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Soil chemical properties and microbial biomass after 16 years of no-tillage farming on the Loess Plateau, China

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Abstract

Data from a 16-year field experiment conducted in Shanxi, on the Chinese Loess Plateau, were used to compare the long-term effects of no-tillage with straw cover (NTSC) and traditional tillage with straw removal (TTSR) in a winter wheat (*Triticum aestivum* L.) monoculture. Long-term no-tillage with straw cover increased SOM by 21.7% and TN by 51.0% at 0–10 cm depth and available P by 97.3% at 0–5 cm depth compared to traditional tillage. Soil microbial biomass C and N increased by 135.3% and 104.4% with NTSC compared to TTSR for 0–10 cm depth, respectively. Under NTSC, the metabolic quotient (CO_2 evolved per unit of MBC) decreased by 45.1% on average in the top 10 cm soil layer, which suggests that TTSR produced a microbial pool that was more metabolically active than under NTSC. Consequently, winter wheat yield was about 15.5% higher under NTSC than under TTSR. The data collected from our 16-year experiment show that NTSC is a more sustainable farming system which can improve soil chemical properties, microbial biomass and activity, and thus increase crop yield in the rainfed dryland farming areas of northern China. The soil processes responsible for the improved yields and soil quality, in particular soil organic matter, require further research.

Keywords: No-tillage; Soil organic matter; Total nitrogen; Available phosphorus; Soil microbial biomass; Metabolic quotient

1. Introduction

Soil organic matter (SOM) is crucial for maintaining soil quality as it stabilises soil structure against erosive forces and increases water capacity and nutrient availability. Increasing SOM on agricultural land may also provide a potential sink for atmospheric carbon (Ellert and Janzen, 1999; Reicosky et al., 1999). Long-term tillage causes severe SOM depletion in agricultural soils (Six et al., 2000) and is responsible for reducing soil organic carbon levels by up to 70% (Lal and Bruce, 1999). The different soil organic matter pools (litter, humus and living microbial biomass) that respond to management are often used as measures of soil quality (e.g. biological productivity, plant and animal health) (Doran and Parkin, 1994). These organic matter pools support plant production and influence many important physical, chemical and biological parameters of soils (Kumar and Goh, 2000). China is one of the main dryland faming countries in the world. The arid and semi-arid areas, mainly located in 16 provinces of northern China, account for 52.5% of the total national land area, i.e. 33 Mha of rainfed arable land for crop production without irrigation (Zhai and Deng, 2000). Dryland farming areas with minimal rainfall, low temperatures (short frost-free period) and high evaporation have very sensitive soils. Traditional tillage practices based on ploughing, low fertilizer or manure input, and little use of crop residue, lead to a decline in SOM and can cause soil degradation. Such degradation leads to reduced water and nutrient availability, low microbial biomass, and fragile soil

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physical structure. Consequently, yields become unstable and tend to decline and fertilizer, water, energy and labor are not used efficiently. Traditional tillage in northern China has already resulted in widespread soil degradation (Gao et al., 1999; Liu, 2004). No-tillage practices featuring residue cover and less soil disturbance have been shown to reduce runoff by 52.5% and reduce erosion by 80.2% compared to traditional tillage (Wang, 2000). Liang et al. (2007) demonstrated that no-tillage significantly increased the concentration of soil organic C in 5–20 cm soil layer by 5.6–5.9% on the clay loam soils after 3 years in the humid northeastern China. In the more arid northern China, Li et al. (2006) conducted a 4 years no-tillage experiment and showed that active C and total organic C down to 10 cm depth were up to 5% higher in no-tillage than traditional tillage systems. The application of no-tillage was also associated with increased yields and water use efficiency. Such improvement is largely due to improved soil quality. Experiments conducted by Liu (2004) in the village of Dingxing in the Hebei province showed that conservation tillage systems can increase organic matter, nitrogen, phosphorus, and potassium in the topsoil layer. Additionally, if crop residue is left in the field, this eliminates straw-burning and the labor requirements for removing straws from the fields.

