African Journal of Agricultural Research Vol. 5(13), pp. 1598-1608, 4 July, 2010
Available online at http://www.academicjournals.org/AJAR
ISSN 1991-637X ©2010 Academic Journals

Full Length Research Paper

Effect of drought on water use efficiency, agronomic traits and yield of spring wheat landraces and modern varieties in Northwest China

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Accepted 20 April, 2010

A pot experiment with five typical landraces (Heshangtou, Hongnong No. 1, Dingxi 24, Damaizi and Jieba), three modern varieties (Qingchun 533, Plateau 602 and Abbondanza) and two water levels was carried out in the present study. The result showed that fertile spike, plant height, grains number of main spike (except Dingxi 24), above ground dry material, grain yield and grain yield water use efficiency of all varieties decreased, but grain weight (except Qingchun 533 and Plateau 602) and harvest index (except Plateau 602) of all varieties increased from 70% to 40% field capacity. The landraces had more fertile spikes, higher plant height, more above ground dry material (except Jieba), higher evaporation transpiration and lower harvest index than modern varieties under both 70% and 40% field capacity. Modern varieties had more grain number of main spike and grain weight than landraces under 70% field capacity on the whole. Although Qingchun 533 and Abbondanza had higher leaf-level water use efficiency than other varieties from heading stage to 30 days after anthesis, still they had lower grain yield water use efficiency than Heshangtou, Dingxi 24 and Damaizi under 40% field capacity. Varieties with higher evaporation transpiration and above ground dry material (higher ability of soil moisture capture) always had higher grain yield, grain yield water use efficiency and drought tolerance under drought stress.

Key words: Landrace, leaf-level water use efficiency, grain yield water use efficiency, drought tolerance.

INTRODUCTION

Northwest China is a vast, semi-arid and arid region which has a land area of 3.15 million km^2, accounting for about 33% of the total area of China (Junlian, 2007). The precipitation ranges from 40 to 600 mm in this region (Zhongkui et al., 2005; Tinglu et al., 2005). However, the annual potential evaporation amounts at 1500 - 3000 mm (Zhongkui et al., 2005). With the population growing rapidly and the limited water resources becoming scarcer, water shortage has become the key factor that constrains the crop production and quality in northwest China. Due to the increasing water resource scarcity (or drought), raising the yield and water use efficiency is an urgent imperative under water-limiting conditions (Hamdy et al., 2003). There are several strategies to raising yield and water use efficiency in irrigated and rain-fed agriculture (Wang et al., 2002), such as better management of the water resource (Junlian, 2007), reducing evaporation by mulching (Zhongkui et al., 2005; Yilong et al., 2005), using advanced irrigation method and schedule (Taisheng Du et al., 2006; Ali et al., 2008) and breeding cultivars with high water use efficiency and drought tolerance (Condon et al., 2002). Among these strategies, breeding cultivars with high water use efficiency and drought tolerance is more practical and economical. With the development of biology water saving, this strategy has become the hot topic (Mark, 2004;

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Abbreviations: AGDM, Above ground dry material; **ET,** evaporation transpiration; **EUW,** effective use of water; **FC,** field capacity; **GNMS,** grain number of main spike; **GY,** grain yield; **GYWUE,** grain yield water use efficiency; **HI**, harvest index; **LWUE,** leaf-level water use efficiency; **P,** photosynthesis; **SSI,** Stress susceptibility index; **T,** transpiration; **TOL,** tolerance; **YI,** Yield index; **YSI,** yield stability index.

Richards et al., 2002). In the last three decades, many reports in relation to this hot topic, including physiology (osmotic adjustment, stem reserve mobilization, stay green, early seedling vigor and flowering time) (Morgan and Condon, 1986; Richards, 1991; López-Castañeda et al., 1996; Blum, 1998; Borrell and Hammer, 2000), morphology (embryo size, coleoptile length, epicuticular wax/Glaucousness, pubescence, specific leaf area, erect upper canopy of leaves and root system) (Schillinger et al., 1998; Richards, 1992; López-Castañeda et al., 1996; Richards et al., 1986; Richards et al., 2002; Premachandra et al.,1994; Sharp et al., 2004) and molecules (genes/QTLs and molecular markers) (Morgan and Tan, 1996; Teulat et al., 1998; Johnson et al., 2000; Lafitte and Courtois, 2002; Sanchez et al., 2002; Robin et al., 2003; Forster et al., 2004;; Verma et al., 2004; Nguyen et al., 2004; Juenger et al., 2005) have been published. Furthermore, lots of transgenic crops have been developed and they showed increased drought tolerance (Bahieldin et al., 2005; Oh et al., 2005; Wang et al., 2005; Yan et al., 2004). However, because of the multigenic nature of water use efficiency and drought tolerance, the introduction of a single gene or QTL into an elite germplasm may result in a subtle phenotypic effect or yield increase; or even sometimes result in shortfalls related to agronomical performance (Wang et al., 2003). The results suggest that a comprehensive understanding of the physiological and gene regulatory networks is essential for developing crops with high yield, water use efficiency and drought tolerance.

Spring wheat is the major crops and is being cultivated for thousands of years in northwest China. The cultivating conditions vary in different places. Even in a small mountain village; farmers may have different type of fields, some in the valley that can be irrigated and some on the hillside that can not be irrigated. Different cultivating conditions need unique varieties to be grown in it. As a result, many landraces have been developed from ancient times with a wide range genetic polymorphism and a few of them were considered as drought sensitive, but most of them were considered as drought tolerant. However, the yield potential, water use efficiency and drought tolerance of them has not been systematically learnt yet. In order to know the effect of drought on water use efficiency (WUE), agronomic traits and yield of these landraces and modern varieties in detail, a pot experiment was carried out in present study to compare their drought tolerance and collect data for breeding varieties with high water use efficiency (WUE) and drought tolerance in the future.

MATERIALS AND METHODS

Plant materials

Three modern varieties that were considered as irritated-field varieties (Qingchun 533, Plateau 602 and Abbondanza) and five typical landraces that were considered as rain-fed varieties (Heshangtou, Hongnong No. 1, Dingxi 24, Damaizi and Jieba) were examined in the present study.

