DOI: http://dx.doi.org/10.22092/cbj.2012.100454

Traits associated with drought tolerance in spring durum wheat (*Triticum turgidum* L. var. *durum*) breeding lines from international germplasm

R. Mohammadi[*], B. Heidari, and R. Haghparast

Dryland Agricultural Research Institute, Kermanshah, Iran.
*Corresponding author's E-mail address: rmohammadi@yahoo.com

Received: September 2013
Accepted: October 2013

ABSTRACT

Mohammadi, R., Heidari, B., and Haghparast, R. 2013. Traits associated with drought tolerance in spring durum wheat (*Triticum turgidum* L. var. *durum*) breeding lines from international germplasm. **Crop Breeding Journal 3(2):87-98.**

Knowledge of traits associated with drought tolerance would be useful for developing breeding materials for target environments. To study these traits, 119 spring durum wheat breeding lines (BLs) from the International Maize and Wheat Improvement Center (CIMMYT) were evaluated along with local checks (one modern cultivar and three landraces) in three experiments under terminal and non-terminal drought stress conditions in the 2009-10 and 2010-11 cropping seasons. Ten agro-physiological traits were measured and recorded. Best linear unbiased prediction (BLUP) data representing adjusted genotypic means were used to analyze trait relations and trait profiles of genotypes. Durum wheat BLs showed considerable variability for yield and agro-physiological traits that could be exploited in the national durum wheat breeding programs. Grain yield reduction due to terminal drought stress ranged from 29.1-64.8%. In contrast to the BLs, the landraces were characterized by minimal responsiveness to improved environmental conditions. Six BLs were identified as having high drought response index (DRI) and low grain yield reduction, and thus may be useful to national spring durum wheat breeding programs. Significant correlations between DRI and traits such as canopy temperature, SPAD reading, plant height, flag-leaf length and heading date suggest these traits could be useful for screening durum wheat BLs for drought tolerance. Results indicated that both grain yield and specific adaptation traits are useful criteria in breeding durum wheat for drought environments and should be incorporated into breeding materials to achieve optimum performance and adaptation to drought stress conditions in Iran.

Keywords: canopy temperature, drought response index, physiological maturity, supplemental irrigation, terminal drought

INTRODUCTION

Durum wheat (*Triticum turgidum* L. var. *durum*) accounts for a relatively small part of the global wheat industry and approximately 5% of total wheat production. Global durum wheat production in recent years has been approximately 30 million tons, nearly 60% of which was produced in the European Union, Canada and the United States (Brennan *et al*., 2002). Durum wheat is one of the most important crops in the Mediterranean region, where about 13 million tons are produced annually. Turkey, Syria, Morocco, Tunisia, Algeria and Iran account for 84% of that production (Brennan *et al*., 2002).

Terminal drought stress constrains wheat production in rainfed regions of Iran. However, grain yield improvement is the major objective of wheat improvement programs in those regions. Rainfed wheat covers two-thirds of Iran's total wheat area, but accounts for only about one-third of total wheat production (Mohammadi and Haghparast, 2011).

International nurseries are a major joint activity of national and international breeding programs. Nurseries are distributed to national programs upon request and tested in a wide range of environmental conditions. International breeding programs aim to help national programs increase agricultural production by developing superior cultivars. The interaction between these programs has been largely a one-way, top-down process (Simmonds and Talbot, 1992), in which international programs develop germplasm and national programs test and eventually release it as cultivars.

Although breeders are continuing to improve wheat yield potential, increasing wheat yield in drought environments is more difficult to achieve (Evans, 1998). Genetic improvement of crop performance in drought-prone regions may be approached either through direct selection for primary traits (e.g., yield) in the target environment, or indirect selection for secondary traits.

Efforts have been made to enhance the efficiency of selection for drought tolerant genotypes based on yield and specific physiological traits (Ludlow and Muchow, 1990; Quarrie *et al*., 1999; Wright and Rachaputi, 2004). The disadvantage of this approach is that there is always large G × E interaction for yield and there is also a lack of precise screening techniques that are not influenced by environmental conditions during measurement for trait selection (Cooper and Hammer, 1996). Selecting a physiological trait for screening drought tolerance requires a comprehensive understanding of the trait, its contribution to yield and its responsiveness to the environment (Ludlow and Muchow, 1990; Mutava *et al*., 2011).

Genetic gains in grain yield improvement will increase if more traits conferring better agronomic and physiological performance and disease resistance are brought together in the same variety in a breeding program. Several main traits show correlations with yield (Olivares-Villegas *et al*., 2007; Lopes and Reynolds, 2010); for example, low canopy temperature (CT) is associated with the ability to extract water from deeper in the soil profile (Lopes and Reynolds, 2010), and high leaf chlorophyll concentration is associated with delayed senescence or stay-green in sorghum (Borrel *et al*., 2000). Measuring these traits in a large set of germplasm is not an easy task, as major traits (such as plant height and days to heading or to maturity) can interact with the trait of interest, e.g., canopy temperature or early ground cover (Olivares-Villegas *et al*., 2007). It is always advisable to measure all these traits, including plant height and phenology, in order to ensure that the traits of interest are not confounded either by phenology or plant height (Lopes *et al*. 2012).

Germplasm evaluation and variety selection must be based on multiple traits or breeding objectives (Yan and Rajcan, 2002; Yan and Frégeau-Reid, 2008). In any breeding program, selection is a dual-purpose task: varietal selection and parental selection (Yan and Frégeau-Reid, 2008). Better adapted and higher yielding wheat genotypes can be bred more efficiently and effectively if traits that confer drought tolerance are identified and used as selection criteria (Acevedo and Ceccarelli, 1989).

