



Responses of water productivity to irrigation and N supply for hybrid maize seed production in an arid region of Northwest China

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Abstract: Water and nitrogen (N) are generally two of the most important factors in determining the crop productivity. Proper water and N managements are prerequisites for agriculture sustainable development in arid areas. Field experiments were conducted to study the responses of water productivity for crop yield (WP_{Y-ET}) and final biomass (WP_{B-ET}) of film-mulched hybrid maize seed production to different irrigation and N treatments in the Hexi Corridor, Northwest China during April to September in 2013 and also during April to September in 2014. Three irrigation levels (70%–65%, 60%–55%, and 50%–45% of the field capacity) combined with three N rates (500, 400, and 300 kg N/hm²) were tested in 2013. The N treatments were adjusted to 500, 300, and 100 kg N/hm² in 2014. Results showed that the responses of WP_{Y-ET} and WP_{B-ET} to different irrigation amounts were different. WP_{Y-ET} was significantly reduced by lowering irrigation amounts while WP_{B-ET} stayed relatively insensitive to irrigation amounts. However, WP_{Y-ET} and WP_{B-ET} behaved consistently when subjected to different N treatments. There was a slight effect of reducing N input from 500 to 300 kg/hm² on the WP_{Y-ET} and WP_{B-ET} , however, when reducing N input to 100 kg/hm², the values of WP_{Y-ET} and WP_{B-ET} were significantly reduced. Water is the primary factor and N is the secondary factor in determining both yield (Y) and final biomass (B). Partial factor productivity from applied N (PF_{PN}) was the maximum under the higher irrigation level and in lower N rate (100–300 kg N/hm²) in both years (2013 and 2014). Lowering the irrigation amount significantly reduced evapotranspiration (ET), but ET did not vary with different N rates (100–500 kg N/hm²). Both Y and B had robust linear relationships with ET, but the correlation between B and ET ($R^2=0.8588$) was much better than that between Y and ET ($R^2=0.6062$). When ET increased, WP_{Y-ET} linearly increased and WP_{B-ET} decreased. Taking the indices of Y, B, WP_{Y-ET} , WP_{B-ET} and PF_{PN} into account, a higher irrigation level (70%–65% of the field capacity) and a lower N rate (100–300 kg N/hm²) are recommended to be a proper irrigation and N application strategy for plastic film-mulched hybrid maize seed production in arid Northwest China.

Keywords: water use efficiency; water stress; nitrogen use efficiency; evapotranspiration; water productivity for yield; water productivity for biomass; arid region

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1 Introduction

Water and nitrogen (N) are two of the most important factors in crop productivity (Gheysari et al., 2009; Du et al., 2010, 2015; Islam et al., 2012; Wei et al., 2012; Fu et al., 2014; Ran et al., 2016). Agriculture in arid region relies heavily on irrigation and groundwater has been over-exploited to meet irrigation requirements, resulting in a serious threat for sustainable crop production. As water resources is scarce in arid areas, water-saving irrigation can largely solve the problem of water scarcity (Kang et al., 2000, 2017; Geerts and Raes, 2009). To obtain a high crop yield and sometimes a high biomass, farmers applied N fertilizer at a rate that is higher than the optimal rate in most cases (Lemaire et al., 1997; Cui et al., 2010). Over-application of N fertilizer results in a lower N use efficiency and also environmental pollution risk (Chen et al., 2011). Thus a combination of effective water and N management that improves water and N use efficiencies is a part of the strategy for the sustainable development of agriculture in arid regions (English and Raja, 1996).

Quantifying crop (seed) yield and final biomass responses to different water and N application treatments can provide scientific references for developing water and N management strategies. Many studies show that reducing the amount of water supplied by irrigation can significantly reduce crop (seed) yield and final biomass (Bryant et al., 1992; Kang et al., 2000; Stone et al., 2000; Çakir, 2004; Farré and Faci, 2006; Gheysari et al., 2009). Other studies show that crop yield and final biomass generally increase with an increasing amount of N application (O'Leary and Rehm, 1990; Uhart and Andrade, 1995; Hammad et al., 2012; Jin et al., 2012). However, the responses of crop yield and final biomass to water and N application amounts vary with the environment in which the crop is grown, and the quantitative relationships of crop and biomass productivities with water and N application treatments are found to be different from site to site. Thus, it is necessary to investigate the responses of crop yield and final biomass to different irrigation amounts and different rates of N application for a specific climate, crop variety, soil type, and agronomy in particular areas.