Site and experimental design

This study was carried out at Northwest Institute of Plateau Biology, Chinese Academy of Science, Xining, Qinghai province (36°37´N, 101°46´E). The physical and chemical properties of the soil was as follows: silt loam soil, organic matter 17.12 mg/g, total N 1.01 mg/g, total P 2.39 mg/g, total K 2.3 mg/g, available N 69.0 mg/g, effective P 65.0 mg/kg and available K 86.0 mg/kg. Before sowing, the soil was mingled sufficiently and each pot (30 × 21cm) filled with 5 kg soil. Three seeds of each variety were sown in plastic pots. Each variety was treated under 70 and 40% of field capacity (FC) respectively, by weighing the pots every day (Hsiao, 1973). Each treatment was replicated three times. After emergence, each pot only kept one seedling. Fungicides and pesticides were applied and weeds were removed by hand to minimize the effect of fungi, pests and weeds.

Measurements

Leaf-level water use efficiency (LWUE)

At heading stage, 10, 20 and 30 days after anthesis, photosynthesis (P) and transpiration (T) of flag leaf were measured using a portable photosynthesis system Li-6400 (Li-Cor, Lincoln, NE, USA) and the leaf-level water use efficiency (LWUE) was calculated using the following equation (Condon et al., 2002; Condon et al., 2004),

$$\mathrm{LWUE} = P/T \qquad (1)$$

Agronomic traits

At maturity, the above-ground material of each plant was harvested separately. After drying 48 h at 80℃, plant height, fertile spikes, grain number of main spike (GNMS), above-ground dry matter (AGDM) and grain yield (GY) of each plant were recorded. The harvest index of each plant was calculated as the fraction of the above-ground dry matter (AGDM) present as grain (Foulkes et al., 2007), as:

$$\mathrm{HI} = \mathrm{GY} / \mathrm{AGDM} \qquad (2)$$

Grain weight of each plant was calculated using the following formula,

$$\text{Grain weight} = \mathrm{GY} / \text{grain number} \qquad (3)$$

Grain yield water use efficiency (GYWUE)

For farmers and agronomists, grain yield is the most important. They consider grain yield as being constructed from a framework of evapotranspiration (ET) and the proportion of that water actually transpired by the crop (T/ET), results in the transpiration efficiency of biomass production (W) and harvest index (HI) (Condon et al., 2004; Passioura, 1977), as:

$$\mathrm{GY} = \mathrm{ET} \times (\mathrm{T}/\mathrm{ET}) \times \mathrm{W} \times \mathrm{HI} \qquad (4)$$

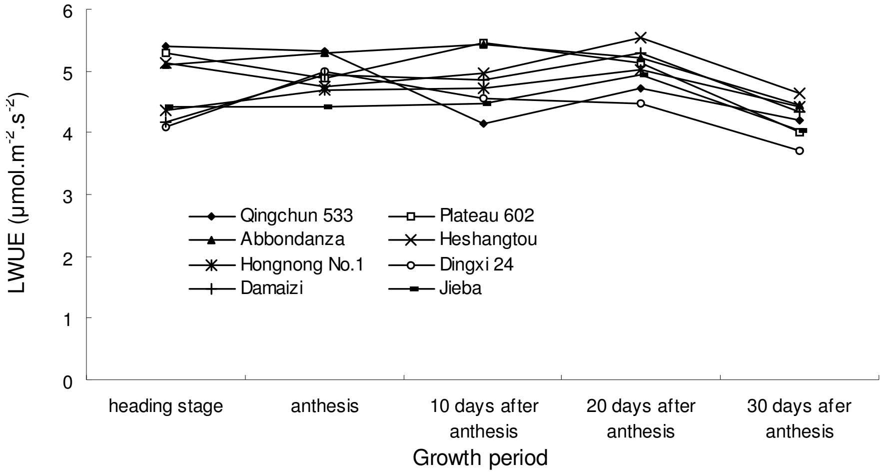

Figure 1. Leaf-level water use efficiency of different varieties from heading stage to 30 days after anthesis under 70% field capacity.

The grain yield water use efficiency (GYWUE) was then calculated using the following formulae,

$$\mathrm{GYWUE} = \mathrm{GY}/\mathrm{ET} \quad (5)$$

Or

$$\mathrm{GYWUE} = [\mathrm{ET} \times (\mathrm{T}/\mathrm{ET}) \times \mathrm{W} \times \mathrm{HI}]/\mathrm{ET} = \mathrm{T}/\mathrm{ET} \times \mathrm{W} \times \mathrm{HI} \quad (6)$$

Evaluation of drought tolerance

Drought tolerance was evaluated using the following equations:

(1) Stress susceptibility index (SSI) = $[1 - (Y_s/Y_p)]/ [1 - (\hat{Y}_s/\hat{Y}_p)]$ (Fischer and Maurer, 1978) (7)

Where Y_s is the yield of variety under stress, Y_p is the yield of variety under irrigated condition. $\hat{Y}_s$ and $\hat{Y}_p$ are the mean yields of all varieties under stress and non-stress conditions, respectively.

2. Tolerance (TOL) = $Y_p - Y_s$ (Hossain et al., 1990). (8)
3. Yield index (YI) = $Y_s/\hat{Y}_s$ (Gavuzzi et al., 1997). (9)
4. Yield stability index (YSI) = Y_s/Y_p (Bouslama and Schapaugh, 1984). (10)

Statistical analysis

Data were analyzed using SPSS for the analysis of variance and correlation. Duncan's multiple range tests was employed for the mean comparisons.

RESULT

Effect of drought on LWUE of different varieties

LWUE trend of the eight varieties was different under 70% FC and only from 20 to 30 days after anthesis; it has a downward trend (Figure 1). LWUE of Qingchun 533 and Abbondanza became higher from 70% FC to 40% FC (Table 1) and were higher than other varieties from heading stage to 30 days after anthesis under 40% FC (Figure 2). LWUE of Plateau 602 reduced sharply from anthesis to 30 days after anthesis under 40% FC and was higher only at anthesis under 40% FC than 70% FC. LWUE of Heshangtou, Hongnong No. 1, Dingxi 24 and Jieba became lower after anthesis and that of Damaizi became lower after heading stage from 70 to 40% FC (Table 1). On the average, LWUE of modern varieties was higher than landraces from heading stage to 30 days after anthesis under both 70 and 40% FC (Figure 3).

