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Effect of ridge tillage, no-tillage, and conventional tillage on soil temperature, water use, and crop performance in cold and semi-arid areas in Northeast China

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Abstract. In cold and semi-arid Northeast China, insufficient soil accumulative temperature and low water use efficiency (WUE) are the limiting factors for the further development of agriculture. Ridge tillage (RT) has been proposed to improve soil temperature and water conservation. Data from a 3-year field experiment conducted at two locations (Sujiatun and Lanxi) in Northeast China were used to compare RT, no-tillage (NT), and conventional tillage (CT) in a spring maize cropping system. At both sites, RT and NT significantly ($P < 0.05$) increased mean soil temperature to 0.10 m depth, relative to CT, by 0.7–2.4°C in the cold season during the spring maize growing stage. Mean soil moisture depletion in the RT treatment was greater by 1.2–4.1% (Sujiatun) and 0.6–3.0% (Lanxi) than in NT and CT, respectively. Mean maize yields over 3 years for RT were ~9.9% greater than for CT, whereas the yield advantage in the NT treatment was only slight. In Sujiatun, WUE was 8.0% and 8.6% greater under RT than under NT and CT, respectively, and in Lanxi, WUE was 7.7% and 9.6% greater under RT than NT and CT. Ridge tillage is recommended to the farmers to obtain higher crop yield and WUE in Northeast China.

Additional keywords: maize, ridge tillage, soil temperature, water use efficiency, yield.

Introduction

In cold and semi-arid Northeast China, spring maize is one of the most important grain crops in terms of area and output. The cropping areas and annual total yields of spring maize in this region are 6.54 Mha and 42.5 Mt, accounting for ~20% of the total national sown area of maize and 31.2% of the total national maize yield, respectively (Liu *et al*. 2002). In the local cropping system, spring maize is planted at the end of April and harvested at the beginning of October. During the growing stage of spring maize, the average daily temperature is <8°C, and the accumulative temperature (~2700°C) cannot meet the heat requirements of local maize varieties (2800–3000°C) (Ma *et al*. 2003), which results in serious yield loss in Northeast China (Ma *et al*. 2004). Furthermore, the average cumulative evapotranspiration is ~1800 mm, which is ~4 times higher than the average total rainfall received during the growing stage of spring maize. Therefore, the low status of soil moisture in the root-zone usually limits productivity of spring maize in this region. Improving soil temperature and conserving moisture accumulated in the root-zone during the rainfall season can increase productivity of spring maize in the cold and dry Northeast China.

More sustainable cropping systems, using ridge tillage (RT) to increase productivity and water conservation, have been demonstrated in many environments. Wheels of heavy equipment are confined to permanent furrows in the RT system, which could be an effective way to reduce soil loss, improve soil temperature and water management, and increase crop yields when it is combined with ridge planting, no tillage, and residue cover (Taylor 1983; Pikul *et al*. 2001). Norton and Brown (1992) and Gaynor and Findlay (1995) found that RT was more resistant to soil erosion than the traditional flat system in Ohio and Ontario, respectively. Radke (1982) reported that the application of RT with residue cover would be expected to increase soil temperature due to the changed micro-topography. In the RT system, the ridge area was never compacted and was left undisturbed except during planting and tillage operations, producing a zone with soil conditions conductive to higher soil moisture and crop yields (Kaspar *et al*. 1995). So, in terms of these positive effects, RT will be essential for improvements of local farming in Northeast China.

Research in China, particularly in Northeast China, has generally confirmed the improvements in soil temperature, water content, and crop development using conventional ridge tillage (ploughing, fresh ridge and residue removal). Yang *et al*. (2005), for instance, demonstrated that in Shandong province of northern China, conventional ridge planting with residue removal increased soil temperature by ~0.3–0.6°C in the 0–0.40 m soil layer compared with conventional flat planting. In Heilongjiang province in colder and more arid Northeast China, Sun (2001) showed that newly formed ridges increased soil temperature by 1–3°C to 0.20 m

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depth relative to traditional flat planting. Wang *et al.* (2007) compared conventional ridge planting and flat planting in maize production over 2 years and demonstrated that fresh ridges improved mean soil water content at 0–0.20 m soil depth by 1.3%. Luo and Gao (2007) indicated that in Liaoning province, conventional ridge planting with residue removal produced ~3% higher soil moisture than conventional flat planting, increasing maize yield by ~21.3%. In most research, however, conventional ridge tillage systems have still involved residue removal and substantial tillage operations to form the ridge before planting for each crop production. Little is known about the effects of RT (with permanent ridge planting, no-tillage, residue cover, standing stubble, etc.) on soil temperature, moisture content, and crop performance in cold and semi-arid Northeast China.

This paper reports the results (2005–07) of an ongoing investigation of spring maize production on RT in Sujiatun and Lanxi, Northeast China. The objective of this study is to identify the effects of RT on soil temperature, crop performance, and water use in cold and semi-arid areas of China. We also present suggestions for further research to enhance the development of RT systems in China.