Water productivity (i.e., efficiency) is an important measure for irrigation management in an arid region and has been intensively studied. Some studies reported that water stress decreases water productivity for yield (WP_{Y-ET}) (Sinclair et al., 1975; Pandey et al., 2000; Farré and Faci, 2006; Payero et al., 2006). However, other studies reported that moderate-level water stress can increase WP_{Y-ET} (Kang et al., 2000; Sampathkumar et al., 2013; Du et al., 2015). As for N fertilizer application, it is widely agreed that a reduction in the N application rate slightly decreases WP_{Y-ET} (Pandey et al., 2000; Ogola et al., 2002; Di Paolo and Rinaldi, 2008). In terms of final biomass, either the ratio of biomass to transpiration (WP_{B-T}) or the ratio of biomass to evapotranspiration (WP_{B-ET}) is often used to assess the productivity (i.e., efficiency). Many studies have dealt with the productivity-related issues (e.g., de Wit, 1958; Fischer and Turner, 1978; Bradford and Hsiao, 1982; Hanks, 1983; Tanner and Sinclair, 1983; Steduto et al., 2007). Although some research demonstrated that WP_{B-T} is relatively stable under water deficit conditions and it tends to decrease under low N supply rates (Steduto et al., 2000; Steduto and Albrizio, 2005; Steduto et al., 2007), few studies has been carried out on the responses of WP_{Y-ET} and WP_{B-ET} to different irrigation and N treatments. This is particularly the case regarding hybrid maize seed production under plastic film mulch conditions in arid Northwest China.

Hexi Corridor in Northwest China is a region of extreme water scarcity. It is also an important area for hybrid maize seed production. Unlike conventional maize, which is self-pollinating, hybrid maize seed production requires female and male parent plants. Female plants are detasseled before flowering to prevent self-pollination. The ears of female plants accept pollen from male plants of a different inbred line to form hybrid seed. To maintain a high yield of hybrid maize seed production, local farmers irrigate with 600 mm water amount and apply N at the rate of 500 kg/hm² during the growing season. Hybrid maize seed production is widely planted under plastic film mulch to maintain soil temperature and water content. We have previously reported

the effects of different irrigation and N treatments on kernel number per plant, 100-kernel weight, harvest index, and biomass partitioning of hybrid maize seed production (Ran et al., 2016). The objectives of this study are (1) to study the effects of different irrigation levels and N rates on the seed yield (Y), final biomass (B), and evapotranspiration (ET) of hybrid maize seed production; (2) to compare the responses of WP_{Y-ET} and WP_{B-ET} of hybrid maize seed production to different irrigation levels and N rates; and (3) to quantify the relationships among Y , B , WP_{Y-ET} and WP_{B-ET} and ET . These objectives, if met, will enable us to develop the suitable water and N application strategies for film-mulched hybrid maize seed production.

2 Materials and methods

The detailed methodology of this study is given in Ran et al. (2016). A brief description is as follow.

2.1 Study area and methods

Shiyanhe Experimental Station of China Agricultural University is located in Wuwei District, Gansu Province, Northwest China (37°52'N, 102°50'E; 1581 m a.s.l.). The experiments were carried out in two periods: between April and September in 2013 and between April and September in 2014. The experiment was conducted in split plot based on randomized complete block design with three replications. Irrigation levels (W) were designed according to targeted limits of soil water content as a percentage of field capacity (FC). N application rates were determined by reducing the normal amounts applied by local farmers. Specifically, three irrigation levels (including $W1$ (irrigation 70%–65% of FC), $W2$ (irrigation 60%–55% of FC), and $W3$ (irrigation 50%–45% of FC)) were combined with three N rates ($N500$ (500 kg N/hm²), $N400$ (400 kg N/hm²) and $N300$ (300 kg N/hm²)), i.e., in total 9 treatments (3 irrigation levels \times 3 N rates) were applied in 2013. Based on the experimental results in 2013, the three N rates were adjusted to $N500$ (500 kg N/hm²), $N300$ (300 kg N/hm²) and $N100$ (100 kg N g/hm²) in 2014. In each case irrigation was started when soil water content was depleted to the lower limit of the irrigation level, the irrigation upper limit being the field capacity.

2.2 Measurement methods

2.2.1 Climate data

The weather data included solar radiation (R_s), air temperature (T), relative humidity (RH), precipitation (P), solar radiation (R_s), and reference evapotranspiration (ET_0). Data were collected from a standard automatic weather station (Hobo, Onset Computer Corp., USA) that was installed in the experimental site. The ET_0 was calculated using the FAO Penman-Monteith equation (Allen et al., 1998). The averages of R_s , T and RH , and the total amounts of P and ET_0 for each month during the growth periods in 2013 and 2014 are shown in Figure 1. The climate in 2013 was hotter and drier than that in 2014, the average T being 1.7 °C higher, and the average RH and the total P being 4.8% and 168 mm lower during the growth period, respectively.