A practical approach for selecting drought tolerant parents is to use a measure or an index of the relative yield of genotypes under stress and their yield under non-stress conditions as an integrative measure of the complex traits that provide drought tolerance. Bidinger *et al*. (1987) developed a drought response index (DRI) to identify genotypes that are tolerant or susceptible to drought and applied it to pearl millet [*Pennisetum americanum* (L.) Leeke]. The DRI corrects grain yield under drought for variation in flowering date and potential yield under non-stress conditions, thus ensuring that the selected genotypes will be drought tolerant. DRI has been used in different crops such as rice, beans and chickpea (Abebe *et al*., 1998; Salim and Saxena, 1993; Garrity and O'Toole, 1994; Pantuwan *et al*., 2002; Yue *et al*., 2005; Ouk *et al*., 2006). It is also used to describe the drought response of individual cultivars of different crops, regardless of phenology and yield potential (non-stress yield), and to determine attributes associated with DRI.

The specific objectives of this study were:

(i) To assess the agronomic performance of breeding lines selected from CIMMYT's durum wheat international nursery and identify introductions that warrant further evaluation.

(ii) To provide information to enable germplasm management and utilization by the national durum wheat breeding program under rainfed conditions of Iran.

(iii) To study the associations between yield and agro-physiological traits under both stress and non-stress conditions in order to find a suitable trait that could be used to improve yield under both conditions.

(iv) To identify drought tolerant breeding lines based on their response to terminal drought stress and determine traits associated with DRI.

MATERIALS AND METHODS

Field experiments and data collection

Spring durum wheat breeding lines developed by the International Maize and Wheat Improvement Center (CIMMYT) were used in the present study. Plant materials were evaluated during two cropping seasons (2009-10 and 2010-11) at one of the Dryland Agricultural Research Institute's (DARI) main research stations, Sararood Research Station, located at Kermanshah, Iran (34°19´ N; 47°17´ E, 1351 masl). This site is characterized as a temperate region for rainfed crop breeding in Iran and has been suggested as a representative location to share durum wheat breeding materials for Iran's warm and cold research stations (Mohammadi *et al*., 2010, 2011).

This research station is located in western Iran, with minimum and maximum temperatures of -20^{o}C and 45^{o}C, respectively, and 60-100 days of freezing temperatures annually. The average long-term annual precipitation is about 455 mm, consisting of 90% rain and 10% snow**.** Climate data were collected from a meteorological station at Sararood Station, at a distance of about 500 m from the experiments. The soil at the site is clay loam.

International durum wheat nurseries are received every year from CIMMYT and evaluated at DARI, Iran. Accordingly, the 41st International Durum Wheat Screening Nursery (41st IDSN) consisting of 119 durum wheat breeding lines was received to be grown and evaluated in the 2009-10 cropping season (rainfall= 453.9 mm; temperature: min. = -8.6 °C; max. = 38.26 °C; average= 11.8 °C). A newly released durum variety (Saji) was used as a check to evaluate the performance of the nursery.

The plant materials were sown in 2 rows, 2.5 m long, in a non-replicated trial. The genotypes in the nursery were evaluated for several traits that are important for preliminary germplasm evaluation under rainfed conditions: days to heading (DH), plant height (PH), thousand kernel weight (TKW) and grain yield (YLD). DH was designated as the number of days until 50% of the plants in the plot had at least one emerged spike. PH of each genotype was measured at physiological maturity stage. YLD of each genotype in each plot was measured after harvest, and TKW was measured on each genotype. The agronomic score (AS) (on a scale of 1 to 5, where 5 is the highest and 1 is the lowest) based on plant physical appearance of each genotype was evaluated visually at grain-filling under both rainfed and irrigated conditions. Finally, based on the studied traits and agronomic scores, 64 genotypes that performed better than check cultivar Saji were selected for further evaluation in the next cropping season.

In the 2010-11 cropping season (rainfall= 342.5 mm; temperature: min. = -10 °C; max. = 39 °C; average = 11.7 °C), the 64 selected BLs along with four checks were evaluated in two field experiments under rainfed conditions and supplemental irrigation (two 25-mm irrigations applied at flowering and grain-filling to mitigate terminal drought stress, a common stress in western Iran) at Sararood Research Station.

Each experiment consisted of 68 genotypes including 64 breeding lines and four check cultivars (cv. Saji, plus Zardak and Gerdish, two durum wheat landraces, and Sardari, a bread wheat landrace); the four checks were repeated and randomly distributed in a systematic diagonal fashion. The genotypes were sown in 6 rows, 2.5 m long, with 20-cm row spacing in a non-replicated trial under terminal (rainfed) and non-terminal drought stress (supplemental irrigation) conditions. The checks were used to adjust for spatial variation.

In both experiments, each of the 68 genotypes was evaluated for 10 agro-physiological traits: plant height (PH), peduncle length (PL), flag-leaf length (FL), spike length (SL), days to heading (DH), days to physiological maturity (DM), chlorophyll content (SPAD: soil plant analysis development), canopy temperature (CT), 1000-kernel weight (TKW) and grain yield (YLD). Days to physiological maturity was recorded when 50% of the plants in a plot had yellow leaves. Traits PH, PL, FL and SL were measured on three samples taken from each genotype at physiological maturity.

Using a chlorophyll meter (SPAD 502 Plus, Spectrum Technologies, Plainfield, IL, USA), chlorophyll content was recorded on three samples from each plot under both conditions. Canopy temperature of each genotype was measured at anthesis on three samples from each rainfed and irrigated plot using a hand-held infrared thermometer. In all three experiments weeds were controlled manually and fertilizer rate was 50 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1} applied at planting.

