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Influence of water deficit and genotype on photosynthetic activity, dry mass partitioning and grain yield changes of winter wheat

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Pn-PAR response curves, gas exchange, dry mass partitioning and grain yield of four different genotypes of wheat were investigated in a randomized complete block design under different watering regimes (85, 55 and 25% FC). The results indicated that genotype differences existed in the adaptation response to water deficit which included change to growth strategies coupled with photo-physiological strategies. Water treatment was the dominating factor which limited plant growth, productivity and yield. As water deficit increased, stomatal conductance (gs), saturation irradiance (SI) and maximum net photosynthetic rate (Pmax) decreased, while irrigation water use efficiency (IWUE), compensation irradiance (CI) and dark respiration (R_D) increased in all genotypes, with a more rapid decline in wet climate cultivars. Differences in photosynthetic responses existed in different climate genotypes at 55% FC. Reduction of Pn for the wet climate cultivar was mainly due to gs, while for the dry climate cultivar, Pn coupled with photosynthetic pigment increased. At 25% FC, water deficit decreased Pn attributed to non-stomatal limitations in four genotypes. Dry mass was reduced in droughted plants and the percentage increased in dry mass allocated to roots. Furthermore, the wet climate genotypes had the greatest decrease in Chla/b ratio. These findings demonstrated that the superior drought resistance in dry climate cultivars could be attributed to higher photosynthetic capacity, dry matter allocation and then grain yield.

Key words: Dry mass partitioning, maximum net photosynthetic rate, Pn-PAR response curves, photosynthetic pigment, genotypes.

INTRODUCTION

Higher photosynthetic activity, productivity and grain yield of wheat is not only influenced by genetic variations, but also by the environment (water stress) (Wang et al., 2007; Zhang et al., 2008). Genotypes decide the genetic productivity; whereas the ecological environment quality often determines the natural productive forces. Nowadays, selecting a genotype with high photosynthetic activity, well-resistance and superior yield is the important task for wheat researchers.

Therefore, it is necessary to investigate how genotype and environmental changes affect the photosynthetic responses, dry mass partitioning and grain yield of wheat.

Water deficit has become a dominant environmental constraint that limits crop photosynthesis, productivity and then yield (Shao et al., 2005; Huang et al., 2009; Zhang et al., 2010). A decline of photosynthesis in water-stressed plants can be caused by stomatal closure and impairments in photochemical and/or biochemical reactions (Tang et al., 2002; Yu et al., 2009). Generally, stomatal closure is seen as the initial stage when slight or mild water deficit happens (Yu et al., 2009; Santosi et al., 2009; Souza et al., 2010), although other non-stomatal factors effects on photosynthesis exist, depending on the extent of drought stress (Yu et al., 2009; Santosi et al., 2009).

In addition, some works have displayed that Chla and Chlb are destroyed under moderate or severe water-stressed condition closely relating to depressed

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photosynthesis ability (Wu et al., 2008); thus, it indicates that damage to light-harvesting complex (LHC, that is, chla/chlb ratio) is also responsible for photosynthesis reduction. Besides, mesophyll conductance restricting photosynthesis has been confirmed (Grassi and Magnani, 2005; Flexas et al., 2009). Also, water deficit normally results in an increased allocation of dry matter to the roots, which can enhance water uptake (Bryla et al., 2001). However, the rate of photosynthesis often limits plant growth when soil water availability is reduced (Huang and Fu, 2000). A negative carbon balance can occur as a result of reduced photosynthetic capacity during water limitations, unless simultaneous and proportionate reductions in growth and carbon consumption takes place (Liu et al., 2005).

On the other hand, genotypic variations related to photosynthetic activity, productivity and grain yield under water deficit has also been extensively reported (Austin et al., 1982; Harsharm, 2010; González et al., 2010). Variability in photosynthesis is associated with stomatal resistance, chlorophyll content and above-ground dry matter (Hobbs and Mahon, 1982). Crop eco-physiological studies comprise different methodologies and techniques mainly related to CO_2 assimilation (gas exchange parameters) and dry matter partition. For wheat, photosynthesis is the primary source of dry matter production and grain yield in crop plants (Shao et al., 2005). Many researchers have seen photosynthesis as the basis of breeding method because wheat yields must be realized by photosynthesis in the field. However, different genotypes from different regions had different response to photosynthetic activity, dry mass partitioning and then grain yield. For the sake of increasing grain yields and finding the high photosynthetic potential of wheat, a study was conducted contrary to climate region genotype, in comparing the effect of water deficit on photosynthetic activity, dry mass partitioning and grain yield. The aims of this study are:

1) To ascertain how the different interactions of genotype and water deficit affect photosynthetic activity, dry mass partitioning and grain yield.
2) To discuss the difference in the drought adaptation strategies of the two contrasting regions of wheat in photosynthetic activity, dry mass partitioning and grain yield.