Materials and methods

Site description

Experiments were conducted at two locations in Northeast China, Sujiatun in Liaoning province and Lianxi in Heilongjiang province, during three growing seasons (2005–07). Sujiatun (41°39′N, 123°19′E, 34.5 m a.s.l.) is in cold and semi-arid region. Average annual temperature is <7.4°C, with 156 frost-free days. Annual rainfall is ~685 mm and ~60–75% of the annual rainfall occurs during summer. According to the FAO/UNESCO Soil Classification (FAO/UNESCO 1993), the soil type in the experimental site is an Albic Luvisol (sand 42%, silt 38%, clay 20%) with bulk density 1.30 Mg/m^3, organic matter 9.8 g/kg, total N 0.7 g/kg, and pH 6.5 in the top 0.20 m soil layer.

The climate of Lanxi (46°27′N, 125°52′E, 172 m a.s.l.) is cold and semi-arid with an average annual temperature of 3.5°C and average annual rainfall of 450 mm. According to the FAO/UNESCO Soil Classification (FAO/UNESCO 1993), the soil in the experimental site is a Luvic Phaeozem (sand 36%, silt 24%, clay 40%) with bulk density 1.25 Mg/m^3, organic matter 21 g/kg, total N 1.7 g/kg, and pH 6.3 in the 0–0.20 m soil layer.

Figure 1 shows the annual mean monthly rainfall, temperature, and solar radiation in Sujiatun and Lanxi during the study from 2005 to 2007. In both sites, the single crop cycle consists of spring maize, sown in April and harvested in October.

Experimental design

In Sujiatun and Lanxi, the experiment was designed as a randomised block with three replications. Each plot was 8 m wide and 60 m long. Three tillage systems were compared: RT, no-tillage (NT), and conventional tillage (CT). The RT system applied no tillage planting (to 0.05 m depth) and fertilising (to 0.10 m depth) on the ridge. The maize stalks were chopped and left as mulch after harvesting. The NT treatment consisted of no tillage planting (to 0.05 m depth) and fertilising (to 0.10 m depth) on a flat field. All chopped maize stalks were left as mulch. The CT system included manual broadcasting of fertiliser, ploughing to 0.20 m depth and tillage for seedbed preparation, and planting (to 0.05 m depth) on a flat field. The majority of maize stalk was removed after harvesting.

The spring maize varieties used in Sujiatun and Lanxi were Tiedan-12 and Fenghe-10, respectively, which are the two most widely seeded, commercial varieties. In Northeast China, seed and fertiliser are commonly applied at very high rates to maximise the chance of good yields. In Sujiatun, spring maize was sown on 23 April 2005, 25 April 2006, and 24 April 2007, and harvested on 4 October 2005, 7 October 2006, and 6 October 2007 (Table 1). The spring maize was seeded with a sowing density of 7 plants/m^2, and a complete fertiliser (N-P_2O_5-K_2O) was applied at a rate of 75 kg N, 37.5 kg P, and 37.5 kg K/ha at planting. In Lanxi, spring maize was sown on 25 April 2005, 28 April 2006, and 26 April 2007, and harvested on 6 October 2005, 9 October 2006, and 7 October 2007 (Table 1). The sowing density of spring maize was 6 plants/m^2, and complete fertiliser (N-P_2O_5-K_2O) was applied to provide 60 kg N, 30 kg P, and 30 kg K/ha at planting.

In the RT system, the overall width (furrow centre) of the ridge was 1.0 m to fit the wheel track width of the tractor and harvester. Ridge height was 0.15 m and ridge surface width was 0.70 m, allowing 2 rows of maize at 0.40 m spacing. This is the same as the row spacing in CT and NT treatments.

Measurements

Rainfall and solar radiation data were monitored throughout the experimental period with a solar-powered automatic weather station at the experimental sites. Soil temperature was recorded at 0.10 m soil depth at 08:00 ($T_{08:00}$), 14:00 ($T_{14:00}$), and 20:00 ($T_{20:00}$) hours, beginning at sowing and every 15 days thereafter. Mean daily soil temperature (T) was estimated by (He *et al.* 2007):