Data analysis

Data were subjected to different types of analyses. First, the data recorded for each of the 10 studied traits were analyzed with a GENSTAT program (Payne *et al*., 2009) for spatial analysis of un-replicated trials in which the response of the checks provided the basis for modeling spatial variability in the field and adjusting genotype performance (Singh *et al*., 2003). Data analysis was carried out in two steps: (i) generation of Best Linear Unbiased Predictors (BLUPs) based on each studied trait in individual trials, and (ii) genotype × trait (GT) biplot analysis based on the genotype × trait table of BLUPs using GGEbiplot software (Yan, 2001). The GT biplot can be used to examine the variation among the genetic materials, explore multiple trait data and aid in multi-trait selection in breeding programs (Yan and Rajcan, 2002).

Broad-sense heritability (h^2b) was estimated based on BLUP data for each trait. To characterize the response of genotypes to terminal drought stress conditions, BLUP data on grain yield were used to calculate the DRI following Pantuwan *et al.* (2002):

$$DRI= (Y_{act} - Y_{est})/SE$$
$$Y_{est}= a + b^*(Y_{ns}) + c^*(DH)$$

Where Y_{act} is the actual grain yield (grain yield under drought stress) of each genotype, Y_{est} is the estimated grain yield of each genotype derived from the calculation using multiple linear regression analysis, SE is the standard error of Y_{est} of all genotypes, DH is days to heading, Y_{ns} is yield under non-stress conditions, and a, b, c are regression coefficients.

RESULTS

Genotype evaluation and selection

In 2009-10, 119 spring durum wheat breeding lines from CIMMYT were tested under rainfed conditions at Sararood Research Station. Under rainfed conditions, the breeding lines were superior to cv. Saji, the improved check, in several important traits (i.e., DH, PH, TKW and YLD) and in their agronomic scores, recorded during the preliminary evaluation. Precipitation during the cropping season was close to the long-term average, but there was no rain during grain-filling, which is a common climatic feature at Sararood Research Station.

Large variation for different attributes was found among the entries. Results showed that it was possible to identify contrasting groups based on the traits used for improving breeding materials in the national spring durum wheat breeding program. As for heading date, 74 entries were earlier than cv. Saji (data not shown). Most (107) of the entries had the same (5 entries) or lower (102 entries) plant height than cv. Saji, while 26 entries had higher TKW and 46 entries out-yielded the check, with an average yield increase of 13.2%; the agronomic scores of 36 entries were better than that of the check.

The relationship among traits and the characterization of genotypes based on the studied traits are presented in Fig. 1. Positive correlation was found between YLD and PH as indicated by the acute angle between their vectors, which shows they ranked the genotypes in the same direction. Poor positive relationships were also found between YLD and AS, and between PH and TKW. These four traits (YLD, AS, PH and TKW) were negatively associated with DH, showing that entries characterized by YLD, AS, PH and TKW tended to flower before other genotypes. A GT biplot is useful for studying the variation among large sets of germplasm and exploring multiple trait data, and can also aid breeding programs in performing multi-trait selection (Yan and Frégeau-Reid, 2008). Fig. 1 also shows that the entries located around the vectors correspond to AS and TKW can be characterized as good candidates for further evaluation in the next cropping season. In general, these entries are lines that were selected based on the original data. Fig. 1 indicates that the agronomic performance of many of the breeding lines was superior to that of cv. Saji, the improved check.

Evaluation of selected genotypes for agro-physiological traits and drought tolerance

Grain yield performance: The mean grain yield of the 68 genotypes (64 entries and four checks) was 1849 kg ha^{-1} under terminal drought stress conditions and 4077 kg ha^{-1} under non-terminal drought stress conditions; mean grain yield was thus 55% lower under terminal drought stress than under non-terminal drought stress. In other words, stress intensity (SI; Fischer and Maurer, 1978) in the study was 0.55, indicating severe stress.

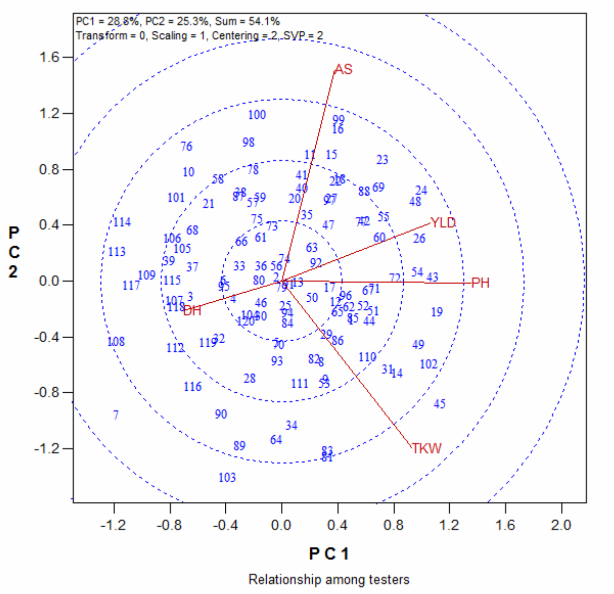

Fig. 1. Genotype × trait biplot showing the relationships among five traits of 119 entries from CIMMYT's 41st IDSN along with the check cultivar (entry no. 1) under rainfed conditions in the 2009-10 cropping season.
DH: days to heading; PH: plant height; TKW: thousand kernel weight; YLD: grain yield; AS: agronomic score.

