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Evaluation of photosynthetic potential of wheat genotypes under drought condition

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Abstract

Water availability is one of the most important limiting factors in agriculture worldwide, particularly in arid and semiarid regions. Six spring wheat genotypes, *i.e.* three UK cultivars Cadenza, Paragon, and Xi-19 and three synthetic-derived lines L-22, L-24, and L-38, were grown in a phytotron under well-watered (until 40 days after sowing) and drought conditions. The aim of the study was to evaluate the traits related to photosynthetic capacity (net photosynthesis rate, stomatal conductance, internal CO_2 concentration, transpiration rate, carboxylation capacity, instantaneous and intrinsic water-use efficiency) and plant biomass production in the cultivars and synthetic derivatives of wheat genotypes under well-watered and water-limited conditions. Genotypic variations in gas-exchange traits including net photosynthetic rate, carboxylation capacity, instantaneous water-use efficiency, and biomass yield were found amongst genotypes. Drought significantly reduced the total dry matter per plant. The synthetic derivatives L-22 and L-24 showed higher performance of stomata for most of the stomatal aperture characteristics. Total dry matter was positively related to net photosynthetic rate and to instantaneous and intrinsic water-use efficiencies. Finally, net photosynthetic rate was also positively related to stomatal conductance and transpiration rate under both the well-watered and water-limited drought conditions.

Additional key words: leaf gas-exchange measurements; pot experiment; water regimes.

Introduction

Wheat (*Triticum aestivum* L.) is an important cereal crop of the world. Wheat is produced under diverse environmental conditions ranging from well-irrigated to water-limited. The wheat yield is reduced by 50–90% by drought on at least 600,000 km^2 in the developing world (Skovmand *et al.* 2001). Water availability is one of the most important limiting factors in agriculture worldwide (Wallac 2000), particularly in arid and semiarid regions. The Mediterranean climate type is characterised by a strong seasonal variability in precipitation (Paredes *et al.* 2006) with severe summer drought. Climate change can further worsen this situation. Due to raise in global temperature, soil looses its moisture holding capacity; as a result, drought is accelerated.

Wheat is the most widely grown arable crop in the UK. Water deficit can commonly limit wheat yield because drought occurs typically late in the season, with the onset of stress broadly coinciding with flowering (Foulkes *et al.* 2001). Typically onset of drought is post-anthesis and yield losses are of 1–2 t ha^{-1} in the UK (Foulkes *et al.* 2002). Some estimations indicate that 50% of the approximately 230 Mha of wheat sown annually in the world is regularly affected by drought (Pfeiffer *et al.* 2005). Drought decreases leaf water content and increases stomatal closure; it limits the supply of CO_2 to mesophyll tissue and the rate of photosynthesis.

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Abbreviations: C_i – intercellular CO_2 concentration; DAS – days after sowing; E – transpiration rate; g_s – stomatal conductance; P_N – net photosynthetic rate; P_N/C_i – carboxylation capacity; TDM – total dry matter; WL – water-limited; WW – well-watered; WUE – instantaneous water-use efficiency (= P_N/E); WUE$_i$ – intrinsic water-use efficiency (= P_N/g_s).
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There is no optimal strategy for developing cultivars better adapted to drought condition. The challenge is to combine physiological traits most effectively to produce well-adapted wheat germplasm. Some of the highest-yielding genotypes under supplementary irrigation can also belong among the highest-yielding ones under rainfed condition. Therefore, evaluation under rainfed condition appears to be necessary to preserve genotypes possessing alleles for responsiveness to irrigation in addition to drought tolerance.

Photosynthesis is a highly complex mechanism and one of the main targets to improve wheat yield (Parry *et al.* 2011). Leaf gas-exchange analysis and chlorophyll fluorescence parameters are crucial tools to screen a new generation of wheat germplasm for enhanced photosynthesis and potential yield. Various infrared gas analyzer (IGRA) portable systems are now available allowing users to make real-time, simultaneous measurements of leaf photosynthetic CO_2 uptake (P_N), transpiration rate (E), stomatal conductance (g_s), intercellular CO_2 mole fraction (C_i), and chlorophyll fluorescence parameters.