MATERIALS AND METHODS

Plant materials and experimental design

Four cultivars of wheat were chosen from contrasting habitats (XN979 and XY22 from dry climate region Shannxi, 34°21'N, 108°10'E, annual rainfall 573 mm). They were the major wheat cultivars in Shaanxi province that were bred by Northwest Agricultural and Forestry University, and were released in 2005. CY23 and SM375 were gotten from the wet climate region of Sichuan (30°85´N, 104°12´E and annual rainfall of 1250 mm). CY17 was bred by Chengdu Institute of Biology, Chinese Academy of Sciences and was released in 2002. SM375 was bred by Sichuan

Agricultural University, and was released in 2007. Wheat seeds were pre-soaked at 4°C for verbalization and five seeds per pot were sown at a depth of 3 cm into plastic pots (25 cm diameters × 20 cm height). Shortly after emergence, seedlings were thinned to one plant per pot and grown for about three months before water treatments. Clay loam (pH 6.98 and 26.54 g/kg organic matter; total N, P and K were 1.59, 0.97 and 17.43 g/kg, respectively, for the top tillage soil layer) was used as the growth media in the pots. The cultivars were grown to full maturity in a naturally light greenhouse under the semi-controlled environment with a day temperature range of 12 to 35°C, a night temperature range of 9 to 20°C and a relative humidity range of 30 to 81%. A total of 4 g slow release fertilizer (7% N, 5% P and 26% K) was added to each pot at the beginning of the experiment.

The two wheat cultivars and three watering regimes [85, 55 and 25% field water capacity (FC)] were tested in a completely randomized design. Individuals of each genotype were watered according to each watering regime by supplying an amount of water equal to transpiration losses every other day. A total of 15 pots for each genotype were used in each watering category. Five plants were harvested at 50% flowering to study the dry matter production, while five plants were used to study the gas exchange and contents of photosynthetic pigments, and the remains were harvested after full maturity. During the experimental period, the soil water content was always maintained at 31.3±0.2, 20.27±0.5 and 7.37±0.7% under 85, 55 and 25% FC water supply regimes, respectively. Evaporation from the soil surface was minimised by covering the soil with a 3 cm layer of quartz gravel (Liu et al., 2004). Transpiration was measured gravimetrically by weighing all pots every other day.

Pn-PAR response curves and gas-exchange measurements

During the anthesis period of each genotype and treatment, flag leaves from five replicates of each condition were sampled (5 replicate readings per leaf at each PAR value), using a portable photosynthesis system (LI-6400p, LiCor, Lincoln, NE, USA). Pn-PAR response curves were measured at 2000, 1800, 1600, 1400, 1200, 1000, 900, 800, 600, 400, 200, 150, 100, 50 and 0 μmol (photon) m^{-2} s^{-1} of PAR under uniform conditions [ambient CO_2 concentration of380 μmol (CO_2) mol^{-1}, leaf temperature of 28°C and 55% relative humidity (inside the leaf chamber)] at 09:30 to 11:30 (local time) on sunny days.

Both leaf gas measurements and photosynthetic gas exchange were measured at 1,200 μmol (photon) m^{-2} s^{-1} of PAR under uniform conditions as Pn-PAR response curves measurements. Linear regressions of irradiance and Pn, over the range of 0 to 200 μmol (photon) m^{-2} s^{-1} of PAR, were applied to determine the dark respiration rate (R_D), compensation irradiance (CI) and apparent quantum yield (AQY) (Yin et al., 2006). However, maximum net photosynthetic rate (Pmax) and saturation irradiance (SI) were estimated according to Walker (1989), while water use efficiency (IWUE) was calculated as net photosynthetic rate (Pn)/transpiration rate.

Contents of photosynthetic pigments

After the determination of photosynthetic activity, all leaves were harvested. About 0.1 g fresh leaves were taken for the determination of photosynthetic pigments. Leaves were ground in 80% acetone for the extraction of chlorophyll (Chl) and carotenoids (Car). Pigment amounts were determined according to Li et al. (2000).

