Dryland Maize Yields and Water Use Efficiency in Response to Tillage and Nutrient Management Practices in China

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Abstract: Rainfed crop production in northern China is constrained by low and variable rainfall. This study explored the effects of tillage and nutrient management practices on maize (Zea mays L.) yield and water use efficiency (WUE), at Shouyang Dryland Farming Experimental Station in northern China during 2003-2008. The experiment was set-up using a split-plot design with 3 tillage methods as main treatments: conventional, reduced (till with crop residue incoperated in fall but no-till in spring), and no-till. Sub-treatments were 3 NP fertilizer rates: 105-46, 179-78 and 210-92 kg N and P ha^{-1}.

Maize grain yields were greatly influenced by the amount of growing season rainfall, and by soil water contents at sowing. Mean grain yields over the 6-year period in response to tillage treatments were 5604, 5347 and 5185 kg ha^{-1}, under reduced, no-till and conventional tillage, respectively. Mean WUE was 13.7, 13.6 and 12.6 kg ha^{-1} mm^{-1} under reduced, no-till, and conventional tillage, respectively. Mean soil water contents at sowing and at harvest were significantly influenced by tillage treatments. At harvest time, the no-till treatment had ~8-12% more water in the soil than the conventional and reduced tillage treatments. Under conventional tillage, grain yields increased with NP fertilizer application rates. However, under reduced tillage, grain yields were highest with lowest NP fertilizer application rate.

In conclusion, grain yields and WUE were highest under reduced tillage at modest NP fertilizer application rates of 105 kg N and 46 kg P per ha. No-till increased soil water storage by 8-12% and improved WUE compared to conventional tillage.

Keywords: *Dryland, Fertilizer, Maize, Reduced tillage, No-till, Water use efficiency (WUE)*

INTRODUCTION

Northern China has a large region of dryland farming, which accounts for about 55% of the nation's total cultivated land area (Xin and Wang 1999). Much of the land in this region is hilly and rainfed. Water scarcity and a large variation in inter-annual and intra-annual rainfall are the main constraints to rainfed crop production, causing unstable food production, and low water use efficiency (Wang et al. 2007a, 2007b). The large seasonal and annual variations in rainfall are also a cause of soil and water losses on sloping lands during the summer rainy season. Seasonal drought with heavy winds often occurs in winter and spring. The wind exacerbates soil drought and causes a reduction in spring maize seedling emergence during most years.

Yields of maize vary greatly from year to year, mainly because of the variable (unpredictable) rainfall and wind erosion in spring (Wang et al. 2006). These effects are exaggerated by the current practices of removing crop residues from the field after harvest, to leave the ploughed soil bare during winter, and to plough the soil again in spring after fertilizer application (for spring maize). These practices commonly lead to soil drying and severe wind erosion in early spring, thus causing a reduction in spring crop seedling emergence. Erosion of fertile top soil by wind and runoff, removal of crop residues and burning of crop residues have led to nutrient depleted soils on various places (Rees et al. 1997; Cai et al. 2002; Peng et al. 2006).

Soil conservation and improved nutrient management practices are gaining interest of Chinese research and policy communities (Wang et al. 1999; 2001; 2003a; Ju et al. 2005). Conservation tillage has been introduced for dryland farming in northern China since the early 1980s (Gao, et al., 1990, 1991; Wang, et al., 1995; Cai et al., 1994, 1995, 1998; Cai and Wang, 2001; Wang and Cai, 2000; Cornelis et al., 2002; Wang et al., 2003b; Cai et al., 2006; Jin et al., 2007), and it showed to be highly effective in decreasing soil drying and wind erosion, and improving rainfed crop yields and water use efficiency, especially with integrated conservation tillage and improved nutrient management practices (Wang et al., 2001, 2003b, 2006, 2007a, 2007b). However, as Riley et al., (1994) reported, optimum fertilization is more critical with no-till than with conventional tillage systems, our studies observed that crop yield responses to fertilizer applications under conservation tillage practices usually differ from those under conventional practices, and these also vary greatly from year to year (Wang and Cai, 2005; Wang et al., 2007a, 2007b).