Effect of drought on fertile spike, plant height, GNMS and grain weight of different varieties

The landraces had more fertile spikes and higher plant height than modern varieties (except plant height of Abbondanza) under both 70 and 40% FC (Tables 2 and 3), while modern varieties had more grain number of main spike and grain weight than that of landraces under 70% FC. On the other hand, modern varieties had more grain number of main spike (except Plateau 602), but less grain weight (except Abbondanza) than landraces under 40% FC. Fertile spike and plant height of all cultivars decreased sharply from 70 to 40% FC. GNMS of Dingxi 24 increased a little and other varieties decreased, while grain weight of Qingchun 533 and Plateau 602 decreased and other cultivars increased from 70% to 40% FC. Among these cultivars, plant height, GNMS and grain weight of Plateau 602 decreased most (Table 4). As a result, Plateau 602 had the greatest grain weight under 70% FC, though it had the least fertile spike and grain weight and the lowest plant height under 40% FC.

Table 1. The difference of LWUE at different growth period between 70 and 40% FC.

Variety	Heading stage	Anthesis	10 days after anthesis	20 days after anthesis	30 days after anthesis
Qingchun 533	0.42	0.75	1.31	0.46	1.65
Plateau 602	-0.38	0.58	-0.63	-1.60	-3.04
Abbondanza	0.81	0.84	0.06	0.47	0.58
Heshangtou	0.16	0.78	-0.45	-0.78	-1.54
Hongnong No.1	0.86	0.11	-0.35	-0.45	-0.39
Dingxi 24	1.28	0.23	-0.13	0.19	-1.22
Damaizi	0.33	-0.24	-0.43	-0.73	-0.42
Jieba	0.36	0.86	-0.13	-0.99	-0.15
average of modern varieties	0.28	0.72	0.25	-0.22	-0.27
average of landraces	0.60	0.35	-0.30	-0.55	-0.74

FC, field capacity; LWUE, leaf-level water use efficiency.

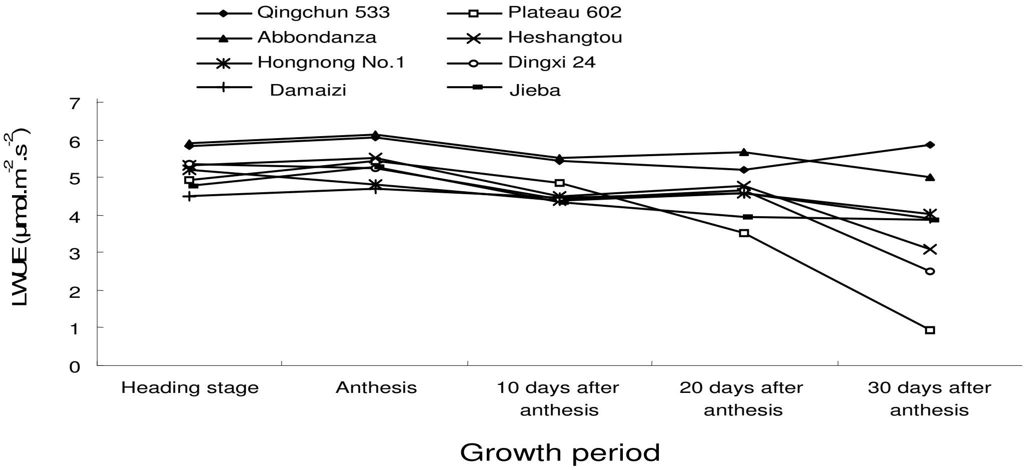

Figure 2. Leaf-level water use efficiency of different varieties from heading stage to 30 days after anthesis under 40% field capacity.

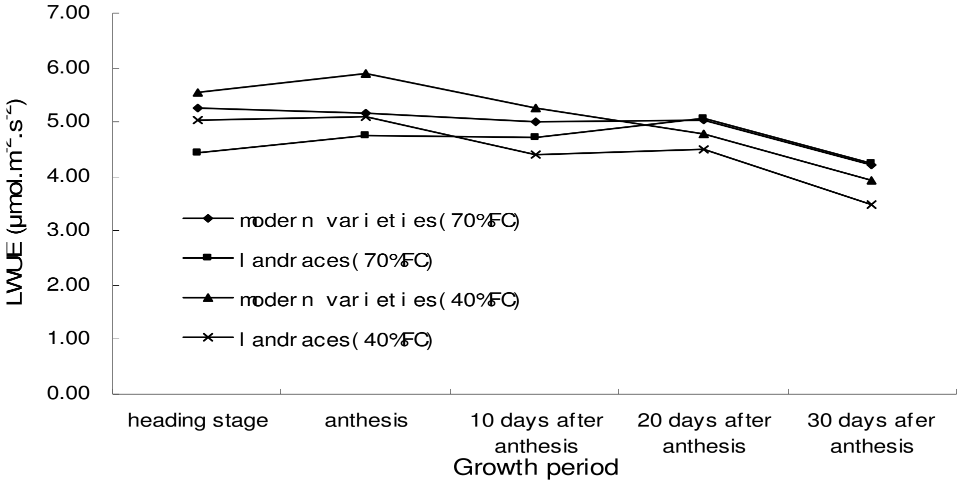

Figure 3. Average leaf-level water use efficiency of modern varieties and landraces from heading stage to 30 days after anthesis under 70 and 40% field capacities.

Table 2. Fertile spike, plant height, grain number of main spike and grain weight of different varieties under 70% FC.

Variety	Fertile spike	Plant height (cm)	GNMS	Grain weight (mg)
Qingchun 533	7.00±0.58^{d}	66.63±1.56^{c}	53.72±2.03^{a}	29.92±2.66^{b}
Plateau 602	6.00±1.00^{d}	73.03±0.54^{b}	46.57±3.11^{b}	42.46±3.08^{a}
Abbondanza	9.33±0.88^{cd}	82.45±1.95^{a}	35.48±2.49^{c}	31.02±2.26^{b}
Heshangtou	16.33±2.19^{b}	80.57±2.19^{a}	26.47±1.71^{d}	20.68±2.09^{c}
Hongnong No. 1	22.00±1.16^{a}	83.20±1.65^{a}	20.33±0.02^{e}	28.77±1.75^{b}
Dingxi 24	15.33±0.88^{b}	83.03±1.16^{a}	26.39±1.03^{d}	20.63±1.75^{c}
Damaizi	14.00±2.65^{b}	78.03±4.29^{ab}	29.55±1.26^{d}	26.17±0.95^{bc}
Jieba	13.67±0.88^{bc}	78.17±1.33^{ab}	29.67±1.73^{d}	21.12±1.54^{c}
Average of modern varieties	7.44	74.04	45.26	34.47
Average of landraces	16.27	80.60	26.48	23.47

FC, field capacity; GNMS, grain number of main spike.
Means within a column followed by the same letters are not significantly different ($P < 0.05$).