Water-use efficiency (above-ground biomass/crop evapotranspiration, WUE) has been identified as one of key parameters for selection of plant genotypes in arid and semiarid areas to reduce the reliance on irrigation water (Condon *et al*. 2004). Accurate measurement of WUE is difficult in the field conditions. It is time-consuming and often expensive. Several alternative approaches for measuring WUE have been consequently proposed, including carbon isotope discrimination for a time-integrated estimation and gas exchange to provide point-in-time estimates at the leaf scale (Condon *et at*. 2004, Rizza *et al*. 2012). Leaf WUE measurement includes both instantaneous water-use efficiency (WUE) and intrinsic water-use efficiency (WUE_i). The objectives of the present study were to evaluate resource-use efficiency of wheat genotypes and total dry mass (TDM) under the drought compared to well-watered condition and to find out the relationship of TDM and P_N with different gas exchange measurements.

Materials and methods

Growing conditions and experimental design: The experiment was conducted in a controlled phytotron (growth room) at the school of Biosciences, University of Nottingham, UK during October–December 2012. Six wheat genotypes, *i.e.* Cadenza, L-22, L-24, L-38, Paragon, and Xi-19 of diverse origin were used as seed materials. Out of six genotypes, L-22, L-24, and L-38 were the synthetic derivatives (F1S4 lines in a UK spring wheat Paragon background). Seeds of each genotype were germinated in small plastic modules filled with *John Innes Compost 1*. After two weeks, seedlings were transferred (two seedlings per pot) to bigger (five litre) plastic pots of 23 cm diameter filled with *John Innes Compost 2*. Plants were grown in the growth room at 20ºC and 14-h light period throughout the experiment. Soil moisture content of all 36 pots was kept at field capacity until 40 d after sowing (DAS) to allow a proper plant development. After 40 DAS, two water regimes were applied through gravimetric analysis of pot moisture: well-watered (WW, the pots were maintained at about 30% soil water content) by supplying water regularly, and water-limited conditions (WL, pots were maintained at about 10% soil water content) by supplying limited water supply (Fig. 1). A factorial experiment was performed using a completely randomised design with two factors (water regimes and genotypes) and three replications.

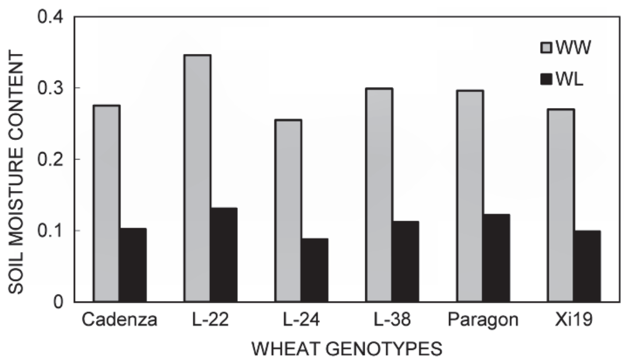

Fig. 1. Soil moisture content of six wheat genotypes at well-watered (WW) and water-limited (WL) conditions.

Gas-exchange measurements: P_N, g_s, C_i, and E were measured four times on young, fully expanded leaves of main shoots at 45, 50, 55, and 60 DAS using an portable infrared gas analysis system (*LI-COR 6400-XT, LI-COR*, Nebraska, USA) in conjunction with a plant leaf cuvette having an area of 2.5 cm^2 of leaf surface. The cuvette conditions were set at 2,000 μmol(photon) m^{-2} s^{-1} to ensure light-saturated photosynthesis and the CO_2 partial pressure was set to 400 ppm. Two measurements per plant were taken for each pot.

Instantaneous water-use efficiency, WUE, was determined as the ratio of P_N to E (Baburai Nagesh 2006).