The objective of our study is to determine dryland maize (Zea mays L.) yield responses to fertilizer application under different tillage practices during 2003-2008. We therefore assessed the effects of integrated tillage and nutrient management practices on maize grain yield and water use efficiency (WUE), at Shouyang Dryland Farming Experimental Station in northern China.

MATERIALS AND METHODS

Site description

The ongoing field experiment started in 2003 at the Dryland Farming Experimental Station in Shouyang, Shanxi province (112°-113°E, 37°-38°N) in northern China. The area has a mean altitude of 1100 m above sea level and a continental monsoon climate with an average annual rainfall of 520 mm. Severe erosion in the past has led to the formation of a hilly landscape. The dominant cropping system is continuous spring maize, which accounts for over 50% of the total area for crop production (Wang et al., 1999). The study area is representative of a typical farming region dependent on rainfall. Spring drought often is a limiting factor for seed germination and the emergence and growth of spring maize. The experimental site has a sandy loam cinnamon soil, classified as Calcaric-Fluvic Cambisols (ISS-CAS 2003; IUSS 2006). At the start in 2003, soil pH was 7.9, and SOC and soil organic N (SON) contents were 15 and 1.0 g kg^{-1}, respectively. Available soil P and soil K in the top 20 cm soil were low to medium, judged on the basis of P-Olsen (7.3 mg kg^{-1}) and NH_4OAc extractable K (84 mg kg^{-1}).

Experimental design and methods

The experiment was set-up using a split-plot design with 3 tillage methods as main treatments: conventional, reduced (till with crop residue incoperated in fall but no-till in spring), and no-till. Sub-treatments were 3 NP fertilizer rates: 105-46, 179-78 and 210-92 kg N and P ha^{-1}, using a NP compound fertilizer (20-8.7-0).

Plot size was 5 x 10 m^2 with 6 replications. The methods of the treatments for tillage, reside, and fertilizer application are described in Table 1. Locally recommended maize varieties were used, i.e., Jindan No. 34 in 2003-2004, Qiangsheng No. 31 in 2005, Qiangshenyundan No. 19 in 2006, and Jindan No. 48 in 2007-2008, at a seeding rate of 30 kg ha^{-1}. The inter-row and row spacing was 30 x 60 cm. Maize seeding was done in spring at the end of April, and harvested in October.

Table 1 Agronomic treatments in Shouyang, Shanxi province in China (2003-2008)

Treatment	Description
CT: conventional	ploughing (22-25 cm depth) and harrowing in fall; ploughing and applying fertilizers next spring; harrowing and seeding by animal (or machinery); weed control by hand
NT: no-till, whole corn stalk mulch	keeping the corn stalk flattened on field after harvest in fall; using one pass seed and fertilizer application with a no-till planter in spring; weed control using herbicides
RT: reduced tillage, fertilizers and maize stover incorporated	deep ploughing (25-28 cm depth), thereby incorporating straw and chemical fertilizers in the fall; harrowing in early spring and rolling before sowing; one pass seeding by machinery or animal

Measurements and calculations

Measurements and analyses included annual rainfall (AR), growing season rainfall (GSR), soil water at sowing (SWS), soil water at harvest (SWH), water use (expressed as evapotranspiration, ET), grain yield of wheat and maize (GY) and water use efficiency (WUE).

Rainfall during the experimental periods was measured using a rain gauge at the experimental site. The 0-200 cm soil profile was sampled before sowing and after harvest to ensure that data was available from the maximum rooting depth. Soil moisture content was determined gravimetrically. Soil samples for moisture determination were taken at seeding (SWS), and after harvest (SWH), taken at depths of 0-10, 10-20, 20-40, 40-60, 60-80, 80-100, 100-120, 120-140, 140-160, 160-180, 180-200 cm. Bulk density (BD), needed to determine soil moisture in the profile, was determined before the start of the experiments (0 to 200 cm depth), using 100 cm^3 soil sample rings. Water use during the growing period, expressed as evapotranspiration (ET), was calculated from seasonal rainfall (GSR) and soil water consumption data during the growing periods, where SWS and SWH (in mm) were calculated as gravimetric moisture content x BD x thickness of soil layer. If no deep drainage or runoff occurs, the following simple equation will apply:

