Long-term effects of returning wheat straw to croplands on soil compaction and nutrient availability under conventional tillage

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ABSTRACT

To investigate the effects of returning wheat straw to croplands on soil compaction and nutrient availability, this trial was designed: (1) planted crops without fertilization (NF); (2) natural land without human activities (CT); (3) applied mineral fertilizers in combination with 7500 kg/ha wheat straw (WS-NPK); (4) applied mineral fertilizers in combination with 3750 kg/ha wheat straw (1/2WS-NPK); and (5) applied mineral fertilizers alone (NPK). It is found that, compared with NPK, the soil bulk density in 1/2WS-NPK and WS-NPK both decreased by more than 10% in the 0 cm to 15 cm layer, and by 6.93% and 9.14% in the 15 cm to 20 cm, respectively. Furthermore, in contrast to NPK, the soil available nitrogen in the 0 cm to 25 cm layer in 1/2WS-NPK and WS-NPK were higher by 17.43% and 35.19%, and the soil available potassium were higher by 7.66% and 17.47%, respectively. For soil available phosphorus in the depth of 5 cm to 25 cm, it was higher by 18.51% in 1/2WS-NPK and by 56.97% in WS-NPK, respectively. Therefore, returning wheat straw to croplands effectively improves soil compaction and nutrients availability, and the improvement in soil nitrogen and phosphorus availability is closely related to the amount of wheat straw.

Keywords: soil organic matter; soil bulk density; soil nitrogen; soil phosphorus; soil water content

By the end of the 20th century, up to 68 million hectares of cropland suffered from the soil degradation caused by high compaction (Flowers and Lal 1998). Soil compaction has become one of the most limiting factors that adversely affects crop production (Mari et al. 2008). For example, a study pointed out that the canola yield under a high soil compaction was only 34% of that under lower soil compaction (Chan et al. 2006). In Turkey, the annual crop yield losses caused by high soil compaction were estimated to be over a billion dollars (Carman 1992).

The mechanism of high soil compaction that affects crop production was first referred from the deteriorated physical properties (Passioura 2002, Hamza and Anderson 2005). In severe compacted soil, the small pores increased by 72% in clay loam and 39% in sandy loam, whereas the macropores were nearly eliminated in both soils (Shestak and Busse 2005). Consequently, soil gases such as oxygen, which is necessary for plant and microorganisms activities and nutrient uptake significantly decreased (Mari et al. 2008). Second, the low availability of soil nutrients caused by high

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soil compaction affects crop production. In highly compacted soil, a large number of mineral fertilizers could be transported by rainfall or irrigation into surface waters and result in agricultural non-point source pollution (Soane and van Ouwerkerk 1995, Pengthamkeerati et al. 2006).

In the HuaiBei Plain in AnHui Province, one of the most important regions for wheat production in China, high soil compaction occurs because of the wide use of agricultural equipments. Subsoiling was widely introduced to minimize soil compaction (Chen et al. 2005). Unfortunately, it has some severe defects, such as high cost, seldom amelioration of the compacted soil structures and easily recompaction (Kooistra and Boersma 1994). In contrast, the addition of crop residues into compacted soil directly reduces soil compaction and increases soil porosity and water holding capacity (Hamza and Anderson 2005). Wheat straw which causes severe environmental pollution because of burning and dumping randomly was one of the most important agricultural byproducts in HuaiBei Plain. Therefore, it is urgent to find a healthy way to utilize the wheat straw and develop sustainable agriculture. The aim of this study is also to find an effective and convenient method for improving soil compaction.