$$T = \frac{2 \times T_{08:00} + T_{14:00} + T_{20:00}}{4} \tag{1}$$

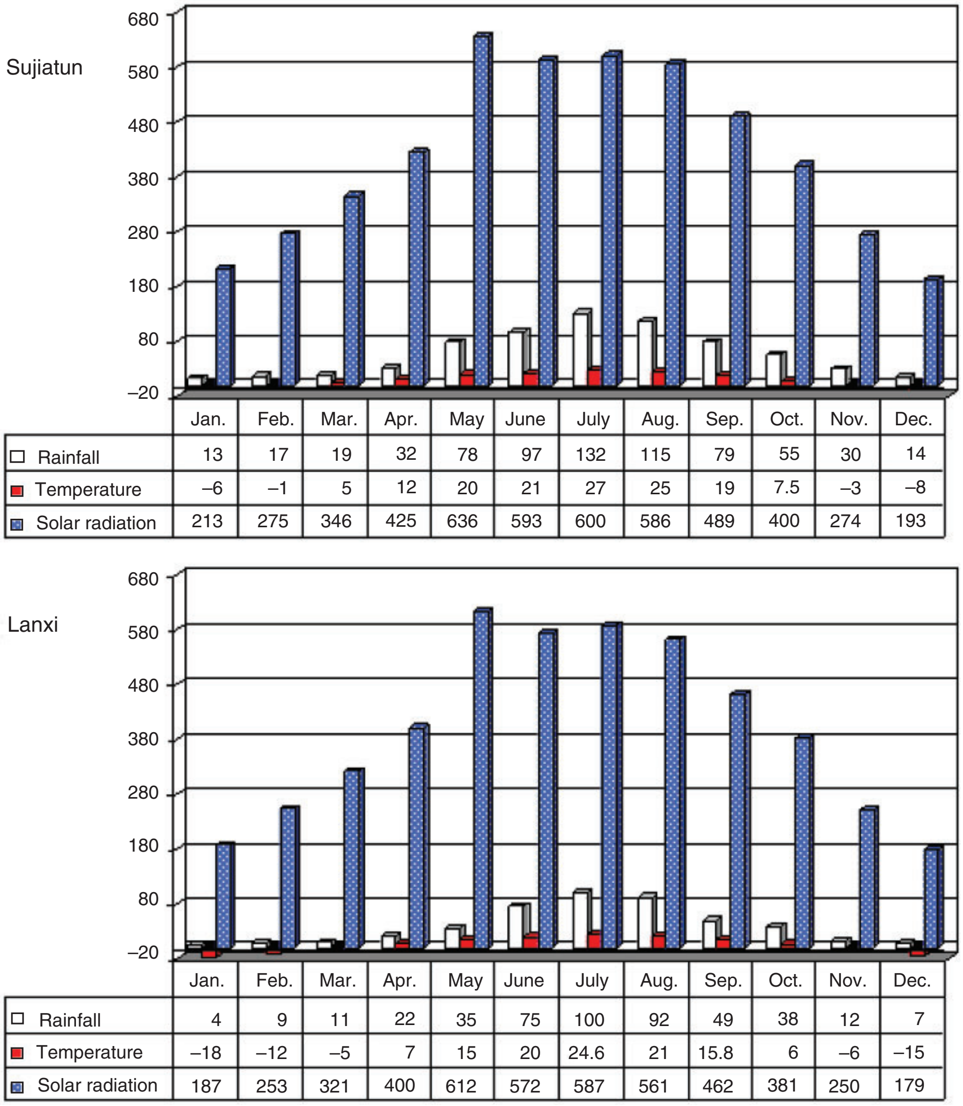
For soil moisture determinations, in each plot, three random soil core samples were taken using a 54-mm-diameter steel core-sampling tube, manually driven into 1.0 m depth at sowing and harvesting for each growing season during the experimental years 2005–07. The soil cores were weighed wet, dried in a fan-aided oven set at 105°C for 48 h, and weighed again to determine soil water content and bulk density (Ferraro and Ghersa 2007). Gravimetric water content was multiplied by soil bulk density to obtain volumetric water content. Soil water storage (mm) was calculated for a 1.0-m-deep profile by multiplying the mean soil volumetric water content by the soil profile depth. Mercury manometric type tensiometers were installed at soil depths 0.85 and 1.15 m to quantify soil water flux at 1.0 m depth.

Water use efficiency (WUE) reported here is the ratio of grain yield to actual evapotranspiration (ET_a) according to the studies of Kang *et al.* (2000):

$$\mathrm{WUE} = \mathrm{Yield}/\mathrm{ET_a} \tag{2}$$

ET_a was calculated using the general water balance equation:

$$\mathrm{ET_a} = P + \Delta W - D \tag{3}$$



Sujiatun

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
□ Rainfall	13	17	19	32	78	97	132	115	79	55	30	14
🟥 Temperature	–6	–1	5	12	20	21	27	25	19	7.5	–3	–8
▨ Solar radiation	213	275	346	425	636	593	600	586	489	400	274	193

Lanxi

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
□ Rainfall	4	9	11	22	35	75	100	92	49	38	12	7
🟥 Temperature	–18	–12	–5	7	15	20	24.6	21	15.8	6	–6	–15
▨ Solar radiation	187	253	321	400	612	572	587	561	462	381	250	179

Fig. 1. Distribution of mean monthly rainfall (mm), temperature (°C), and solar radition (MJ/m^2) at Sujiatun and Lanxi from 2005 to 2007.

where P is growing season rainfall (mm), ΔW is soil water storage depletion (mm), and D is drainage flux (mm) in a vertical direction through the 1.0 m depth. ΔW was taken as the change in stored soil water (mm) of the soil profile (0–1.0 m depth) from sowing to harvesting; D was calculated according to Sarkar and Kar (1992) as:

$$D = \int_{t_1}^{t_2} V_z dt = \int_{t_1}^{t_2} -K\frac{\partial H}{\partial Z} dt \tag{4}$$

where V_z is vertical flux (mm/day) at 1.0 m depth at a time interval of t_1 (sowing time) and t_2 (harvesting time), K is the hydraulic conductivity (mm/day) at 0.85–1.15 m depth, and $\partial H/\partial Z$ is hydraulic gradient at the 0.85–1.15 m horizon.

Aboveground (shoot) and root samples were taken at seedling stage for spring maize from three areas (1 m^2) per plot, respectively. Roots were dug out and collected from a soil depth of 0.20 m. All samples were oven-dried at 65°C to constant weight and weighed to determine plant and root dry weight.