The crop received 111.4 mm less rainfall than during the previous cropping season (2009-10). Under these conditions, grain yield of the breeding lines was 1343-2449 kg ha^{-1}, with an average of 1857 kg ha^{-1}. All landraces were out-yielded by this mean grain yield (Table 1). Saji yielded 2250 kg ha^{-1} and only one breeding line (entry no. 41 with 2449 kg ha^{-1}) performed better than the check. In 2009-10, the crop received good rainfall (453.5 mm), and 46 entries performed better than the check. In 2010-11, rainfall decreased by 111.4 mm, and all selected breeding lines (except one) were out-yielded by the check. This indicates that the germplasm received from CIMMYT was more suitable for favorable conditions (good rainfall) in cold temperate rainfed areas of Iran. In contrast to terminal drought stress conditions in 2010-11, the mean grain yield of breeding lines under non-terminal drought stress conditions was 4096 kg ha^{-1}, which was higher than the yield of all landraces. Under these conditions, grain yield of the entries ranged from 4176 to 4616 kg ha^{-1}, while the improved check produced 4602 kg ha^{-1}. There were also 26 entries that yielded more than Saji, the improved check.

Table 1. Minimum, maximum, average, heritability and coefficient of variation (CV%) based on BLUP data for grain yield and nine agro-physiological attributes of 64 breeding lines selected from an international nursery compared with the improved check cultivar (MC, Saji) and durum landraces (DL1; Zardak; DL2: Gerdish) and bread wheat landrace (WL; Sardari) under terminal and non-terminal drought stress conditions in 2010-11.

	Breeding lines			Checks				Descriptive statistics		
Traits	**Average**	**Min.**	**Max.**	**MC**	**DL1**	**DL2**	**WL**	**Mean**	**H^{2}b**	**CV%**
				Terminal drought stress						
YLD (kg/ha)	**1857.0**	**1343.0**	**2449.0**	**2250.0**	**1553.0**	**1287.0**	**1778.0**	**1849.0**	**0.558**	**14.20**
TKW (gr)	**21.4**	**19.9**	**23.4**	**21.3**	**23.4**	**21.8**	**21.2**	**21.4**	**0.340**	**9.61**
SPAD	**56.0**	**50.2**	**59.6**	**56.2**	**52.0**	**53.1**	**48.9**	**55.8**	**0.525**	**4.67**
CT (^{o}C)	**43.2**	**41.8**	**44.9**	**43.0**	**43.2**	**41.7**	**42.9**	**43.1**	**0.162**	**4.97**
PH (cm)	**73.6**	**60.4**	**100.3**	**90.7**	**100.3**	**110.0**	**102.0**	**75.2**	**0.772**	**5.80**
DH (day)	**198.0**	**192.0**	**203.0**	**192.1**	**199.1**	**203.4**	**199.5**	**198.4**	**0.788**	**0.73**
DM (day)	**237.0**	**230.0**	**262.0**	**232.6**	**238.4**	**239.6**	**239.3**	**236.9**	**0.933**	**0.46**
SL (cm)	**7.4**	**6.6**	**8.2**	**6.9**	**7.9**	**8.2**	**9.4**	**7.4**	**0.475**	**8.92**
PL (cm)	**8.5**	**6.8**	**11.5**	**11.5**	**9.5**	**9.5**	**9.7**	**8.6**	**0.234**	**30.96**
FL (cm)	**15.2**	**14.5**	**16.0**	**13.9**	**15.7**	**15.6**	**14.7**	**15.2**	**0.08**	**12.71**
				Non-terminal drought stress						
YLD	**4091.0**	**3719.0**	**4617.0**	**4602.0**	**3745.0**	**3239.0**	**3855.0**	**4077.0**	**0.140**	**25.90**
TKW	**33.0**	**28.3**	**37.4**	**32.3**	**33.3**	**32.4**	**33.8**	**33.0**	**0.335**	**13.35**
SPAD	**50.6**	**48.0**	**54.0**	**54.0**	**49.1**	**48.9**	**46.6**	**50.5**	**0.237**	**8.16**
CT	**39.6**	**38.6**	**41.1**	**40.1**	**39.2**	**38.2**	**39.5**	**39.6**	**0.216**	**4.38**
PH	**78.1**	**64.9**	**113.3**	**93.3**	**113.3**	**128.3**	**102.2**	**80.0**	**0.756**	**7.06**
DH	**197.0**	**192.0**	**202.4**	**192.0**	**199.0**	**204.0**	**200.0**	**197.0**	**0.489**	**1.69**
DM	**235.8**	**232.0**	**242.9**	**234.0**	**240.0**	**241.0**	**241.0**	**236.0**	**0.989**	**0.50**
SL	**6.7**	**5.8**	**8.6**	**6.3**	**8.6**	**8.5**	**9.6**	**6.8**	**0.399**	**15.84**
PL	**14.8**	**10.3**	**25.9**	**19.2**	**25.9**	**24.8**	**20.3**	**15.3**	**0.482**	**24.00**
FL	**16.7**	**14.6**	**21.1**	**15.4**	**18.5**	**20.5**	**18.7**	**16.8**	**0.395**	**17.52**

SPAD: SPAD reading; CT: canopy temperature; PL: peduncle length; SL: spike length; FL: flag leaf length; PH: plant height; DH: days to heading; DM: days to maturity; TKW: thousand kernel weight; YLD: grain yield; DRI: drought response index.

No relationship was found between grain yields under terminal and non-terminal drought stress conditions (data not shown). Although a significant number of breeding lines had high grain yield under both conditions, there were some that had high yield only under non-terminal stress and did not perform well under terminal drought stress. Genotypic variation for grain yield was significant within each of these growing conditions. Improved check Saji consistently produced high grain yield in both environments; however, the three landraces were out-yielded by most of the breeding lines.

Agro-physiological traits: Thousand-grain weight differed narrowly among breeding lines under terminal drought stress conditions, ranging from 19.9 to 23.4 g, with a mean value of 21.4 g (Table 1). Considerable differences in TKW (28.3–37.4 g) were observed among breeding lines under non-stress conditions. However, results show that under both stress and non-stress conditions, some breeding lines produced heavier grains than the checks.