Carboxylation capacity (P_N/C_i) was measured as the ratio of net photosynthetic rate to internal CO_2 concentration (Baburai Nagesh 2006). Intrinsic water-use efficiency, WUE_i at leaf scale was calculated as the ratio of the P_N to g_s (Gulias *et al*. 2012). The total biomass (TDM) was determined at 60 DAS as aboveground dry matter per plant. At the end of the experiment (60 DAS), the fresh biomass was oven-dried for 48 h at 85ºC and then weighed with a digital balance.

Statistical analysis: Data in *Excel* spreadsheets were analysed using *GenStat 15th edition* statistical package for

Windows (*VSN International*, Hemel Hempsted, UK). Treatment means were compared using least significance differences (LSD) calculated from standard errors of the difference of the means using appropriate degrees of freedom when analysis of variance (*ANOVA*) indicated significant differences. Relationships between TDM and P_N, WUE and WUE_i and P_N and g_s, E and C_i were evaluated using a simple regression analysis for both the WW and WL conditions.

Results

***P*N**: Results showed that the interaction effect of water regime and genotype was significant at 45 and 60 DAS (Table 1). The main effect of genotypes and water regimes on P_N was significant at all the DAS except at 50 DAS. All the genotypes had higher P_N under WW compared to WL conditions, except the Xi-19 genotype at 55 DAS. The synthetic derivative line, L-22, showed higher P_N compared with other two cultivars (Xi-19 and Cadenza).

***g*s**: Drought reduced g_s in all genotypes at the final assessment date (Table 1). The interaction effect of water regime and genotype was significant at 55 and 60 DAS, and the main effect of genotype and water regime was significant at 50, 55, and 60 DAS. The synthetic derivative genotype, L-22, showed overall higher g_s compared to Paragon, Cadenza, and Xi19. At 55 DAS, Cadenza and L-22 maintained g_s relatively higher than other cultivars under drought. At 60 DAS, synthetic derivative, L-24, maintained g_s relatively higher than other genotypes under drought.

***C*i**: Drought increased the mean C_i in all six genotypes at 45 DAS, soon after water availability was limited in the WL treatment (Table 2). At this stage, the interaction of water regime and genotype was not significant and three synthetic derivatives (L-22, L-24, and L-38) and Paragon showed higher C_i compared to other genotypes (Xi-19 and Cadenza). But after 45 DAS, drought decreased C_i significantly in all genotypes. In later stages, the interaction effect of genotype and water regime and the main effect of water regime and genotype were significant at 55 and 60 DAS. Synthetic derivative L-38 exhibited the highest internal C_i under both the WW and WL conditions at 50, 55, and 60 DAS and maintained C_i better under water stress than Paragon.

Table 1. Net photosynthetic rate (P_N) and stomatal conductance (g_s) of six wheat genotypes under well-watered (WW) and water-limited (WL) conditions. G – genotype; W – water regime. *,** – significant at the 0.05*, 0.01** probability level, respectively; NS – not significant at the 0.05 probability level.

Genotype	Water regime	P_N [μmol(CO_2) $m^{-2}s^{-1}$] 45 DAS	50 DAS	55 DAS	60 DAS	g_s [mol(H_2O) $m^{-2}s^{-1}$] 45 DAS	50 DAS	55 DAS	60 DAS
Cadenza	WW	11.73	16.17	16.78	14.63	0.194	0.306	0.167	0.176
	WL	4.49	15.66	10.99	5.75	0.140	0.125	0.136	0.111
L-22	WW	12.99	20.63	16.39	18.79	0.242	0.367	0.165	0.429
	WL	7.62	16.34	12.71	10.41	0.202	0.294	0.134	0.255
L-24	WW	11.18	15.08	13.75	11.55	0.214	0.218	0.175	0.134
	WL	6.58	14.84	10.20	6.89	0.200	0.130	0.119	0.148
L-38	WW	10.85	13.57	15.44	13.87	0.219	0.258	0.290	0.217
	WL	6.01	12.59	12.43	5.71	0.201	0.204	0.152	0.147
Paragon	WW	11.11	15.12	15.30	14.77	0.236	0.261	0.274	0.235
	WL	6.38	14.60	11.78	6.77	0.234	0.157	0.151	0.122
Xi 19	WW	8.09	12.46	11.11	6.80	0.158	0.202	0.171	0.136
	WL	7.50	11.39	11.33	5.85	0.234	0.129	0.117	0.101
ANOVA									
Source of variation	df								
G	5	**	*	**	**	NS	*	**	**
W	1	**	NS	**	**	NS	**	**	**
G × W	5	**	NS	NS	**	NS	NS	**	**
LSD (G)		1.59	3.63	1.93	1.93	-	0.094	0.027	0.056
LSD (W)		0.918	-	1.11	1.12	-	0.054	0.016	0.032
LSD (G × W)		2.24	-	-	2.73	-	-	0.039	0.079
CV [%]		15.3	20.5	12.3	16.0	19.9	36.1	13.5	25.6
SE (±)		1.33	3.05	1.62	1.62	0.04	0.07	0.023	0.047