Leaf area index (LAI) was calculated using the formula:

$$LAI = \frac{LA}{A_f} \tag{5}$$

where LA is leaf area and A_f is field area. Leaf area was measured by SHY-150, made by Haerbin Optical Apparatus Factory, China.

Spring maize yields were determined at 12% moisture content by manually harvesting three lengths of rows, each 3 m, taken randomly in each plot.

Statistical analysis

The SPSS analytical software package (2003) was used for all of the statistical analyses. Mean values were calculated for each of the measurements, and ANOVA was used to assess the treatment

Table 1. Effect of three treatments on phenological growth stage of spring maize during 2005, 2006, and 2007

RT, Ridge tillage; NT, no tillage; CT, conventional tillage

Treatments		Phenological stage			
		Sowing	Seedling	Silking	Harvesting
		Sujiatun, Liaoning			
2005	RT	23 Apr.	5 May	23 July	4 Oct.
	NT	23 Apr.	7 May	26 July	4 Oct.
	CT	23 Apr.	8 May	30 July	4 Oct.
2006	RT	25 Apr.	5 May	25 July	7 Oct.
	NT	25 Apr.	8 May	31 July	7 Oct.
	CT	25 Apr.	7 May	1 Aug.	7 Oct.
2007	RT	24 Apr.	6 May	22 July	6 Oct.
	NT	24 Apr.	9 May	25 July	6 Oct.
	CT	24 Apr.	9 May	24 July	6 Oct.
		Lanxi, Heilongjiang			
2005	RT	25 Apr.	7 May	23 July	6 Oct.
	NT	25 Apr.	10 May	26 July	6 Oct.
	CT	25 Apr.	9 May	30 July	6 Oct.
2006	RT	28 Apr.	9 May	28 July	9 Oct.
	NT	28 Apr.	9 May	1 Aug.	9 Oct.
	CT	28 Apr.	11 May	3 Aug.	9 Oct.
2007	RT	26 Apr.	7 May	25 July	7 Oct.
	NT	26 Apr.	9 May	27 July	7 Oct.
	CT	26 Apr.	10 May	27 July	7 Oct.

effects on the measured variables. When ANOVA indicated a significant *F*-value, multiple comparisons of annual mean values were made on the basis of the least significant difference (l.s.d.).

Results and discussions

Soil temperature

In Northeast China, high soil temperature is important for spring maize germination and growth because the accumulative temperature from April to October is insufficient for the full heat requirements of spring maize. Figure 2 shows the mean daily soil temperature at 0.10 m depth during the spring maize growth stage in 2005–07 in the three different treatments at Sujiatun. In general, soil temperature in residue cover treatments (RT and NT) was higher than that in CT, particularly in cold weather. In 2005, RT and NT increased mean daily soil temperature by 0.7–1.8°C during 15–30 days after sowing (DAS) (end April–mid May) and by 0.2–1.3°C during 150–162 DAS (end September–mid October) compared with CT. The soil temperature advantage in residue cover treatments was more evident in the cold seasons in 2006 and 2007. Under RT and NT, respectively, soil temperature (0–0.10 m) at 30 and 162 DAS in 2006 was 1.2–1.6°C and 1.3–1.8°C greater ($P < 0.05$) than under CT, while significant ($P < 0.05$) increases (1.6–1.8°C) under residue cover treatments were observed at 162 DAS in 2007 relative to CT. However, in the warm seasons (July–August), soil temperature advantages in RT and NT treatments were negligible or negative during 60–120 DAS in 2005–07. In the residue cover treatments, the mean daily soil temperature during the maize growth stage in RT was slightly higher than that in NT treatment, and the difference was evident in the warm seasons. Compared with NT treatment, RT increased mean daily soil temperature by 0.3–0.8°C from 90 to 135 DAS in 2005, and the improvements were 0.1–1.0°C in 2006 and 0.1–0.9°C in 2007.