SPAD chlorophyll meter readings for breeding lines ranged from 50.2 to 59.6, with an average value of 56.0 under stress conditions, and from 48.0 to 54.0, with an average value of 50.6, under non-stress conditions (Table 1). Results showed greater SPAD values for breeding lines relative to landraces. No breeding line had a higher SPAD reading than Saji, the improved check, under non-stress conditions, but some had higher SPAD values under stress conditions.

Genotypes exhibited differences in mean canopy temperature under stress and non-stress conditions. Among breeding lines, canopy temperature varied from 41.8 to 44.9 ^{o}C, with an average of 43.2 ^{o}C under terminal drought stress, and from 38.6 to 41.1 ^{o}C, with an average of 39.6 ^{o}C under non-terminal drought stress, showing that the crop had a cooler canopy under non-terminal drought stress. However, it was also possible to identify breeding lines that maintained a cooler canopy under both conditions (Table 1).

Among breeding lines, considerable variation was found for PH under both terminal and non-terminal drought stress. Most breeding lines (> 95%) were shorter than the checks under both conditions, which suggests these materials carry genes for reduced height and resistance to lodging, diseases, insects, and environmental stresses (Fufa *et al.*, 2005). Check cultivar Saji tended to be shorter, flower earlier and yield more than the three landraces. Variation among genotypes for flowering (DH) and maturity (DM) revealed that some breeding lines were earlier than cv. Saji which, in turn, was earlier (7-10 days) in flowering and maturity than the landraces. Spike length (SL) among breeding lines varied from 6.6 to 8.2 cm, with an average of 7.4 cm under terminal stress conditions, while under non-terminal stress conditions, it ranged from 5.8 to 8.6 cm, with an average of 6.7 cm. Average SL for breeding lines under both conditions was higher than than that of Saji but lower than that of the landraces (Table 1).

The average peduncle length (PL) of breeding lines was 8.5 cm, which was shorter than PL of cv. Saji and landraces under terminal stress conditions. In contrast to terminal drought stress conditions, under non-terminal drought stress conditions considerable variation was observed for PL, which varied from 10.3 to 25.9 cm, with an average of 14.8 cm. As in terminal stress conditions, the average PL for breeding lines was lower than that of the improved check and the landraces (Table 1).

Flag-leaf length (FL) differed little among the genotypes under terminal stress conditions. It varied from 14.5 to 16 cm among breeding lines with an average of 15.2 cm and was higher than that of cv. Saji and bread wheat landrace Sardari, but lower than that of two durum wheat landraces. Greater variation was observed among genotypes for FL under non-terminal stress conditions. The average FL for breeding lines was 16.7 cm, which was higher than that of Saji but lower than that of the three landraces.

The coefficient of variation (CV%) for each of the studied traits was calculated for both terminal and non-terminal drought stress conditions (Table 1). The CV% ranged from 0.46% (for DM) to 30.96 (for PL) under terminal drought stress, and from 0.5% (for DM) to 25.9% (for YLD) under non-terminal drought stress conditions. Average CV% under non-terminal drought stress conditions was greater than under stress conditions (11.84% vs. 9.30%), indicating that greater phenotypic variation for the studied traits was observed under non-stress conditions.

Broad-sense heritability

The magnitude of heritability was, in general, similar under terminal and non-terminal drought stress conditions, except for grain yield (Table 1). Broad-sense heritability under stress conditions varied from 8% and 93.3%. Heritability estimates under terminal drought stress for DM was 93.3%, followed by DH (78.8%), PH (77.2%), YLD (55.8%), SPAD (52.5%), SL (47.5%), TKW (34.0%), PL (23.4%), CT (16.2%) and FL (8.0%). Under non-terminal drought stress, the highest broad-sense heritability was estimated for DM (98.9%), followed by PH (75.6%), DH (48.9%), PL (48.2), SL (39.9%), FL (39.5%), TKW (33.5%), SPAD (23.7%), CT (21.6%) and the lowest for YLD (Table 1). Hence, under both conditions, broad-sense heritability was high for DM, DH, and PH, low for CT, low to medium for YLD, and reasonable for other traits.

Broad-sense heritability of DM under both conditions was high (> 90 %), indicating that genetic factors had greater influence than the environment on the expression of this trait. However, the heritability of grain yield was low (14%) to medium (55.8%), which implies that environment had greater influence than genetic factors on the expression of grain yield. Selection for grain yield is empirical due to its low broad-sense heritability and high GE interaction (Reynolds *et al*., 1999), and also requires evaluating a large number of advanced lines in field trials over several years and locations (Ball and Konzak, 1993). An indirect selection method that gives early yield prediction is a potential alternative for screening large numbers of genotypes in breeding programs when identifying and selecting high-yielding lines (Marti *et al*., 2007; Gutierrez *et al*., 2012).

Relationships among traits and genotype characterization

Trait profiles of genotypes and relationships among traits are frequently influenced by unpredictable conditions in rainfed Mediterranean regions (Mohammadi and Amri, 2011). Relationships among breeding objectives influence how selection and breeding strategies are chosen. Figs. 3 and 4 represent polygon views of GT biplots developed from data on 10 agro-physiological attributes of 68 genotypes under terminal and non-terminal drought stress, which accounted for 42.2 to 45.5% of total observed variation. The relatively low goodness-of-fit reflects the complexity of the relationships among the measured traits. According to Kroonenberg (1995), the fundamental patterns among the traits should be captured by the biplots. Under terminal drought stress conditions (Fig. 2), genotype 65 (cv. Saji), followed by breeding lines no. 41, 34, 39 and 43, had the highest YLD and longest PL, and tended to flower and mature earlier than other genotypes. Genotype 68 (bread wheat landrace Sardari) had the highest PH, whereas genotype 67 (durum landrace Gerdish) had the longest SL and heaviest TKW. Genotype 59 had the highest SPAD and CT (Fig. 3).