Table 3. Fertile spike, plant height, grain number of main spike and grain weight of different varieties under 40% FC.

Variety	Fertile spike	Plant height (cm)	GNMS	Grain weight (mg)
Qingchun 533	2.00±0.00^{b}	52.80±1.96^{c}	42.83±4.23^{a}	27.75±3.15^{bc}
Plateau 602	1.33±0.33^{b}	47.93±4.33^{c}	21.50±0.29^{cd}	23.90±2.98^{c}
Abbondanza	2.00±0.00^{b}	61.70±4.01^{ab}	35.00±5.41^{ab}	37.91±0.15^{a}
Heshangtou	4.33±0.33^{a}	63.60±2.45^{a}	24.68±2.62^{cd}	33.60±2.04^{ab}
Hongnong No. 1	5.00±0.58^{a}	65.10±0.87^{a}	16.11±1.71^{d}	37.11±0.02^{a}
Dingxi 24	3.67±0.67^{a}	61.33±0.29^{ab}	28.22±1.18^{bc}	32.77±1.19^{ab}
Damaizi	4.67±0.67^{a}	67.57±1.77^{a}	26.29±0.02^{c}	28.40±1.37^{bc}
Jieba	4.00±0.58^{a}	55.30±1.45^{bc}	21.67±0.96^{cd}	24.64±0.21^{c}
Average of modern varieties	1.78	54.14	33.11	29.85
Average of landraces	4.33	62.58	23.39	31.30

FC, field capacity; GNMS, grain number of main spike.
Means within a column followed by the same letters are not significantly different ($P < 0.05$).

Table 4. The difference of fertile spike, plant height, grain number of main spike and grain weight between 70 and 40% FC.

Variety	Fertile spike	Plant height (cm)	GNMS	Grain weight (mg)
Qingchun 533	-5.00	-13.83	-10.89	-2.17
Plateau 602	-4.67	-25.10	-25.07	-18.56
Abbondanza	-7.33	-20.75	-0.48	6.89
Heshangtou	-12.00	-16.97	-1.79	12.92
Hongnong No. 1	-17.00	-18.10	-4.22	8.34
Dingxi 24	-11.66	-21.70	1.83	12.14
Damaizi	-9.33	-10.46	-3.26	2.23
Jieba	-9.67	-22.87	-8.00	3.52
Average of modern varieties	-5.67	-19.89	-12.15	-4.61
Average of landraces	-11.93	-18.02	-3.09	7.83

FC, field capacity; GNMS, grain number of main spike.

Effect of drought on AGDM, GY and HI of different varieties

Landraces (except Jieba) had more AGDM than modern varieties under both 70 and 40% FC, while modern varieties had higher HI than landraces under 70% FC. The difference between these two types of varieties (except Abbondanza) was significant. Among the landraces, Dingxi 24 and Heshangtou had the lowest HI. As a result, they had the most AGDM, though they had

Table 5. AGDM, GY and HI of different varieties.

Variety	AGDM (g)		GY (g)		HI	
	70% FC	40% FC	70% FC	40% FC	70% FC	40% FC
Qingchun 533	23.53±3.24^{c}	4.71±0.67^{bc}	11.13±1.68^{abc}	2.43±0.50^{ab}	0.48±0.00^{a}	0.51±0.03^{a}
Plateau 602	23.97±2.51^{c}	1.83±0.47^{d}	11.67±1.52^{abc}	0.80±0.26^{c}	0.48±0.02^{a}	0.42±0.03^{a}
Abbondanza	27.80±2.13^{bc}	4.85±1.03^{bc}	10.23±1.94^{abc}	2.35±0.70^{ab}	0.36±0.04^{b}	0.52±0.01^{a}
Heshangtou	37.65±0.09^{ab}	7.87±0.66^{a}	9.13±2.13^{abc}	3.53±0.22^{a}	0.24±0.06^{c}	0.45±0.02^{a}
Hongnong No. 1	37.10±0.74^{ab}	6.67±0.27^{ab}	12.65±0.03^{ab}	2.77±0.27^{ab}	0.34±0.00^{b}	0.41±0.03^{a}
Dingxi 24	39.00±4.83^{a}	7.40±1.56^{ab}	8.25±0.03^{c}	3.43±0.75^{a}	0.22±0.03^{c}	0.48±0.00^{a}
Damaizi	32.17±5.65^{abc}	7.97±1.26^{a}	13.10±0.12^{a}	3.27±0.43^{ab}	0.35±0.01^{b}	0.41±0.01^{a}
Jieba	25.10±0.00^{c}	3.70±0.00^{cd}	8.47±0.38^{bc}	1.73±0.43^{bc}	0.34±0.01^{b}	0.47±0.12^{a}
Average of modern varieties	25.10	3.80	11.01	1.86	0.44	0.48
Average of landraces	34.20	6.72	10.32	2.95	0.30	0.44

Means within a column followed by the same letters are not significantly different ($P < 0.05$).
AGDM, above ground dry material; FC, field capacity; GY, grain yield; HI, harvest index.

Table 6. The difference of AGDM, GY and HI between 70% FC and 40% FC.

Variety	AGDM (g)	GY (g)	HI
Qingchun 533	-18.82	-8.70	0.03
Plateau 602	-22.14	-10.87	-0.06
Abbondanza	-22.95	-7.88	0.16
Heshangtou	-29.78	-5.60	0.21
Hongnong No. 1	-30.43	-9.88	0.07
Dingxi 24	-31.60	-4.82	0.26
Damaizi	-24.20	-9.83	0.06
Jieba	-21.40	-6.74	0.13
Average of modern varieties	-21.30	-9.15	0.04
Average of landraces	-27.48	-7.37	0.15

AGDM, above ground dry material; FC, field capacity; GY, grain yield; HI, harvest index.

the least GY under 70% FC. On the contrary, modern varieties (except Plateau 602) had higher HI than landraces under 40% FC, but the difference between them was still not significant (Table 5). At the same time, AGDM and GY of all cultivars decreased sharply and HI increased (expect Plateau 602) from 70 to 40% FC (Table 6).