Table 2. Intercellular CO_2 concentration (C_i) and transpiration rate (E) of six wheat genotypes under well-watered (WW) and water-limited (WL) conditions. G – genotype; W – water regime. *,** – significant at the 0.05*, 0.01** probability level, respectively; NS – not significant at the 0.05 probability level.

Genotype	Water regime	C_i [mmol(CO_2) mol(air)$^{-1}$] 45 DAS	50 DAS	55 DAS	60 DAS	E [mmol(H_2O) m^{-2} s^{-1}] 45 DAS	50 DAS	55 DAS	60 DAS
Cadenza	WW	282.5	297.4	230.5	299.0	2.88	4.22	3.00	2.38
	WL	331.4	167.6	225.0	248.5	2.08	2.29	2.19	1.53
L-22	WW	284.5	308.2	227.7	323.5	3.19	4.83	3.03	4.91
	WL	325.8	236.1	225.8	308.0	2.95	4.42	2.50	3.02
L-24	WW	297.3	272.0	236.0	308.6	2.98	3.42	3.12	1.81
	WL	340.9	196.2	220.2	246.7	2.75	2.60	2.02	1.91
L-38	WW	298.6	304.0	299.9	324.0	2.97	4.12	4.65	2.70
	WL	345.2	247.4	257.9	282.8	2.86	2.65	2.78	2.00
Paragon	WW	304.2	283.0	289.8	296.8	3.31	4.20	4.43	2.87
	WL	358.2	202.5	256.4	280.3	3.07	2.80	2.73	1.70
Xi 19	WW	303.5	295.2	283.3	304.1	2.25	3.51	3.02	1.79
	WL	340.5	221.0	218.5	300.6	3.22	1.67	2.24	1.75
ANOVA									
Source of variation	df								
G	5	**	NS	**	**	NS	NS	**	**
W	1	**	**	**	**	NS	**	**	**
G × W	5	NS	NS	**	**	*	NS	*	*
LSD (G)		15.65	-	19.10	19.11	-	-	0.49	0.62
LSD (W)		9.03	21.53	11.03	11.38	-	0.68	0.28	0.36
LSD (G × W)		-	-	27.01	27.86	0.77	-	0.69	0.87
CV [%]		4.1	12.4	6.5	5.6	16.0	29.0	13.9	21.9
SE (±)		13.13	31.30	16.03	16.54	0.46	0.99	0.41	052

E: Results showed that the interaction effect of genotype and water regime was significant at all assessments except 50 DAS (Table 2). The main effect of genotype and water regime was significant at 55 and 60 DAS. Drought reduced the E and the WW plants of all genotypes clearly showed the higher E at all stages with the exception of Xi-19 at 45 DAS. Synthetic derives (L-22, L-24, and L-38) and Paragon showed overall the higher E with few exceptions. The synthetic derivatives maintained E better than Paragon, *e.g.* L-22 at 55 DAS and L-24 at 60 DAS, although effects were not consistent across assessment dates.