The studies mentioned above have shown that conservation tillage can improve soil physical properties, reduce wind and water erosion and increase soil fertility in northern China (e.g. Li et al., 2005; Luo et al., 2005; Zhou et al., 2007). However, comparatively little information is available on the changes in soil organic matter and nutrients, in particular microbial biomass for different tillage systems. A better understanding of the long-term effects of no-tillage and straw management practices on SOM, nutrients, microbial biomass and activity is also necessary for the further development of conservation tillage in dryland farming areas in China. Since 1992, the Australian Centre for International Agricultural Research (ACIAR) and the Chinese Ministry of Agriculture have conducted experimental research on conservation tillage in the Loess Plateau of Shanxi province, northern China. The objective of this research is to identify the long-term effects of no-tillage with full straw cover to traditional tillage with full straw removal on soil chemical properties and microbial biomass on a rainfed dryland farming system on the Chinese Loess Plateau.

2. Materials and methods

2.1. Site description

The study was conducted at the site of a long-term experiment (1992–2007) located in the village of Chenghuang near the city of Linfen (38°6 N, 113°E, 456 m a.s.l.) on the Loess Plateau in the south-central Shanxi province. Linfen lies in a semi-arid and warm temperate zone and has a continental climate. The mean annual temperature in the region is 10.7 °C and precipitation is about 555 mm (Fig. 1), but highly variable between years. About 65% of the annual precipitation occurs as rainfall during the summer season (June–September). The frost-free season lasts 180 days. A single crop system of winter wheat is common, with crops sown in September and harvested in June. In the experimental plots, the soil type is a Chromic Cambisol (sand 23.1%, silt 43.3%, clay 33.6%, pH 8.1) according to the FAO/UNESCO soil classification. In the top 30 cm layer, soil bulk density was 1.3 Mg m^{-3}, and total porosity was about 40%. The field capacity and wilting point were 21% and 4% by weight, respectively.

2.2. Experimental design

At the beginning of the experiment in 1992, the entire field was ploughed to a depth of 40 cm to mix soil thoroughly and ensure uniform soil conditions in each experimental plot. The experiment was designed as a randomized block with three replications. Each plot was 9 m wide and 78 m long. The two tillage systems, traditional tillage with straw removal (TTSR) and no-tillage with straw cover (NTSC), were applied to the experimental plots from 1992 to 2007. The TTSR system included spreading of fertilizer, ploughing to 15 cm depth and tillage for seedbed preparation, planting between September 20th and 30th, herbicide (2,4-D butylate) and insecticide (40% dimethoate) spraying in April, and manual harvesting between June 1st and 10th. While the majority of straw was removed, a small amount of standing stubble of 8 to 15 cm in height (0.7 t ha^{-1}) remained after the winter wheat was harvested. A fallow period followed harvest until mid-September when the soil was ploughed to 15 cm depth again. The NTSC system was applied as follows: no-tillage planting and fertilizing between September 20th and 30th, herbicide (2,4-D butylate) and insecticide (40% dimethoate) spraying in April, and harvesting between June 1st and 10th by mechanized harvester. Standing stubble of 15 to 25 cm in height was retained with all wheat straw left as mulch cover (3.8 t ha^{-1}) Properties of the winter wheat residue were showed in Table 1. A fallow period followed harvest until mid-September, with chemical weed control applied when necessary. During the experimental period of 1992–2007, for each crop cycle, 2,4-D butylate and 40% dimethoate were applied at the rate of 0.9 and 0.3 kg (a.i.) ha^{-1} using a knapsack sprayer with a flat fan nozzle. The winter wheat variety was

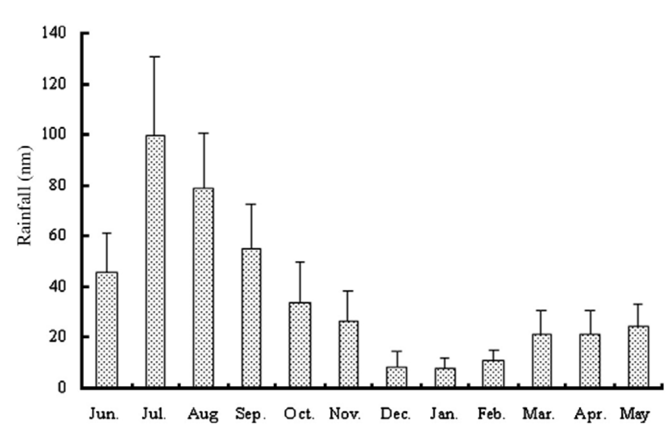

Fig. 1. Distribution of mean monthly rainfall at the experimental site from June 2002 to May 2007. Error bars represent standard deviation.

