CSIRO PUBLISHING
www.publish.csiro.au/journals/ajsr Australian Journal of Soil Research, 2009, 47, 362–371

Influence of conservation tillage practices on soil properties and crop yields for maize and wheat cultivation in Beijing, China

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Abstract. Conservation tillage is becoming increasingly attractive to farmers because it involves lower production costs than does conventional tillage. The long-term effects of sub-soiling tillage (ST), no tillage (NT), and conventional tillage (CT) on soil properties and crop yields were investigated over an 8-year period (2000–07). The study was conducted in a 2-crop-a-year region (Daxing) and a 1-crop-a-year region (Changping) of the Beijing area in China. At 0–0.30 m soil depth, water stability of macro-aggregates (>0.25 mm) was much greater for ST (22.1%) and NT (12.0%) than for CT in Daxing, and the improvements in Changping were 18.9% and 9.5%, respectively. ST and NT significantly ($P < 0.05$) improved aeration porosity by 14.5% and 10.6%, respectively, at Daxing and by 17.0% and 8.6% at Changping compared with CT treatment. Soil bulk density after 8 years was 0.8–1.5% lower in ST and NT treatments than in CT at both sites. Soil organic matter and available N and P followed the same order ST ≈ NT > CT at both sites. Consequently, crop yields in ST and NT plots were higher than in CT plots due to improved soil physical and chemical properties. Within the conservation tillage treatments, despite similar economic benefit, the effects on crop yields for ST were better than for NT. Mean (2000–07) crop yields for ST were 0.2% and 1.5% higher than for NT at Daxing and Changping, respectively. We therefore conclude that ST is the most suitable conservation tillage practice for annual 2-crop-a-year and 1-crop-a-year regions in the Beijing area.

Additional keywords: sub-soiling tillage, soil fertility, aggregate stability, soil porosity, bulk density, yield.

Introduction

Conventional tillage has been practiced for centuries in China. This method is believed to reduce compaction, provide a favourable seed bed, increase root growth and development, control weeds, and maintain crop yields (Gao *et al*. 1999). On the other hand, many areas in which it is practiced suffer from soil structural degradation and poor fertility, which result in decreased and unstable crop yields. Many researchers have demonstrated that the excessive tillage of conventional system seriously degrades soil structure, accelerates soil erosion, and reduces crop yields (Freebairn and Boughton 1985; Chan and Heenan 2005; Fabrizzi *et al*. 2005). Mou *et al*. (1999) pointed out that excessive cultivation and removal of stubble from the soil surface depleted soil organic matter and exposed the soil to water erosion. Huang and Zhong (2003) reported that the average rate of soil erosion on the Chinese Loess Plateau was 150 t/ha.year (maximum 390 t/ha.year). Severe erosion of topsoil resulted in loss and/or degradation of arable land and build-up of heavy silt in the river systems.

Conservation tillage is defined as any tillage and planting system that leaves ≥30% of crop residue on the soil surface after planting (Uri *et al*. 1998; Gao *et al*. 2003). Shallow surface tillage, sub-soiling, no tillage, and residue mulching are often included in this system (Jin *et al*. 2007). Conservation tillage has often shown higher efficiency than conventional tillage in improving soil properties and crop yields (Lal 1989; Havlin *et al*. 1990). It has also been designed to decrease the manpower and energy required for crop production (Zang *et al*. 2003) and offers long-term benefits from improved soil structure (Wang *et al*. 2008), decreased traffic, and reduced soil erosion. Application of conservation tillage also has been shown to reduce water and wind erosion, to increase crop water-use efficiency (Zhou and Lu 2004), and to maintain agricultural sustainability.

Funded by the Australian Centre for International Agricultural Research (Gao *et al*. 2003), China Agricultural University, and the University of Queensland began experimental research on conservation tillage in 1991 in Shanxi province in China. The results of 16 years of experimentation have shown that conservation tillage can help ease environmental problems, improve crop productivity, and maintain agricultural sustainability (Gao and Li 2003). Wang *et al*. (2000, 2001) established that conservation tillage could increase water-use efficiency by 11%, reduce water erosion of soil by 52%, and decrease soil loss by 80% on sloping farmland (<5°) over values produced by traditional tillage practices. Zero tillage, rotations with short-season crops (such as peanut or maize), and stubble retention are

 10.1071/SR08110 0004-9573/09/040362

being introduced as options for combating erosion and improving yields, and therefore increasing income in the Loess Plateau of China. As a result, these practices are rapidly being adopted (Wang *et al*. 2006).

In the Beijing region, farmers continue to use intensive conventional tillage for wheat and maize crops, and the central and provincial governments of China have become conscious of the resulting degradation of soil structure, lack of water, and problems associated with dust storms (MOA 2001). In 2002, the central government of China developed a plan to adopt conservation tillage practices, particularly in the Beijing area. Over 1 million ha of farmland is now estimated to be under conservation tillage in arid and semi-arid regions of northern China (McGarry 2005). Although the acreage of conservation tillage has increased, no systemic research on conservation tillage techniques has been conducted in China, and little work has explored the long-term effect of conservation tillage on soil structure and crop yields, especially in the Beijing area. The objective of our study was therefore to evaluate long-term effects of sub-soiling tillage (ST), no-tillage (NT), and conventional tillage (CT) practices on soil properties and productivity in the Beijing region.