Under non-terminal drought stress, the profile of genotypes differed from that under terminal drought stress (Fig. 3). Genotype 65 (cv. Saji), followed by entries 30, 45, 13 and 29, had the highest YLD and SPAD, whereas the three landraces (i.e., 67 followed by 66 and 68) had the highest PH, PL, DM, FL, DH and SL. These landraces tended to flower later than all other genotypes. Entry 15, followed by 38, 4, 1 and 53, had the highest TKW, and genotypes 52,

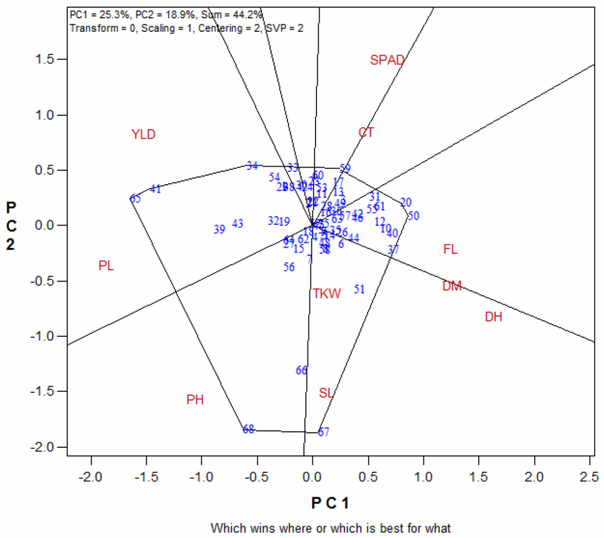

Fig. 2. Polygon view of a GT biplot generated from data on 10 agro-physiological attributes of 68 durum wheat genotypes under terminal drought stress conditions in the 2010-11 cropping season.
SPAD: SPAD reading; CT: canopy temperature; PL: peduncle length; SL: spike length; FL: flag leaf length; PH: plant height; DH: days to heading; DM: days to maturity; TKW: thousand kernel weight; YLD: grain yield.

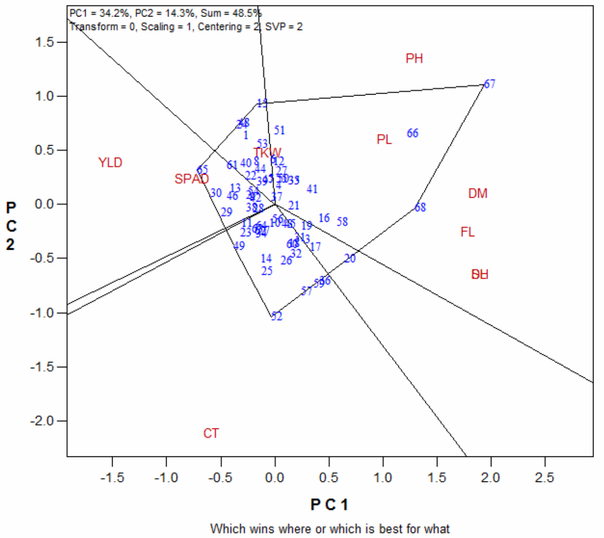

Fig. 3. Polygon view of a GT biplot generated from data on 10 agro-physiological attributes of 68 genotypes under non-terminal drought stress conditions in the 2010-11 cropping season.
SPAD: SPAD reading; CT: canopy temperature; PL: peduncle length; SL: spike length; FL: flag leaf length; PH: plant height; DH: days to heading; DM: days to maturity; TKW: thousand kernel weight; YLD: grain yield.

followed by 57, 59, 36, 25, 14, 26 and 32, had the highest CT (Fig 3).

In a GT biplot, vectors are drawn from the biplot origin to markers of the traits to facilitate visualization of the relationships among traits. These biplots can be visualized from two perspectives. First, they show the associations among traits across the test genotypes. Second, they show the trait profiles of the genotypes, particularly those that are located farther away from the biplot origin (Yan and Frégeau-Reid, 2008). The most prominent associations among traits under terminal drought stress were positive correlations between SPAD and CT; between FL, DM and DH; between SL, TKW and PH; and between YLD and PL, as indicated by the acute angles between their vectors (Fig. 4). This can also be verified from computed Pearson's correlation coefficients (Table 2). There is a negative association for YLD with FL, DH and DM, as indicated by the large obtuse angles between vectors of these three traits and that of YLD. These negative associations appear to be strong because the traits have long vectors.

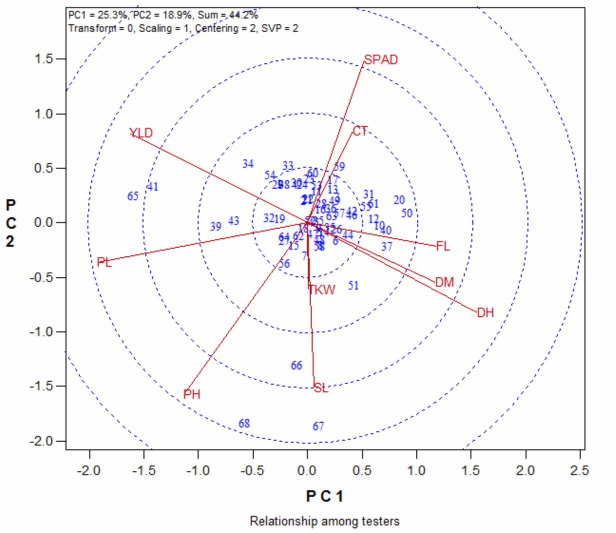

Fig. 4. GT biplot shows relationships among 10 agro-physiological attributes of 68 genotypes under terminal drought stress conditions in the 2010-11 cropping season.
SPAD: SPAD reading; CT: canopy temperature; PL: peduncle length; SL: spike length; FL: flag leaf length; PH: plant height; DH: days to heading; DM: days to maturity; TKW: thousand kernel weight; YLD: grain yield.