2.2.2 Soil water content

A calibrated time domain reflectometer (TRIME-PICO IPH, IMKO, Germany) was used to measure soil water content at intervals of 7 days within the maximum root depth of the hybrid maize seed production (about 100 cm). Table 1 showed the targeted irrigation amount, calculated as the difference between field capacity and actual soil water content in the 0–100 cm soil layer.

2.2.3 Seed yield and final biomass

Sixty female plants were randomly selected from each treatment regime. They were harvested for seed yield after crop maturity. Grains were first dried at 105 °C for 30 min, and then dried at 70 °C to constant weight. The seed yield of each treatment was normalized to 13% moisture content to ensure uniform comparison of the differences between treatments. The aboveground biomass of another 9 randomly-chosen female plants from each treatment regime were cut and then dried at 70 °C to constant mass to obtain the final biomass for each treatment.

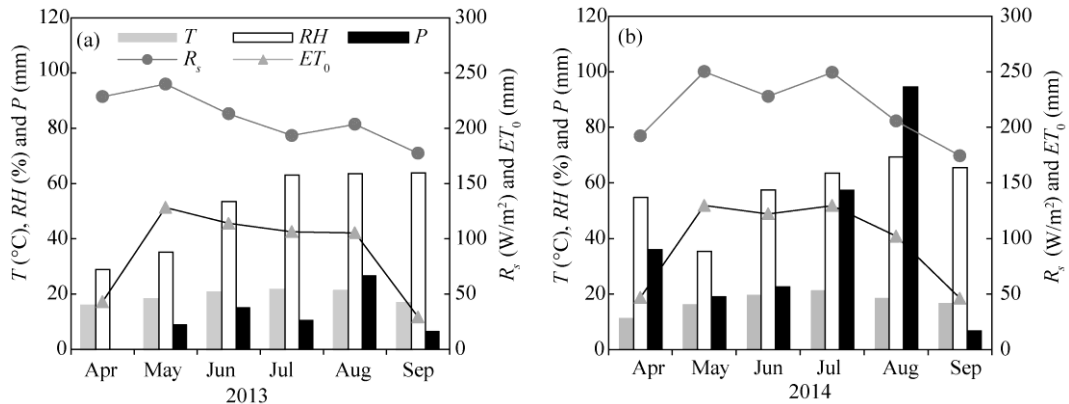


Fig. 1 Monthly meteorological data over the growth periods of hybrid maize seed production under plastic film mulch in (a) 2013 (from 20 April to 11 September) and (b) 2014 (from 14 April to 20 September) at Shiyanghe Experimental Station, Gansu Province, Northwest China. *T*, air temperature; *RH*, relative humidity; *P*, precipitation; *R_s*, solar radiation; and *ET₀*, reference evapotranspiration.

Table 1 Seasonal irrigation amount and N fertilizer rate applied to plastic film-mulched hybrid maize seed production in 2013 and 2014

Treatments in 2013 (N rate)	Percentage of field capacity (%)	<i>I</i> (mm)	Treatments in 2014 (N rate)	Percentage of field capacity (%)	<i>I</i> (mm)
W1 (N500)	70–65	339	W1 (N500)	70–65	274
W2 (N500)	60–55	238	W2 (N500)	60–55	179
W3 (N500)	50–45	132	W3 (N500)	50–45	115
W1 (N400)	70–65	280	W1 (N300)	70–65	265
W2 (N400)	60–55	230	W2 (N300)	60–55	227
W3 (N400)	50–45	157	W3 (N300)	50–45	117
W1 (N300)	70–65	288	W1 (N100)	70–65	333
W2 (N300)	60–55	243	W2 (N100)	60–55	242
W3 (N300)	50–45	133	W3 (N100)	50–45	115

Note: W, irrigation level; W1, 70%–65% of filed capacity; W2, 60%–55% of filed capacity; W3, 50%–45% of filed capacity; *I*, irrigation amount. Data in the table are cited from Ran et al. (2016).

2.2.4 Crop evapotranspiration

Actual crop evapotranspiration (*ET*) for each treatment was calculated using a soil water budget method (Ran et al., 2016).

2.2.5 Water productivity and partial factor productivity from applied nitrogen

The values of water productivity for seed yield (*WP_{Y-ET}*) and water productivity for final biomass (*WP_{B-ET}*) were calculated as follows:

$$WP_{Y-ET} = \frac{Y}{ET}, \quad (1)$$

$$WP_{B-ET} = \frac{B}{ET}, \quad (2)$$

where *Y* is the seed yield; *B*, the final biomass; *ET*, the actual crop evapotranspiration.