Effect of drought on ET and GYWUE of different varieties

ET and GYWUE of all the cultivars decreased sharply from 70 to 40% FC. Landraces (except Jieba under 70% FC) had more ET than modern varieties, especially Heshangtou which had most ET under both 70% and 40% FC (Table 7). On the other hand, landraces had lower GYWUE than modern varieties under 70% FC, but higher under 40% FC on the whole. Plateau 602 had the highest GYWUE under 70% FC, but had the lowest GYWUE under 40% FC. On the contrary, Dingxi 24 and Heshangtou had the lowest GYWUE under 70% FC, but had the highest GYWUE under 40% FC. The difference between Plateau 602 and the two landraces (Dingxi 24 and Heshangtou) was significant under both 70% FC and 40% FC.

The relationship between LWUE, GYWUE, ET and some agronomic traits

GYWUE was negatively correlated with fertile spike (not significant), plant height (not significant), AGDM (not significant) and ET ($P<0.05$) under 70% FC, but positively correlated with fertile spike ($P<0.01$), plant height ($P<0.01$), AGDM ($P<0.01$) and ET ($P<0.01$) under 40% FC

Table 7. ET and GYWUE of different varieties.

Variety	ET (kg)		GYWUE (g kg^{-1})	
	70% FC	40% FC	70% FC	40% FC
Qingchun 533	22.06±1.83^{c}	11.68±0.01^{bc}	0.50±0.04^{ab}	0.21±0.04^{a}
Plateau 602	23.16±0.78^{bc}	11.15±0.02^{c}	0.56±0.00^{a}	0.07±0.02^{b}
Abbondanza	21.03±1.71^{c}	11.64±0.00^{bc}	0.49±0.08^{ab}	0.20±0.06^{a}
Heshangtou	28.36±0.14^{a}	13.87±0.33^{a}	0.32±0.07^{c}	0.26±0.02^{a}
Hongnong No. 1	25.71±0.45^{abc}	13.10±0.16^{a}	0.49±0.00^{ab}	0.17±0.02^{a}
Dingxi 24	27.23±1.24^{ab}	13.26±0.29^{a}	0.30±0.01^{c}	0.26±0.05^{a}
Damaizi	24.81±2.72^{abc}	13.45±0.02^{a}	0.48±0.00^{ab}	0.24±0.03^{a}
Jieba	22.71±0.95^{bc}	12.07±0.65^{b}	0.38±0.03^{bc}	0.14±0.03^{ab}
Average of modern varieties	22.08	11.49	0.52	0.16
Average of landraces	25.76	13.15	0.39	0.21

Means within a column followed by the same letters are not significantly different ($P < 0.05$).
ET, evapotranspiration; FC, field capacity; GYWUE, grain yield water use efficiency.

Table 8. Pearson correlation coefficient between GYWUE and some agronomic traits and ET under 70% FC.

Variety	Fertile spike	Plant height	AGDM	GY	HI	GNMS	Grain weight	ET
Plant height	0.607**							
AGDM	0.767**	0.614**						
Grain yield	0.102	-0.143	0.098					
HI	-0.573**	-0.677**	-0.642**	0.574**				
GNMS	-0.832**	-0.766**	-0.594**	0.18	0.778**			
Grain weight	-0.533**	-0.366	-0.418*	0.553**	0.811**	0.614**		
ET	0.643**	0.361	0.873**	0.062	-0.543**	-0.445*	-0.388	
GYWUE	-0.303	-0.36	-0.357	0.795**	0.868**	0.516**	0.824**	-0.405*

*and ** significant at P□0.05 and P□0.01, respectively. AGDM, above ground dry material; ET, evapotranspiration; FC, field capacity; GNMS, grain number of main spike; GY, grain yield; GYWUE, grain yield water use efficiency; HI, harvest index.

(Tables 8 and 9). In correlations between GYWUE and GY, grain weight was positively significant both under 70 and 40% FC. Significant correlations were noted between GYWUE and HI, GNMS under 70% FC, but not under 40% FC. LWUE was positively correlated with GY at heading stage, 20 and 30 days after anthesis, but negatively correlated with GY at anthesis and 10 days after anthesis under both 70% and 40% FC (Table 10). LWUE was positively correlated with GYWUE at growth period from heading stage to 30 days after anthesis and the correlation between them was significant at heading stage under 70% FC (Table 11). LWUE was positively correlated with GYWUE at heading stage (not significant), 20 (P□0.01) and 30 days after anthesis (not significant), but negatively correlated with GYWUE at anthesis (not significant) and 10 days after anthesis (not significant) under 40% FC.

Drought tolerance of different varieties

The lower the TOL and SSI value and the greater the YI and YSI value, the higher the drought tolerance. The results in Table 12 showed that landraces were more drought tolerant than modern varieties in general. Dingxi 24 and Heshangtou had the lowest TOL and SSI value and the greatest YI and YSI value which indicated that they were the two varieties with the highest drought tolerance. Plateau 602 had the greatest TOL and SSI value and the lowest YI and YSI values, indicating it was the variety with the lowest drought tolerance.

DISCUSSION

A widely accepted equation for grain yield (GY) under water-limited environments is a function of four components. They are evapotranspiration (ET, the consumption of soil water during the crop cycle, mainly transpiration by crop and evaporation from the soil surface), the proportion of that water actually transpired by the crop (T/ET), the transpiration efficiency of biomass production (W or LWUE) and the proportion of the achieved biomass translate into grain yield (HI)

Table 9. Pearson correlation coefficient between GYWUE and some agronomic traits and ET under 40% FC.

