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Effect of alternative tillage and residue cover on yield and water use efficiency in annual double cropping system in North China Plain

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ABSTRACT

In the annual double cropping areas of North China Plain, low crop yield and water availability are the main limiting factors to crop production. Conservation tillage has been proposed to improve water conservation and sustain soil productivity. The objectives of the study were to compare conservation tillage (CT) with conventional tillage (CV) under the current double cropping system of corn-winter wheat in the Hebei, North China Plain. The field study consisted of eight conservation tillage treatments and two conventional tillage treatments, with different surface ground cover (0%, 50% and 100%). The tillage treatments consisted of no-till, subsoiling, rototilling and plowing. The CT treatments maintained soil temperatures that were approximately 0.4 °C greater during cold condition and about 0.5 °C lower during warm condition at 5 and 10 cm soil depths than the CV treatments, respectively. The greatest differences were achieved by the double no-till system with 100% residue cover treatment in terms of soil temperature and crop growth. Winter wheat yield and water use efficiency (WUE) were improved by 6.7% and 30.1% with CT compared to the CV treatments, and for corn, 8.9% and 6.8%, respectively. We conclude that conservation tillage for the annual double cropping system is feasible, and the double no-till with 100% residue cover is the most effective way of improving crop yields and WUE on the North China Plain.

1. Introduction

China has the highest population and is the largest producer (by volume) of agricultural products. According to data from the national land and resources survey of the Ministry of Land and Resource, only 122 million hectares land or 10% of total land area of China is arable and the per capita arable land area was only 0.09 ha in 2005 (MLR, 2005). Furthermore, the population rate is 10 million people per year. The total population of China reached 1.30 billion in 2005. Therefore, China has to feed 22% of the world's population on only 7% of global arable land (NBSC, 2005). Food security can only be sustained with intensified cropping practices, more efficient use of resources and protection of the soil resource.

As the main agricultural production base, the North China Plain, which includes the provinces of Hebei, Henan, Shandong, Beijing, and Tianjin, has about 18 million hectares of farmland (18.3% of the national total) and represents 20% of total food production in China (Sun et al., 2007). Since the 1980s, in order to ensure national food security, the cropping system on the North China Plain has changed from a single to a double-cropping system (Liu, 2004). Double cropping corn and winter wheat with an average total yearly yield of 15 t ha^{-1} (Li et al., 1997), is the main cropping system used on the North China Plain. In this cropping system, corn is seeded in early June, immediately after the winter wheat harvest and harvested in the middle September; winter wheat is then seeded in early October and harvested in the following June. Conventional tillage is the commonly used practice for this double cropping system. However, serious problems with soil degradation are experienced, resulting in decreased crop yields and low water use efficiency (Zhou, 2001). Wind and water erosion experienced with conventional tillage threatens long-term agricultural sustainability on the North China Plain (Wang et al., 2001b; Zhou et al., 2001). In other countries with similar growing conditions, results with conservation tillage using either minimum-till or no-till to maximize residue cover demonstrated the sustainability of these cropping systems (Boone, 1988; Derpsch, 1998; Lampurlanes et al., 2002). It is postulated that conservation tillage will be necessary to sustain crop production on the North China Plain.

Research with annual cropping systems has generally confirmed improvements in soil moisture, water use efficiency, crop

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yield and economic benefit with conservation tillage. Gao et al. (1999, 2003) and Liao et al. (2002) demonstrated that conservation tillage increased soil moisture and water use efficiency of winter wheat in the Shanxi and Shaanxi provinces. Results from other studies also reported that no-tillage systems were effective in improving soil structure and increasing crop yield in northern China (Gao et al., 2000; Zang and Gao, 2003; Su et al., 2004). The application of conservation tillage was also shown to reduce production costs and increase farm income (Fang et al., 2003).

Most of these studies, however, have shown the effects of conservation tillage in single annual cropping systems. Few countries have adopted conservation tillage for double copping systems. The success of conservation tillage with double cropping systems has been demonstrated in southern Brazil and Paraguay (Derpsch, 2007). More evaluations of conservation tillage effects on overall crop production are required for double cropping systems in the North Plain of China (Gao, 2002). The objectives were to evaluate tillage/residue systems and their effects on crop yield, crop water use and crop water use efficiency for the annual double cropping system in Northern China.