Table 1
Some characteristics of the winter wheat residue retained in the experimental plots

N (g/kg)	C (g/kg)	Ca (g/kg)	Lignin (g/kg)	Cellulose (g/kg)
5.2	272	2.1	202	340

The residue samples were air-dried before testing.

Linfen 225 with a seeding rate of 225 kg/ha. The $CO(NH_2)_2$, $(NH_4)_2HPO_4$ and KCl (K_2O content: 60%) fertilizers were applied to provide 150 kg N/ha, 140 kg P_2O_5/ha and 62 kg K_2O/ha. Winter wheat yields were determined by manual harvesting, threshing, and air-drying grain from three 1 m^2 areas sampled at random in each plot.

2.3. Soil sampling and analysis

Soil cores (54 mm diameter) were collected from the plots of the two tillage systems in May 2007. In each plot, one soil sample formed by 3 subsamples was taken at 0–5, 5–10, 10–20 and 20–30 cm depths. In order to minimize compression and to obtain a representative sample of the soil, the cores were removed by inserting a trowel into the soil at the lower level of each sampling depth. The soil samples were stored in clean plastic containers for chemical analysis. Each soil sample was first passed through an 8 mm sieve by gently breaking the soil clods, pebbles and stable clods larger than 8 mm were discarded. Before the analyses, soil samples were air-dried for 24 h in the laboratory.

Soil organic matter (SOM) was determined by wet oxidation (Black, 1965) and the percentage of organic carbon was calculated by applying the Van Bemmelen factor of 1.73 (Piper, 1950). Soil total nitrogen (STN) was determined using the Kjeldahl digestion method. Plant available phosphorus (P) was extracted with 0.5 M $NaHCO_3$ (Hedley and Stewar, 1982). All the measurements were replicated three times.

Microbial Biomass Carbon (MBC) was determined by a fumigation–extraction method (Vance et al., 1987). Fumigated and non-fumigated soils were extracted with 0.5 M K_2SO_4 for 30 min (1:5 soil: extractant ratio), filtered and the aliquot was analyzed for organic C by acid-dichromate oxidation. The additional oxidisable C obtained from the fumigated soils represents the microbial C flush and was converted to MBC using the relationship: microbial C=C flush/0.35. Microbial biomass nitrogen (MBN) was measured following the method described by Ross (1992). The K_2SO_4 extracts from fumigated and non-fumigated soil samples were digested in aqueous $K_2S_2O_8$ (0.165 M) for 30 min at 121 °C. The resultant NO_3^-–N and NH_4^+–N were measured by an auto analyser. MBN was estimated using the relationship: Microbial N=N flush/0.45 (Jenkinson, 1988). All the measurements were replicated three times.

Respiration was measured as CO_2 evolution according to Alef (1995). Soil samples were placed in 300 ml glass containers closed with rubber stoppers, moistened at 60% of the maximum water holding capacity and incubated for 7 days at 25 °C. Glass vials holding 10 ml of 0.5 N NaOH to trap the evolved CO_2 were placed in the above containers. On day 7 after the incubation, the glass vials were removed and the CO_2 trapped in NaOH was determined by titration. The metabolic quotient (qCO_2) was obtained by dividing the basal respiration by the microbial biomass C. The basal respiration measurement was replicated three times.

2.4. Statistical analysis

Mean values were calculated for each of the variables, and ANOVA was used to assess the effects of no-tillage with straw cover and traditional tillage with straw removal on the measured soil proprieties. When ANOVA indicated a significant *F*-value, multiple comparisons of annual mean values were performed by the least significant difference method. In all analyses, a probability of error smaller 5% ($P < 0.05$) was considered statistically significant. The SPSS analytical software package (13.0) was used for all the statistical analyses.