$$ET = SWS + GSR - SWH \quad \text{(in mm)} \qquad [1]$$

Maize yields were determined at harvest, and apparent water use efficiency (WUE, in kg ha^{-1} mm^{-1}) was calculated from GY and ET, according to

$$WUE = GY/ET \qquad [2]$$

Statistical analysis was conducted using the GLM and REG procedure of the SAS institute, Inc. (2004).

RESULTS

Variation in annual rainfall

During the 6-year experimental period (2003-2008), annual rainfall averaged about 473 mm, ranging from 385 mm in the dry year 2005 to 612 mm in the wet year 2007. Growing seasonal rainfall (GSR) averaged about 400 mm, ranging from 332 mm in 2008 to 535 mm in 2007. On average, rainfall during the growing season accounted for 85% of the annual rainfall, indicating that the growing season for maize (May-October) is well synchronized to the rainy season (June-September). However, seasonal variations in rainfall were large and spring drought at sowing often occurred (Figure 1). Dry conditions at seeding impede seedling emergence and generally lead to low grain yield and nutrient uptake by maize (Cai et al. 1994).

Mean grain yields, soil water and water use

Mean grain yields (GY), water use (ET), water use efficiency (WUE), soil water contents at sowing (SWS) and at harvest (SWH) in responses to tillage and fertilizer treatments are shown in Figure 2.

Under reduced tillage (RT), grain yields and WUE were the highest with the lowest NP fertilizer application rate (Figure 2a and 2b), under which the yields at N105 were about 6% higher than that at N179 and N210 rates. Under no-till (NT), grain yields and WUE usually increased with fertilizer rates, under which the yields at N210 were about 3-4% higher than that at N105 and N179 rates. Under conventional tillage (CT), grain yields and WUE were also higher with the highest NP fertilizer rate, under which the yields at N210 rate were about 2-8% higher than that at N105 and N179 rates.