2. Materials and methods

2.1. Site and climatic conditions

The experiment was conducted in Dingxing County (39°5′–39°20′N, 115°30′–115°58′E), situated in northern Hebei province, North China Plain, in 2002 and 2003. Dingxing is located in a typically semi-arid region and has a continental climate. Average annual temperature for this area is 11.7 °C with 185 frost-free days. The average annual rainfall is 552 mm with 80% falling in June, July, August and September. Annual evaporation is reported as 1712 mm. The soil was a light loam with a clay proportion of 27.8%, silt 38.4% and sand 33.8%, and a pH of 7.9. In the top 40 cm layer, soil bulk density was 1.34 Mg m^{-3}, and soil organic matter determined from soil organic C using the Walkley–Black wet oxidation method was 8.8 g kg^{-1} (Nelson and Sommers, 1982). The soil water content at field capacity and wilting point were 30% and 6.8% by weight, respectively.

2.2. Experimental design and crop management

The experiment included three replicates of each treatment in a randomized complete block design. Each plot was 4 m wide and 100 m long. The treatments consisted of a total of eight conservation tillage (CT) treatments and two conventional tillage (CV) treatments. In Dingxing, mouldboard plowing and all residue removed are adopted widely by farmers in the conventional tillage systems. While in conservation tillage systems, no-till, subsoiling + no-till, rototilling + no-till and half or full of residue cover are the most popular tillage and residue cover practices, respectively. So in our experiment, the ten treatments combined the crop residue retention involving 0%, 50% and 100% surface residue cover and specific tillage operations (no-till, subsoiling, rototilling and plowing). Residue cover was calculated on a mass basis as a percentage of the amount of residue necessary for complete ground cover. The three kinds of surface residue cover were generated as follows:

- 0%. All the wheat or maize residues were manually removed after harvesting.
- 50%. Half of wheat stalk were cut by the harvester, then manually removed after harvesting, and the rest in place were retained as stubble. Half of corn stalks were cut and removed by hands, and the rest were chopped and left as mulch.
- 100%. All the wheat or maize residues were retained as mulch after harvesting.

The complete list of treatments and operation schedules for ten treatments are provided in Tables 1 and 2. Before the start of the study, all the conventional tillage plots were managed by plowing with all residue removed. The conservation tillage plots had been managed with no-till and 50% residue cover since October 2001, and the eight conservation tillage treatments were imposed at the beginning of the experiment after one season's winter wheat production in June 2002.

The winter wheat and corn varieties used in the experiment were Chaoyou 66 and Jidan 26, respectively, which are the two most widely seeded commercial varieties. The study was carried out for 1.5 cycles, two crops of corn and one crop of winter wheat. Corn seeding dates were 15 June 2002 and 17 June 2003 and harvesting dates were 4 October 2002 and 6 October 2003. Winter wheat was grown during the period of 7 October 2002 to 15 June 2003. In Dingxing, seed and fertiliser are commonly applied at very high rates by farmers to maximise the chance of good yields. In this study, winter wheat was seeded at 5 cm depth with a seedling density of 500 plants per m^2. The $CO(NH_2)_2$, $(NH_4)_2HPO_4$ and KCl (K_2O content: 60%) fertilizers placed by seeder at 10 cm depth in seeding row were applied to provide 79 kg N/ha, 88 kg P/ha and 37 kg K/ha as the basal fertilizer at planting and the $CO(NH_2)_2$ was broadcasted to provide 61 kg N/ha at first node stage. Corn was seeded at 5 cm depth with a sowing density of 7 plants/m^2 and a complete fertilizer (N-P_2O_5-K_2O) placed by seeder at 10 cm depth in seeding row was applied at the rate of 75 kg N/ha, 37.5 kg P/ha and 37.5 kg K/ha at planting. Weeds within corn growing season were controlled by means of specific herbicides: glyphosate (2.50 kg ai ha^{-1}) + acetochlar (2.25 kg ai ha^{-1}).

Table 1
Summary of the 10 tillage and residue cover treatments under investigation.

	Treatment identifiers	Corn		Wheat	
		Wheat residue cover	Tillage	Chopped corn stalk cover (%)	Tillage
Conservation tillage (CT)	a	100	No-till	100	No-till
	b	100	No-till	100	Rototilling
	c	100	No-till	100	Subsoiling
	d	50	No-till	100	Subsoiling
	e	100	Subsoiling	100	No-till
	f	100	Subsoiling	100	Rototilling
	g	100	Subsoiling	50	No-till
	h	100	Subsoiling	0	No-till
Conventional tillage (CV)	i	100	No-till	0	Plowing
	j	0	Plowing	0	Plowing

0%, no residue cover; 50%, half residue cover; 100%, all residue cover.

Table 2
The main operation schedules for 10 treatments.