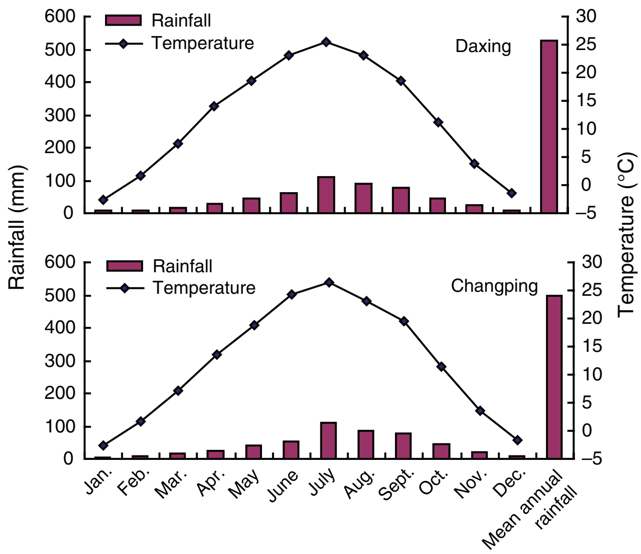

Fig. 1. Mean annual rainfall (8 years) and distribution of mean monthly rainfall and temperature at Daxing and Changping during the experimental years 2000–07.

Materials and methods

Site description

Sets of experiments were conducted at 2 locations in the Beijing area: one in the Daxing (39°7′N, 116°4′E) region and one in the Changping (40°22′N, 116°2′E) region, during the period between 2000 through 2007.

Daxing is in south Beijing in a semi-humid region 45 m above sea level. Average annual temperature is 11.9°C with 186 frost-free days. Average annual rainfall is 526 mm, and >70% of the rainfall occurs during June–September. Double cropping of winter wheat and summer maize is the main cropping system practiced in this region. Summer maize is seeded in early June and harvested in the middle of September; winter wheat is then seeded in early October and harvested in the following June.

Changping, in north Beijing, is semi-arid and 400 m above sea level. Its average annual temperature is 11.8°C, and it has 163 frost-free days. Average annual rainfall is 496 mm, and >65% of the rainfall occurs during June–September. A single crop of spring maize is typically sown in March and harvested in July.

Figure 1 shows the mean annual rainfall (8 years) and distribution of mean monthly rainfall and temperature at the 2 sites during the study from 2000 to 2007. During the experimental period, the weather conditions were close to the long-term average; although some deviations occurred, these were not closely linked to patterns found in the experimental data. At both sites, the soils are defined as silt loam according to the USDA texture classification system. Soil chemical and physical properties used in the study (in 1999) at both sites are reported in Table 1.

Experimental design

At both the Daxing and Changping sites, 3 tillage treatments were used: ST, NT, and CT. ST included sub-soiling with retention of all surface plant residues. NT consisted of zero tillage; planting was through the previous plant residues. CT consisted of manually removing all plant residues from the soil surface, followed by mouldboard ploughing and planting. The operation schedules of the 3 treatments in both Daxing and Changping are shown in Table 2. During the experimental years 2000–07, maize was planted on the same date for ST, NT, and CT treatments in each year in the 1-crop-a-year region of Changping, while in the annual double-cropping region of Daxing, the planting time of maize and wheat for CT was 2–3 days later than for ST and NT

Table 1. Soil chemical and physical properties at the start of experiment (in 1999)

Site	Soil depth (m)	pH	Soil organic matter (g/kg)	Available N (m/kg)	Available P	Bulk density (Mg/m^3)
Daxing	0–0.10	8.35	17.92	64.51	17.13	1.32
	0.10–0.20	8.05	15.23	58.47	15.21	1.41
	0.20–0.30	8.21	12.41	53.92	10.42	1.36
Changping	0–0.10	7.93	17.03	63.79	20.75	1.37
	0.10–0.20	7.69	15.16	62.26	13.64	1.39
	0.20–0.30	7.82	12.72	51.78	12.08	1.43

Table 2. Operation schedules for ST, NT, and CT treatments in Daxing and Changping during the experimental years from 2000 to 2007

Site	Treatment	Schedule
Daxing	ST	Harvesting maize (late Sept.); no-till planting wheat (early Oct.); irrigating (late Nov., late Mar., mid May); harvesting wheat (early June); subsoiling; no-till planting maize (mid June); spraying (late June); harvesting maize (late Sept.)
	NT	Harvesting maize (late Sept.); no-till planting wheat (early Oct.); irrigating (late Nov., late Mar., mid May); harvesting wheat (early June); no-till planting maize (mid June); spraying (late June); harvesting maize (late Sept.)
	CT	Harvesting maize (late Sept.); manually removing all maize residues; ploughing; planting wheat (early Oct.); irrigating (late Nov., late Mar., mid May); harvesting wheat (early June); manually removing all wheat residues; ploughing; planting maize (mid June); spraying (late June); harvesting maize (late Sept.)
Changping	ST	Subsoiling (end Mar.); no-till planting maize (early Apr.); spraying (mid Apr.); harvesting maize (late Aug.); fallowing to Mar.
	NT	No-till planting maize (early Apr.); spraying (middle Apr.); harvesting maize (late Aug.); fallowing to Mar.
	CT	Ploughing (end Mar.); planting maize (early Apr.); spraying (mid Apr.); harvesting maize (late Aug.); manually removing all maize residues; fallowing to Mar.

treatments due to excessive tillage (ploughing, harrowing, levelling, etc.) for seedbed preparation.