3. Results and discussion

3.1. Soil organic matter

The mean SOM in 0–30 cm soil layer for TTSR was slightly higher (2.3%) than for NTSC. These differences were not significant at the beginning of the experiment in 1992, but pronounced treatment effects on SOM could be observed after long-term different tillage management in 2007 (Table 2). SOM to 30 cm depth for NTSC in 2007 was 0.3 g kg^{-1} higher than that in 1992, while TTSR decreased by 0.2 g kg^{-1} in 2007 compared to 1992. Consequently, SOM to 30 cm depth in NTSC was 1.5% higher than in TTSR after 16 years. In the surface soil layer (0–10 cm), the average SOM was even more strongly increased for NTSC (33.6% in 0 to 5 cm and 9.8% in 5 to 10 cm) than TTSR. However, the SOM content declined in the 10 to 20 cm and 20 to 30 cm layer (2.9 and 2.7 g kg^{-1}) on NTSC.

The significant improvement of SOM in the NTSC treatment was probably due to increased carbon input from residue

Table 2
Treatment effects on soil organic matter (SOM), total nitrogen (TN) and available phosphorus (P) for 0–5, 5–10, 10–20 and 20–30 cm depths

Soil depth (cm)	Treatment	SOM (g kg^{-1})		TN (g kg^{-1})		Available P (mg kg^{-1})	
		1992	2007	1992	2007	1992	2007
0–5	TTSR	14.2 a	14.6 a	0.73 a	0.70 a	23.0 a	22.4 a
	NTSC	13.9 a	19.5 b	0.65 a	1.29 b	23.2 a	44.3 b
5–10	TTSR	14.5 a	15.3 a	0.65 a	0.66 a	25.2 a	31. 9 a
	NTSC	14.7 a	16.8 b	0.64 a	0.77 a	24.8 a	25.6 b
10–20	TTSR	14.7 a	13.8 a	0.74 a	0.66 a	21.8 a	22.9 a
	NTSC	13.9 a	11.1 b	0.70 a	0.67 a	20.8 a	10.5 b
20–30	TTSR	10.2 a	9.2 a	0.57 a	0.35 a	15.2 a	7.6 a
	NTSC	9.7 a	6.3 b	0.59 a	0.40 a	14.8 a	6.4 a

Values within a column followed by the same letters are not significantly different ($P<0.05$). The data in 1992 were tested at the beginning of experiment (after the ploughing to 40 cm depth, but before the planting in September).

retention (Brevik et al., 2002). For the TTSR, when soils are ploughed, some standing wheat stubble is moved into deeper soil layers (10–30 cm), resulting in higher SOM content below 10 cm depth than under NTSC. The higher organic matter in the topsoil layer achieved by NTSC shows that results from other arid regions can be applied in China. In Texas, Zibilske et al. (2002) recorded that no-tillage resulted in soil organic matter increase of up to 58% in the top 4 cm of soil for no-till treatment. In the 4–8 cm layer, organic matter was 15% greater than on the plow-till control. Roldan et al. (2005) recorded that no-tillage resulted in soil organic matter increase of up to 33% in the 0–5 cm layer in Mexico. Similarly, Koch and Stockfisch (2006) also reported that conservation tillage concentrated soil organic matter and carbon in the top soil layer (0–10 cm) in Germany.

3.2. Soil total nitrogen

Soil total Nitrogen showed the same trend than SOM in relation to tillage treatments (Table 2). Compared to 1992, overall STN (0–30 cm) improved by 21.3% on NTSC while it decreased by 11.9% on TTSR. In the 0–5 cm layer, STN under NTSC was increased by 81.25% compared to TTSR, while in the 5–10 cm layer STN was increased by only 16.44% compared to TTSR. Below 10 cm, the STN differences were not significant. The results support earlier studies by Chowdhury et al. (2007) and Embacher et al. (2007), who demonstrated that total nitrogen decreased with increasing soil depth. The higher total N under no-tillage was also consistent with the findings of other researchers (e.g. Rasmussen and Collins, 1991; Torbert and Reeves, 1995; Thomas et al., 2007). However, in our study the increase (51.47%) of nitrogen in 0–10 cm depth appears to be higher than in other tests. For example, Thomas et al. (2007) recorded that the total N to 10 cm depth under no-tillage was only 21% higher than for traditional tillage.