N use efficiency was evaluated by partial factor productivity from applied N (*PFP_N*) (Dobermann, 2005; Meng et al., 2012), and was calculated as:

$$PFP_N = \frac{Y}{N}, \quad (3)$$

where *N* is the total amount of N applied.

More details of the measurements of climate data, soil water content, yield and final biomass,

and crop evapotranspiration are given in Ran et al. (2016).

2.3 Statistical analysis

Two-factor analysis of variance (ANOVA) and regression analysis were performed using SPSS 21.0 software (IBM SPSS Statistics, USA) and Microsoft Excel.

3 Results

3.1 Yield, final biomass and partial factor productivity from applied N

The irrigation amount had a significant effect on the yield ($P < 0.001$), and the yield decreased at all N rates when the irrigation amount reduced (Table 2). In 2013, the average yields from the W2 and W3 treatments decreased by 32.6% and 64.3%, respectively, as compared with W1 treatment. In 2014, they decreased by 24.7% and 54.3%, respectively. In 2013, the amount of N applied did not significantly affect the yield, but in 2014 the yield was significantly affected ($P < 0.05$). The different responses of yield to N between the two years were related to the difference of N application rates. They were 500, 400, and 300 kg/hm² with a gradient of 100 kg/hm² between treatments in 2013; however, the gradient was increased to 200 kg/hm² in 2014. In 2013, the differences in yield among three N treatments were within 5%. In 2014, as compared with the yield of treatment N500, the yields of N300 and N100 treatments decreased by 4.1% and 16.5%, respectively. Thus, lowering irrigation level caused a significant yield loss, while decreasing N rate had a relatively small influence on yield.

Table 2 shows that irrigation level had a significant effect on the final biomass (B) of hybrid maize seed production in both 2013 and 2014 ($P < 0.001$). In 2013, the average B from treatments W2 and W3, as compared with W1 treatment, decreased by 13.0% and 21.5%, respectively. The average B from treatments W2 and W3 decreased by 14.7% and 26.5%, respectively in 2014. N rate had no significant effect on B in 2013, but significantly affected B ($P < 0.05$) in 2014 (Table 2), because of the decreasing N gradient between treatments in the latter year. In 2013, the difference in average B among three N treatments was within 5%. In 2014, as compared with the treatment N500, treatments N300 and N100 decreased the average B by 2.3% and 6.3%, respectively.

In 2013 and 2014, both irrigation level and N rate showed significant effects on the partial factor productivity from applied N (PFP_N). PFP_N was reduced with the decrease in the irrigation amount at all N rates. In 2013, compared with the W1 treatment, the W2 and W3 treatments reduced the average PFP_N by 32.2% and 64.6%, respectively. In 2014, they reduced the average PFP_N by 24.8% and 59.5%, respectively. However, PFP_N significantly increased with the lowering of N rate at all irrigation levels. N400 and N300 treatments increased the average PFP_N by 27.5% and 54.2%, respectively, as compared with N500 treatment in 2013. In 2014, they were increased by 60.8% and 333.9%, respectively.

3.2 Crop evapotranspiration

Crop evapotranspiration (ET) was significantly affected by the amount of irrigation in both 2013 and 2014 ($P < 0.001$; Table 3). ET decreased as the irrigation amount decreased for all N rates. In 2013, average ET decreased by 14.0% and 28.1% under treatments W2 and W3, respectively, as compared with treatment W1. In 2014, average ET decreased by 8.9% and 21.2% under treatments W2 and W3, respectively. However, there was no significant effect on ET from N rates in 2013 and 2014. And the difference in ET among all the N treatments was within 4.6% in 2013 and within 6.0% in 2014.

3.3 Water productivity for yield/final biomass

In both 2013 and 2014, the water productivity for yield (WP_{Y-ET}) of hybrid maize seed production was significantly affected by irrigation levels ($P < 0.05$). In both years, WP_{Y-ET} generally decreased with the reduction in irrigation amounts at all N rates (Table 3). In 2013, as compared with treatment W1, average WP_{Y-ET} obtained from treatments W2 and W3 decreased by 20.1% and 48.6%, respectively. In 2014, they decreased by 16.8% and 41.8%, respectively. N rate showed a significant effect on WP_{Y-ET} ($P < 0.05$) in 2014, but no significant effect was found in 2013.