The experimental design was a randomised block with 3 replications. At both locations, each plot was 10 m wide and 50 m long. At Daxing, winter variety Jingdong-6 was planted at a seeding rate of 120 kg/ha, and summer maize variety Jingyu-13, the most widely used commercial seed variety in the region, was planted at a seeding rate of 37.5 kg/ha. Urea ($CO[NH_2]_2$), $(NH_4)_2HPO_4$, and KCl (K_2O content: 60%) was applied to provide 95 kg N/ha, 75 kg P/ha, and 40 kg K/ha as the basal N, P, K fertiliser at planting time. An additional 50 kg N/ha was applied at first-node stage for winter wheat. Summer maize sowing density was 7 plants/m^2 and a complete fertiliser (N-P_2O_5-K_2O) was applied at the rate of 85 kg N/ha, 45 kg P/ha, and 40 kg K/ha at planting. Roundup (glyphosate, 10%) was used for weed control during the summer maize growing season.

At Changping, the spring maize variety Nongda-108 (seeding rate: 37.5 kg/ha) was used in the experiment. The complete fertiliser (N-P_2O_5-K_2O) was applied to provide 150 kg N/ha, 95 kg P/ha, and 70 kg K/ha in each plot. Weeds were controlled during the maize-growing season by means of specific herbicides: 41% Roundup (2.25 L/ha) + 40% Acetochlar (2.25 L/ha).

The 2BMFS-5/10 no-tillage wheat-maize seeder (Fig. 2), matched with a 37 kW class tractor, was used for no-tillage seeding of both wheat and maize for ST and NT treatments in both sites. The no-till seeder cleans strips by residue chopping and rotary hoeing in front of knife-type tine openers, and the seeder can drop the seed for wheat after maize harvesting. The metal press wheels are used to firm the seed and fertiliser at depths of 50 and 100 mm, respectively. The seeder can plant 10 rows of wheat or 5 rows of maize simultaneously. For wheat, the seed openers were set to 20-cm row space to provide maximum residue coverage. For maize, they were set to the 50-cm row space commonly used by local farmers, with an operating width of 2.0 m. In CT treatment at both sites, wheat and maize were planted in ploughed fields using the local 12-row and 4-row seed drill, respectively, which were set to the same row spaces (wheat: 20 cm; maize: 50 cm) as the 2BMFS-5/10 no-tillage seeder for ST and NT treatments.

Fig. 2. The 2BMFS-5/10 no-tillage wheat–maize seeder.

Parameters

Rainfall

Rainfall was monitored throughout the experiment by a solar-powered automatic weather station, and data were recorded automatically by data loggers.

Soil sampling and preparation

Soil samples at both sites were collected in October 2007 (at Daxing, after maize harvesting and before wheat seeding; at Changping, fallow). In each plot, 1 soil sample was formed by 5 subsamples for aggregate-stability analysis, soil organic matter (SOM), and available N and P determination, which were taken at 0–0.10, 0.10–0.20, and 0.20–0.30 m depths. Each soil sample was first passed through an 8-mm sieve by gently breaking apart the soil. Clods, pebbles, and aggregates >8 mm were discarded. Five undisturbed soil cores were taken from the same 3 depths in each plot for determination of soil porosity. All the soil samples were air-dried for 24 h in the laboratory before analysis.

Soil organic matter, available N and P

Soil organic matter content of air-dried soil samples was determined by dry combustion (Nelson and Sommers 1982). Nitrate was extracted with 1 M KCl and analysed by the cadmium reduction method (Dorich and Nelson 1984). Available phosphorus was extracted with 0.5 M $NaHCO_3$ solution adjusted to pH 8.5. Concentrations of extracted P were determined by the modified Murphy–Riley ascorbic acid procedure (Olsen and Sommers 1982). All the measurements were replicated 5 times.

Water-stable aggregation

We determined water-stable aggregate distribution by placing the soil samples on a nest of sieves, immersing them directly in water, and agitating the sieves up and down 35 mm at 30 cycles/min for 15 min in a water bath. Proportions of water-stable aggregates >2, 2–1, and 1–0.25 mm, and <0.25 mm (micro-aggregates) were determined (Oades and Waters 1991).

Soil porosity

Soil porosity was classified as aeration porosity (>60 µm) and capillary porosity (<60 µm) (Li *et al*. 2007). Aeration porosity was calculated as the volumetric water content difference (suction) between 0 and –5 kPa (matric potential). Capillary porosity was calculated as the volumetric water content difference between –5 and –1500 kPa matric potential. All measurements were replicated 5 times.

Bulk density

Soil bulk density was progressively determined by the core method (Blake 1965). In each plot, 5 random soil samplers were taken using a 54-mm-diameter steel core sampling tube, manually driven into 0.30 m depth. The soil cores were weighed wet, dried at 105°C for 48 h, and weighed again to determine bulk density.

Yield

Wheat and corn grain yields were determined at 12% moisture content by manually harvesting three 3-m lengths of rows taken randomly in each plot.