3.3. Plant available phosphorus

Table 2 shows that the available P in both treatments was very similar in 1992, but significant differences developed across the soil profile during the 16-year experiment. In 2007, the available P under NTSC was 97.5% higher than under TTSR in the 0–5 cm layer, significant at $P < 0.05$. In the 5–10 and 10–20 cm soil layers, the P content was 19.75% and 54.06%, respectively, lower under NTSC than under TTSR, both significant at $P < 0.05$. In the 20–30 cm layer the difference was not significant. Long-term no-tillage management commonly leads to a stratification of available P in soils (Zibilske et al., 2002). The topsoil accumulation of P in NTSC is attributed to the limited downward movement of particle-bound P in no-tillage soils and the upward movement of nutrients from deeper layers through nutrient uptake by roots (Urioste et al., 2006). A similar result was found in a five-year experiment conducted by Kang et al. (2001) on the Chinese Loess Plateau. However, in their test no-tillage increased soil available P to 10 cm depth only by 5% compared to ploughing in winter wheat production in northern China.

3.4. Microbial biomass

The effects of tillage practices on MBC and MBN concentrations were significant, but less pronounced during the 16-year experiment (Fig. 2). In the 0–5 and 5–10 cm soil layers, MBC and MBN were significantly ($P < 0.05$) higher under NTSC than under TTSR. This pattern was reversed below 10 cm depth where differences between treatments were not significant ($P < 0.05$). The results show that the trend of MBC and MBN with depth is similar, but that the tillage method had no significant effect on MBC and MBN below 10 cm. Higher levels of microbial biomass under NTSC can be explained by

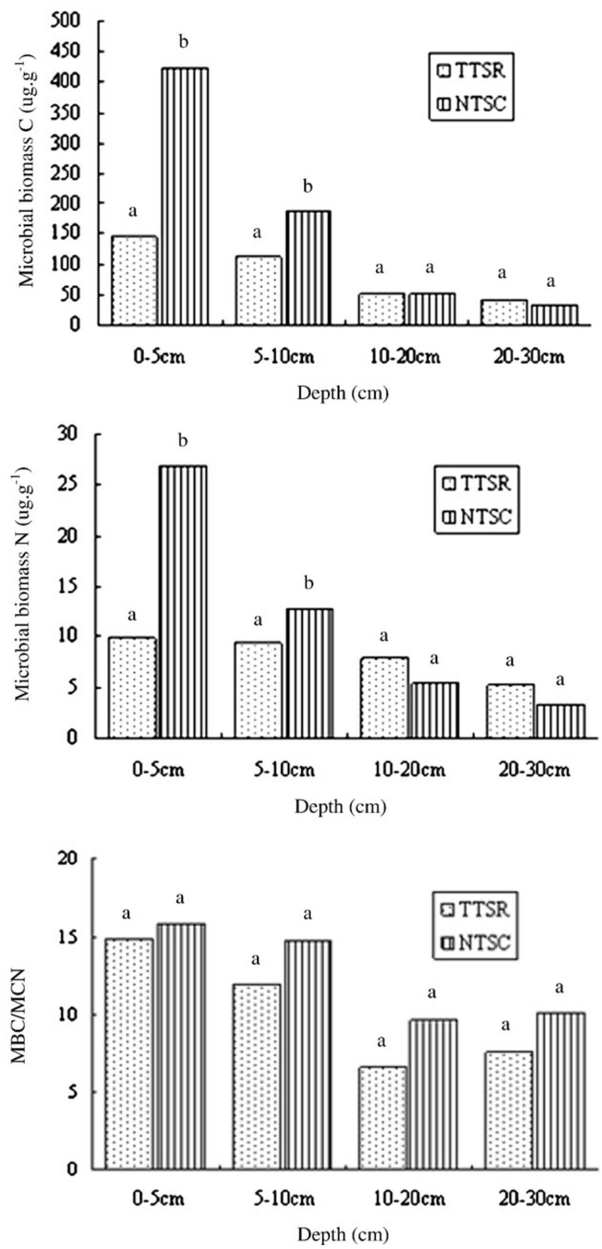

Fig. 2. Microbial biomass C (MBC), microbial biomass N (MBN) and MBC/MBN ratio at 0–5, 5–10, 10–20 and 20–30 cm depth intervals for TTSR and NTSC in 2007. Means within each depth followed by the same letter were not significantly different ($P<0.05$).