Treatment identifiers	Schedule
a	No-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, no-till seeding of winter wheat (100% chopped corn stalk cover)-irrigation-harvesting of winter wheat
b	No-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, rototilling (to 5 cm depth), no-till seeding of winter wheat (100% chopped corn stalk cover)-irrigation-harvesting of winter wheat
c	No-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, subsoiling (to 30 cm depth), no-till seeding of winter wheat (100% chopped corn stalk cover)-irrigation-harvesting of winter wheat
d	No-till seeding of corn (50% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, subsoiling (to 30 cm depth), no-till seeding of winter wheat (100% chopped corn stalk cover)-irrigation-harvesting of winter wheat
e	Subsoiling (to 30 cm depth), no-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, no-till seeding of winter wheat (100% chopped corn stalk cover)-irrigation-harvesting of winter wheat
f	Subsoiling (to 30 cm depth), no-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, rototilling (to 5 cm depth), no-till seeding of winter wheat (100% chopped corn stalk cover)-irrigation-harvesting of winter wheat
g	Subsoiling (to 30 cm depth), no-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-chopping corn stalk, no-till seeding of winter wheat (50% chopped corn stalk cover)-irrigation-harvesting of winter wheat
h	Subsoiling (to 30 cm depth), no-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-manually removing all the corn stalks, no-till seeding of winter wheat (no corn residue cover)-irrigation-harvesting of winter wheat
i	No-till seeding of corn (100% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-manually removing all the corn stalks, plowing (to 20 cm depth), seeding of winter wheat (no corn residue cover)-irrigation-harvesting of winter wheat
j	Plowing (to 20 cm depth), seeding of corn (0% wheat straw cover)-chemical weed control-irrigation-harvesting of corn-manually removing all the corn stalks, plowing (to 20 cm depth), seeding of winter wheat (no corn residue cover)-irrigation-harvesting of winter wheat

Four irrigation applications were applied to winter wheat. During the winter dormancy, stem-elongation, heading and grain-filling stages, plots were irrigated when the soil water content in the upper 40, 60, 80 and 100 cm soil profiles reached 60% of field capacity, respectively. While for corn, irrigation was applied at stem-elongation stage and plots were irrigated when the soil water content in the up 100 cm soil profile reached 60% of field capacity. Irrigation was applied by the tubes and irrigation amount was recorded by a flow meter.

2.3. Equipment

The 2BMFS-5/10 no-till wheat-corn seeder (Fig. 1a) matched with a 37 kW class tractor was used for seeding corn and winter wheat and for all treatments of the study. A fluted roller type seed metering system was used for wheat and corn. This machine cleans strips by residue chopping and rotary hoeing before knife type tine openers, so the seeder can no-till plant winter wheat after corn. The metal presswheels are used to place and firm the seed and fertilizer at depths of 5 and 10 cm, respectively. The planting machine seeds 10 rows of winter wheat or 5 rows of corn. In winter wheat seeding, the 10 openers are spaced to alternate between 11 and 39 cm to achieve maximum residue clearance. The row spacing used in corn was 50 cm.

Subsoiling treatments were carried out with a subsoiler with adjustable wings designed by China Agricultural University (Fig. 1b). The machine operates an anti-blocking disk, a soil leveling device and a subsoiling chisel with adjustable wings. The front disk cuts crop residues in the subsoiling line thus preventing blockage around the tine. The subsoiling chisel, with two symmetrical wings, is able to loosen soil on a large scale without soil inversion. Through controlling the bolts, the vertical position of two symmetrical wings in the subsoiling tool can be adjusted according to different soil conditions. The soil leveling device after subsoiling chisel is used to compact the soils and ensure the evenness of subsoiling row.

2.4. Variables measured

Rainfall was monitored throughout the experimental period with a solar-powered automatic weather station (WeatherMaster® 2000-Environdata Pty Ltd., QLD, Australia).

Soil temperature was measured using model 125 WatchDog data loggers with external soil temperature thermocouples. The thermocouples have the ability to record soil temperatures with accuracy of ±0.2 °C. Soil temperatures were recorded every 3 days for the 5 and 10 cm soil depths at 8:00 h from 8 October to 7 November 2002 during the growth season of winter wheat, whereas for corn soil temperatures were recorded for the 5 and 10 cm soil depths at 14:00 h from 18 June to 18 July 2003. In each plot, six thermocouples were placed in-row at 5 and 10 cm soil depths (three for each soil depth) for all treatments. The data loggers were mounted on fiberglass poles 1 m above the ground.

For soil water determinations, soil cores samples were taken randomly using a 54 mm diameter steel core sampling tube, manually driven into the soil. The soil cores were weighed wet, dried at 105 °C for 48 h, and weighed again to determine gravimetric soil water content and bulk density. Gravimetric water content was multiplied by soil bulk density to obtain volumetric water content.