Table 2 Effects of different combinations of irrigation and N treatments on yield (Y), final biomass (B) and partial factor productivity from applied nitrogen (PFP_N) of plastic film-mulched hybrid maize seed production in an arid region of Northwest China in 2013 and 2014

Irrigation					Irrigation				
in 2013					in 2014				
	N level					N level			
	N500	N400	N300	Mean		N500	N300	N100	Mean
Y (t/hm ²)									
W1	4.871 ^a	4.484 ^{abc}	4.605 ^{ab}	4.653	W1	6.418 ^a	5.757 ^{ab}	5.642 ^{ab}	5.939
W2	2.848 ^{cd}	3.598 ^{abc}	2.963 ^{bcd}	3.136	W2	4.359 ^c	4.927 ^{bc}	4.140 ^{cd}	4.475
W3	1.876 ^d	1.488 ^d	1.615 ^d	1.660	W3	3.321 ^{de}	2.832 ^{ef}	1.984 ^f	2.712
Mean	3.198	3.190	3.061		Mean	4.699	4.505	3.922	
B (t/hm ²)									
W1	15.041 ^a	14.225 ^a	13.434 ^{ab}	14.233	W1	20.828 ^a	19.248 ^{ab}	18.187 ^{bc}	19.421
W2	10.780 ^{cd}	13.072 ^{ab}	13.300 ^{ab}	12.384	W2	16.446 ^{cd}	16.350 ^{cd}	16.907 ^c	16.568
W3	11.357 ^{bcd}	11.853 ^{bcd}	10.290 ^d	11.167	W3	14.459 ^{de}	14.947 ^{de}	13.401 ^e	14.269
Mean	12.393	13.050	12.341		Mean	17.244	16.848	16.165	
PFP_N (kg/kg)									
W1	9.916 ^b	11.668 ^{ab}	15.101 ^a	12.228	W1	13.065 ^{de}	19.655 ^c	59.704 ^a	30.808
W2	5.797 ^c	9.361 ^b	9.714 ^b	8.291	W2	8.873 ^e	16.824 ^{cd}	43.807 ^b	23.168
W3	3.820 ^c	3.873 ^c	5.296 ^c	4.330	W3	6.759 ^e	9.669 ^c	20.998 ^c	12.475
Mean	6.511	8.301	10.037		Mean	9.566	15.383	41.503	
Significance test	Y	B	PFP_N		Y	B	PFP_N		
Irrigation (I) level	***	***	***		***	***	***		
N level	NS	NS	**		*	*	***		
I×N	NS	NS	NS		NS	NS	***		

Note: Means within each column followed by different lowercase letters are statistically different at $P<0.05$ level. NS, no significance; *, ** and *** indicate significances at $P<0.05$, $P<0.01$ and $P<0.001$ levels, respectively.

In 2013, the difference in WP_{Y-ET} among three N treatments was within 5%. In 2014, the WP_{Y-ET} of treatments N300 and N100 decreased by 6.5% and 22.3%, respectively as compared with the WP_{Y-ET} of treatment N500. Thus, lowering irrigation level significantly decreased WP_{Y-ET} , while reducing N rate from 500 to 300 kg/hm² had little effect on WP_{Y-ET} . However, reducing the N rate to 100 kg/hm² lowered the WP_{Y-ET} significantly.

Overall, the treatment W1N500 had the highest WP_{Y-ET} values of 1.186 (2013) and 1.063 kg/m³ (2014). In 2013, the WP_{Y-ET} value reached 1.111 kg/m³ with W1N300 treatment, being only 6.3% lower than that with W1N500 treatment. In 2014, the WP_{Y-ET} value was 0.926 kg/m³, being only 12.9% lower than that with W1N500 treatment (Table 3). In brief, lowering N fertilizer rate (100–300 kg/hm²) does not significantly affect the WP_{Y-ET} if the soil water content were kept above 70%–65% of the field capacity.

In both years the irrigation level showed no significant effect on the water productivity for final biomass (WP_{B-ET}) (Table 3). In 2013, the differences of WP_{B-ET} between W1 and W2 and between W1 and W3 were 2.8% and 9.4%, respectively. In 2014, they were 6.1% and 6.9%, respectively. The N rate showed no significant effect on WP_{B-ET} in 2013, but significantly affected WP_{B-ET} in 2014 ($P<0.05$). In 2013, the differences of WP_{B-ET} between N500 and N400 and between N500 and N300 were 1.1% and 4.1%, respectively. In 2014, the differences of WP_{B-ET} between N500 and N300 and between N500 and N100 were 4.8% and 11.2%, respectively.