MATERIAL AND METHODS

Description of the study areas. The experiment was conducted in the Huaibei Plain of AnHui province of China. The annual mean temperature at the experimental site was 14.8°C. The mean annual rainfall was 872 mm, ranging from 505 mm to 1444 mm, and the annual average potential evaporation was 1027 mm. The soil is a Vertisol with pH ranging from 6.0 to 8.6 (Calcic Kastanozems, FAO Taxonomy), containing about 10–13 g/kg soil organic matter, and consisting of 32.8–49.5% coarse silt (0.05~0.01 mm), 42.8–45.4% fine silt (0.01~0.001 mm) and 24.5–25.8% clay (< 0.001 mm) (Li et al. 2011). In this research, the trial was conducted based on a long-term fertilized experiment ranging from 1982 to 2011 and included five treatments: (1) planted crops without fertilization (NF); (2) natural land without human activities (CT); (3) applied mineral fertilizers in combination with 7500 kg/ha of wheat straw (WS-NPK); (4) applied mineral fertilizers combined with 3750 kg/ha wheat straw (1/2WS-NPK); and (5) applied mineral fertilizers alone (NPK). In the experiment, all treatments were arranged randomly with four replicates, and the area of each experimental plot was 66.7 m^2 (15.0 m × 4.44 m). At the beginning of the experiment, the average soil organic matter in the 0 cm to 15 cm layer was 11.74 ± 0.27 g/kg, with no significant differences among all plots. During the experiment, the quantities of applied mineral fertilizers, which were equal to the number of fertilizers applied conventionally by local farmers, were 180 kg/ha of nitrogen, 39 kg/ha of phosphorus, and 112 kg/ha of potassium. Prior to annual wheat seeding in autumn, the mineral fertilizers and wheat straw cut into small pieces were both applied as base fertilizer. Across the experiment, the crops were wheat-soybean except from 1993 to 1997 during which wheat-corn was used.

Sampling and measurements. From 1982 to 2011, all crops were sown under conventional tillage. The wheat and soybean were planted at 187.5 kg/ha and 75.0 kg/ha, about 4×10^6 plants/ha and 2.25×10^5 plants/ha, respectively. After harvesting the wheat in June of the experimental years, the harvested wheat grain was calculated to determine wheat production (kg/ha).

All soil samples were taken in June 2011 immediately after the wheat harvest using a cylindrical steel corer and divided into two subgroups: one for soil water content analysis and the other was air-dried for soil organic matter and nutrients analysis. The soil bulk density sampled using ring kits (V = 100 cm^3) from the 0 cm to 25 cm layer was determined via oven drying at 105°C for 24 h.

For soil parameters analysis, soil pH was measured using deionized water at a 1:1 soil solution ratio. Soil organic carbon (SOC) was measured using the Walkley-Black dichromate oxidation method (Nelson and Sommers 1982). Soil total nitrogen (N_t) was determined via the semimicro-Kjeldahl digestion procedure (Bremner and Mulvaney 1982), and the available nitrogen concentration, including ammonium, nitrate and some easily decomposable and hydrolysable organic nitrogen (e.g., amides, amino acids, and protein) were measured via alkali distillation; Soil total phosphorus (P_t) was determined colorimetrically after digestion using perchloric and sulfuric acid, and the available P was determined by Olsen et al. (1954). Soil available potassium was extracted (weight$_{(soil)}$/volume$_{(1\ mol/L\ NH_4\text{-}OAc,\ pH\ =\ 7)}$ = 1:5) then measured via atomic absorption spectrophotometry (Richards and Bates 1989).

Statistical methods. Analysis in this research on soil parameter was carried out using SAS 9.1.3 (SAS institute Inc., Cary, USA), and the graphs were plotted using OriginPro 7.5 (Northampton, USA).

RESULTS AND DISCUSSION

Soil pH, soil water content, bulk density, and wheat yield. Long-term fertilization helped decrease soil pH (Figure 1A). Similar to the results of Guo et al. (2010) who pointed out that the differences between the inputs and outputs of ammonium and nitrate N because of low using efficiency of nitrogen fertilizer resulted in a large number of H^+ generation in the agricultural system, the significantly lower soil pH in the NPK, 1/2WS-NPK, and WS-NPK than other treatments might be attributed to the higher soil nitrogen caused by annual application of mineral fertilizers.