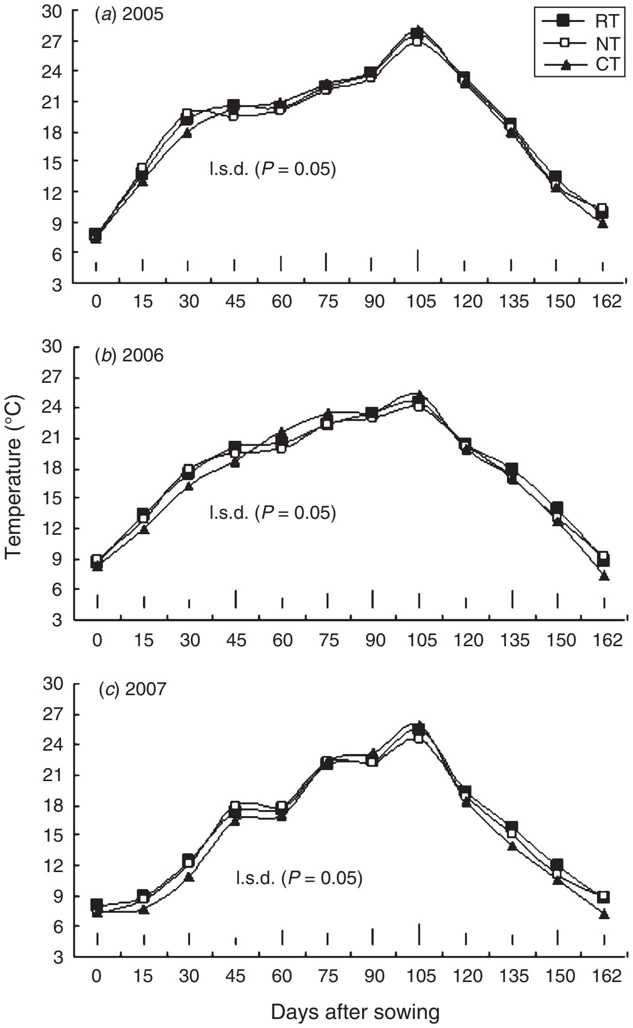


Fig. 2. Mean daily soil temperature at 0.10 m depth as influenced by different treatments in Sujiatun during 2005–07. *Significant difference at $P = 0.05$ among treatments.

In colder Lanxi, variation in soil temperature due to different treatments followed a similar trend to that in Sujiatun, but the improvements in soil temperature observed in residue cover treatments were more significant than the values in Sujiatun (Fig. 3). During 15–30 DAS, the mean daily soil temperature in 2005, 2006, and 2007 for residue cover treatments was 1.5–2.4, 1.0–1.9, and 1.6–2.4°C greater ($P < 0.05$) than for CT, and increases in soil temperature during 150–162 DAS were 0.3–1.8°C (2005), 1.0–1.6°C (2006), and 1.3–2.4°C (2007), respectively. Among the residue cover treatments during the experimental years 2005–07, RT again produced higher soil temperature than NT, especially in the warm seasons.

The data for Sujiatun and Lanxi demonstrated that RT could effectively retain heat and improve soil temperature in the cold condition due to the residue cover (Aggarwal *et al.* 2003) and ridge configurations (Hatfield *et al.* 1998). These were consistent with a soil temperature experiment conducted in Fumeng, Northeast China, which indicated that compared with traditional ploughing, RT with straw cover increased soil temperature at 0.10 m depth by ~1.0°C in April (Wang *et al.* 2007). Furthermore, in NT and RT treatments, zero-tillage appeared to produce better soil particle contacts (compared with traditional ploughing in CT), and thus increase thermal conductivity and soil temperature in cold seasons (Abu-Hamdeh 2000). A similar result was found at our demonstration site in Fuxin, Northeast China, where RT also showed ~1.0°C higher soil temperature in 0–0.10 m layer in cold seasons compared with NT and CT treatments, but the difference in deeper soil (0.10–0.20 m) was minimal among the treatments (Q. Wang, J. He, H. Li, W. Li, unpubl. data). In the present study, the slightly lower soil temperature during 60–120 DAS in 2005–2007 for residue cover treatments (RT and NT) also indicated that residue cover had a negative effect on soil temperature in warm conditions, confirming the findings of Sarkar and Singh (2007).

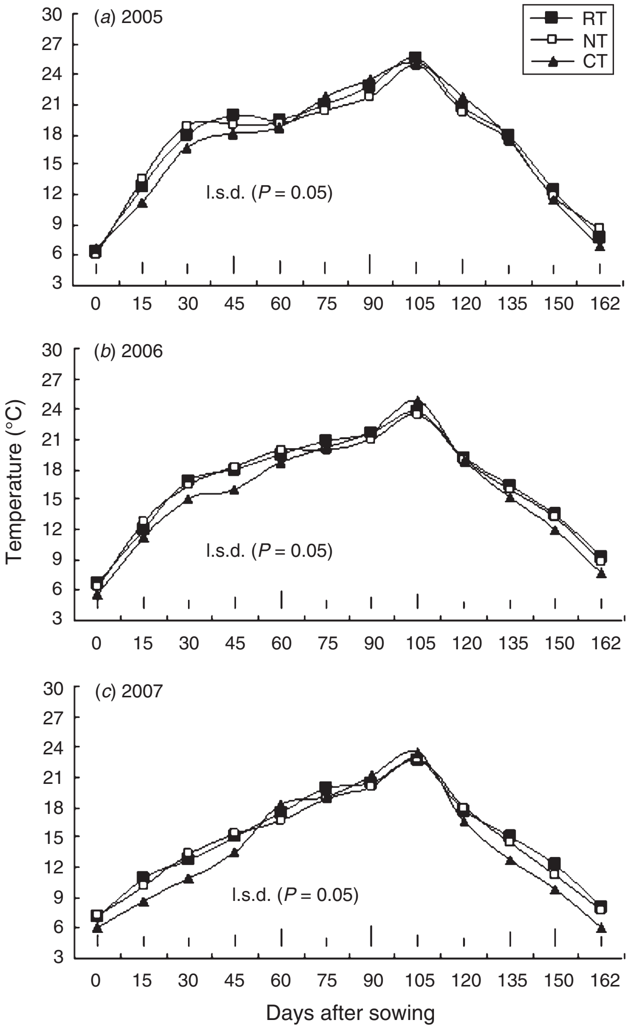


Fig. 3. Mean daily soil temperature at 0.10 m depth as influenced by different treatments in Lanxi during 2005–07. *Significant difference at $P = 0.05$ among treatments.