Aboveground (shoot) and root samples were taken at stem-elongation and maturation stages for corn and stem-elongation and grain-filling stages for winter wheat from three areas (1 m^2) per plot, respectively. Roots were dug out and collected in a 40 cm deep soil depth. All samples were oven-dried at 65 °C to constant weight and weighed to determine shoot biomass and root dry weight.

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

Evapotranspiration (*ET*) is usually calculated using the water balance equation:

$$ET = (P + I) - \Delta S \quad (1)$$

where *P* is growing seasonal rainfall (mm), *I* is irrigation (mm) and ΔS is the change in stored soil water of the soil profile. ΔS (mm) was taken as the difference between the initial (seeding) and final (harvesting) water content of the 100 cm soil profile during the growing period.

Water use efficiency (WUE) is calculated as the crop yield (kg ha^{-1}) divided by the growing-season evapotranspiration

Fig. 1. The 2BMFS-5/10 no-till wheat-maize seeder (a) and subsoiler with adjustable wings (b).

(mm):

$$\mathrm{WUE} = \frac{\mathrm{Yield}}{ET}. \quad (2)$$

2.5. Statistical analysis

The SPSS analytical software package (2003) was used for all of the statistical analyses. Mean values and standard errors (SE) were calculated for each set of measurements, and ANOVA used to assess treatment effects on the measured variables. Means were declared significantly different using a protected LSD (0.05) value.

3. Results and discussion

3.1. Soil temperature

The soil temperature measurements for 5 and 10 cm soil depths at 8:00 h from 8 October to 7 November for 10 treatments in 2002 are presented in Fig. 2. Using daily temperature measurements taken in the morning at 8:00 h, the 30 day mean soil temperatures at 5 and 10 cm depths were 7.1 ± 0.80 and 7.9 ± 0.68 °C under conservation tillage treatments (a–h) and 6.5 ± 0.69 and 7.3 ± 0.65 °C for the conventional tillage treatments (i and j) after winter wheat planting and the mean soil temperature at 5 and 10 cm depths in soils under CT was approximately 0.6 and 0.6 °C greater than under CV, but the differences were non-significant ($P < 0.05$) in most of 30 days. Among the CT treatments, the mean soil temperatures at 5 and 10 cm depths in 4 of 5 treatments with 100% residue cover for both crops (a, b, c and f) were higher (0.3–0.9 °C) than in 50% (d and g) and 0% (h) residue cover treatments and the differences were highest from 25 to 30 days after winter wheat seeding. Under 100% residue cover for both crops, soil temperature associated with double no-till treatment (a) increased mean soil temperature by 0.3–0.8 °C at 5 cm depth and by 0.3–0.7 °C at 10 cm depth as compared to subsoiling and rototilling treatments (b, c, e, and f), respectively. Our results indicated that residue cover with no-till, particularly the treatment of double no-till with 100% residue cover (a) appears to keep the heat and enhance soil temperature under cold weather conditions.

Soil temperature in relation to tillage/straw practices at 14:00 h during the summer showed an opposite trend to the daily results collected in October at 8:00 h (Fig. 3). The mean soil temperature at 14:00 h for 50% of CT treatments was 0.4–1.0 °C lower than for CV treatments in corn post-planting. In the 100% residue cover treatments of a, b, c and e, the mean soil temperature was lower by 0.3–1.0 and 0.3–0.8 °C at the 5 and 10 cm depths when compared to the treatments consisting of 50% (d and g) and 0% (h) residue cover, respectively. In 100% residue cover for both crops treatments, soil temperature at 5 and 10 cm depths in double no-till treatment (a) was 0.5–0.8 and 0.4–0.7 °C lower than that in 3 out of 4 subsoiling and rototilling treatments (b, e, and f), respectively. This would suggest that the 100% residue cover with no-till modulated the soil temperatures such that lower temperatures were observed. During the growth period of corn, the air

