338[ab]	6,048[a]	7,430[a]	
PRB	5,989[a]	5,700[a]	7,464[a]	6,455[a]	6,282[a]	7,269[ab]	

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

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which were significantly ($P < 0.05$) higher than those under NT and TT treatments. No-tillage also followed the same trend of the stratification ratios of PRB beds in 2011. These results are in agreement with those of Bauer et al. (2002) who reported that N, K, Ca, and Mg tended to accumulate near the surface in conservation tillage. López-Fando and Pardo (2011) also found that stratification ratios of soil N, P, and K and SOC increased under conservation tillage more than twofold the levels obtained under conventional tillage. The topsoil accumulation of chemical nutrients in PRB beds and NT can be partially attributed to the limited downward movement of particle bound nutrients in no-tilled soils and the upward movement of nutrients from deeper layers through nutrient uptake by roots (Urioste et al., 2006). Franzluebbers (2002) disclosed the consistent results that the redistribution of soil chemical properties especially in the top soil layers could improve the soil quality.

Crop Yield

Average winter wheat and summer maize yields in PRB were slightly higher compared with those in TT, namely, 1.6% and 4.1%, whereas in NT, the winter wheat yield increased by 0.3% but the summer maize yield decreased negligibly. After application of PRB, the yield (Table 6) of winter wheat decreased in the first 2 years but finally increased significantly ($P < 0.05$) in 1 of 6 years. For NT, the yield of the winter wheat and summer maize also decreased in the first few years. This situation is to be considered as normal when using PRB and NT because the soil is meant to undergo a natural and relatively time-demanding amelioration process (He et al., 2011). The unnaturally loosened soil environment in TT maintained the yield in the first few years, but the negative inputs of soil degradation gradually appeared in the latter years of the study. In the last 2 years, PRB resulted in increased wheat yields of 4.8% to 6.2% ($P > 0.05$) and maize yield of 2.0% to 7.2% ($P > 0.05$) in comparison with those in TT. In all treatments, eight rows of wheat and three rows of maize were planted in the 160-cm-wide zones. Because PRB has larger vacancy lands, that is, PRB furrows, the row spacing for wheat on the PRB beds (120-cm wide) was smaller compared with those on the planting zones of the other two treatments. With the same fertilizer and irrigation application, the increased maize yield in PRB supports the conclusion that better soil quality resulted from PRB. Meanwhile, the increased wheat yield in PRB may result from the higher planting density and the better soil quality.

CONCLUSIONS

The experiment conducted from 2005 to 2011 in the North China Plain demonstrated that the PRB treatment was an effective method for the improvement of soil chemical properties. The SOC, total N, P, and K, and available N, P, and K contents were significantly increased. Soil fertility and quality improved overall under PRB and NT, especially in the 0- to 10-cm soil layer. The crop yield also appeared to be an increasing trend in PRB. Exhibiting the best soil chemical properties and the highest stratification ratios, PRB is potentially the most effective cultivation method for erosion control, water infiltration promotion, nutrient conservation, enhancement of crop growth, and, overall, for sustained food security. The results reported here are encouraging, and ongoing research is needed on several aspects of this cropping system, including the correlation between the soil physical and chemical properties, the relationship between fertilizer rate, straw coverage and the changes in soil chemical properties, the suitability of the currently adopted fertilizers and the balance between grain productivity, and soil quality and environmental conditions.

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