3.4 Correlation analyses

Robust linear relationships were found between yield (Y), final biomass (B), and evapotranspiration (ET) under different irrigation and N treatments for both 2013 and 2014 (Figs. 2a and b) and the fitting of linear relationship is better ($R^2=0.8588$) between B and ET than

between Y and ET ($R^2=0.6062$), meaning that we can make a more accurate estimate of yield responses to ET through B if the relationship between Y and B is robust. Yield-based water productivity (i.e., efficiency) increased slightly with increasing ET under different irrigation levels and N rates (Fig. 2c). Biomass-based water productivity decreased, as a power function, with increasing ET (Fig. 2d). Partial factor productivity from applied N (PPF_N) showed a good exponential relationship with ET (Fig. 2e). And, Y showed a robust linear relationship with the total irrigation amount (I) (Fig. 2f).

Table 3 Effects of different combinations of irrigation (W) and nitrogen (N) treatments on crop evapotranspiration (ET), water productivity for yield (WP_{Y-ET}) and water productivity for final biomass (WP_{B-ET}) of plastic film-mulched hybrid maize seed production in an arid region of Northwest China in 2013 and 2014

Irrigation level					Irrigation level				
in 2013	N level				in 2014	N level			
	N500	N400	N300	Mean		N500	N300	N100	Mean
<i>ET</i> (mm)									
W1	420.0 ^a	419.3 ^a	414.5 ^a	417.9	W1	604.2 ^a	577.2 ^a	608.6 ^a	596.7
W2	369.0 ^{ab}	363.4 ^{ab}	346.1 ^{abc}	359.5	W2	501.3 ^{bc}	552.7 ^{ab}	576.7 ^a	543.5
W3	290.7 ^{bc}	341.5 ^{abc}	268.9 ^c	300.4	W3	457.6 ^c	480.6 ^c	471.9 ^c	470.0
Mean	359.9	374.7	343.2		Mean	521.0	536.8	552.4	
<i>WP_{Y-ET}</i> (kg/m ³)									
W1	1.186 ^a	1.078 ^{ab}	1.111 ^{ab}	1.125	W1	1.063 ^a	0.996 ^{ab}	0.926 ^{ab}	0.995
W2	0.779 ^{ab}	1.053 ^{ab}	0.866 ^{ab}	0.899	W2	0.868 ^{bc}	0.899 ^{abc}	0.718 ^{cd}	0.828
W3	0.676 ^{ab}	0.435 ^b	0.622 ^{ab}	0.578	W3	0.727 ^{cd}	0.590 ^d	0.421 ^e	0.579
Mean	0.880	0.855	0.866		Mean	0.886	0.828	0.688	
<i>WP_{B-ET}</i> (kg/m ³)									
W1	3.611 ^{ab}	3.407 ^{ab}	3.242 ^{ab}	3.420	W1	3.454 ^a	3.340 ^{ab}	2.998 ^{bc}	3.264
W2	2.955 ^b	3.729 ^{ab}	3.862 ^{ab}	3.515	W2	3.282 ^{abc}	2.962 ^{bc}	2.951 ^{bc}	3.065
W3	3.932 ^a	3.472 ^{ab}	3.820 ^{ab}	3.741	W3	3.161 ^{abc}	3.113 ^{abc}	2.841 ^c	3.038
Mean	3.499	3.536	3.641		Mean	3.299	3.139	2.930	
Significance test									
Irrigation (I) level	***	*	NS		***	***		NS	
N level	NS	NS	NS		NS	***		*	
I×N	NS	NS	NS		NS	NS		NS	

Note: Means within each column followed by different lowercase letters are statistically different at $P<0.05$ level. NS: no significance; * and *** indicate significances at $P<0.05$ and $P<0.001$ levels, respectively.

4 Discussion

4.1 Effects of irrigation and N level on yield

As expected, lowering irrigation amount significantly reduced the yield, while lowering N application rate had less effect on the yield. However, when we further analyzed the four most significant treatments (W1N500, W3N500, W1N100, and W3N100) in 2014, we found some interesting phenomena. When the irrigation level was lowered from W1 to W3, the yield was reduced by 48.3% and 64.8% at N500 level and at N100 level, respectively. This indicates that severe water stress reduced yield more pronouncedly at the lower N level. The reason might be that water stress depresses seed N uptake and assimilation under lower N conditions. On the other hand, when the N application rate increased from N100 to N500, the yield increased by 13.8% and 67.4% at W1 level and at W3 level, respectively. This suggests that increasing the amount of N application under severe water stress helps to reduce the yield loss. This result is beyond our expectation because previous studies reported that the increment of yield by increasing N level was lower under low irrigation level than under high irrigation level (Pandey et al., 2000; Di

Paolo and Rinaldi, 2008). However, it is consistent to other studies that increasing N application rate helps to improve crop drought tolerance (Sadras and Richards, 2014), and the improvement was achieved by adjusting osmotic potential, maintaining turgor and increasing water absorption capacity (Garcia et al., 2007).