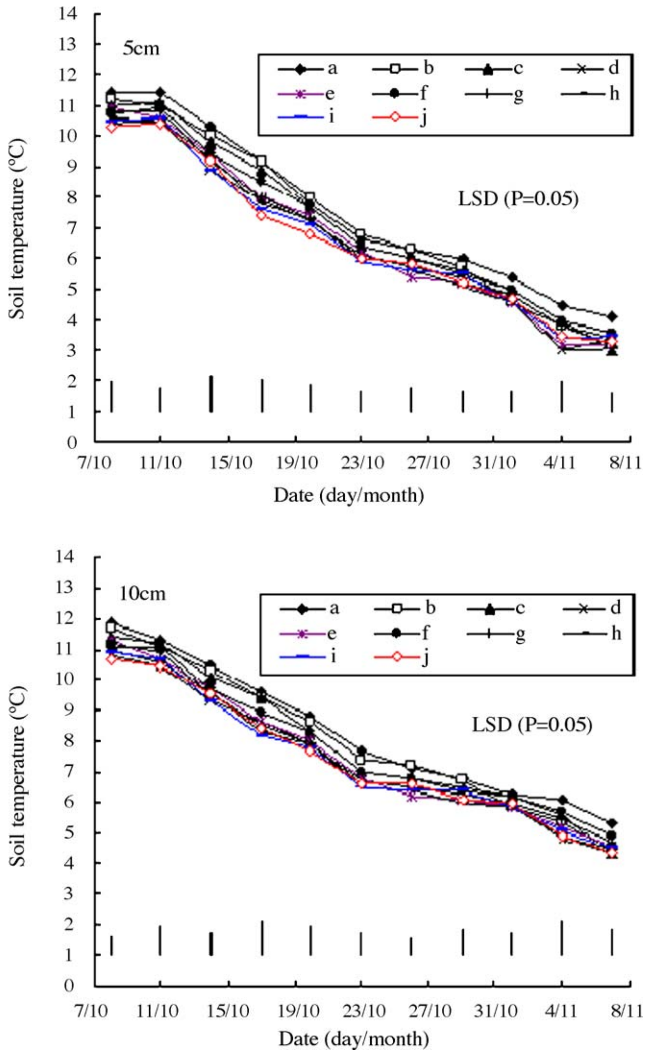

Fig. 2. Soil temperature at 5 and 10 cm soil depths as influenced by different treatments at 08:00 h from 8 October to 7 November 2002 in the growth season of winter wheat.

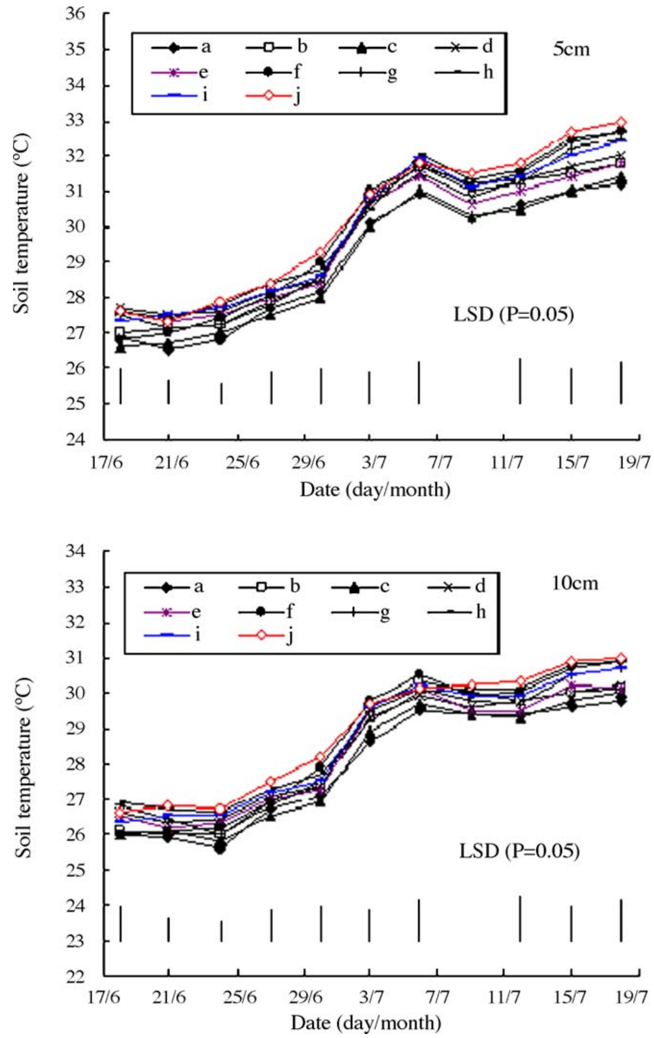

Fig. 3. Soil temperature at 5 and 10 cm soil depths as influenced by different treatments at 14:00 h from 18 June to 18 July 2003 in the growth season of corn.

temperature in North China Plain is very high, and lower soil temperatures in the conservation tillage plots have been shown to be important for corn growth and grain yield (Liu, 2004). These results are consistent with another two-year soil temperature experiment conducted in Hengshui, North China Plain, which demonstrated that compared with traditional plowing, no-tillage with straw cover could increase soil temperature by about 2 °C in November and decrease soil temperature by approximately 2 °C in July in the 0–20 cm soil layer. This may explain the increased grain yields of 2.4% (Wang et al., 2001a).