WUE: Drought had significant effect on instantaneous water-use efficiency. It reduced the WUE of all genotypes at all assessments with few exceptions at 55 DAS (Table 3). At 55 DAS, drought increased the WUE in L-24, L-38, Paragon, and Xi-19. The main effect of water regime was significant at all assessments and the main effect of genotype was significant at 55 and 60 DAS. Synthetic-derived genotypes L-22 and L-38 showed the highest WUE in most cases. Cadenza tended to maintain WUE lower under WL than other genotypes at 55 DAS. L-22 maintained WUE better than Paragon at 60 DAS.

Carboxylation capacity (P_N/C_i): WW conditions increased P_N/C_i in all genotypes compared to the WL condition (Table 3). The interaction effect of genotype and water regime was significant at all assessments except 50 DAS and the main effect of genotype and water regime was significant at all assessments. At 60 DAS, the genotype L-22 showed the highest, whereas Xi-19 attained the lowest P_N/C_i. The water regime *vs.* genotype interaction was mainly associated with Xi-19 maintaing P_N/C_i relatively higher than other genotypes.

WUE$_i$: Results showed that drought adversely affected the WUE$_i$ in all genotypes (Table 4). The interaction effect of genotype and water regime was significant at 55 and 60 DAS and the main effect of genotype and water regime was significant at all assessments except 55 DAS in all genotypes. Overall synthetic derivative L-22 had the highest WUE$_i$ at 50 DAS.

TDM per plant (aboveground parts) was measured at 60 DAS. The interaction effect of genotype and water regime on TDM was not significant (Table 4). The main effect of genotype and water regime was significant individually. Drought reduced the TDM per plant in all genotypes compared to WW conditions. There were considerable variations in TDM among the six wheat genotypes at both the water conditions. Synthetic-derived genotype L-24 attained the highest TDM both in WW (7.50 g per plant) and WL condition (3.41 g per plant), whereas L-38 showed the lowest TDM in both the growing conditions.

Table 3. Instantaneous water-use efficiency (WUE) and carboxylation capacity (P_N/C_i) of six wheat genotypes at different days after sowing (DAS) under well-watered (WW) and water-limited (WL) conditions. G – genotype; W – water regime. *,** – significant at the 0.05*, 0.01** probability level, respectively; NS – not significant at the 0.05 probability level.

Genotype	Water regime	WUE [µmol(CO_2) mmol(H_2O)$^{-1}$] 45 DAS	50 DAS	55 DAS	60 DAS	P_N/C_i [µmol(CO_2) mmol(air)$^{-1}$] 45 DAS	50 DAS	55 DAS	60 DAS
Cadenza	WW	4.082	7.22	5.623	6.17	0.041	0.097	0.072	0.058
	WL	2.099	3.69	5.01	3.99	0.013	0.052	0.048	0.019
L-22	WW	4.058	5.23	5.41	3.86	0.046	0.092	0.072	0.061
	WL	2.587	3.41	5.06	3.51	0.023	0.053	0.056	0.032
L-24	WW	3.749	5.68	4.47	6.40	0.037	0.075	0.058	0.046
	WL	2.368	4.35	5.21	3.77	0.019	0.054	0.046	0.022
L-38	WW	3.678	5.51	3.34	5.10	0.036	0.054	0.051	0.049
	WL	1.983	3.08	4.45	2.93	0.017	0.041	0.048	0.017
Paragon	WW	3.360	5.72	3.47	5.18	0.036	0.071	0.052	0.052
	WL	2.275	3.70	4.34	4.11	0.017	0.053	0.045	0.022
Xi 19	WW	3.606	3.68	3.69	3.80	0.026	0.056	0.039	0.022
	WL	2.312	3.22	5.08	3.14	0.022	0.038	0.052	0.020
ANOVA									
Source of variation	df								
G	5	NS	NS	**	**	*	**	**	**
W	1	**	**	**	**	**	**	**	**
G × W	5	NS	NS	**	*	**	NS	**	**
LSD (G)		-	-	0.56	0.76	0.005	0.015	0.008	0.006
LSD (W)		0.218	0.66	0.32	0.48	0.003	0.008	0.004	0.004
LSD (G × W)		-	-	0.79	1.07	0.008	-	0.011	0.009
CV [%]		10.5	20.4	10.3	14.70	17.3	20.40	13.01	16.4
SE (±)		0.317	0.96	0.47	0.64	0.004	0.012	0.007	0.005