Economic benefit

Input (seeds, fertiliser, labour, etc.) quantities and direct cost of all mechanical operations was recorded throughout the field trial, together with the value of outputs (crop yield × value), on a common basis (US$/ha).

Statistical analysis

Mean values were calculated for each of the variables, and ANOVA was used to assess the effects of ST, NT, and CT on the soil parameters and crop yields. Significance of the *F*-value was determined from ANOVA tables. Multiple comparisons of annual mean values were performed by the least significant difference method (l.s.d.). In all analyses, a probability of error <5% ($P < 0.05$) was considered significant. The SPSS analytical software package was used for all the statistical analyses.

Results

Soil organic matter, available N and P

The mean SOM and available N and P in ST, NT, and CT were very similar at the beginning of the experiment in 1999, but significant differences developed across the soil profile during the 8-year experiment (Fig. 3). At Daxing, the average SOM in 2007 in 0–0.10 m layer of ST and NT plots was 12.5% and 10.5% higher, respectively, than that in CT plots. In the 0.10–0.20 m layer, the average SOM in ST and NT soils was 11.2% and 13.6% greater than in the CT treatment. In deeper (0.20–0.30 m) soil layers, however, no significant differences were observed among the tillage treatments.

Results for N and P were similar. In the 0–0.10 m layer, available N and P under ST were 36.5% and 40.2% higher, respectively, than those under CT; those under NT were 45.8% and 48.7% higher. In the 0.10–0.20 m soil layer, available N in ST and NT was 15.3% and 17.1% greater than in CT, and available P was 19.5% greater under ST and 21.6% greater under NT than under CT. Again, no significant difference between treatments was observed in the 0.20–0.30 m layer.

At Changping, in the 0–0.10 and 0.10–0.20 m soil layers, the average SOM under ST was 16.3% and 12.5% higher than under CT, whereas those under NT were 15.3% and 10.5% higher. Again in the 0.20–0.30 m layer, no significant differences between tillage treatments were observed.

Results for available N and P were similar. In the 0–0.10 m layer, available N and P were 36.5% and 40.2% higher under ST, and 45.2% and 50.6% higher under NT, than those under CT, and the improvements for the 0.10–0.20 m layer were 15.3% and 20.5% under ST and 17.1% and 30.5% under NT. Again, no significant differences were apparent in the 0.20–0.30 m layer.

Water-stable aggregates

Soil aggregation is an important determinant of soil fertility and productivity and a key factor in the global carbon (C) cycle (Baldock and Skjemstad 2000). Soil aggregation has a major influence on root development, water and C cycling, and soil resistance to erosion (Kay 1998). Table 3 shows treatment effects on aggregate water stability in our study. At Daxing, in all 3 layers (0–0.10, 0.10–0.20, and 0.20–0.30 m), water-stable aggregates of the largest size class (>2 mm) were 50.0–104.2% higher ($P < 0.05$) under ST and NT than under CT, but the percentage of water-stable aggregates of the smallest size class (<0.25 mm) in ST and NT plots was 9.8–23.2% lower ($P < 0.05$) than that in CT plots.

The results at Changping were similar. With the exception of 0–0.10 m depth, the percentages of water-stable aggregates of the largest size class (>2 mm) in 0.10–0.20 and 0.20–0.30 m soil layers for ST were 109.9% and 40.0% greater ($P < 0.05$) than for CT, respectively. In contrast, the soils under CT treatment had a higher percentage of water-stable aggregates of the smallest size class (<0.25 mm) than the ST treatment. No tillage was associated with a non-significant improvement in water-stable aggregates of the largest size class (>2 mm) compared with conventional tillage.