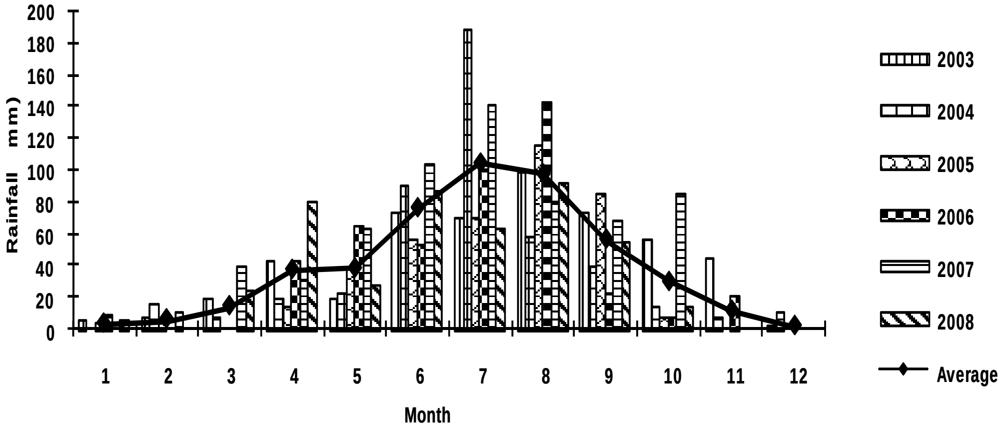

Figure 1 Monthly rainfall distribution in Shouyang during 2003-2008

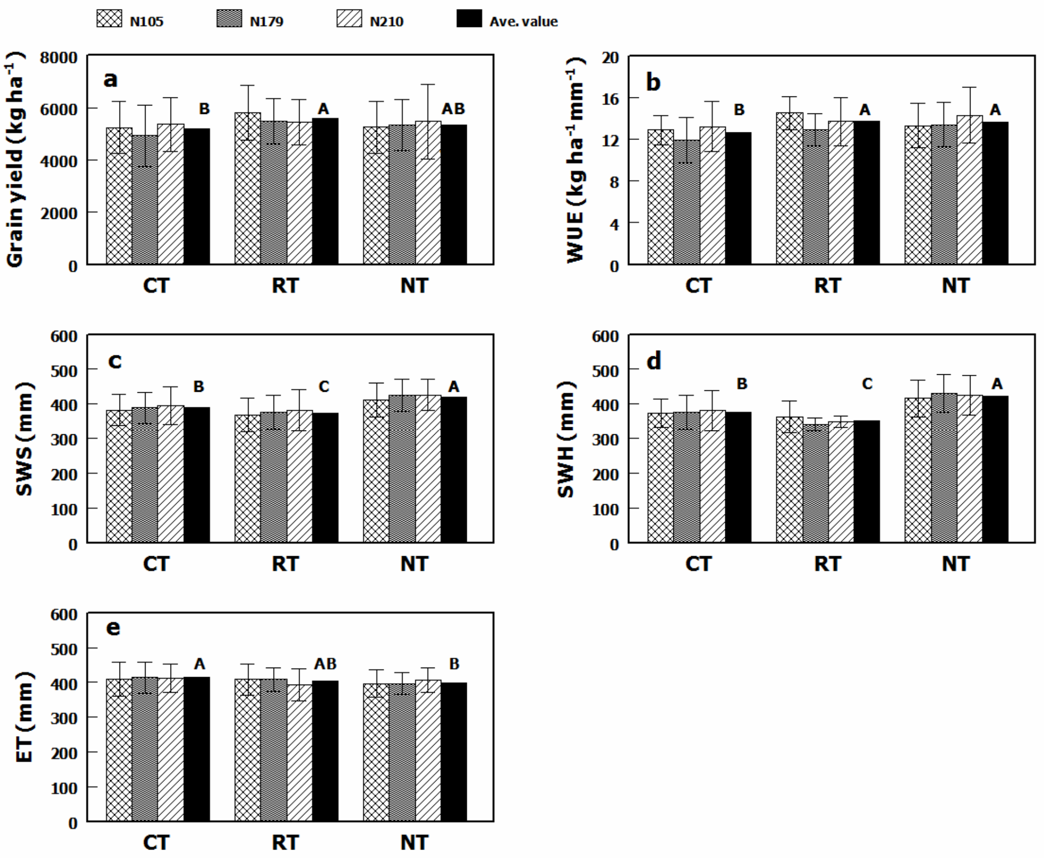

Figure2 Mean maize yield, water use (ET), water use efficiency (WUE), soil water at sowing (SWS) and after harvest (SWH) in responses to NP fertilizer application (N fertilizer rates: 105, 179 and 210 kg N, N:P = 1:0.44) under different tillage practices in Shouyang during 2003-2008

Mean grain yields over the 6-year period in responses to tillage treatments were 5604, 5347 and 5185 kg ha^{-1} and WUE were 13.7, 13.6 and 12.6 kg ha^{-1} mm^{-1} under RT, NT and CT, respectively (Figure 2a and 2b). The grain yields under RT were about 8% higher than CT (P<0.05). Statistic analysis showed sighnifcant differences in grain yields between years (P<.0.001), between tillage treatments (P<.0.042), and significant interaction bwteen years and tillage treatments (P<.0.055), but no significant difference between NP fertilizer rates. The grain yields showed stronger responses to tillage treatments than to fertilizer applications.

Soil water contents at sowing and at harvest were significantly influenced by tillage treatments. Mean SWS over the 6-year period was 389, 375 and 421 mm, and mean SWH was 378, 353 and 424 mm under CT, RT and NT, respectively (Figure 2c and 2d). At sowing and harvest time, the NT treatment had 8-12% more water in the soil than CT and RT treatments ($P<0.05$).