Table 4. Intrinsic water-use efficiency (WUE_i) and total dry mass (TDM) of six wheat genotypes at different days after sowing (DAS) under well-watered (WW) and water-limited droughted (WL) conditions. G – genotype; W – water regime. *,** – significant at the 0.05*, 0.01** probability level, respectively; NS – not significant at the 0.05 probability level.

Genotype	Water regime	WUE_i [µmol(CO_2) mol(H_2O)$^{-1}$] 45 DAS	50 DAS	55 DAS	60 DAS	TDM [g plant^{-1}] 60 DAS
Cadenza	WW	60.78	133.5	101.0	83.8	7.46
	WL	31.45	52.4	81.0	56.4	3.00
L-22	WW	63.98	85.5	99.2	44.7	5.60
	WL	34.94	46.5	94.5	42.3	2.96
L-24	WW	52.54	159.8	86.5	86.6	7.50
	WL	32.96	68.0	80.0	49.5	3.41
L-38	WW	53.45	72.5	81.1	63.5	5.40
	WL	28.00	49.0	53.6	40.1	2.30
Paragon	WW	47.03	94.2	77.8	64.0	6.55
	WL	32.61	60.4	55.9	57.5	2.81
Xi 19	WW	51.29	98.8	97.6	50.8	5.76
	WL	31.85	55.6	65.6	54.1	2.63
ANOVA						
Source of variation	df					
G		*	NS	**	**	**
W		**	**	**	**	**
G × W		NS	NS	**	**	NS
LSD (G)		6.33	-	11.34	12.65	0.75
LSD (W)		3.65	23.52	6.55	7.30	0.43
LSD (G × W)		-	-	16.03	17.89	-
CV [%]		12.2	42.0	11.7	18.4	15.7
SE (±)		5.31	34.19	9.51	10.62	0.031

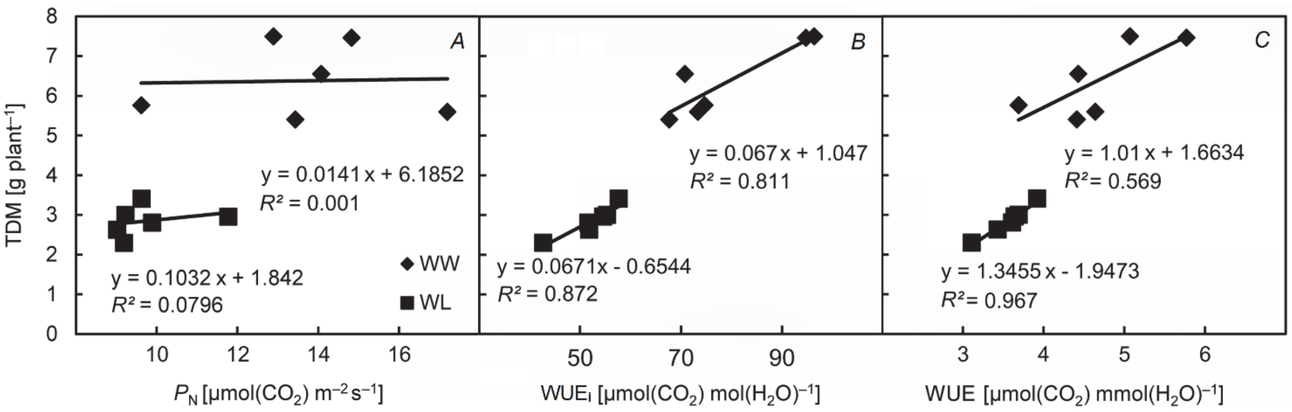

Fig. 2. Relationship of total dry matter (TDM) with (*A*) net photosynthetic rate (P_N), (*B*) intrinsic water-use efficiency (WUE_i), and (*C*) instantaneous water-use efficiency (WUE) under well-watered (WW) and water-limited (WL) conditions ($R^2 = 0.73$, $p<0.05$).