Plant dry matter and grain yield

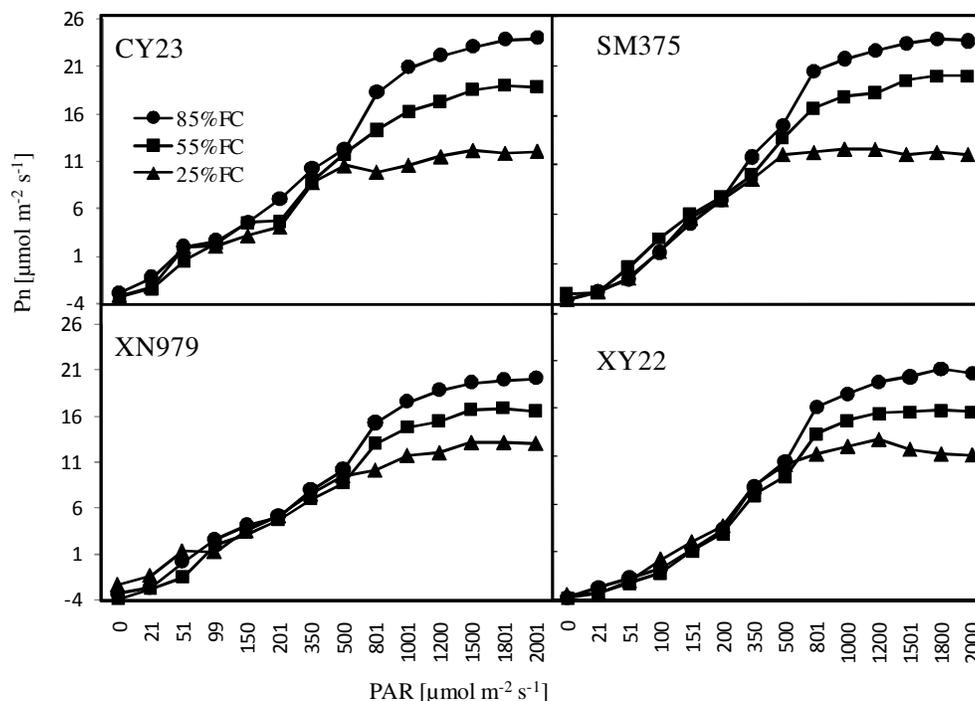Five plants samples were divided into root stem and leaf and

Figure 1. Pn-PAR response curves for four wheat genotypes (CY23, SM375, XN979 and XY22) at different water conditions. All the values are means of five replications.

dried in an oven for 48 h at 70°C for dry mass determination. Above-ground dry mass (AGM) was the sum of the stem and leaf dry mass, while root to shoot ratio (R/S) was calculated as the root dry mass (RDM) divided by above-ground dry mass. Grain yield (GY) was collected after the remaining plants had reached full maturity.

Statistical analysis

Two-way analyses of variance (ANOVA) of the experimental data were used for testing the cultivar and treatment differences. Statistical analyses and figures were done with the statistical analysis system (SAS version 8.0 for Windows, SAS Inc., IL, USA) software package.

RESULTS

Pn-PAR response curves

Water deficits affected the Pn-PAR response curve with Pmax and Pn decreasing above 500 μmol (photon) m^{-2} s^{-1} of PAR as water deficit increased (Figure 1). Although both water deficit and genotype affected Pmax, their interaction was not statistically significant (p>0.05) (Table 1). Pmax decreased with the increase of water deficit. Under 85% FC water condition, CY23 and SM375 had the higher Pmax values as compared to other genotypes, and there was no significant difference among the four genotypes at 55% FC, while under 25% FC water level, Pmax was highest in dry climate genotypes (XN979 and

XY22) and least in wet climate genotype (CY23 and SM375). Differences between genotypes can be explained by the percentage decline in Pmax. Pmax significantly decreased by 51.65 and 52.73% on CY23 and SM375 climate genotype at 25% FC, respectively, whereas it increased by 34.82 and 36.5% on XN979 and XY22 climate genotype at 25% FC, respectively, as compared to 85% FC. It suggested that XN979 and XY22 are more tolerant than CY23 and SM75. Moreover, AQY, R_D, SI and CI were significantly (p<0.05) affected by water deficit and genotypes, while only SI and CI were affected by their interaction. Water deficit increased R_D and CI, but decreased AQY and SI in all genotypes (Table 1). Nonetheless, under 85% FC water condition, CY23 and SM375 had higher AQY, SI and R_D values, but lower CI value, while under water deficits conditions, they had higher SI, CI and R_D, but lower AQY were found on CY23 and SM375.