3.2. Crop growth

Winter wheat growth on conservation tillage was faster than that of conventional tillage treatments (Table 3), possibly because of the effects of more favorable soil conditions (e.g. more comfortable soil temperature, higher soil moisture) induced by residue cover and less soil disturbance on seedling development. Compared with the CV treatments, CT increased shoot biomass at the stem-elongation stage by 15.7%. In the grain-filling stage, improvements in shoot and root biomass of CT treatments were 5.9% and 5.3% higher than the CV treatments, respectively. Furthermore, the CT treatment of double no-till with 100% residue cover (a) produced higher winter wheat biomass at both the elongation and grain-filling stages than the CV treatments.

Similar results were observed for corn (Table 4). Compared with CV, CT increased shoot biomass at the elongation stage by 7% and root biomass at maturity by 3%. In the conservation tillage treatments, corn biomass in the 100% residue cover for both crops treatments (a, b, c, e and f) was higher while in the 50% (d and g) and 0% (h) residue cover treatments, the biomass was lower. The highest corn biomass was observed for the treatment of double no-till with 100% residue cover (a). At the stem-elongation stage, the double no-till with 100% residue cover (treatment a) had 13% greater shoot biomass and 15% more root biomass compared to 50% and 0% residue cover treatments. At maturity, these differences were 14.0% and 4.8%, respectively. The positive effects of residue cover were similar to a two-year experiment conducted by Fu et al. (2005), who observed an increase in shoot biomass with a 100 percent residue cover compared to no residue cover, also on the North China Plain.

3.3. Grain yield and some yield components

Winter wheat yield and some yield components were affected by tillage/residue treatments in the first growing season of 2002–2003 (Table 5). The mean yields for CT and CV treatments were 4.6 and 4.5 t ha^{-1}, and CT treatments increased 2.2% of winter wheat

Table 3
Shoot biomass (t ha^{-1}) and root dry weight (t ha^{-1}) for winter wheat under 10 treatments in stem-elongation stage (March) and grain-filling stage (May) in 2003.

Treatments identifiers		Stem-elongation stage		Grain-filling stage	
		Shoot biomass	Root dry weight	Shoot biomass	Root dry weight
Conservation tillage (CT)	a	4.1^{ac}	1.45^{a}	16.4^{a}	3.11^{bc}
	b	4.0^{ac}	1.15^{cde}	14.1^{bcd}	3.25^{ab}
	c	5.5^{b}	1.15^{cde}	15.5^{ab}	3.15^{bc}
	d	3.1^{d}	1.34^{ab}	13.6^{cd}	3.34^{a}
	e	3.5^{cd}	1.06^{de}	13.1^{d}	2.91^{d}
	f	4.5^{ab}	1.21^{bcd}	12.6^{d}	2.86^{d}
	g	3.2^{d}	1.01^{e}	14.1^{bcd}	3.20^{ab}
	h	4.5^{ab}	1.39^{a}	15.0^{abc}	3.11^{bc}
Conventional tillage (CV)	i	3.9^{ac}	1.29^{abc}	13.9^{bcd}	3.01^{cd}
	j	3.1^{d}	1.20^{bcd}	13.1^{d}	2.91^{d}

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

Table 4
Shoot biomass (t ha^{-1}) and root dry weight (t ha^{-1}) for corn under 10 treatments in stem-elongation stage (July) and maturing stage (October) in 2003.

Treatments identifiers		Stem-elongation stage		Maturation stage	
		Shoot biomass	Root dry weight	Shoot biomass	Root dry weight
Conservation tillage (CT)	a	13.2^{a}	0.185^{a}	6.99^{a}	2.905^{ab}
	b	12.5^{ab}	0.175^{ab}	6.49^{bc}	2.945^{ab}
	c	12.1^{b}	0.165^{bc}	5.85^{d}	3.015^{a}
	d	10.1^{d}	0.165^{bc}	5.38^{e}	2.820^{bcd}
	e	12.7^{a}	0.135^{d}	6.65^{abc}	2.860^{bc}
	f	12.4^{ab}	0.150^{cd}	6.92^{ab}	3.015^{a}
	g	12.4^{ab}	0.165^{bc}	6.25^{cd}	2.780^{cd}
	h	12.6^{ab}	0.155^{c}	6.77^{ab}	2.715^{d}
Conventional tillage (CV)	i	11.9^{b}	0.160^{bc}	6.52^{abc}	2.780^{cd}
	j	11.0^{c}	0.160^{bc}	6.30^{cd}	2.815^{bcd}

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

yield as compared to CV treatments. The greater yield was associated with better yield components. The mean grains per spike and thousand kernel weight for CT treatments were 3.0% and 6.3% higher than for CV treatments, respectively. In the CT treatments, winter wheat under 100% and 50% residue cover had similar mean grain yield, both higher than that under 0% residue cover. Furthermore, 3 out of 5 100% residue cover treatments (a, b and e) showed significantly ($P < 0.05$) higher winter wheat yield and yield components.