greater availability of substrate to sustain the microbial biomass when crop residues are retained. Furthermore, NTSC improves the soil MBC/MBN ratio in the topsoil, which is reflected by the increased microbial C and N pools compared to TTSR (Powlson et al., 1987). In TTSR on the other hand, the crop residues were removed and resulted in a lower MBC and MBN in 0–10 cm depth. Similar results were reported by Wright et al. (2005) who found that microbial biomass C was increased by 80% and microbial biomass N by 65% under no-tillage compared to conventional ploughing in the topsoil (0–10 cm). They also found no significant treatment effects below 10 cm at the end of a 10-year experiment.

3.5. Soil microbial respiration and metabolic quotient

The value of basal respiration (BR) to a depth of 30 cm varied from 3.4 to 9.7 μg CO_2–C g^{-1} per day under TTSR and from 3.0 to 10.9 μg CO_2–C g^{-1} per day under NTSC (Table 3). Long-term tillage had a significant effect on BR, particularly in the 0–5 and 5–10 cm soil depths, where NTSC significantly ($P < 0.05$) improved BR by at least 12% compared to TTSR. In the 10–30 cm depth, there was no significant difference in BR between treatments TTSR and NTSC. Our result was consistent with the findings of Franzluebbers and Arshad (1996) who also observed a tillage effect that varied from 4 to 28 μg CO_2–C g^{-1} per day under conventional tillage and from 4 to 31 μg CO_2–C g^{-1} per day under no-tillage in Northwestern Canada.

The metabolic quotient (soil respiration per unit of microbial C (qCO_2)) ranged from 66.3 to 85.1 under TTSR and from 25.7 to 91.4 mg CO_2–C g^{-1} MBC per day under NTSC (Table 3). Averaged across the depths, qCO_2 in soil under NTSC was 21.8% lower than under TTSR. In 0–5 and 5–10 cm depths, qCO_2 values for NTSC were 61.2% and 31.6% significantly ($P <$ 0.05) lower than for TTSR, while below 10 cm depth values for both treatments were similar, indicating that tillage effects on qCO_2 were pronounced in the topsoil. The inverse relationship between MBC and qCO_2 was similar to a four-year experiment conducted by Wang et al. (2007), who observed an increase in MBC of 93.1% and decrease of 18.8% in the qCO_2 in no-tillage soils as compared with conventional ploughing soils in northern China. These differences may be due to differences of accessibility to C substrates by microorganisms, changes in the metabolic rates and changes in microbial community composition (Alvarez et al., 1995). NTSC soils also may have a greater amount of larger aggregates, which protect microorganisms from adverse conditions. This has potentially important implications for the impact of Chinese agriculture on climate, because less C is emitted from the NTSC soils and more can be stored in soil organic matter.

Table 3
Treatment effects on soil basal respiration (BR) and respiratory quotient (qCO_2) for 0–5, 5–10, 10–20 and 20–30 cm depths

Soil depth	Treatment	Basal respiration ($\mu g\ CO_2$–C g^{-1} d^{-1})	qCO_2 (mg CO_2–C g^{-1} d^{-1})
0–5 cm	TTSR	9.7 [a]	66.3 [a]
	NTSC	10.9 [b]	25.7 [b]
5–10 cm	TTSR	8.9 [a]	78.8 [a]
	NTSC	10.0 [b]	53.9 [b]
10–20 cm	TTSR	4.0 [a]	76.8 [a]
	NTSC	3.6 [a]	69.1 [a]
20–30 cm	TTSR	3.4 [a]	85.1 [a]
	NTSC	3.0 [a]	91.4 [a]

Values within a column followed by the same letters are not significantly different ($P<0.05$).