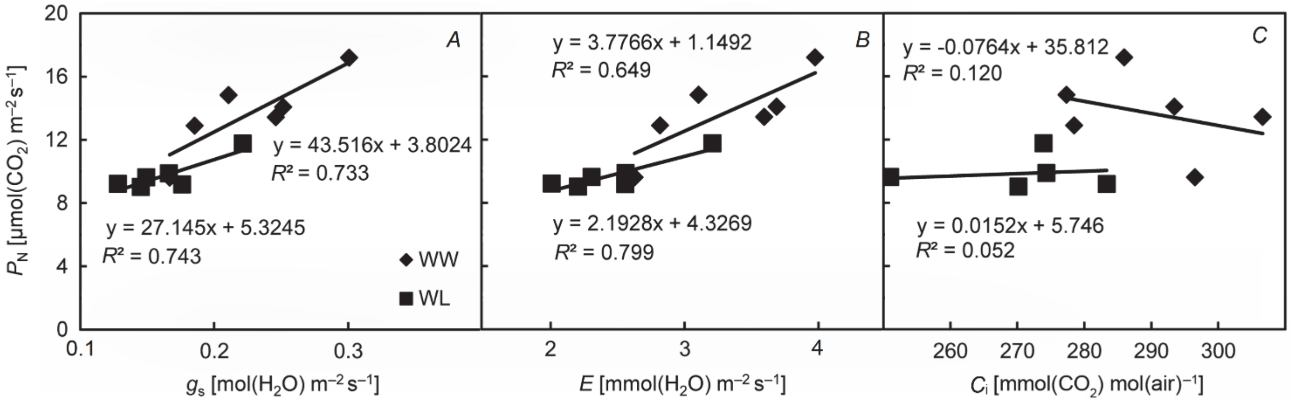

Fig. 3. Relationship of net photosynthetic rate (P_N) with (*A*) stomatal conductance (g_s), (*B*) transpiration rate (*E*), and (*C*) intercellular CO_2 concentration (C_i) under well-watered (WW) and water-limited (WL) conditions ($R^2 = 0.73$, $p<0.05$).

Regression analysis: The genotypes exhibited variations in TDM and P_N. There was a positive relationship between TDM and WUE and WUE_i under both WW and WL conditions, but the linear relationships between TDM and P_N were not significant (Fig. 2). The relationships between P_N and g_s, *E* and C_i were positive with an exception that between P_N and C_i at WW conditions (Fig. 3). But this relationship between P_N and g_s, and *E* were significant only at 5% level.

Discussion

The main objective in the present investigation was to identify genetic variation amongst elite cultivars and synthetic-derived wheat lines in drought tolerance by assessing net photosynthesis and other gas-exchange parameters (carboxylation capacity, water-use efficiency) and total dry matter of wheat genotypes under WL compared to WW conditions.

In the present study, as expected, drought reduced the P_N. There were significant variations among six genotypes in P_N under both WW and WL conditions similarly as in Van Den Boogaard *et al*. (1997). The same effect was also found by Rodgers *et al*. (2012) in C_3 species, by Anyia and Herzog (2004) in cowpea, and by Gulias *et al*. (2012) in grasses.

Stomatal conductance is an important biological determinate of carbon accumulation and transpiration by plants, because CO_2 flows to photosynthetic sites *via* the stomata. The g_s is related to CO_2 movement into leaf which is controlled by stomatal regulatory processes. Conductance to CO_2 is directly convertible to conductance to H_2O. In the present study, the effect of g_s is positively related to P_N. Other studies reported reduced g_s under drought conditions in wheat (Van Den Boogaard *et al*. 1997), in *Plantago lanceolata* (Rodgers *et al*. 2012), and in grasses (Gulias *et al*. 2012). They also found much genotypic variations in g_s both under the well-watered and drought conditions in different species. All these findings agree with results of our present study.