Crop performance

Seedling stage

At seedling stage at both sites, treatment, year, and treatment × year interaction significantly affected spring maize performance (Table 2). In the highest rainfall year of 2007, LAI, plant dry weight, and root dry weight were greater than in lower rainfall years of 2005 and 2006. For the different treatments, low soil temperature in NT and CT treatments affected spring maize growth and retarded emergence by 2–3 days compared with RT (Table 1); this led to better spring maize performance with RT (Table 2). Compared with CT and NT, RT improved mean (2005–07) LAI by 5–54% at Sujiatun and 7–34% at Lanxi, and the difference between RC and CT treatments was significant ($P < 0.05$) at both sites in 2007. Plant height in RT was greater than that in NT and CT, but there was only a slight difference among treatments over the whole experiment. Furthermore, RT improved plant condition, especially in the root-zone, where RT significantly ($P < 0.05$) increased dry weight by 46–57% at Sujiatun and 18–29% at Lanxi compared with CT, from 2005 to 2007. These improvements show that RT was effective in facilitating spring maize growth. Differences in plant growth were inconspicuous between NT and CT.

Table 2. Leaf area index, plant height (cm), plant dry weight (g/plant) and root dry weight (g/plant) of spring maize for two treatments in the seedling stage during 2005, 2006, and 2007

RT, Ridge tillage; NT, no tillage; CT, conventional tillage

	Sujiatun, Liaoning			Lanxi, Heilongjiang		
	RT	NT	CT	RT	NT	CT
			Leaf area index			
Year 1 (2005)	0.39	0.32	0.35	0.39	0.31	0.29
Year 2 (2006)	0.37	0.30	0.27	0.32	0.30	0.30
Year 3 (2007)	0.43	0.41	0.28	0.43	0.35	0.34
l.s.d. $(0.05)_{\text{treatment}}$		0.021			0.030	
l.s.d. $(0.05)_{\text{year}}$		0.021			0.030	
l.s.d. $(0.05)_{\text{year} \times \text{treat.}}$		0.036			0.049	
			Plant height			
Year 1 (2005)	28.3	27.9	27.5	28.3	27.5	27.9
Year 2 (2006)	29.3	28.1	28.1	29.3	28.1	28.1
Year 3 (2007)	28.8	27.6	28.0	28.8	27.6	28.0
l.s.d. $(0.05)_{\text{year}}$		0.42			0.56	
l.s.d. $(0.05)_{\text{year} \times \text{treat.}}$		0.72			0.91	
			Plant dry weight			
Year 1 (2005)	23.7	22.3	19.9	23.7	17.3	18.9
Year 2 (2006)	20.3	17.3	19.6	20.3	17.3	17.6
Year 3 (2007)	25.7	23.3	20.1	25.7	19.3	23.1
l.s.d. $(0.05)_{\text{treatment}}$		0.50			0.49	
l.s.d. $(0.05)_{\text{year}}$		0.50			0.49	
l.s.d. $(0.05)_{\text{year} \times \text{treat.}}$		0.87			0.86	
			Root dry weight			
Year 1 (2005)	5.5	4.5	3.5	5.3	5.0	4.1
Year 2 (2006)	5.1	3.3	3.4	5.7	4.2	4.6
Year 3 (2007)	6.0	6.0	4.1	5.9	4.8	5.0
l.s.d. $(0.05)_{\text{treatment}}$		0.41			0.48	
l.s.d. $(0.05)_{\text{year}}$		0.41			0.48	
l.s.d. $(0.05)_{\text{year} \times \text{treat.}}$		0.71			0.83	

Maturing stage

At both Sujiatun and Lanxi, there were significant treatment and year effects as well as a significant treatment × year interaction for grain yield of spring maize (Table 3). On average, the lowest maize yield was recorded in 2006 when rainfall was lowest (Table 3). In 2007 when rainfall was highest, maize yield was highest at both sites. For different treatments, in the first growing season of 2005, RT significantly improved maize yields by 11.2% and 12.1% compared with CT at Sujiatun and Lanxi, respectively, while differences between NT and CT were negligible at both sites. In 2006, RT produced the highest maize yields, up to 12.9% and 12.1% greater than CT at Sujiatun and Lanxi, while the increase with NT was 1.0% (Sujiatun) and 1.6% (Lanxi) compared with CT. A similar result was found in 2007, but the differences among treatments were not significant. Lower soil temperature and more evaporation due to traditional ploughing and residue removal were responsible for the poor performance of spring maize under CT. In RT, the edge effect as a result of ridge configuration and improved soil temperature (Figs 2 and 3) and available soil water due to residue cover and no-tillage played a key role in accelerating spring maize growth and elongating the maturity period (Table 1), thereby boosting yield characteristics of spring maize. Grains per spike and 100-grain weight were enhanced by 3–6% in the RT treatment. These positive effects on crop yields were consistent with the results of Chen *et al.* (2007) and Jia *et al.* (2007). They demonstrated that in Northeast China, compared with traditional flat ploughing, RT with residue cover improved crop yields 5–10%. Similar results have also been found for our demonstration site at Fuxin, where the 2-year mean maize yield for RT and NT was 4.5% and 2.1% higher than that in CT (Q. Wang, J. He, H. Li, W. Li, unpubl. data).