Returning wheat straw combined with mineral fertilizers could improve wheat yield (Figure 1B). The higher yield in 1/2WS-NPK and WS-NPK treatments than that in other treatments could be attributed to two aspects. On one hand, returning wheat straw helped improve soil physical properties. Firstly, wheat straw performed better on improving soil water content than other treatments (Figure 1C). In contrast to NPK with the lowest soil water content, the average soil water content in the 0 cm to 25 cm layer under the NF, CT, 1/2WS-NPK, and WS-NPK treatments were

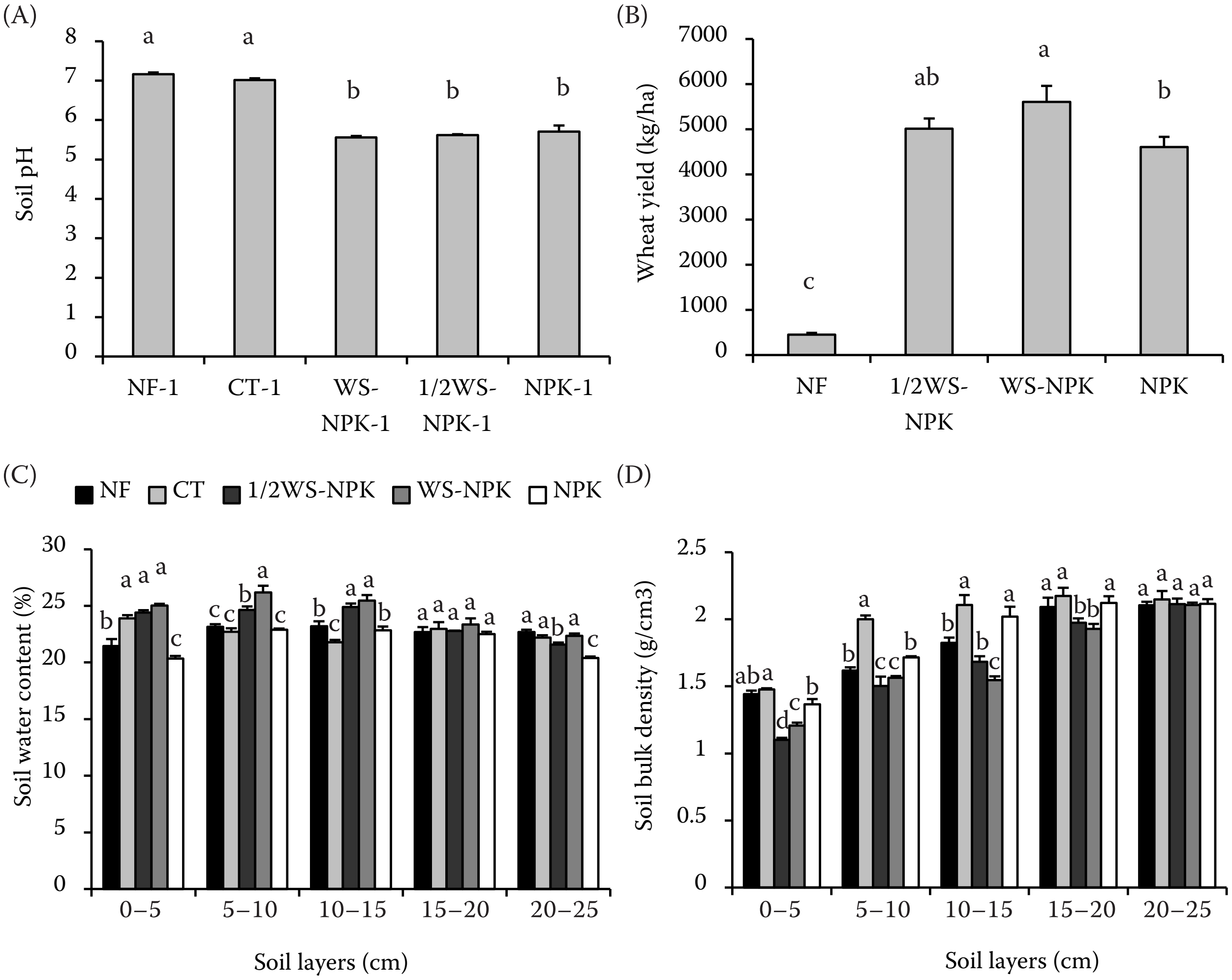

Figure 1. Soil pH in 0–20 cm layer (A), average wheat yield from 2008 to 2011 (B), soil water content (C) and soil bulk density in 0-25 cm layers (D) under the NF, CT, 1/2WS-NPK, WS-NPK, and NPK treatments. Error bars represent standard errors ($n = 4$). Columns with different letters indicate significant differences at $P < 0.05$. NF – planted crops without fertilization; CT – natural land without human activities; WS-NPK – applied mineral fertilizers in combination with 7500 kg/ha of wheat straw (WS-NPK); 1/2WS-NPK – applied mineral fertilizers combined with 3750 kg/ha wheat straw, and NPK – applied mineral fertilizers alone. The same as follow

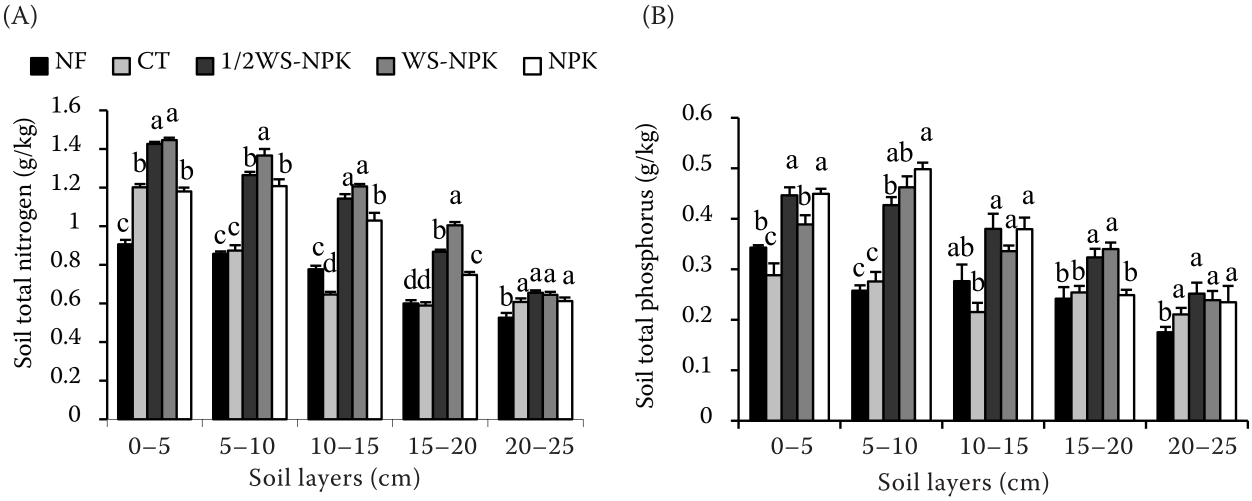

Figure 2. Soil total nitrogen (A) and total phosphorus (B) in the 0 cm to 25 cm layers under the NF, CT, 1/2WS-NPK, WS-NPK, and NPK treatments. Error bars represent standard errors ($n = 4$). Columns with different letters indicate significant differences at $P < 0.05$

higher by 3.85, 4.20, 8.58, and 12.29%, respectively. Furthermore, doubling the wheat straw helped improve the soil water content in the 0 cm to 15 cm layer, and specifically increasing by 2.46% in the 0 cm to 5 cm layer, by 6.25% in the 5 cm to 10 cm, by 2.30% in the 10 cm to 15 cm layer, and by 2.45%