Relationships among traits under non-terminal drought stress were not similar to those under terminal drought stress (Fig. 4), which suggests that there was a differential response of genotypes to different growing conditions. Positive correlations were found between SL, DH, FL, PL and PH, and between YLD and SPAD under non-terminal drought stress. However, CT was not positively associated with any trait under non-terminal stress.

The distance between a genotype and the biplot origin is a unique measure of that genotype (i.e., how it differs from an "average" genotype), which is a hypothetical genotype that has an average level for all traits and is represented by the biplot origin (Yan and Frégeau-Reid, 2008). Therefore, genotypes with

Table 2. Pearson correlation coefficients between 10 agro-physiological traits and drought response index (DRI) under terminal (below diagonal) and non-terminal (above diagonal) drought stress conditions

	SPAD	CT	PL	SL	FL	PH	DH	DM	TKW	YLD	DRI
SPAD		**0.09**	**-0.01**	**-0.33****	**-0.07**	**-0.19**	**-0.23**	**-0.18**	**0.12**	**0.33****	**0.42****
CT	**0.07**		**-0.22**	**-0.17**	**-0.05**	**-0.42****	**-0.16**	**-0.12**	**-0.25***	**-0.02**	**0.31****
PL	**-0.18**	**-0.19**		**0.35****	**0.18**	**0.71****	**0.02**	**0.08**	**0.13**	**-0.17**	**0.03**
SL	**-0.32****	**-0.09**	**-0.07**		**0.44****	**0.53****	**0.41****	**0.42****	**-0.11**	**-0.45****	**-0.16**
FL	**0.08**	**0.04**	**-0.30***	**-0.02**		**0.13**	**0.60****	**0.63****	**-0.05**	**-0.42****	**0.02**
PH	**-0.39****	**-0.24***	**0.59****	**0.32***	**-0.08**		**0.06**	**0.06**	**0.08**	**-0.27***	**-0.29***
DH	**-0.04**	**0.01**	**-0.44****	**0.18**	**0.20**	**-0.04**		**0.76***	**-0.11**	**-0.50****	**0.01**
DM	**0.12**	**-0.06**	**-0.21**	**0.06**	**0.04**	**-0.04**	**0.50**		**-0.01**	**-0.37****	**-0.01**
TKW	**-0.08**	**-0.04**	**0.08**	**0.11**	**0.12**	**0.07**	**0.01**	**0.03**		**0.15**	**0.19**
YLD	**0.18**	**0.01**	**0.49****	**-0.12**	**-0.47****	**0.06**	**-0.42****	**-0.29***	**-0.05**		**-0.01**
DRI	**0.05**	**-0.01**	**0.46****	**-0.09**	**-0.43****	**0.13**	**-0.33***	**-0.29***	**-0.04**	**0.97****	

*** and **: significant at the 5% and 1% probability levels, respectively.**

SPAD: SPAD reading; CT: canopy temperature; PL: peduncle length; SL: spike length; FL: flag leaf length; PH: plant height; DH: days to heading; DM: days to maturity; TKW: thousand kernel weight; YLD: grain yield; DRI: drought response index.

long distances are those that have extreme levels for one or more traits. Such genotypes may or may not be superior, but they may be useful as parents for certain traits (Yan and Frégeau-Reid, 2008). Thus under terminal drought stress conditions (Fig. 4), genotypes 65 (cv. Saji) and 41 for YLD, PL and earliness (low DH and DM); landraces (entries 66, 67, 68) for PH, SL, TKW; and entry 59 for SPAD and CT could be used as parents in spring durum wheat breeding programs.

Similarly, under non-terminal stress conditions, there were genotypes with extreme levels of one or more traits, including 65 (cv. Saji) for YLD and SPAD; landraces (entries 66, 67, 68) for PH, PL, DM, FL, DH and SL; breeding line 52 for CT; and BLs 15, 48, 24 and 53 for TKW (Fig. 5).

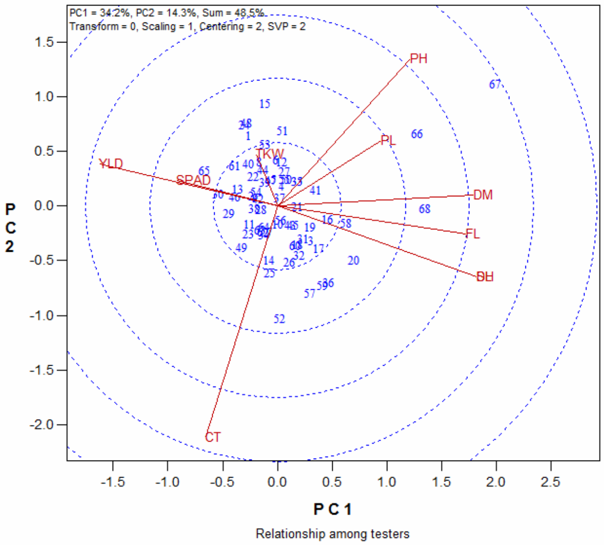

Fig. 5. GT biplot shows relationships among 10 agro-physiological attributes of 68 genotypes under non-terminal drought stress conditions in the 2010-11 cropping season. SPAD: SPAD reading; CT: canopy temperature; PL: peduncle length; SL: spike length; FL: flag leaf length; PH: plant height; DH: days to heading; DM: days to maturity; TKW: thousand kernel weight; YLD: grain yield.