Table 3. Grains per spike, 100-grain weight (g), and yield (kg/ha) of spring maize for three treatments in the maturing stage during 2005, 2006, and 2007

RT, Ridge tillage; NT, no tillage; CT, conventional tillage

	Sujiatun, Liaoning			Lanxi, Heilongjiang		
	RT	NT	CT	RT	NT	CT
			Grains per spike			
Year 1 (2005)	724.3	746.7	724.1	789.3	738.9	756.5
Year 2 (2006)	768.9	784.5	769.7	777.2	754.3	721.6
Year 3 (2007)	755.9	746.6	735.6	781.3	768.7	754.3
l.s.d. (0.05)$_{\text{treatment}}$		4.71			4.93	
l.s.d. (0.05)$_{\text{year}}$		4.71			4.93	
l.s.d. (0.05)$_{\text{year × treat.}}$		8.16			8.53	
			Hundred-grain weight			
Year 1 (2005)	34.5	32.2	32.3	35.0	31.4	32.8
Year 2 (2006)	33.5	30.1	31.7	34.8	31.9	33.1
Year 3 (2007)	33.1	32.0	32.1	35.0	32.1	32.6
l.s.d. (0.05)$_{\text{treatment}}$		2.44			2.45	
			Yield			
Year 1 (2005)	10 361	9425	9318	10 721	9496	9566
Year 2 (2006)	10 151	9081	8992	10 506	9523	9369
Year 3 (2007)	11 088	10 623	10 554	11 039	10 899	10 308
l.s.d. (0.05)$_{\text{treatment}}$		632			612	
l.s.d. (0.05)$_{\text{year}}$		632			612	
l.s.d. (0.05)$_{\text{year × treat.}}$		1094			1060	

Soil moisture depletion

Soil moisture depletion from any soil layer during a dry cycle would be due to the loss of water through evapotranspiration, drainage, and lateral seepage. Data on profile soil moisture depletion in between sowing and harvest of Sujiatun and Lanxi are presented in Table 4.

For the top 0–0.15 m soil layer, moisture depletion under CT was 6.7% and 4.9% higher than under RT and NT in Sujiatun, and 5.6% and 3.1% higher in Lanxi. Under CT, exposure of soil without residue cover and excessive soil disturbance as a esult of frequent ploughing were the reasons for the fast rate of moisture depletion in the topsoil layer. Residue cover was effective in reducing the loss of evaporation from the soil surface by forming a barrier between the soil surface and the atmosphere and thus reducing moisture loss (Gupta and Acharya 1993). In the middle soil layer, the trend was reversed; RT had the greatest moisture depletion, particularly at 0.15–0.45 m, significantly ($P < 0.05$) increasing moisture depletion by 5.7–8.9% and 6.3–9.1% at 0.15–0.30 and 0.30–0.45 m depths compared with CT. NT also showed a trend to greater mean moisture depletion in the middle soil layer, but the difference was not significant. The greater moisture depletion in the middle soil layer under RT could be explained by faster growth of spring maize (Tables 2 and 3), which consumed more soil water from this soil layer. Furthermore, under RT, capillary continuity is least disturbed due to no-tillage and controlled traffic (Li *et al.* 2007), and this accelerated the water sucking of the spring maize

Table 4. Treatment effects on soil moisture depletion (mm) from different layers for a period of 162 days in Sujiatun and Lanxi (averaged over 2005, 2006, and 2007)

RT, Ridge tillage; NT, no tillage; CT, conventional tillage. Means within a column followed by the same letters are not significantly different ($P > 0.05$)

Site	Treatment	Soil depth (m)				
		0–0.15	0.15–0.30	0.30–0.45	0.45–0.60	0.60–1.0
Sujiatun, Liaoning	RT	12.1a	12.2b	10.8b	10.8a	26.4a
	NT	12.3a	11.5a	10.2ab	11.1a	25.9a
	CT	12.9b	11.2a	9.9a	10.8a	26.0a
Lanxi, Heilongjiang	RT	12.5a	12.9b	11.9b	11.1a	28.3a
	NT	12.8ab	12.4ab	11.3a	10.8a	28.5a
	CT	13.2b	12.2a	11.2a	10.9a	28.0a

roots from the surrounding soils. In the deepest soil layer (0.60–1.0 m), the differences in soil moisture depletion between the different treatments were only slight in both Sujiatun and Lanxi.

Field water balance

As indicated in Table 5, on average, CT resulted in the lowest soil water storage depletion (ΔW). NT enhanced the magnitude of ΔW by 1.0% in both Sujiatun and Lanxi. In comparison to NT, ΔW under RT increased by 2.1% (Sujiatun) and 1.2% (Lanxi). Favourable hydrothermal regime due to residue cover and no-tillage encouraged root growth and thus enhanced utilisation of conserved soil moisture by rainfed crops (Acharya and Sharma 1994), and this effect was particularly marked in RT when minimum tillage and straw mulch were combined with ridge configuration in cold and semi-arid Northeast China.