Variety	Fertile spike	Plant height	AGDM	GY	HI	GNMS	Grain weight	ET
Plant height	0.673**							
AGDM	0.732**	0.804**						
GY	0.638**	0.744**	0.947**					
HI	-0.113	0.033	-0.048	0.233				
GNMS	-0.468*	-0.069	0.077	0.243	0.401			
Grain weight	0.252	0.618**	0.479*	0.495*	0.227	0.075		
ET	0.802**	0.677**	0.773**	0.735**	0.068	-0.303	0.335	
GYWUE	0.548**	0.724**	0.908**	0.986**	0.287	0.367	0.518**	0.624**

*and ** significant at P□0.05 and P□0.01, respectively. AGDM, above ground dry material; ET, evapotranspiration; FC, field capacity; GNMS, grain number of main spike; GY, grain yield; GYWUE, grain yield water use efficiency; HI, harvest index.

Table 10. Pearson correlation coefficient between LWUE and GY at different growth period.

Water level %	Heading stage	Anthesis	10 days after anthesis	20 days after anthesis	30 days after anthesis
70 FC	0.128	-0.060	-0.106	0.185	0.002
40 FC	0.050	-0.256	-0.220	0.386	0.219

FC, field capacity; GY, grain yield water use efficiency; LWUE, leaf-level water use efficiency.

Table 11. Pearson correlation coefficient between LWUE and GYWUE at different growth period.

Water level %	Heading stage	Anthesis	10 days after anthesis	20 days after anthesis	30 days after anthesis
70 FC	0.440*	0.061	0.096	0.153	0.107
40 FC	0.112	-0.176	-0.113	0.444*	0.275

* Significant at P□0.05. FC, field capacity; GYWUE, grain yield water use efficiency; LWUE, leaf-level water use efficiency.

Table 12. Drought tolerance indices of different cultivars.

Variety	TOL	YI	YSI	SSI
Qingchun 533	8.70	0.96	0.22	1.03
Plateau 602	10.87	0.31	0.07	1.23
Abbondanza	7.88	0.93	0.23	1.01
Heshangtou	5.60	1.39	0.39	0.81
Hongnong No. 1	9.88	1.09	0.22	1.03
Dingxi 24	4.82	1.35	0.42	0.77
Damaizi	9.83	1.29	0.25	0.99
Jieba	6.73	0.68	0.20	1.05
Average of modern varieties	9.15	0.73	0.17	1.09
Average of landraces	7.37	1.16	0.30	0.93

SSI, Stress susceptibility index; TOL, Tolerance; YI, Yield index; YSI, Yield stability index.

(Condon et al., 2004; Passioura, 1977). The relationship between these four components is complex. Sometimes, an improvement of one of them may result in an increase in grain yield, but sometimes may have detrimental effect on the other components and reduce the grain yield finally. High LWUE genotypes tend to grow slower than low LWUE genotypes under drought stress (Condon et al., 1993; 2002).

In Mediterranean or similar environments, where crop strongly relies on within - season rainfall, the faster first growth of low LWUE genotypes means that they shade the soil surface quickly and thus restrict soil evaporation successfully. As a result, low LWUE genotypes can use soil water more efficiently and quickly and usually produce more final biomass and grain yield, namely, LWUE is negatively correlated with the biomass production and grain yield (Condon et al., 1987; 1993; Fischer et al., 1998). On the one hand, in stored-moisture environments, where crop is strongly reliant on subsoil moisture from out-of-season rains because the low LWUE genotypes may exhaust the stored moisture quickly, there is likely to be a yield penalty that will make LWUE to be positively correlated with the grain yield (Condon et al., 2002). In present study, the drought stressed (40% FC) pots were watered everyday which was similar with the first environment mentioned above. The lower LWUE landraces produced more above ground dry material (AGDM) and grain yield than the higher LWUE modern varieties and the result was in accordance to previous studies (Condon et al., 1987; 1993; Fischer et al., 1998). However, the negative correlation between LWUE and grain yield only existed at anthesis and 10 days after anthesis, while the correlation between LWUE and grain yield was positive at heading stage, 20 and 30 days after anthesis. Although the HI of Plateau 602 decreased from 70% to 40% FC, a general trend was seen for an increase in harvest index under drought stress. This general trend was different from A. Blum and his colleagues' study (1989), but a strong genotypic effect might be expected in this study, too. An increase in HI under drought stress in two modern varieties (Qingchun 533 and Abbondanza) and all the landraces (Heshangtou et al), indicated that depending on genotype, vegetative growth might be relatively more sensitive than reproductive growth. The difference between HI of the eight varieties was not significant and the correlation between HI and GY was also not significant (r = 0.233) under 40% FC, indicating that there was no apparent advantage in using HI as a selection criterion under drought stress.

In present study, above ground dry material (AGDM), grain yield (GY), evapotranspiration (ET) and grain yield water use efficiency (GYWUE) of all the varieties decreased sharply from 70 to 40% FC. The rate of descend were 75.23 - 92.37, 58.42 - 93.14, 44.65 - 51.86 and 13.33 - 87.50%, respectively and we could find that the rate of ET was lower than AGDM and GY. Then we could draw a conclusion that the variation of GYWUE from 70 to 40% FC is mainly due to the variation of GY (or AGDM to some extent) rather than the variation of ET. On the other hand, landraces had higher AGDM, GY, ET and GYWUE on the whole, indicating that higher water use (ET) always result in higher GYWUE under 40% FC. This result was different from the previous studies to some extent (Blum, 2005). AGDM, ET, GY and GYWUE were positively correlated with each other ($P<0.01$), indicating that varieties with higher ET and AGDM always had higher GY and GYWUE. Namely, selecting of varieties with higher ET and AGDM would be more efficient to develop varieties with high GY and GYWUE under 40% FC. Furthermore, it was shown that varieties with higher ET, AGDM and GY were always the varieties with higher drought tolerance under 40% FC. Higher ET and AGDM meant more water was consumed and more proportion of it was captured from soil for transpiration. Then we could draw a conclusion that varieties with higher ability of soil moisture capture were always the varieties with higher GY, GYWUE and drought tolerance and this was similar with the opinion of Blum (2009) that effective use of water (EUW) and not WUE (LWUE, here) is the target of crop yield improvement in within-season rainfall environments. A deep root system means higher tapping of water from the deep soil layer and better performance under drought stress (Hoad et al., 2001; Sharp et al., 2004). However, in this research, root system of wheat was constrained in a pot, thus varieties with deep or long root system would no longer have advantage in soil water uptake. Osmotic adjustment is an important mechanism enabling crop under drought stress to maintain water uptake and cell turgor pressure (Ali et al., 1999; Tangpremsri et al., 1991). As a result, crop will sustain higher photosynthesis rate and hence the yield-forming processes. It was probably because landraces had higher rate of osmotic adjustment than modern varieties. Landraces could absorb more water for transpiration and produce more grain yield than modern varieties under 40% FC. In fact, Plateau 602 was a drought tolerant variety in field research (Bai Qin`an, 1989), but in this study, Plateau 602 was the variety with the lowest drought tolerance. It was very likely that Plateau 602 had long or deep root system but low rate of osmotic adjustment and this was the acceptable reason why it was drought tolerant in field research, but drought sensitive in pot experiment.