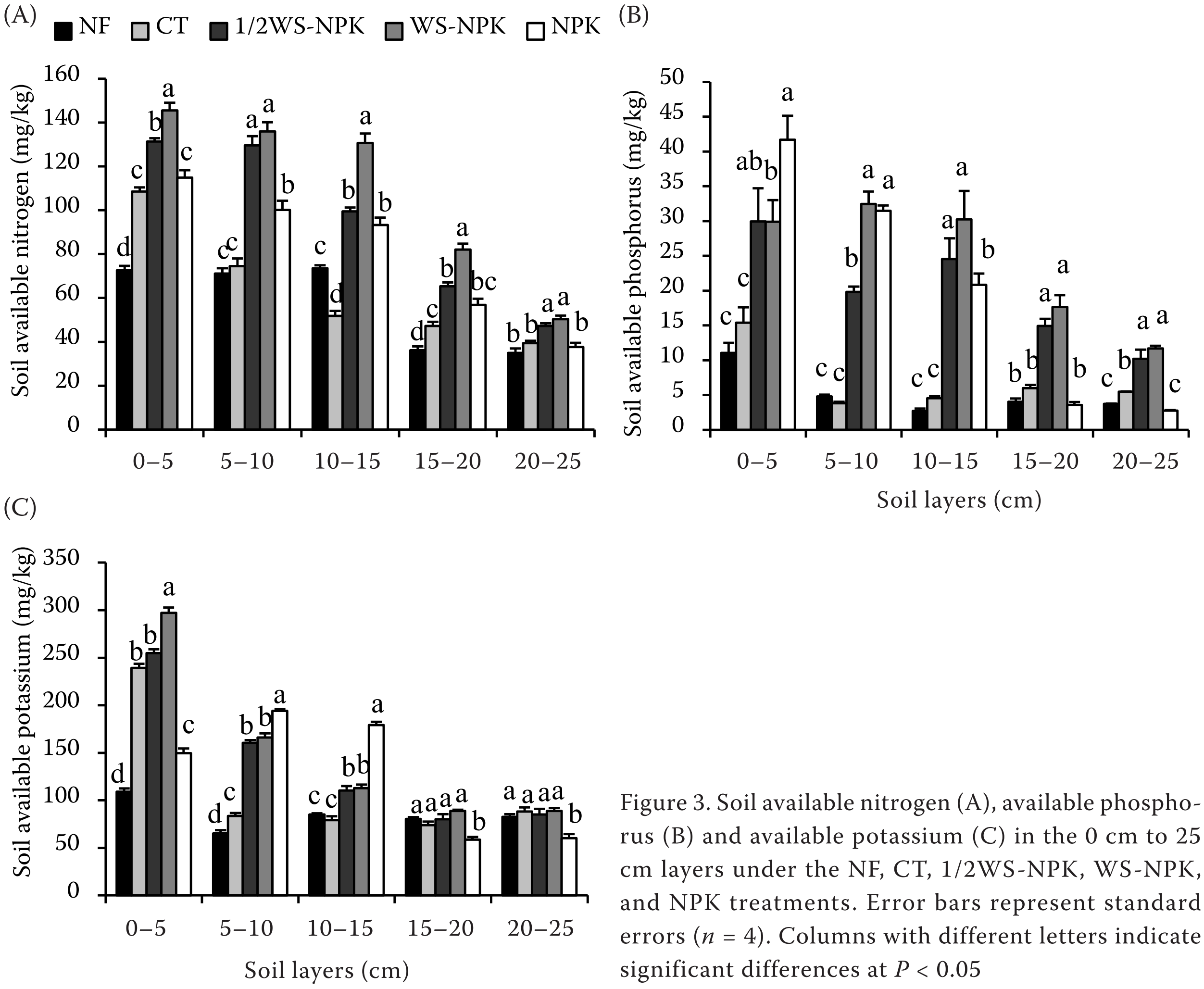

Figure 3. Soil available nitrogen (A), available phosphorus (B) and available potassium (C) in the 0 cm to 25 cm layers under the NF, CT, 1/2WS-NPK, WS-NPK, and NPK treatments. Error bars represent standard errors ($n = 4$). Columns with different letters indicate significant differences at $P < 0.05$