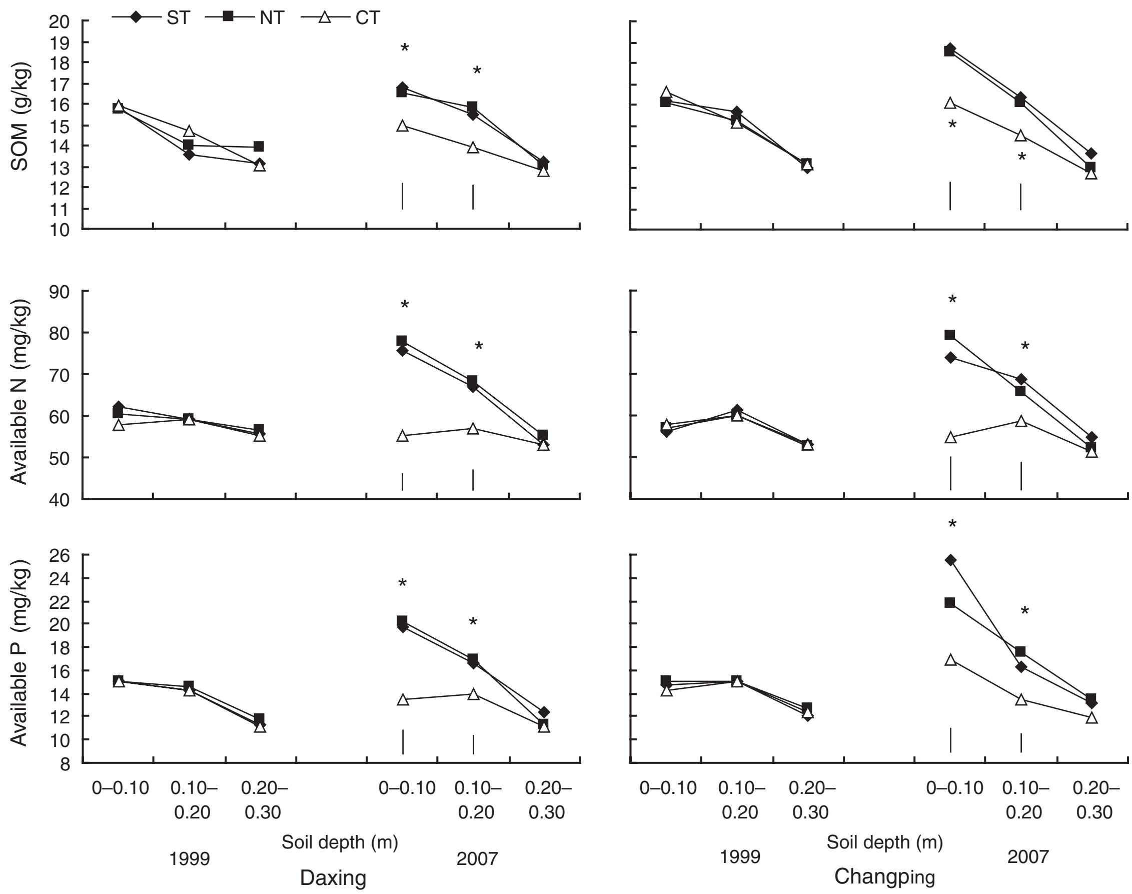

Fig. 3. Soil organic matter (g/kg), available N (mg/kg) and P (mg/kg) for ST, NT, and CT treatments at 0–0.10, 0.10–0.20, and 0.20–0.30 m depths at Daxing and Changping in 1999 and 2007. * Significant difference at $P = 0.05$ among treatments. Vertical bars represent l.s.d. ($P = 0.05$).

Table 3. Soil wet stable aggregate size classes for ST, NT, and CT treatments at 0–0.10, 0.10–0.20, and 0.20–0.30 m depths (%) in Daxing and Changping in 2007

Values within a column followed by the same letter are not significantly different ($P > 0.05$)

Site	Soil depth (m)	Treatment	Aggregate size classes (mm) >2	2–1	1–0.25	<0.25	Macro-aggregates >0.25 mm	Micro-aggregates <0.25 mm
Daxing	0–0.10	ST	13.11a	23.14a	20.09a	43.66a	56.34a	43.66a
		NT	11.56a	18.26a	19.37a	50.81a	49.19a	50.81a
		CT	6.42b	10.37b	26.35b	56.86b	43.14b	56.86b
	0.10–0.20	ST	20.42a	13.74a	19.73a	46.11a	53.89a	46.11a
		NT	17.05a	13.21a	19.35a	50.39a	49.61a	50.39a
		CT	10.03b	12.36a	21.72a	55.89b	44.11b	55.89b
	0.20–0.30	ST	19.76a	17.34a	27.15a	35.75a	64.25a	35.75a
		NT	18.52a	16.35a	26.35a	38.78a	61.22a	38.78a
		CT	12.35b	17.28a	26.04a	44.33b	55.67b	44.33b
Changping	0–0.10	ST	7.23a	13.16a	40.63a	38.98a	61.02a	38.98a
		NT	13.11b	23.14b	20.09b	43.66b	56.34b	43.66b
		CT	11.56b	18.26b	19.37b	50.81b	49.19b	50.81b
	0.10–0.20	ST	12.53a	12.30a	38.96a	36.21a	63.79a	36.21a
		NT	8.95b	11.36a	38.02a	41.67b	58.33b	41.67b
		CT	5.97b	10.28a	37.96a	45.96b	54.04b	45.96b
	0.20–0.30	ST	9.59a	11.48a	38.26a	40.67a	59.33a	40.67a
		NT	7.53b	10.23a	37.12a	45.12b	54.88b	45.12b
		CT	6.85b	9.55a	35.23a	48.38b	51.62b	48.38b

Soil porosity

Research has shown (Golabi *et al*. 1995) that long-term no-tillage crop production practices positively affect the aeration porosity (equivalent pore diameter >60 μm) as well as total porosity of the soil (Table 4). Our results also showed that the ST and NT plots had significantly ($P < 0.05$) greater aeration porosity and total porosity than the CT plots at both sites. The ST and NT treatments registered 14.5% and 10.6% higher aeration porosity than CT at Daxing and 11.7% and 8.6% higher at Changping. Both ST and NT treatments also showed significantly ($P < 0.05$) greater total porosity than CT at both sites, but they did not differ significantly from each other in either aeration porosity or total porosity.

Bulk density

The ANOVA values for the soil bulk density for all 3 treatments and for all the sampling dates from 2000 to 2007 are given in Fig. 4. Soil bulk density was significantly affected by all treatments, as expected. Mean soil bulk densities (0–0.30 m) during the sampling period for ST, NT, and CT were 1.40, 1.41, and 1.42 Mg/m^3, respectively, at the Daxing site, and 1.39, 1.40, and 1.41 Mg/m^3 at the Changping site. The bulk density in conservation tillage (ST, NT) was lower than that in CT, particularly in the last several years of the study (Fig. 4). At Daxing, from 2003 to 2007, ST and NT treatments showed decreased mean soil bulk density by 2.0% and 1.4%, respectively, and the differences in 2004 and 2005 were significant ($P < 0.05$). At Changping, ST and NT showed decreased mean soil bulk density in 2002–07 by 1.5% and 1.2%, respectively, compared with CT, and significant differences were observed in 2005.