In corn production, there was statistical treatment effect and treatment × year interaction but no significant year effect for yield and some yield components (Table 6). In the first growing season of 2002 (year 1), CT treatments produced yield that were 5.7% higher than on CV treatments. In the CT treatments, 100% and 50% residue cover improved corn yields by 5.1% and 5.6% relative to 0% residue cover, respectively, and the highest corn yield (9.9 t ha^{-1}) was observed in double no-till with 100% residue cover (treatment a). Furthermore, compared with 0% residue cover, double no-till with 100% residue cover also increased 8.7%, 5.2% and 6.6% of kernel rows per ear, kernel numbers per row and hundred kernel weight, respectively. In the second growing season of 2003 (year 2), the yield advantages in CT were negligible as compared to CV treatments. However, the double no-till with 100% residue cover (treatment a) again produced the highest yield and significantly ($P < 0.05$) enhanced 6.8% of mean corn yield in comparison with CV treatments. Among the CT treatments, compared with 0% residue cover, 100% residue cover enhance 2.6% of corn yield, but enhancement in 50% residue cover treatments was slight. Some yield components were also improved on conservation tillage treatments, especially for the 100% residue cover treatments.

Our results indicated that residue cover treatments, particularly all residue cover combined with no-till appears to

Table 5
Winter wheat yield and qualitative parameters under 10 treatments during 2002–2003 growing season.

Treatments identifiers		Grains per spike	Thousand kernel weight (g)	Yield (t ha^{-1})
Conservation tillage (CT)	a	43^{a}	40.3^{ab}	4.8^{a}
	b	40^{b}	39.2^{abcd}	4.7^{a}
	c	36de	35.8^{efg}	4.3^{cd}
	d	37^{cde}	38.6^{bcd}	4.6^{ab}
	e	43^{a}	39.6^{abc}	4.9^{a}
	f	35^{e}	34.8^{fg}	4.2^{d}
	g	39^{bc}	40.3^{a}	4.7^{a}
	h	36de	37.6^{de}	4.4^{bcd}
Conventional tillage (CV)	i	37^{cde}	37.8^{cde}	4.6^{ab}
	j	38^{bcd}	34.2^{g}	4.4^{bc}

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

Table 6
Corn yield and qualitative parameters under 10 treatments during 2002 and 2003 growing seasons.

Yield (t ha^{-1})	a	b	c	d	e	f	g	h	i	j
Year 1 (2002)	9.9	9.5	9.0	9.6	9.3	9.6	9.4	9.0	9.0	8.8
Year 2 (2003)	10.2	8.8	9.2	9.0	9.4	9.1	9.3	9.1	9.4	9.7
LSD (0.05) $_{treatment}$ = 0.56; LSD (0.05)$_{treatment \times year}$ = 0.68										
Hundred kernel weight (g)										
Year 1 (2002)	38.5	37.8	36.1	38.0	36.8	38.0	37.2	36.1	36.7	36.0
Year 2 (2003)	39.8	36.8	37.4	37.0	37.8	37.3	37.5	37.4	38.3	38.5
LSD (0.05)$_{treatment}$ = 2.2; LSD (0.05)$_{treatment \times year}$ = 2.6										
Kernel row number per ear										
Year 1 (2002)	13.8	13.5	12.9	13.6	13.1	13.9	13.4	12.7	12.6	12.6
Year 2 (2003)	14.8	13.1	13.5	12.5	13.8	12.8	13.7	13.1	13.7	14.2
LSD (0.05)$_{treatment}$ = 0.89; LSD (0.05)$_{treatment \times year}$ = 0.94										
Kernel number per row										
Year 1 (2002)	34.3	35.0	32.7	33.3	33.0	34.2	33.1	32.6	32.0	32.1
Year 2 (2003)	35.8	32.3	33.0	32.7	33.4	32.7	33.0	32.5	33.1	33.5
LSD (0.05)$_{treatment}$ = 1.8; LSD (0.05)$_{treatment \times year}$ = 2.1										

Table 7
Water use efficiency (WUE) for winter wheat under 10 treatments during 2002–2003 growing season.