in the 15 cm to 20 cm, respectively. Secondly, returning wheat straw to cropland combined with mineral fertilizers was beneficial to decreasing soil compaction (Figure 1D). Low soil bulk densities are beneficial to crop production (Beylich et al. 2010). When the soil bulk densities were > 1.2 g/cm^3 in the 0 cm to 20 cm layer, the loss of crop yield could be up to 30% (Ressia et al. 1998). The reasons were that high soil compaction because of its adverse effects on soil mechanical impedance, porosity and hydraulic conductivity could reduce root penetration and plant growth, limit water and air transport, and cause nutrient stress and retard seed germination (Hamza and Anderson 2005). In this experiment, compared with the CT, the soil bulk density in the 0 cm to 15 cm layer under the NF, 1/2WS-NPK, WS-NPK, and NPK treatments decreased by 12.52, 23.26, 22.71, and 8.66%, respectively. Moreover, wheat straw helped decrease deeper soil compaction, and the maximum referred soil depth affected by wheat straw was up to 20 cm. In contrast to the NPK treatment, the bulk density in 1/2WS-NPK and WS-NPK both decreased more than 18% in the 0 cm to 5 cm layer, 20% in the 5 cm to 10 cm layer, 20% in the 10 cm to 15 cm layer, and 9% in the 15 cm to 20 cm layer, respectively.

On the other hand, returning wheat straw into cropland in combination with mineral fertilizers helps improve soil nutrients and their availability

Table 1. Correlation coefficient (*R*) among soil bulk density (SBD); organic matter (SOM); total nitrogen (TN); available nitrogen (AVN); available phosphorus (AVP), and available potassium (AVK) in NF, CT, 1/2WS-NPK, WS-NPK, and NPK

Treatment	Variables	SOM	TN	AVN	AVK	AVP
NF	SBD	−0.550*	−0.929***	−0.842***	−0.378	−0.693**
	SOM	–	0.631*	0.698**	0.008	0.062
	TN	–	–	0.929***	0.256	0.587*
	AVN	–	–	–	0.171	0.351
	AVK	–	–	–	–	0.658**
CT	SBD	−0.935***	−0.920***	−0.918***	−0.932***	−0.895***
	SOM	–	0.964***	0.959***	0.907***	0.884***
	TN	–	–	0.975***	0.880***	0.861***
	AVN	–	–	–	0.887***	0.868***
	AVK	–	–	–	–	0.934***
1/2WS-NPK	SBD	−0.889***	−0.957***	−0.920***	−0.944***	−0.822***
	SOM	–	0.957***	0.964***	0.775***	0.706**
	TN	–	–	0.972***	0.853***	0.813***
	AVN	–	–	–	0.824***	0.740**
	AVK	–	–	–	–	0.714**
WS-NPK	SBD	−0.962***	−0.921***	−0.923***	−0.805***	−0.814***
	SOM	–	0.954***	0.931***	0.809***	0.834***
	TN	–	–	0.980***	0.708**	0.873***
	AVN	–	–	–	0.614*	0.921***
	AVK	–	–	–	–	0.453
NPK	SBD	−0.822***	−0.778***	−0.780***	−0.545*	−0.896***
	SOM	–	0.917***	0.936***	0.767***	0.904***
	TN	–	–	0.955***	0.900***	0.927***
	AVN	–	–	–	0.849***	0.941***
	AVK	–	–	–	–	0.792***

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; NF – planted crops without fertilization; CT – natural land without human activities; WS-NPK – applied mineral fertilizers in combination with 7500 kg/ha of wheat straw (WS-NPK); 1/2WS-NPK – applied mineral fertilizers combined with 3750 kg/ha wheat straw, and NPK – applied mineral fertilizers alone

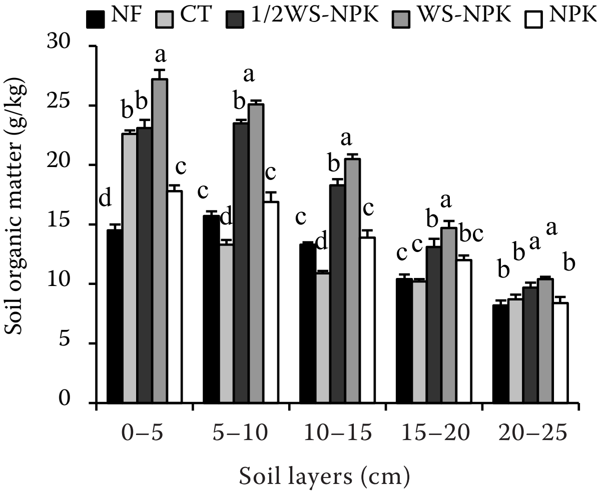

Figure 4. Soil organic matter in soil profile ranging from 0 cm to 25 cm in the NF, CT, 1/2WS-NPK, WS-NPK, and NPK treatments. Error bars represent standard errors ($n = 4$). Columns with different letters indicate significant differences at $P < 0.05$