Yield

Yields from all treatment plots from 2000 to 2007 at both study sites are presented in Fig. 5. At Daxing, tillage treatments had no effect on winter wheat yields during the first 3 years or on summer maize yields during the first 2 years, but during the remainder of the experiment, yields of both crops were significantly ($P < 0.05$) higher under ST and NT than under CT; yields under ST and NT did not differ significantly. As indicated in Fig. 5, average winter wheat yields in 2004–07 under ST and NT were 438 kg/ha (7.72%) and 423 kg/ha (7.46%) higher than those from CT; those for summer maize were 141 kg/ha (3.31%) and 138 kg/ha (3.24%) higher.

At Changping, tillage treatments significantly affected spring maize yields from 2000 to 2007. Compared with CT, conservation tillage treatments (ST and NT) increased mean (2000–07) spring maize yields by 376 kg/ha (5.80%) and 276 kg/ha (4.25%), respectively, and the improvements were significant ($P < 0.05$) in 5 of 8 years. Again, the differences between ST and NT were non-significant during the whole experiment.

Table 4. Soil porosity ($cm^3/100\,cm^3$) for ST, NT, and CT treatments at 0–0.30 m depth in Daxing and Changping in 2007

Values within a column followed by the same letter are not significantly different ($P > 0.05$)

Treatment	Total porosity	Aeration porosity (>60 μm)	Capillary porosity (<60 μm)
		Daxing	
ST	52.36a	42.64a	9.72a
NT	51.86a	41.19a	10.67a
CT	45.58b	37.24b	8.34a
		Changping	
ST	54.25a	46.32a	7.93a
NT	53.01a	42.99a	10.02a
CT	45.74b	39.59b	6.15a

Economic benefit

Mean annual input costs for the 3 treatments varied from US$766/ha in NT to $979/ha in CT at Daxing and from $415/ha in NT to $511/ha in CT at Changping, respectively (Table 5). ST and NT treatments cost less with reduced mechanical operation costs and labour. Mean crop yields of ST and NT were also greater than CT, so the farmer profits for ST and NT treatments were, respectively, 31.2% and 35.8% greater at Daxing and 19.8% and 24.2% greater at Changping than those of CT. However, the difference between ST and NT in farmer income was slight at both Daxing ($40/ha) and Changping ($26/ha).

Discussion

The experiments conducted from 2000 to 2007 clearly demonstrate that conservation tillage practices (ST and NT) were associated with a substantial and significant improvement

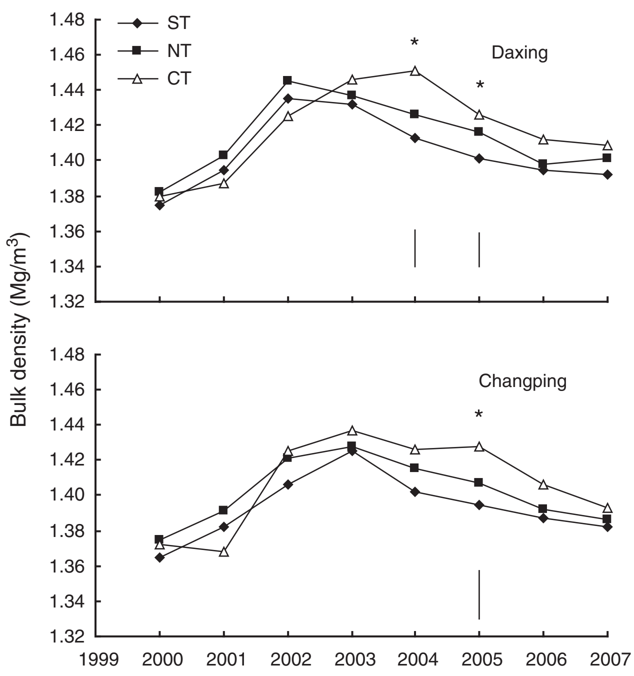

Fig. 4. Mean bulk density (Mg/m^3) to depth 0.30 m for ST, NT, and CT treatments at Daxing and Changping. Samples were taken immediately after maize harvesting in both sites. * Significant difference at $P = 0.05$ among treatments. Vertical bars represent l.s.d. ($P = 0.05$).