Mean apparent water use over the 6-year period was 415, 405, 399 mm under CT, RT and NT, respectively (Figure 2e). Water use under NT was about 4% lower than that under CT ($P<0.05$).

Annual grain yields, soil water and water use in responses to tillage methods

Annual maize grain yields, water use, water use efficiency, soil water contents at sowing and at harvest in responses to tillage treatments are shown in Figure 3.

Annual variations in maize grain yield were large, ranging from 4264 in the dry 2006 to 6959 kg ha^{-1} in the wet 2007, on average, for CT treatment, while ranging from 4495 to 6666 kg ha^{-1} for RT treatment, and from 5087 to 6499 kg ha^{-1} for NT treatment (Figure 3). The RT treatment generally had the highest yields, which were about 5-20% higher than that of the CT treatment, except for 2007. However, for the dry 2006, the NT treatment had the highest yield, which was about 19% higher than that of the CT treatment, while for the wet 2007, the grain yield under NT was the lowest, about 7% lower than that under CT. The coefficients of variation (CV) for yield fluctuations from the dry 2006 to the wet 2007 were about 28%, 23%, and 20% under CT, RT and NT treatment, respectively.

Annual variations in WUE ranged from 11 in the dry 2006 to 15 kg ha^{-1} mm^{-1} in the wet 2007 on average, for CT treatment, while ranged from 12 to 17 kg ha^{-1} mm^{-1} for RT treatment and from 14 to 15 kg ha^{-1} mm^{-1} for NT treatment (Figure 3). The CT treatment usually had the lowest WUE and the RT treatment the highest WUE. The WUE under RT was about 13% higher and under NT about 9% higher than that under CT.

Annual variations in soil water contents at sowing and at harvest ranged from 353 in 2005 to 459 mm in 2008, on average, for CT treatment, while ranged from 332 to 450 mm for RT treatment and from 400 to 495 mm for NT treatment (Figure 3). Soil water contents at sowing and at harvest were greatly influenced by tillage treatments. The NT treatment had the highest SWS and SWH, which were 6-11% and 10-14% more water in soil than the CT and RT treatments, respectively.

Annual variations in apparent water use (ET) by maize ranged from 361 mm in 2005 to 459 mm in 2007, on average, for CT treatment, while from 358 to 450 mm for RT treatment and from 380 to 441 mm for NT treatment (Figure 3). The NT treatment generally had the lowest water use, which were 4-5% lower than the RT and CT treatments, except for 2005.