Leaf gas exchange

Water deficit and genotype significantly (p<0.01) influenced Pn, gs, Ci and IWUE, while the interaction between water deficit and genotype affected only Ci and IWUE (Table 2). With the increase of water deficit, Pn, gs and Ci decreased, while IWUE increased in the evaluation of CY23 and SM375 (Table 2). For XN979 and XY22, the highest Pn was observed at 55%FC (P>0.05). Additionally, a similar tendency of both genotypes was

Table 1. The maximum net photosynthetic rate (Pmax), apparent quantum yield (AQY), dark respiration rate (R_D), saturation irradiance (SI), and compensation irradiance (CI) of four wheat genotypes (CY23, SM375, XN979 and XY22) at different water conditions.

	Wheat genotypes	Pmax [$\mu mol\ m^{-2}\ s^{-1}$]	AQY [$\mu mol\ \mu mol^{-1}$]	R_D [$\mu mol\ m^{-2}\ s^{-1}$]	CI [$\mu mol\ m^{-2}\ s^{-1}$]	SI [$\mu mol\ m^{-2}\ s^{-1}$]
	CY23	24.2±1.32	0.0832±0.0014	-2.44±0.19	61.7±2.17	1433±11.29
85%FC	SM375	23.7±0.93	0.0738±0.0023	-2.30±0.21	55.0±1.98	1409±17.21
	XN979	20.1±1.53	0.0720±0.0008	-2.22±0.09	68.8±1.49	1379±9.54
	XY22	20.0±1.49	0.0728±0.0017	-2.26±0.17	75.0±2.23	1390±11.27
	CY23	18.8±2.11	0.0628±0.0044	-3.15±0.19	84.0±1.77	1381±10.07
55%FC	SM375	19.2±1.35	0.0563±0.0029	-3.08±0.08	88.9±1.60	1352±8.76
	XN979	18.0±0.80	0.0830±0.0035	-2.60±0.15	79.7±1.87	1355±10.00
	XY22	18.7±0.79	0.0779±0.0046	-2.64±0.05	74.6±2.06	1377±9.98
	CY23	11.7±1.67	0.0385±0.0072	-3.67±0.03	92.0±1.87	1325±7.79
25%FC	SM375	11.2±1.00	0.0284±0.0008	-3.63±0.11	89.6±1.60	1307±14.46
	XN979	13.1±0.55	0.0450±0.0061	-3.43±0.16	84.6±1.85	1336±11.27
	XY22	12.7±1.12	0.0463±0.0087	-3.54±0.15	83.0±1.74	1354±9.13
Fw		8.64**	21.44**	3.46*	115.78**	136.62**
Fg		4.26*	4.10*	3.01*	50.92**	73.28**
Fw×g		0.56	1.53	1.94	3.5**	4.51**

Water treatment (w), genotype (g). Means ± SE, n = 5, *$p<0.05$, **$p<0.01$. Fw– ANOVA of water treatment; Fg – ANOVA of genotype treatment; Fw×g – ANOVA together with interactions between water and genotype treatments.

Table 2. Net photosynthetic rate (Pn), stomatal conductance (gs), intercellular CO_2 concentration (Ci) and water use efficiency (IWUE) of four wheat genotypes (CY23, SM375, XN979 and XY22) at different water conditions.

	Wheat genotypes	Pn [$\mu mol\ m^{-2}\ s^{-1}$]	gs [$mol\ m^{-2}\ s^{-1}$]	Ci [$\mu mol\ mol^{-1}$]	IWUE [$\mu mol\ mol^{-1}$]
	CY23	21.2±2.02	0.81±0.023	298±14.21	3.34±0.18
85%FC	SM375	18.7±1.78	0.88±0.050	336±12.23	2.85±0.20
	XN979	18.5±0.99	0.72±0.039	296±10.04	2.89±0.18
	XY22	19.0±1.78	0.92±0.043	310±13.27	2.96±0.30
	CY23	17.5±1.15	0.26±0.019	195.5±12.01	4.53±0.27
55%FC	SM375	17.5±1.89	0.23±0.031	199.5±9.88	6.33±0.18
	XN979	19.3±2.02	0.30±0.034	230±9.89	8.21±0.20
	XY22	19.5±2.19	0.31±0.011	227±10.22	9.58±0.10
	CY23	9.18±1.98	0.16±0.020	189±12.14	5.87±0.22
25%FC	SM375	9.85±1.91	0.06±0.015	196±11.89	9.65±0.19
	XN979	12.44±0.88	0.15±0.019	228±10.91	12.25±0.25
	XY22	11.70±1.01	0.23±0034	222±9.70	12.65±0.26
Fw		9.87**	28.12**	6.89*	16.19**
Fg		8.81**	9.16*	48.87**	21.63**
Fw×g		3.06	2.63	11.92**	8.25*