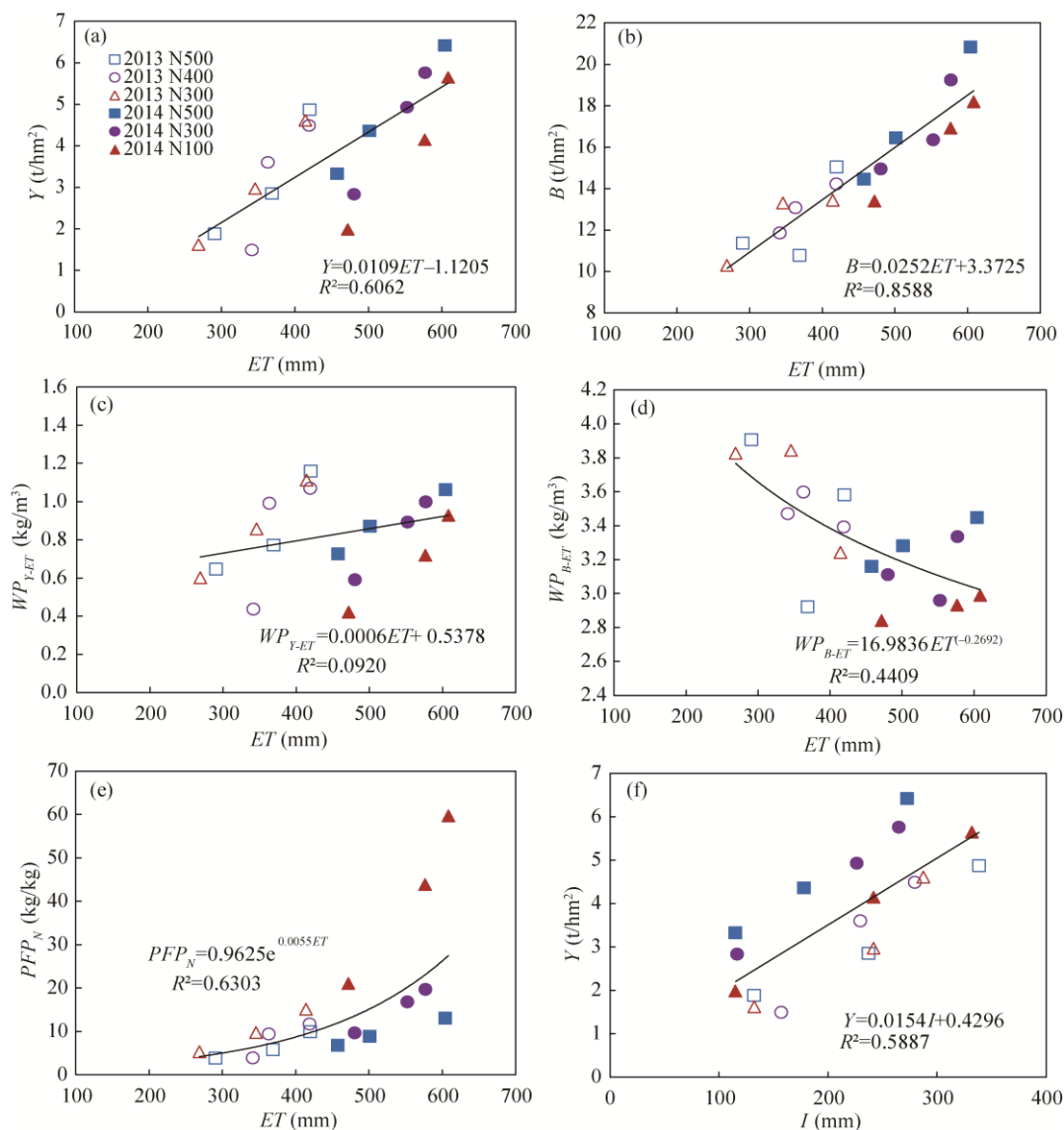


Fig. 2 Regression equations for yield (Y), final biomass (B), water productivity (WP_{Y-ET} , WP_{B-ET}) and partial factor productivity from applied N (PFP_N) of plastic film-mulched hybrid maize seed production in response to evapotranspiration (ET) or irrigation (I) under different N rates in an arid region of Northwest China in 2013 and 2014