Rainfall pattern also influenced the loss of water through drainage from the root-zone profile. In Sujiatun and Lanxi, both quantity and intensity of rainfall were lowest in 2006 cropping season. Consequently, there was the least mean drainage loss (Sujiatun 27.5 mm, Lanxi 24.4 mm) in that season. In the highest rainfall year of 2007, the greatest mean drainage loss was observed in all the treatments. Compared with CT, on average RT and NT reduced drainage loss by 2.5–16.9% in Sujiatun and Lanxi. An artificial barrier with residue cover in RT and NT treatments helped for low and steady entry of water and thus reduced drainage loss (Moitra *et al*. 1996).

At both experimental sites in Sujiatun and Lanxi, the experimental plots were levelled and runoff was considered negligible. Rainfall, soil water storage depletion and drainage contributed to the majority of actual evapotranspiration (ET_a). Compared with RT and NT treatments, lower ΔW together with higher drainage loss produced smaller ET_a under conventional tillage. The difference between RT and NT was slight and not significant at $P = 0.05$ in both Sujiatun and Lanxi.

Table 5. Impact of treatment effects on seasonal water use (actual evapotranspiration, ET_a, mm) and water use efficiency (WUE, kg/ha.mm) of spring maize in different cropping seasons

RT, Ridge tillage; NT, no tillage; CT, conventional tillage. Means within a column followed by the same letters are not significantly different ($P > 0.05$)

Year	Treatment	Components of soil water balance (mm)			ET_a	WUE
		Rainfall	ΔW	Drainage		
			Sujiatun, Liaoning			
2005	RT	529	72.9a	29.4a	572.5a	18.1b
	NT	529	71.9a	29.2a	571.7a	16.5a
	CT	529	71.6a	32.5a	568.1a	16.4a
2006	RT	511	76.4b	25.5a	561.2a	18.1b
	NT	511	73.7a	26.2ab	558.5a	16.3a
	CT	511	73.1a	30.7b	553.4a	16.2a
2007	RT	583	68.2a	36.4a	614.8a	18.0a
	NT	583	67.5a	38.6ab	611.9a	17.4a
	CT	583	67.3a	41.2b	609.1a	17.3a
			Lanxi, Heilongjiang			
2005	RT	416	76.2a	27.0a	465.2a	23.0b
	NT	416	75.9a	27.5a	464.4a	20.4a
	CT	416	75.6a	30.3a	461.3a	20.7ab
2006	RT	401	83.1b	23.8a	460.3a	22.8b
	NT	401	81.1ab	23.6a	458.5a	20.8a
	CT	401	80.3a	25.7a	455.6a	20.6a
2007	RT	477	70.7a	33.6a	514.1a	21.5a
	NT	477	70.3a	34.5a	512.8a	21.3a
	CT	477	70.2a	35.4a	511.8a	20.1a

Water use efficiency

Water use efficiency was significantly affected by different treatments in both sites (Table 5). In Sujiatun, the mean WUE values for 2005–07 in RT, NT, and CT were 18.1, 16.7, and 16.6 kg/ha.mm; compared with CT, RT significantly ($P < 0.05$) improved WUE by 4.0–11.7%. Similar results were found in Lanxi. During 2005–07, WUE was 7.0–11.1% greater for RT than for CT. In the NT treatment, the yield advantage in 2005–07 was negligible, so the mean improvements in WUE were only 0.6% and 1.8% in Sujiatun and Lanxi, respectively, compared with CT. In the RT treatment, the improved yield and reduced evaporation and drainage due to residue cover and no-tillage were responsible for higher WUE (Aggarwal and Sharma 2002). The improved water use efficiency under RT is of particular importance for the growth of spring maize in semi-arid Northeast China. Our result agreed with those of Xie *et al*. (2007), who demonstrated that in Northeast China, RT with straw mulching enhanced WUE by 0.73–1.82 kg/ha.mm compared with traditional tillage with residue removal.

Conclusions

Results from this research indicated that the RT system (no-tillage, residue cover, and ridge planting) was effective in improving soil temperature and water use in cold and semi-arid areas of Northeast China. Mean data indicate that adoption of the RT system increased soil temperature by 0.7–2.4°C in cold conditions and enhanced WUE by 4.0–11.7%, which has profound implications in this environment of insufficient accumulative temperature and drastically decreasing water availability. The faster crop growth and improved (9.9%) mean yield in the RT treatment also demonstrated that the radical change from the conventional flat planting, ploughing, and residue removal system to the permanent ridge planting, no-tillage, and residue cover system did not negatively affect maize production. No tillage with residue cover also appeared to provide some advantage in soil temperature, yield, and WUE, compared with CT.

Ridge tillage cropping systems clearly have the potential to make an important contribution to agricultural productivity. Ongoing research is needed on several aspects of this cropping system, including the balance of soil temperature and water content and the relationships between ridge tillage, productivity, soil quality, and environmental conditions. The absence of a suitable no-tillage planter for ridge tillage is likely to be a significant constraint to adoption and must be investigated in cold and semi-arid Northeast China.

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