Water treatment (w), genotype (g), Means ± SE, n = 5, *$p<0.05$, **$p<0.01$. Fw– ANOVA of water treatment; Fg – ANOVA of genotype treatment; Fw×g – ANOVA together with interactions between water and genotype treatments.

Table 3. Changes of chlorophyll (Chl) a, b and Chl (a+b) contents, Car content, Chl a/b and Car/Chl ratio of four wheat genotypes (CY23, SM375, XN979 and XY22) at different water conditions.

	Wheat genotypes	Chla [g kg^{-1}(FM)]	Chlb [g kg^{-1}(FM)]	Chl (a+b) [g kg^{-1}(FM)]	Car [g kg^{-1}(FM)]	Chla/b	Car/Chl
85%FC	CY23	2.95±0.24	1.29±0.11	4.24±0.34	1.36±0.19	2.29±0.07	0.32±0.05
	SM375	2.09±0.28	0.92±0.12	3.01±0.39	1.02±0.03	2.27±0.04	0.34±0.00
	XN979	2.85±0.58	1.10±0.22	3.96±0.80	1.13±0.08	2.59±0.49	0.29±0.00
	XY22	2.88±0.14	1.15±0.04	4.03±0.18	1.01±0.04	2.50±0.05	0.25±0.01
55%FC	CY23	2.71±0.16	1.19±0.06	3.80±0.21	1.16±0.03	2.28±0.01	0.31±0.00
	SM375	1.98±0.37	0.98±0.11	2.96±0.27	0.92±0.06	2.02±0.44	0.32±0.02
	XN979	3.16±0.23	1.14±0.09	4.30±0.32	1.20±0.04	2.77±0.01	0.28±0.02
	XY22	3.53±0.01	1.33±0.01	4.86±0.01	1.19±0.01	2.65±0.02	0.24±0.00
25%FC	CY23	1.93±0.11	0.96±0.04	2.89±0.15	0.97±0.02	2.01±0.02	0.28±0.00
	SM375	1.32±0.12	0.99±0.06	2.31±0.18	0.89±0.07	1.33±0.02	0.30±0.02
	XN979	2.79±0.28	1.11±0.11	3.90±0.39	1.12±0.03	2.51±0.02	0.28±0.00
	XY22	2.34±0.37	1.02±0.14	3.37±0.05	1.03±0.06	2.29±0.03	0.33±0.00
Fw		10.58**	78.65**	19.65**	123.96**	5.02**	20.8**
Fg		5.25**	40.05**	8.73**	7.03**	38.16**	2.32
Fw×g		1.62	4.34**	1.45	6.80**	4.03**	1.55

Water treatment (w), genotype (g). Means ± SE, n = 5, *p<0.05, **p<0.01. Fw– ANOVA of water treatment; Fg – ANOVA of genotype treatment; Fw×g – ANOVA together with interactions between water and genotype treatments.

observed in gs, but the reduction in XN979 and XY22 was smaller than CY23 and SM375 under water deficit conditions.

Photosynthetic pigments

Water deficit significantly (p<0.01) affected the contents of photosynthetic pigments, while genotypes also exhibited marked difference among photosynthetic pigments parameters except Car/Chl; moreover, the interaction of water treatment and genotype, statistically (p<0.01) affected Chlb, Car and Chl a/b only (Table 3). Conversely, it was found that different genotypes responded to 55% FC water deficit on these parameters differently. For CY23 and SM375, water deficit decreased the contents of Chla, Chlb, Car and Chl (a+b), and the ratios of Chl a/b and Car/Chl; thus, CY23 had the highest Chla, Chlb, Car and Chl (a+b) values. However, for XN979 and XY22, 55% FC water deficit increased Chla, Chlb, Car and Chl (a+b) values, while 25% FC reduced the values of Chla, Chlb, Car and Chl (a+b) more in XN979 and XY22 than in CY23 and SM375 under water deficit.