This study showed the general difference between modern varieties and landraces, as well as the genetic diversity in the eight varieties. Modern varieties had sturdier stems and more grain number of main spike (more grains per spike to some extent) and landraces had higher ability of soil moisture capture on the whole. Genetic diversity is an important resource for crop breeding. If these favorable traits could be pyramided together, then lines with higher grain yield (GY), grain yield water use efficiency (GYWUE) and drought tolerance would be developed. In fact, this work is already been done.

ACKNOWLEDGMENT

This work was partially supported by the "Light of the West" talent cultivation plan of the Chinese Academy of Sciences.

REFERENCES

Blum A, Golan G, Mayer J, Sinmena B, Shpiler L, Burra J (1989). The drought response of landraces of wheat from the northern Negev Desert in Israel. Euphytica, 43: 87-96.

Blum A (1998). Improving wheat grain filling under stress by stem reserve mobilization. Euphytica, 100: 77-83.

Blum A (2005). Drought resistance, water-use efficiency, and yield potential—are they compatible, dissonant, or mutually exclusive? Aust. J. Agric. Res., 56: 1159-1168.

Blum A (2009). Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Res., 112: 119-123.

Ali MH, Mohammad AE, Simon B (2008). The effects of irrigation methods with effluent and irrigation scheduling on water use efficiency and corn yields in an arid region. Agric. Water Manage., 96(1): 93-99.

Ali M, Jensen CR, Mogensen VO, Andersen MN, Henson IE (1999). Root signaling and osmotic adjustment during intermittent soil drying sustain grain yield of field grown wheat. Field Crops Res., 62: 35-52.

Bahieldin A, Hesham HT, Eissa HF, Saleh OM, Ramadan AM, Ahmed IA, Dyer WE, El-Itriby HA, Madkour MA (2005). Field evaluation of transgenic wheat plants stably expressing the *HVA1* gene for drought tolerance. Physiologia Plantarum, 123: 421-427.

Bai Q (1989). A new spring wheat variety Plateau 602. Seed, (in Chinese), 2: 38.

Borrell AK, Hammer GL (2000). Nitrogen dynamics and the physiological basis of stay-green in sorghum. Crop Sci., 40: 1295-1307.

Bouslama M, Schapaugh WT (1984). Stress tolerance in soybean. Part 1: evaluation of three screening techniques for heat and drought tolerance. Crop Sci., 24: 933-937.

López-Castañeda C, Richards RA, Farquhar GD, Williamson RE (1996). Seed and seedling characteristics contributing to variation in seedling vigor among temperate cereals. Crop Sci., 36: 1257-1266.

Condon AG, Richards RA, Farquhar GD (1987). Carbon isotope discrimination is positively correlated with grain yield and dry matter production in field-grown wheat. Crop Sci., 27: 996-1001.

Condon AG, Richards RA (1993). Exploiting genetic variation in transpiration efficiency in wheat: an agronomic view. In: Ehleringer JR, Hall AE, Farquhar GD, eds. Stable isotopes and plant carbonwater relations. San Diego, CA: Academic Press, pp. 435-450.

Condon AG, Richards RA, Farquhar GD (1993). Relationships between carbon isotope discrimination, water-use efficiency and transpiration efficiency for dryland wheat. Aust. J. Agric. Res., 4: 1693-1711.

Condon AG, Richards RA, Rebetzke GJ, Farquhar GD (2002). Improving intrinsic water-use efficiency and crop yield. Crop Sci., 42: 122-131.

Condon AG, Richards RA, Rebetzke GJ, Farquhar GD (2004). Breeding for high water-use efficiency. J. Experimental Bot., 55: 2447-2460.

Fischer RA, Maurer R (1978). Drought resistance in spring wheat cultivars. Part 1: grain yield response. Aust. J. Agric. Res., 29: 897-912.

Fischer RA, Rees D, Sayre KD, Lu ZM, Condon AG, Larque SA (1998). Wheat yield progress is associated with higher stomatal conductance, higher photosynthetic rate and cooler canopies. Crop Sci., 38: 1467-1475.

Forster BP, Ellis RP, Moir J, Talame` V, Sanguineti MC, Tuberosa R, This D, Teulat-Merah B, Ahmed I, Mariy SAE, Bahri H, El Ouahabi M, Zoumarou-Wallis N, El-Fellah M, Ben SM (2004). Genotype and phenotype associations with drought tolerance in barley tested in North Africa. Ann. Appl. Biol., 144: 157-168.

Gavuzzi P, Rizza F, Palumbo M, Campaline RG, Ricciardi GL, Borghi B (1997). Evaluation of field and laboratory predictors of drought and heat tolerance in winter cereals. Canadian J. Plant Sci., 77: 523-531.

Hamdy A, Ragab R, Scarascia-Mugnozza E (2003). Coping with water scarcity: water saving and increasing water productivity. Irrigation and drainage, 52: 3-20.

Hoad SP, Russell G, Lucas ME, Bingham IJ (2001). The management of wheat, barley and oat root systems. Adv. Agron., 74: 193-246.

Hossain ABS, Sears AG, Cox TS, Paulsen GM (1990). Desiccation tolerance and its relationship to assimilate partitioning in winter wheat.Crop Sci., 30: 622-627.

Johnson WC, Jackson LE, Ochoa O, van Wijk R, Peleman J, St. Clair DA, Michelmore RW (2000). A shallow-rooted crop and its wild progenitor differ at loci determining root architecture and deep soil water extraction. Theor. Appl. Genet., 101: 1066-1073.

Juenger TE, Mckay JK, Hausmann N, Keurentjes JJB, Sen S, Stowe KA, Dawson TE, Simms EL, Richards JH (2005). Identification and characterization of QTL underlying whole plant physiology in Arabidopsis thaliana: d13C, stomatal conductance and transpiration efficiency. Plant Cell Environ., 28: 697-708.