(Figures 2 and 3). Figure 2A shows that returning wheat straw to cropland in combination with mineral fertilizers was beneficial to improving soil nitrogen. For soil nitrogen in the 0 cm to 25 cm layer, NF treatment exhibited the lowest increase. By contrast, the average total nitrogen in the 0 cm to 25 cm layer increased by 46.1% in the 1/2WS-NPK treatment, 54.6% in the WS-NPK treatment, and 30.3% in the NPK treatment. For soil total phosphorus, similar trend exists (Figure 2B). Furthermore, wheat straw treatments performed better on improving the availability of soil nutrients than other treatments (Figures 3A–C, Table 1), and the maximum distributed depth of soil available nitrogen and phosphorus affected by wheat straw was deeper than in the NPK treatment up to a 25 cm depth. In comparison with NPK treatment, in the 20 cm to 25 cm layer, the soil available phosphorus in the 1/2WS-NPK and WS-NPK were higher by 266.3% and by 319.7%, respectively, and the available nitrogen in the 20 cm to 25 cm layer under the 1/2WS-NPK and WS-NPK treatments were higher by 25.4% and 33.8%, respectively. In 0 cm to 25 cm layer, the average available potassium under the 1/2WS-NPK and WS-NPK treatments was higher than in the NPK by 7.7% and 17.5%, respectively. The improved availability of soil nutrients was closely correlated to the higher soil organic matter after returning wheat straw into cropland. Soil organic matter helped improve soil nutrients availability. Specially, on the one hand, soil organic matter was the source and sink of plant nutrients (Duxbury et al. 1989), and a number of available nutrients were released during its decomposition; on the other hand, higher organic matter was associated with better soil physical properties which helped stabilize soil nutrients. There were close relationships between soil organic matter and soil water-holding capacity, soil buffering, rates of gas exchange, and soil biological activities (Powers et al. 2005). In this experiment, compared with the NF treatment, the average soil organic matter in the 0 cm to 25 cm layer under the 1/2WS-NPK, WS-NPK, and NPK treatments were higher by 41.2, 57.6, and 11.1%, respectively (Figure 4).

Soil compaction and nutrients availability. Consistent with the results of Hamza and Anderson (2005) who reported that high soil compaction reduces nutrient availability, the experimental results also has shown that the available nutrients were negatively correlated to soil compaction (Table 1). For soil compaction, its influence on nutrient availability is referred to two aspects: on the one hand, high soil compaction increases the susceptibility of soil available nutrients and inorganic mineral fertilizers to rain and drainage renders conventional fertilization highly inefficient (Renck and Lehmann 2004). For example, as the increase of soil bulk density from 1.2 g/cm^3 to 1.8 g/cm^3, the soil inorganic nitrogen decreased by 16% to 45% (Pengthamkeerati et al. 2006). On the other hand, compacted soil could decrease the using efficiencies of mineral fertilizers. In comparison with uncompacted soil, compacted soil could reduce the electron acceptors such as NO_3 then result in the release of N_2, and decrease the amount of N required for plant growth (Soane and van Ouwerkerk 1995). Consequently, the nitrogen using efficiency declined and more nitrogen was required for plant growth.

Above all, returning wheat straw to croplands combined with mineral fertilizers helps alleviate soil compaction and improves soil nitrogen and phosphorus availability in the plough horizon. Consequently, returning wheat straw to croplands results in high wheat yields. Therefore, adding wheat straw to croplands is an effective and convenient method for decreasing soil compaction.

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