Plant dry matter partitioning and grain yield

Water treatment, genotype and their interaction significantly

affected plant dry matter partitioning and grain yield (Table 4). Water treatment had more effect than genotype and interaction. Water deficit reduced AGM, RDM and GY but increased R/S ratio in all genotypes. Under 85% FC water treatment, CY23 had the highest AGM, RDM and GY values, while under 25% FC water treatment, XN979 and XY22 had higher AGM, RDM and GY values than CY23 and SM375. This suggested that the reduction of percentage dry matter allocation was more in CY23 and SM375 than in XN979 and XY22. Furthermore, the R/S ratio increased from 33 to 35% for CY23, 33 to 58% for SM375, 11 to 31% for XN979 and 10 to 32% for XY22. Thus, with increasing in the water deficit, the increase of the R/S ratio was the highest and lowest in XN979 and CY23, respectively.

DISCUSSION

As it is known, crop productivity and yield can be limited by insufficient photosynthesis during water deficit (Liu and Li, 2005; Mokhtar et al., 2009). This study demonstrated that different genotypes showed different photosynthetic trend at 55% FC. For CY23 and SM375, reductions in Pn and gs were accompanied by reductions in Ci. This suggested that stomatal conductance was the dominating factor which limits assimilation, irrespective of any metabolic impairment (Chaves and Oliveira, 2004; Flexas et al., 2006; Lopes and Araus, 2006; Wu et al., 2008).

Table 4. Change of above-ground dry matter (AGM), root dry matter (RDM), root to stem ratio (R/S) and grain yield (GY) of four wheat genotypes (CY23, SM375, XN979 and XY22) at different water conditions.

	Wheat genotypes	AGM [g plant^{-1}(DM)]	RDM [g plant^{-1}(DM)]	R/S	GY [g plant^{-1}]
85%FC	CY23	7.08±0.04	0.73±0.03	0.103±0.007	5.24±0.13
	SM375	6.51±0.65	0.62±0.04	0.095±0.003	4.56±0.09
	XN979	6.46±0.68	0.68±0.11	0.105±0.004	4.47±0.72
	XY22	6.76±0.68	0.67±0.03	0.099±0.010	4.80±0.21
55%FC	CY23	5.03±0.13	0.60±0.03	0.119±0.008	3.45±0.07
	SM375	4.50±0.15	0.52±0.04	0.116±0.010	2.77±0.09
	XN979	5.76±0.51	0.68±0.04	0.118±0.002	3.89±0.12
	XY22	6.00±0.31	0.64±0.04	0.107±0.010	4.17±0.18
25%FC	CY23	3.79±0.26	0.53±0.01	0.140±0.008	1.98±0.03
	SM375	2.66±0.46	0.38±0.15	0.142±0.018	1.27±0.01
	XN979	4.36±0.31	0.66±0.02	0.151±0.005	2.00±0.15
	XY22	4.41±0.08	0.64±0.03	0.145±0.005	2.54±0.11
Fw		86.16**	137.49**	118.34**	157.21**
Fg		4.52*	11.41**	9.88**	88,16**
Fw×g		4.24*	7.28**	5,21**	7.79**

Water treatment (w), genotype (g). Means ± SE, n = 5, *p<0.05, **p<0.01. Fw– ANOVA of water treatment; Fg – ANOVA of genotype treatment; Fw×g – ANOVA together with interactions between water and genotype treatments.

While for XN979 and XY22, higher Pn was observed at 55% FC, this may be associated with higher Chl content (Table 3). However, under 25% FC water level, a reduction in Pn and gs was observed among four genotypes, but with relatively higher Ci values (Table 2). It indicated that stomatal closure was not the principal cause of decreased assimilation (Chaves et al., 2004). Some other factors, such as, photochemistry of PSII, Mesophyll conductance, etc., may be the dominant factor which could be responsible for the reduction of Pn (Grassi and Magnani, 2005; Flexas et al., 2009). Santosi et al. (2009) and Souza et al. (2010) showed that, stomatal closure often acts in the initial stage when slight or mild water deficit happens. Tang et al. (2002) argued that a combination of stomatal and non-stomatal effects on photosynthesis exists. Additionally, it was found that water deficit seemed to play the primary limitation roles in photosynthetic capacity (Tables 1 and 2). It showed that environmental factors had more effect than genetic factors.