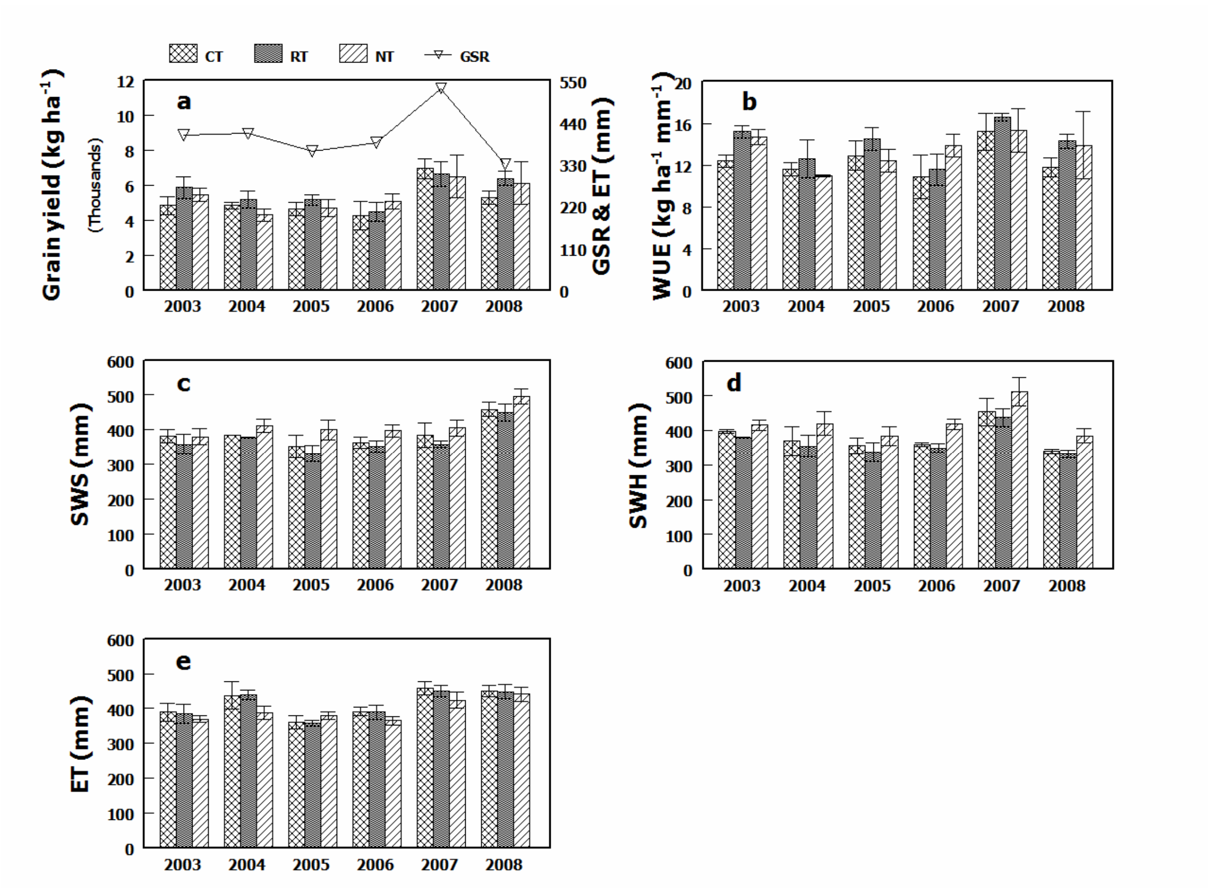

Figure 3 Annual variations in maize grain yield, water use (ET), water use efficiency (WUE), soil water at sowing (SWS) and after harvest (SWH) in responses to different tillage practices in Shouyang during 2003-2008

Annual grain yields, soil water and water use in responses to fertilizer application rates

Annual maize grain yields, ET, WUE, SWS and SWH in responses to fertilizer applications under tillage treatments are shown in Figure 4.

Maize grain yields tended to be higher at N210 rate for CT and NT treatments, while tended to be higher at N105 rate for RT treatments after the first three years of the experiment (Figure 4a, 4b, and 4c).

The changes in water use efficiencies had the same trends with the changes in grain yields over time. The WUE also tended to be higher at N210 rate for CT and NT treatments, while tended to be higher at N105 rate for RT treatments after the first three years of the experiment (Figure 4d, 4e, and 4f).

Apparent water use did not show much difference between fertilizer application rates under tillage treatments (Figure 4j, 4h, and 4i). There was also no much difference in soil water contents both at sowing and at harvest between NP fertilizer application rates under tillage treatments (not shown).

Relations between grain yield and water factors

Correlation coefficients (r) for dryland maize yield factors in Shouyang during 2003-2008 are shown in Table 2.

Maize grain yields were greatly influenced by the amount of growing season rainfall (Figure 3), and by soil water contents at sowing (Table 2). The significant linear relations were found between GY and water factors (GSR and SWS /SWH), and between WUE and GSR /and SWH. Apparent water use (ET) was significantly related to both SWS and GSR, indicating that water use by maize was highly associated with soil water contents at sowing and growing season rainfall.