In the present study, all the genotypes, irrespective of their origin, showed increased C_i under WL compared to

WW condition at the initial stage (45 DAS). But at later stages, the reduced C_i was observed in WL plants. Anyia and Herzog (2004) reported increased C_i under drought condition in cowpea. Baburai Nagesh (2004) found also both increased and decreased C_i under drought condition compared to well-watered condition. In the present study, drought reduced the E in all genotypes irrespective of their origin. Other studies reported reduced E also in cowpea (Anyia and Herzog 2004) and in wheat (Van Den Boogaard *et al.* 1997, Baburai Nagesh 2006) under drought conditions.

The ratio of P_N/E was used to determine the WUE. In the present study, considerable variations in WUE were observed among wheat genotypes and drought reduced WUE in maximum cases compared to WW conditions. Anyia and Herzog (2004) observed drought-reduced WUE in cowpea. But Van Den Boogaard *et al.* (1997) and Gulias *et al.* (2012) reported drought-increased WUE in wheat and grasses, respectively. Therefore, our present results were consistent with others.

In the present study, the drought condition reduced the carboxylation capacity in all genotypes at all the days after sowing compared to WW condition. Baburai Nagesh (2006) found similar results in wheat. Gulias *et al.* (2012) also found higher WUE_i in perennial grasses under drought condition. But in few cases they observed droughted plant showing lower WUE_i.

Drought significantly reduced TDM per plant in all genotypes and there were prominent variations in TDM among six wheat genotypes. In fact, TDM is the output of net photosynthesis. In the present study, the photosynthetic performances of wheat genotypes were reflected in TDM under WW and WL conditions. Similar results were found by Van Den Boogaard *et al*. (1997) in wheat and by Gulias *et al*. (2012) in grasses. They found reduced TDM under drought condition compared to WW condition. They also found clear genotypic variations in TDM. All these findings were confirmed in the present study. Therefore, TDM was positively correlated with P_N, WUE, and WUE_i. There were also positive relationships between P_N and g_s, and E under both the WW and WL conditions. Positive relationships between WUE and P_N, g_s, and WUE_i were found by Gulias *et al*. (2012) in grasses.

Finally, we might conclude that genotypic variations in P_N and other photosynthesis-related characteristics were very prominent in six wheat genotypes under WW and WL conditions. Some of the synthetic derivative lines showed evidence for improved performance compared to the Paragon check cultivar under drought. For example, L-24 showed greater TDM and P_N than that of Paragon under drought conditions. L-22 and L-24 also showed greater WUE_i than that of Paragon at 55 DAS. Drought adversely affected most of the characteristics. The synthetic genotypes L-22 and L-24 exhibited relatively better maintenance of g_s, E, WUE, and CE compared to Paragon and other cultivars under drought. To select or develop drought tolerant genotypes, emphasis should be given on these characteristics, particularly WUE_i, which showed the closest correlation with TDM under drought in the present study.

Higher photosynthetic rate occurs in wild relatives of wheat (Evans and Dunstone 1970) and has been suggested as a mechanism to increase grain yield of wheat (Austin *et al.* 1982). There is some evidence that domestication and breeding of wheat resulted in lower photosynthetic rate. A higher photosynthetic rate may be advantageous when grain sink strength (grain number, grain mass) is increased, as it seems to be the case in synthetic-derived wheat (Del Blanco 1999). Del Blanco *et al.* (2000) reported that synthetic-derived lines from three BC2F2:6 populations of wheat (synthetic-derived from crossing of durum wheat, *Triticum turgidum* L. ssp. *durum* and *Aegilops tauschii*) showed higher or equal maximum photosynthetic rate than their respective recurrent parents. Our results also showed enhanced P_N in the synthetic-derived line L-22 compared to the recurrent parent, Paragon, and enhanced WUE_i in two lines L-22 and L-24 compared to recurrent parent. These results suggest that synthetic-derived wheat can be source of genetic diversity for important traits, such as P_N and WUE_i under both WW and WL conditions.

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