In theory, Pmax determines the plant potential photosynthetic capacity. Increasing CI and decreasing SI will reduce the time of effective Pn, while increasing R_D will denote that plants consume more carbohydrate at night (Jia and Gray, 2003; Wu et al., 2008; Zhang et al., 2010). In this study, the wet climate genotypes (CY23 and SM375) had higher and lower Pmax, AQY and SI values at 85% FC water supply and water deficit conditions,

respectively, relative to XN979 and XY22 (Table 1). It implied that CY23 and SM375 were more sensitive to water deficit, and it further explained that XN979 and XY22 were more drought-resistant than CY23 and SM375. This was in agreement with the study of Yin et al. (2006). On the other hand, although CY23 had greater photosynthetic potential capacity than the other three genotypes at 85% FC, they might consume more photosynthate at night, thereby reducing plant growth and productivity.

Generally, chloroplast, as the place of the occurrence of photosynthesis, was important in that it affected the photosynthetic potential. Water deficit reduced photosynthesis and this may be associated with the decreasing Chl and Car contents (Wu et al., 2008). Reduction in Chla, b, Car and Chl (a+b) has been ascribed to the loss of chloroplast membranes, excessive swelling, distortion of the lamellae vesiculation and the appearance of lipid droplets (Kaiser et al., 1981; Zhang et al., 2010). In addition, a decline of Chla/b ratios has been associated with lower drought resistance, while a decline of Car/Chl suggested that the development of LHC and the dissipation of thermal energy might be strongly affected by water deficit since Cars of chloroplast are major components of antenna systems (Jeon et al., 2006; Wu et al., 2008). This study's experiment showed that CY23 and SM375 had greater decrease in Chl a/b ratio than XN979 and XY22, which increased in water deficit

(Table 3). Accordingly, using these criteria of pigment content and composition, it is further suggested that drought resistance of XN979 and XY22 may be greater than CY23 and SM375.

Lower photosynthates during water deficit may result in lower plant productivity and poor yield. The biological or primary productivity is normally evaluated in terms of biomass (as dry mass) (Zhang et al., 2008). In this experiment, water deficit reduced both above-ground and root growth, and this was in agreement with some other studies (Liu and Stützel, 2004; Singh and Singh, 2006; Wang et al., 2007). In addition, an increase of R/S was found with an increase of limited water (Table 4), in that water deficit decreased AGM and altered dry mass allocation to root systems resulting in high root to shoot ratio (Table 4) (Rane et al., 2001; Kozlowski and Pallardy, 2002; Zhang et al., 2010). This study also found that XN979 and XY22 had higher AGM and RDM values than CY23 and SM375 under water deficits condition. This suggests that XN979 and XY22 are most tolerant. Moreover, higher F values of water deficit were more than the genotype that confirmed the primary limitation roles in plant productivity.

As previously discussed, a decline of photosynthesis associated with water deficit often affected plant growth and yield. This study indicated that a larger proportion of photosynthates were allocated to the root, while higher R/S has been considered as one of the mechanisms involved in the adaptation of plants to drought (Turner, 1997). It was found that the ratio of R/S showed significant variation with water supply and with the four genotypes that had different sensitivities to water deficit. The percent increase in R/S allocation was the highest and lowest in dry (XN979 and XY22) and wet (CY23 and SM375) climate genotypes, respectively with increasing water deficit. This meant that dry climate genotypes might have a well developed root system with the stronger drought resistance, while wet climate genotypes might be contrary. On the other hand, higher photosynthetic parameters were also shown in dry climate genotypes under water deficit, which indicated that more light could be captured by dry climate genotypes and higher photosynthesis and grain yield were shown in the experimental results of this study.

In conclusion, water deficit, genotype and their interaction notably affected photosynthetic characters, dry matter allocation and grain yield of four genotype wheat. Water deficit played the primary limitation roles in these parameters (except Ci, Cha/b and TWK). Nevertheless, there were obvious differences in adaptation to varying water deficit through changed growth strategies coupled with photo-physiological adjustments among four genotypes. The dry climate genotypes demonstrated more drought-resistant than genotypes from the wet climate area, as indicated by their higher photosynthetic characters, dry matter allocation and grain yield parameters.

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