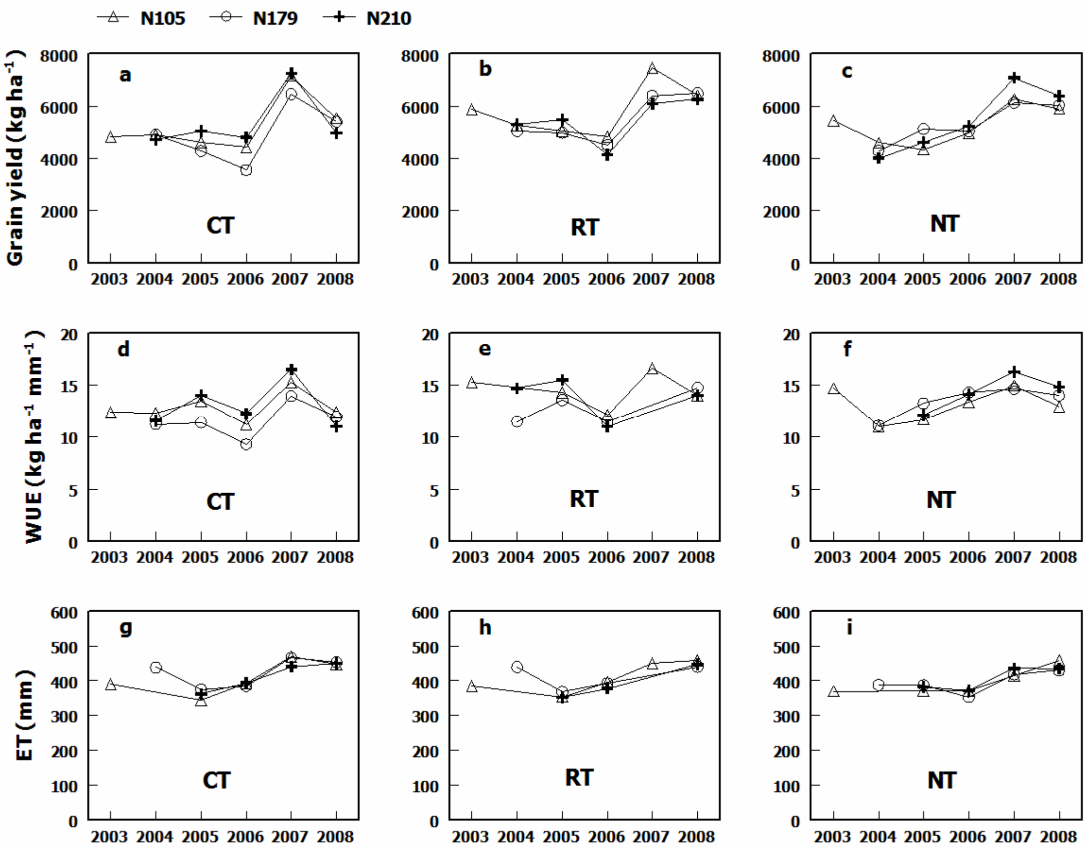

Figure 4 Annual variations in maize grain yield, water use (ET), water use efficiency (WUE), soil water at sowing (SWS) and after harvest (SWH) in responses to NP fertilizer applications (N fertilizer rates: 105, 179 and 210 kg N, N:P = 1:0.44) under different tillage practices in Shouyang during 2003-2008

Table 2 Correlation coefficients (r) for dryland maize yield factors in Shouyang during 2003-2008

	GY	*WUE*	*ET*	*GSR*	*SWS*	*SWH*
GY	1					
WUE	0.867**	1				
ET	0.573**	0.088	1			
GSR	0.430**	0.354**	0.221*	1		
SWS	0.256*	-0.030	0.589**	-0.287**	1	
SWH	0.290**	0.341**	0.092	0.742**	0.137	1

Note: * and ** refer to significance at P< 0.05 and P< 0.01 respectively. * r (0.05)=0.217; ** r (0.01)=0.283; n > 80
Grain yield (GY), and water use efficiency (WUE), water use (ET), growing season rainfall (GSR), soil water at sowing (SWS) and after harvest (SWH).

DISCUSSIONS AND CONCLUSIONS

The dryland maize grain yields, WUE, and water use in Shouyang showed stronger responses to tillage treatments than to fertilizer application rates during the experimental periods. The grain yield and WUE responses to tillage practices also vary greatly from year to year, influenced by variable water conditions (e.g. GSR and SWS), and affected by the strong interaction between tillage methods and weather conditions. As Lampurlanés et al., (2002) reported, in terms of yields, the best tillage system is often a function of the weather experienced in that year.