Treatments identifiers		Rainfall (mm)	Total irrigation (mm)	ΔS (mm)	WUE (kg ha^{-1} mm^{-1})
Conservation tillage (CT)	a	132	66.8	40.0	20.1^{a}
	b	132	109.5	59.8	15.6^{de}
	c	132	71.9	43.2	17.4^{b}
	d	132	100.0	46.8	16.5^{bcd}
	e	132	60.5	39.7	21.1^{a}
	f	132	66.6	44.2	17.3^{bc}
	g	132	89.3	44.2	17.7^{b}
	h	132	89.9	43.2	16.6^{bcd}
Conventional tillage (CV)	i	132	105.9	53.2	15.8^{cde}
	j	132	105.3	54.1	15.1^{e}

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

improve grain yield and some yield components, but for all the treatments, the year effects on corn yield and yield components were non-significant during the first several years that the treatments were imposed. The positive effects of CT (residue cover and no or minimum tillage) on grain yields are consistent with other reported results (Radford et al., 1995; Zhang and Lou, 2002; Fang et al., 2003). Compared to traditional plowing systems, no tillage with residue cover improved grain yields by 10–40% in the similar climatic conditions. Similar results have also been reported from the national conservation tillage demonstration sites located also on the North China Plain. In a total of 45 demonstration sites, grain yields were higher in CT on 44 of the demonstration sites compared to CV. Mean yields for CT and CV in the 45 sites were 5.61 and 5.37 t ha^{-1}, respectively, an overall 4.5% increase in grain yield (unpublished data).

3.4. Water use efficiency

In 2002–2003, the amount of irrigation water added to CT and CV treatments were 82 and 106 mm, respectively, for winter wheat production (Table 7), representing a decrease of 23% in

Table 8
Water use efficiency (WUE) for corn under 10 treatments during 2002 and 2003 growing seasons.

Rainfall (mm)	a	b	c	D	e	f	g	h	i	j
Year 1 (2002)	368	368	368	368	368	368	368	368	368	368
Year 2 (2003)	342	342	342	342	342	342	342	342	342	342
Total irrigation (mm)										
Year 1 (2002)	29.7	29.9	25.8	29.1	31.2	31.9	32.5	22.7	31.0	33.2
Year 2 (2003)	34.3	20.6	47.8	24.9	54.9	47.7	60.9	48.5	34.7	54.1
ΔS (mm)										
Year 1 (2002)	50.3	50.2	38.9	45.3	41.6	42.5	38.8	35.8	35.8	43.2
Year 2 (2003)	59.6	35.6	54.6	38.5	57.2	47.8	59.8	51.2	33.8	48.9
WUE (kg ha^{-1} mm^{-1})										
Year 1 (2002)	22.1	21.2	20.8	21.7	21.1	21.7	21.4	21.1	20.7	19.8
Year 2 (2003)	23.4	22.1	20.7	22.2	20.7	20.8	20.1	20.6	22.9	21.8
LSD (0.05)$_{treatment}$ = 1.2; LSD (0.05) $_{treatment \times year}$ = 1.6										

irrigation water with CT. With the exception of treatment b, WUE for CT was 6.5–36.1% greater than CV treatments. Within the CT treatments, 100% residue cover in both crops reduced irrigation water use by 19.3% when compared to the 50% and 0% residue cover treatments. This resulted in a WUE that was 8.1% higher for the treatments with of 100% straw cover, particularly for the treatments a and e.

As indicated in Table 8, treatment and treatment × year interaction had statistically effects on WUE in corn production. In the first growing season of 2002 (year 1), total irrigation water in the CT treatments for corn was 9.4% less than in CV resulting in 5.6% higher WUE values (21.4 kg ha^{-1} mm^{-1} vs. 20.3 kg ha^{-1} mm^{-1}). The highest WUE was observed in double no-till with 100% residue cover (treatment a), which significantly improved 11.6% of WUE relative to CV treatments. In the second growing season of 2003 (year 2), the differences of mean WUE between CT and CV treatments were slight, but double no-till with 100% residue cover (treatment a) again produced the highest WUE and significantly increased 7.3% of WUE compared to the CV treatment of j. The greater WUE in conservation tillage treatments was similar to a one-year experiment conducted by Liu et al. (2004), who showed an increase in WUE of 10.6% in winter wheat and corn production in no-tillage with 100% residue cover soils as compared with plowing without residue cover soils in North China Plain.

4. Conclusions

Results from this research have demonstrated that radical changes in tillage methods for corn and winter wheat production, from conventional tillage (plowing + residue removal) to conservation tillage (no-tillage, rototilling, subsoiling + residue cover), did not show negative effects on crop yield and WUE when using an annual double cropping system in the North China Plain. The results showed that adopting CT reduced irrigation water requirements by 15.8% with some small grain yield benefits. The results also showed that the best results obtained with the CT were when the double no-till with 100% residue cover was used. Conservation tillage in annual double cropping system clearly has the potential to make an important contribution to more efficient use of irrigation water on the North China Plain.

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