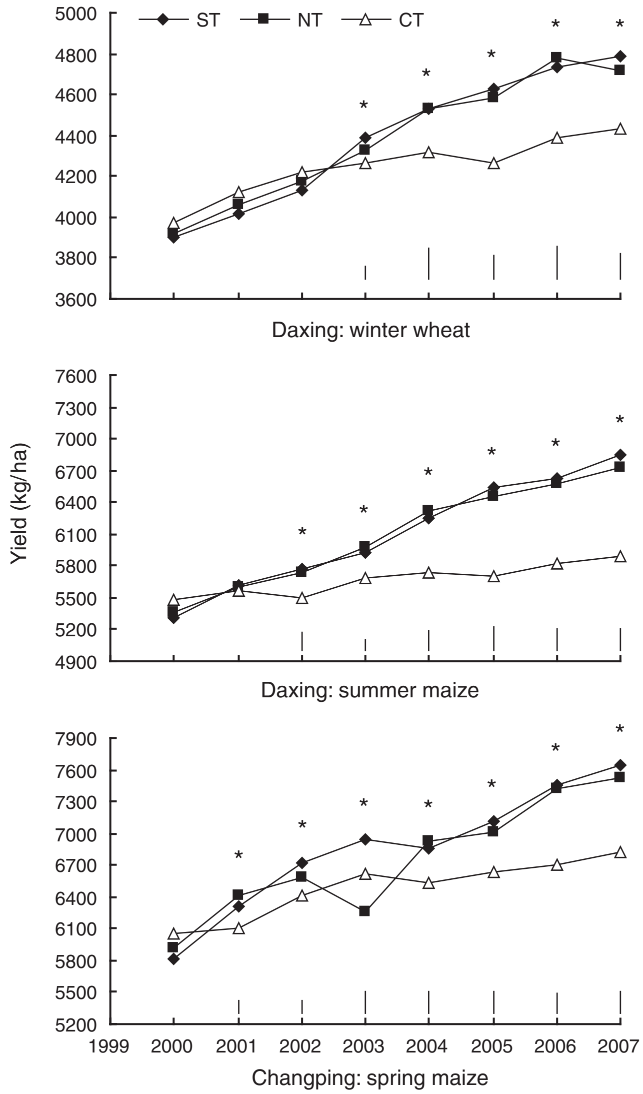

Fig. 5. Crop yield (kg/ha) for ST, NT, and CT treatments at Daxing and Changping from 2000 to 2007. * Significant difference at $P = 0.05$ among treatments. Vertical bars represent l.s.d. ($P = 0.05$).

in soil structure, nutrient status and yields in both 2-crop and 1-crop per year regions of Beijing, compared with conventional tillage. In both Daxing and Changping, the significantly higher SOM in the ST and NT treatments was attributed to reduced biological oxidation of soil organic C to CO_2, increased carbon input from residue retention, and less soil disturbance (Brevik *et al*. 2002). On the other hand, frequent and excessive tillage and residue removal in CT treatment resulted in significant SOM loss. Tillage-induced changes in soil organic N are often directly related to changes in soil organic C. ST and NT had significantly ($P < 0.05$) higher concentrations of available N in the surface soil layers (0–0.10 and 0.10–0.20 m), while deeper layers (0.20–0.30 m) were not affected. Soil available P was also significantly ($P < 0.05$) improved under ST and NT, mostly in the soil depth of 0–0.20 m. The topsoil accumulation of P in ST and NT can be explained by the limited downward movement of particle-bound P in no-till and minimum-till soils and the upward movement of nutrients from deeper layers through uptake by roots (Urioste *et al*. 2006). In the North China Plain, Huang *et al*. (2006) reported that sub-soiling tillage and no-tillage improved soil organic matter by ~6.0% and 4.0% in the top 0.20 m compared with traditional tillage. Roldan *et al*. (2005) reported that no-tillage and sub-soiling treatments increased SOM by up to 15% in the 0–50 mm layer in Mexico. The significant increases of available N and P in conservation tillage treatments were also consistent with the findings of other researchers (Campbell *et al*. 1998; Díaz-Zorita and Grove 2002; Thomas *et al*. 2007).

Greater benefits of soil C, N, and P in conservation tillage treatments (ST and NT) were observed at Changping than at Daxing, probably because 1-season spring maize in Changping consumed less soil nutrient than 2 seasons of winter wheat and summer maize per year at Daxing. Our data also showed that sub-soiling tillage offered little benefit to soil fertility compared with no tillage in both 2- and 1-crop-a-year regions of Beijing. In 2007 at Daxing, ST slightly increased mean SOM and available P by 0.4% and 0.9%, respectively, in the 0–0.30 m layer relative to NT. At Changping, the ST treatment showed only a slight improvement in SOM and available P compared with NT, similar to the findings of Li *et al*. (2006).

Table 5. Economic benefit analysis for ST, NT, and CT treatments in Daxing and Changping

Data for mechanical operation cost, water, and yield are the mean values from 2000 to 2007. Values are in US$

	Daxing						Changping		
	ST		NT		CT		ST	NT	CT
	Wheat	Maize	Wheat	Maize	Wheat	Maize	Maize	Maize	Maize
Inputs									
Seed ($/ha)	55	38	55	38	55	38	43	43	43
Fertiliser ($/ha)	165	107	165	107	165	107	176	176	176
Herbicide ($/ha)	0	26	0	26	0	26	35	35	35
Mechanical operation cost ($/ha)	129	193	129	150	225	225	193	150	225
Water and labour ($/ha)	68	28	68	28	89	49	11	11	32
Total ($/ha)	809		766		979		458	415	511
Outputs									
Yield (kg/ha)	4390	6111	4386	6097	4249	5674	6860	6760	6484
Price ($/kg)	0.21	0.17	0.21	0.17	0.21	0.17	0.17	0.17	0.17
Income ($/ha)	1961		1958		1857		1166	1149	1102
Farmer income ($/ha)	1152		1192		878		708	734	591