Grain yield and WUE responses to tillage methods

The RT treatment generally had the highest yields, about 5-20% higher than the CT treatment. However, for NT treatment, the grain yield was the highest in the dry 2006, about 19% increase relative to the CT treatment, but the lowest in the wet 2007, about 7% decrease compared to the CT treatment. Previous studies for dryland farming in northern China also show that yields under no-till are usually higher in dry years (4-22%), but lower (10-15%) during wet years (Wang et al., 2007c). The similar results were also documented by other studies that weather conditions in the growing season appear to play a part in the success of reduced and no-till systems, such as in the North Central and Northeastern USA (Johnson and Lowery, 1985; Griffith et al., 1986). Eckert (1984) reported no-till maize yielded more in drier than in normal years. Riley et al. (1994) reviewed that in Norway, better results were often observed in dry years than in wet years. Hussain et al. (1999) reported that no-till yields were 5-20% lower than with the moldboard plow system in wet years, but were 10-100% higher in relatively dry years. The higher yields with NT in dry years can be explained by our study due to significantly increased soil water storage, such as the highest SWS and SWH with NT, about 8-12% more water in soil than CT and RT treatments. This indicates that in dry years water is a more important yield-limiting factor for CT than for NT treatment, while in wet years nutrient becomes a more important yield-limiting factor for NT than for CT treatment.

The changes in water use efficiencies had the same trends with the changes in grain yields over time. The RT treatment usually had the highest WUE, and the CT treatment the lowest WUE. The WUE under NT and RT was about 9-13% higher than that under CT. Annual variations in WUE ranged from 11 in the dry 2006 to 17 kg ha^{-1} mm^{-1} in the wet 2007. This range of WUE is similar to the range (11-20 kg ha^{-1} mm^{-1}) measured in a long-term maize field experiment in Gansu in China (Fan et al. 2005).

Grain yield and WUE responses to fertilizer applications

The grain yields and WUE under reduced tillage were generally the highest at N105 rate. This fertilizer rate is same to the recommendation rate (at modest NP fertilizer rates of 105-46 kg N and P ha^{-1}) suggested in a long-term maize field experiment with various fertilization treatments in Shouyang in China (Wang et al., 2007a, 2007b). However, for CT and NT treatments, maize grain yields tended to be higher at high NP fertilizer rates (210-92 kg N and P ha^{-1}). This indicates that dryland maize yield and WUE responses to fertilizer applications differ under different tillage practices, and vary greatly from year to year, this also influenced by the interaction between tillage methods and weather conditions. As for the optimum fertilizer applications and nutrient availability with tillage systems, Riley et al., (1994) reported that the optimum fertilization is more critical with no-till than with CT systems. Rasmussen (1999) also reported adequate fertilizer inputs were generally more critical with conservation tillage systems (particularly no-till) than with conventional tillage systems, and over the long term, requirements could decline as a result of accumulation and mineralization of organic matter. This is reflected in lower fertilizer N availability to crops under conservation tillage as compared with conventional tillage (Doran, 1980), at least in the initial years of reduced tillage, but also documented potential nutrient availability associated with conservation tillage.

Water use responses to tillage methods

The NT treatment generally had the lowest apparent water use, about 4-5% lower than the RT and CT treatments, probably due to reduced water loss by evaporation. A previous study in Shouyang also showed that the evapotranspiration during spring maize growing periods mostly was reduced with conservation tillage practices relative to conventional tillage system (Wang et al., 2003c).

Conclusions

This study suggests that the optimum fertilizer rate is a critical component for successful adoption of conservation tillage practices under conditions of variable rainfall.

In conclusion, dryland maize grain yields and WUE were highest under reduced tillage at modest NP fertilizer application rates of 105 kg N and 46 kg P per ha. No-till increased soil water storage by 8-12% and improved WUE compared to conventional tillage.

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