4.2 Responses of water productivity to irrigation and N supply

Different results exist among studies on the response of WP_{Y-ET} to water stress. Our results showed that WP_{Y-ET} generally decreases with an increased degree of water stress, which is confirmed by other studies (Sinclair et al., 1975; Pandey et al., 2000; Zwart and Bastiaanssen, 2004; Farré and Faci, 2006; Payero et al., 2006). However, in the semi-arid Chinese Loess Plateau, Kang et al. (2000) found that, compared with treatment of a high amount of water, treatments with low and medium amounts of water at the seedling stage and with a low amount of water at the jointing stage can substantially improve WP_{Y-ET} . Sampathkumar et al. (2013) also found that

proper water stress increases WP_{Y-ET} in a semi-arid tropical climate. The reason underlying this discrepancy might be that crop growth in a semi-arid climate, as studied by Kang et al. (2000) and by Sampathkumar et al. (2013), depends less on irrigation than it does in the arid climate of Northwest China. Moreover, in our study, WP_{Y-ET} of hybrid maize seed production decreased when the irrigation level was below 70%–65% of the field capacity, since any further lowering of the irrigation amount caused severe water stress, resulting in physiological damage to the plants. Therefore, to guarantee a high WP_{Y-ET} in this region, soil water content should not be lower than 70%–65% of the field capacity.

As for WP_{B-ET} , final biomass is highly correlated with transpiration because carbon assimilation and transpiration processes are tightly coupled (de Wit, 1958; Fischer and Turner, 1978; Bradford and Hsiao, 1982; Hanks, 1983; Tanner and Sinclair, 1983; Steduto et al., 2007). The study by Ogola et al. (2002) showed that N application increases maize WP_{B-ET} through increasing biomass and decreasing soil evaporation. The amount of WP_{B-ET} is close to the amount of WP_{B-T} when soil evaporation accounts for only a small proportion of evapotranspiration (Sinclair et al., 1984). In our study, soil evaporation was rather low under plastic film mulch, so WP_{B-ET} was similar to WP_{B-T} under different irrigation and N treatments. Figure 2d shows that the relationship between WP_{B-ET} and ET was different over the two years. The main reason may lie in the difference of precipitation amounts between the two years (Fig. 1). That is, there was very little precipitation in 2013 while the climate was relatively humid and WP_{B-ET} was more stable in 2014.

Our results suggest that WP_{Y-ET} can be reduced significantly by lowering irrigation amount and that WP_{B-ET} is relatively insensitive to water stress. It should be particularly noted that both WP_{Y-ET} and WP_{B-ET} showed consistent behaviors under different N treatments. In general, WP_{Y-ET} and WP_{B-ET} changed insignificantly when N application rate was lowered from 500 to 300 kg/hm², however, they decreased significantly when N rate was further lowered to 100 kg/hm².

4.3 Irrigation and N management for sustainable development

This study also shows that yield and biomass will significantly decrease when irrigation level is lower than 70%–65% of the field capacity. Moreover, yield is more sensitive to irrigation amount than biomass (Table 2). Appropriate irrigation management is therefore essential for achieving acceptable crop yield and associated income, particularly when the available water does not meet the crop water requirements throughout the growth period. This study also shows that decreasing N application rate from 500 kg N/hm² to 300 kg N/hm² has no significant effect on seed yield. The results also suggest that the $PPFN$ increased significantly with the decrease of N application rate. The reduction of fertilizer application was an important measure to improve N use efficiency. It should be admitted here that the number of N treatments in this study was rather limited so that we cannot provide the optimal N application rate yet. It can be concluded that 70%–65% of the field capacity with a lower application rate of N (100–300 kg N/hm²) can significantly improve $PPFN$. The low N application rate combined with the high irrigation level can maintain high values of Y , B , WP_{Y-ET} , WP_{B-ET} for hybrid maize seed production using plastic film mulch in the arid region of Northwest China.

5 Conclusions

The field experimental study on the responses of water productivity for crop yield (WP_{Y-ET}) and final biomass (WP_{B-ET}) of film-mulched hybrid maize seed production to different irrigation and N treatments indicates that water is the primary factor and N is the secondary factor in determining crop yield and final biomass. WP_{B-ET} is much more stable than WP_{Y-ET} under water stress conditions. Both WP_{B-ET} and WP_{Y-ET} tend to decrease under low N rates. A higher irrigation level (70%–65% of the field capacity) combined with a lower nitrogen application rate (100–300 kg N/hm²) is recommended to be a proper irrigation and N management practice for hybrid maize seed production in the arid region of Northwest China.

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