Conservation tillage practices (ST and NT) were associated with a greater percentage of macro-aggregates (>0.25 mm) than CT. Mean macro-aggregates in 0–0.30 m soil depth at Daxing were 22.1% and 12.0% greater under ST and NT than CT, and the improvements at Changping were 18.9% under ST and 9.5% under NT. These results were consistent with the increase in aggregation occurring as a result of greater biological activity in minimum tillage soils, demonstrated by Tisdall and Oades (1982), and with a reduction in breakdown of surface soil aggregates as a result of residue cover of soil surface and the absence of tillage (Oyedele *et al*. 1999). These findings are similar to the results of Six *et al*. (1998) and Gale *et al*. (2000). Notably, the percentage macro-aggregates (>0.25 mm) in the 0–0.30 m soil depth at Changping for ST was ~8.6% higher ($P < 0.05$) than for NT, but the difference between ST and NT at Daxing was not pronounced, which indicated that the positive effects of sub-soiling tillage on soil aggregates were greater in 1-crop-a-year regions.

Results for both sites illustrate the significant effects of conservation tillage treatments on mean aeration porosity in the top 0–0.30 m, compared with conventionally tilled soil. Mean effects on capillary porosity are smaller, but consistently positive. This improvement in soil porosity under conservation tillage is most probably related to beneficial effects of soil organic matter (Fig. 3) caused by minimum tillage and residue cover. The increased porosity is especially important to crop development since it may have a direct effect on soil aeration and enhances root growth (Oliveira and Merwin 2001). The improved root growth hence increases plant water as well as nutrient uptake. Within the conservation tillage treatments, ST produced more aeration porosity than NT, but the effect on capillary porosity appeared to be reversed in the 0–0.30 m soil layer. The significant improvement in macropore volume in the ST treatment is consistent with the findings of Xu and Mermoud (2001), who also demonstrated that sub-soiling tillage significantly increased the volume of the larger pores (>50 µm diameter) in the 0–0.40 m soil layer compared with no-tillage in the North China Plain.

The changes in soil bulk density in 0–0.30 m soil layer are consistent with the porosity results at that layer. After 8 years of different management, the mean soil bulk density in 2007 was 0.8–1.5% lower in ST and NT treatments than in CT at Daxing and Changping. The reduced bulk density in ST and NT could be attributed to higher organic matter content and better aggregation (Tiarks *et al*. 1974; Schjonning *et al*. 1994). Crop residue retention has been reported to increase soil organic carbon and biotic activity (Lal 1989; Karlen *et al*. 1994), thereby decreasing bulk density, particularly near the soil surface in the ST and NT plots under investigation. Dao (1996) also found that increased crop residue led to decreased bulk density in the 0–50 mm layer and that conventional tillage initially decreased bulk density, but the conservation tillage treatment had a lower bulk density than the conventional tillage by the end of the growing season. The bulk density values in our study also showed that sub-soiling tillage could eliminate the soil compaction caused by random traffic relative to no tillage, but the effects were not significant during the experimental years in both Daxing and Changping, confirming the findings of Jin *et al*. (2007) in the Chinese Loess Plateau.

In our study, the improved soil chemical and physical properties were probably responsible for the increased crop yields in the conservation tillage treatments (ST and NT) in both sites. Also the 2–3 days earlier planting was responsible for higher yields under conservation tillage in the 2-crop-a-year region of Daxing. As reported by Liao *et al*. (2002) and Xue *et al*. (2005), conservation tillage treatments have been shown to increase crop yield considerably. Wesley *et al*. (2001) also emphasised that sub-soiling in a non-irrigated environment recorded 46% greater soybean yield and net return than conventionally tilled fields. Our results also agree with those of Li *et al*. (2005). Compared with NT treatment, ST produced the higher crop yields at both sites. Consequently, although it resulted in an increased mechanical operation cost due to sub-soiling tillage, ST still had similar economic benefits to NT and improved farmer incomes by US$274/ha at Daxing and US$117/ha at Changping compared with CT.

Conclusions

This study clearly indicated that long-term (8 years) conservation tillage practices (no-tillage or sub-soiling, residue cover) induced an increase in soil quality and higher crop yield in both annual mono-cropping and dual-crop rotation in the area around Beijing. The enhanced parameters included SOM and available N and P of the soils under study. Despite higher mechanical operation cost and similar economic benefits, the integrated effects for sub-soiling tillage treatment were better than for no tillage treatment at both sites. Through the adoption of sub-soiling tillage, mean macro-aggregates (>0.25 mm) could be improved by 9.0%, mean aeration porosity (>60 µm) increased by 5.6%, mean bulk density (8 years) reduced by 0.7%, and mean yield increased by 0.7% under conservation tillage farming systems. Sub-soiling tillage could therefore be a significant improvement for current farming under conservation tillage, and make an important contribution to improve soil properties and crop yields. While the results on the use of sub-soiling tillage in this study are encouraging, further long-term research on soil sensitivity to compaction and the relationships between conservation tillage, soil structure, crop productivity, and environmental integrity is needed for Beijing and similar areas in China.

Acknowledgments

This work was financed by Australian Centre for International Agricultural Research (ACIAR) and Ministry of Agriculture (MOA), China. We are grateful to Mr Mao Ning and Mr Wang Shudong for managing the field experiments. Our thanks also go to all the postgraduate students working in Conservation Tillage Research Centre of MOA, who provided their input to this study.

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Manuscript received 3 May 2008, accepted 2 February 2009