Junlian Z (2007). Barriers to water markets in the Heihe River Basin in Northwest China. Agric. Water Manage., 87: 32-40.

Lafitte HR, Courtois B (2002). Interpreting cultivar x environment interactions for yield in upland rice assigning value to drought-adaptive traits. Crop Sci., 42: 1409-1420.

Foulkes MJ, Sylvester-Bradley R, Weightman R, Snape JW (2007). Identifying physiological traits associated with improved drought resistance in winter wheat. Field Crops Res., 103(1): 11-24.

Mark AB (2004). Water use efficiency in plant biology. Blackwell Bublishing.

Morgan JM, Condon AG (1986). Water use grain yield and osmoregulation in wheat. Aust. J. Plant Physiol., 13: 523-532.

Morgan JM, Tan MK (1996). Chromosomal location of a wheat osmoregulation gene using RFLP analysis. Aust. J. Plant Physiol., 23: 803-806.

Nguyen TT, Klueva N, Chamareck V, Aarti A, Magpantay G, Millena AC, Pathan MS, Nguyen HT (2004). Saturation mapping of QTL regions and identification of putative candidate genes for drought tolerance in rice. Mole. Genet. Genomics, 272: 35-46.

Oh SJ, Song SI, Kim YS, Jang HJ, Kim SY, Kim M, Kim YK, Kim NYK, Nahm BH, Kim JK (2005). Arabidopsis CBF3/DREB1A and ABF3 in transgenic rice increased tolerance to abiotic stress without stunting growth. Plant Physiol., 138: 341-351.

Passioura JB (1977). Grain yield, harvest index and water use of wheat. J. Aust. Inst. Agric. Sci., 43: 117-120.

Premachandra GS, Hahn DT, Axtell JD, Joly RJ (1994). Epicuticularwax load and water use efficiency in bloomless and sparse bloom mutants of *Sorghum bicolor L.* Environ. Exp. Bot., 34: 293-301.

Richards RA, Rawson HM, Johnson DA (1986). Glaucousness in wheat: Its development and effect on water-use efficiency gas exchange and photosynthetic tissue temperatures. Aust. J. Plant Physiol., 13: 465-473.

Richards RA (1991). Crop improvement for temperate Australia: future opportunities. Field Crops Res., 26: 141-169.

Richards RA (1992). The effect of dwarfing genes in spring wheat in dry environments. II. Growth, water use and water use efficiency. Aust. J. Agric. Res., 43: 529-539.

Richards RA, Rebetzke GJ, Condon AG, van Herwaarden AF (2002). Breeding opportunities for increasing the efficiency of water use and crop yield in temperate cereals. Crop Sci., 42: 111-121.

Robin S, Pathan MS, Courtois B, Lafitte R, Carandang S, Lanceras S, Amante M, Nguyen HT, Li Z (2003). Mapping osmotic adjustment in an advanced back-cross inbred population of rice. Theor. Appl. Genet., 107: 1288-1296.

Sanchez AC, Subudhi PK, Rosenow DT, Nguyen HT (2002). Mapping QTLs associated with drought resistance in sorghum (*Sorghum bicolor L Moench*). Plant Mole. Biol., 48: 713-726.

Schillinger WF, Donaldson E, Allan RE, Jones SS (1998). Winter wheat seedling emergence from deep sowing depths. Agron. J., 90: 582-586.

Sharp RE, Poroyko V, Hejlek LG, Spollen WG, Springer GK, Bohnert HJ, Nguyen T (2004). Root growth maintenance during water deficits: physiology to functional genomics. J. Exp. Bot., 55: 2343-2351.

Hsiao TC (1973). Plant response to water stress. Ann. Rev. Plant Physiol., 24: 519-570.

Taisheng Du, Shaozhong K, Jianhua Z, Fusheng L, Xiaotao H (2006). Yield and physiological response of cotton to partial root-zone irrigation in the oasis field of northwest China. Agric. Water Manage., 84: 41-52.

Tangpremsri T, Fukai S, Fischer KS, Henzell RG (1991). Genotypic variation in osmotic adjustment in grain sorghum. 2. Relation with some growth attributes. Aust. J. Agric. Res., 42: 759-767.

Teulat B, This D, Khairallah M, Borries C, Ragot C, Sourdille P, Leroy P, Monneveux P, Charrier A (1998). Several QTLs involved in osmotic adjustment trait variation in barley (*Hordeum vulgare L*). Theor. Appl. Genet., 96: 688-698.

Tinglu F, Shuying W, Tang X, Junjie L, Bob AS, Yufeng G (2005). Grain yield and water use in a long-term fertilization trail in Northwest China. Agric. Water Manage., 76: 36-52.

Verma V, Foulkes MJ, Worland AJ, Sylvester-Bradley R, Caligari PDS, Snape JW (2004). Mapping quantitative trait loci for flag leaf senescence as a yield determinant in winter wheat under optimal and drought-stressed environments. Euphytica, 135: 255-263.

Wang HX, Liu CM, Zhang L (2002). Water-saving agriculture in China: an overview. Adv. Agron., 75: 135-171.

Wang W, Vinocur B, Altman A (2003). Plant response to drought, salinity and extreme temperatures: toward genetic engineering for stress tolerance. Planta, 218: 1-14.

Wang Y, Ying J, Kuzma M, Chalifoux M, Sample A, McArthur C, Uchacz T, Sarvas C, Wan J, Tennis DT, McCourt P, Huang Y (2005). Molecular tailoring of farnesylation for plant drought tolerance and yield protection. Plant J., 43: 413-424.

Yan J, He C, Wang J, Mao Z, Holaday SA, Allen RD, Zhang H (2004). Overexpression of the Arabidopsis 14-3-3 protein GF14 lambda in cotton leads to a ‘‘stay-green’’ phenotype and improves stress tolerance under moderate drought conditions. Plant Cell Physiol., 45: 1007-1014.

Yilong H, Liding C, Bojie F, Zhilin H, Jie G (2005). The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. Agric. Water Manage., 72: 209-222.

Zhongkui X, Yajun W, Fengmin L (2005). Effect of plastic mulching on soil water use and spring wheat yield in arid region of Northwest China. Agric. Water Manage., 75: 71-83.