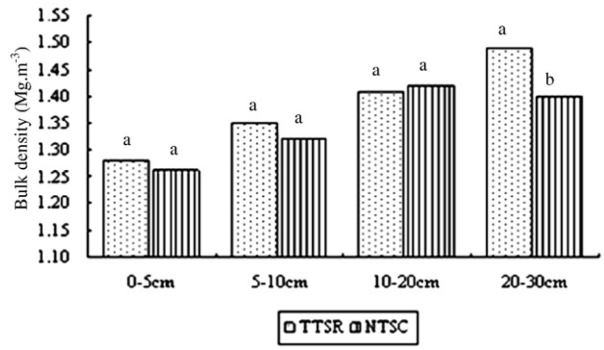

Fig. 3. Mean bulk density for 2 treatments at 0–5, 5–10, 10–20 and 20–30 cm depths. Samples were taken before harvesting in May, 2007. Means within each depth followed by the same letter were not significantly different ($P<0.05$).

3.6. Soil bulk density

The mean soil bulk density to 30 cm depth for TTSR and NTSC was about 1.30 Mg m^{-3} before planting in 1992. After 16 years of no-tillage, bulk density to 30 cm depth was just 2.2% lower on NTSC than TTSR (Fig. 3). The differences were stratified again, with the most pronounced decline on NTSC between in 20 and 30 cm depth (6.0%). The lower bulk density in NTSC can be attributed to the increased soil organic C and biotic activity after long-term no-tillage practice (Karlen et al., 1994).

3.7. Winter wheat yield

Mean winter wheat yields, as indicated in Fig. 4, were 15.5% higher for NTSC than for TTSR during 2003 to 2007, and a further significant ($P<0.05$) improvement of 42.3% was achieved

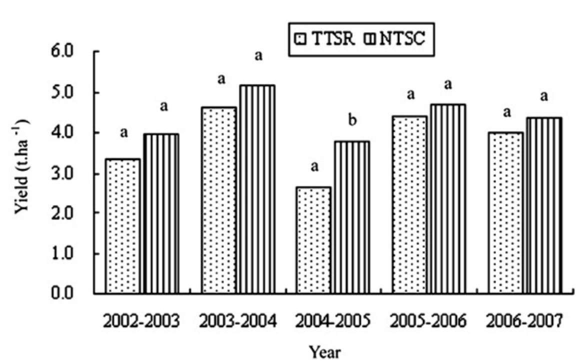

Fig. 4. Mean winter wheat yield for NTSC and TTSR from 2003 to 2007. Means followed by the same letter were not significantly different ($P<0.05$).

in 2005. These varied, but significant improvements are consistent with the experimental results of He et al. (2007), Ma and Tong (2007) and Su et al. (2007). Their research showed that the winter wheat yields for conservation tillage were 9–23% higher than for conventional tillage in arid northern China. This significant improvement under no-tillage management was attributed to increased soil nutrient and organic matter status.

4. Conclusions

No-tillage with straw cover and conventional tillage with straw removal had different effects on soil physical properties, organic matter content, nutrient concentrations, and microbial biomass and activity during the 16-year experiment presented in this study. Continuous long-term conservation tillage practice (no-tillage, straw cover) significantly increased SOM, TN, available P, soil microbial biomass C and N in the topsoil (0 to 10 cm) layer. Furthermore, the results of qCO_2 show that a greater microbial biomass respiration at a lower rate could be achieved by conservation tillage, which is attributed to higher nutrient availability for microorganisms in no-tillage with straw cover soils. Below 10 cm, the trends were reversed. This is attributed to lower degree of mixing straw below the topsoil under no-tillage treatments. Overall, no-tillage with straw cover also appears to improve nutrient supply. The long-term effect on yields is positive, but appears to be highly variable. This indicates that NTSC might require fertilizing for stabilizing yields.

This study demonstrated that conservation tillage offers a significant improvement for the current farming systems in dryland areas of northern China. While generally in agreement with other studies, a range of effects of no-tillage soil management on soil condition and yields differed from those reported in the literature, for example the strong increase in N or the moderate and stratified increase in SOM, which is of particular interest due to its implications for climate change. These differences indicate that further research into the soil processes responsible for the long-term effects of no-tillage soil management is required. A particular emphasis should be given to understanding the influence of time under no-tillage required to achieve equilibrium soil conditions and stable yields. Only by identifying the role of time, the range of data from studies in China and worldwide can be compared comprehensively.

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