Response of genotypes to drought stress

The mean grain yield of genotypes in the stress environment was 55% lower than in the non-stress environment. In other words, a stress intensity (SI; Fischer and Maurer, 1978) of 0.55 indicates that genotypes experienced severe drought stress in this study. Thus, genotypic yields under both terminal and non-terminal drought stress conditions were used to estimate the response of breeding lines to drought stress in the rainfed areas of western Iran. There was a significant difference among the genotypes for DRI, which varied from 75.3 to 81.2 (Fig. 6).

Two of the 68 genotypes had a DRI of between +1.3 and -1.3, which indicates that the two lines had no specific response to drought. In addition, 38 lines had negative DRI values and 28 lines had positive DRI values, indicating susceptibility and tolerance to drought, respectively. Among 28 lines, entries 41, 64, 21, 19, 43 and 36 with DRI > 41 were more responsive to drought stress in comparison with cv. Saji (DRI = 40.6). The six top genotypes also performed well under terminal drought stress conditions. All three landraces had negative DRI values and were not responsive to drought stress. This result suggests that it would be possible to use these genotypes as parents in rainfed durum breeding programs for developing drought tolerant durum wheat. Thus, DRI appears to be a useful index for identifying drought tolerant genotypes. In addition, because DRI was not confounded by YLD or DH under non-terminal drought stress conditions, selection for high DRI should not have a negative effect on grain yield potential and early maturity (Bidinger *et al*., 1987; Pantuwan *et al*., 2002; Ouk *et al*., 2006).

The strong correlation between DRI and Y_s, and the lack of correlation with Y_{ns}, indicate that DRI could be useful for identifying lines with high grain yield potential in drought stress environments, but not for identifying lines with high performance across a range of environments.

Correlations between DRI and Y_s and PL was

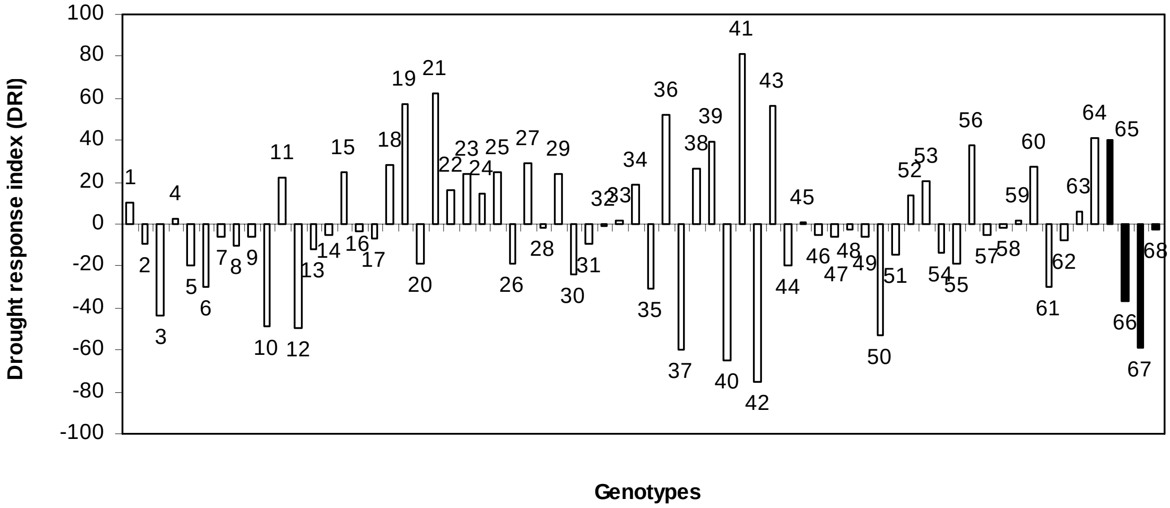

Fig. 6. Drought response index (DRI) for 64 durum wheat breeding lines (1-64) and four checks (entry 65= cv. Saji; entry 66= durum landrace Zardak; entry 67 durum landrace Gerdish; and entry 68: bread wheat landrace Sardari).

positive ($P<0.01$) and negative with FL, DH ($P<0.01$) and DM ($P<0.05$) under terminal drought stress (Table 2), indicating that these traits could be used for indirectly identifying drought tolerant genotypes. The result of multiple regression incorporating three of these traits along with PH was significant ($R^2 = 0.96$; $P<0.01$). The equation is as follows:

DRI= -423.3 + 0.15 (Ys) + 0.76 (DH) + 0.59 (PH) – 4.98 (PL)

Under non-terminal drought stress, DRI was positively associated ($P<0.01$) with SPAD and CT and negatively correlated ($P<0.05$) with PH (Table 2). According to multiple regression analysis, DRI was significantly ($R^2= 0.26$; $P<0.05$) influenced by SPAD, CT and TKW. The equation is as follows:

DRI= -1394.4 + 9.0 (SPAD) + 21.0 (CT) + 3.3 (TKW)

From the above equations, it can be concluded that traits entered in the regression models are significantly related to DRI, and can be identified as adaptive traits for drought stress conditions.

DISCUSSION

Grain yield comparison of CIMMYT germplasm under terminal and non-terminal drought stress conditions showed that grain yields under these two conditions are not associated. These findings are in agreement with the statement by Ceccarelli *et al.* (1987) that yield potential is not a useful criterion when breeding for superior performance in drought stress environments.

However, according to van Ginkel *et al.* (1998), many CIMMYT wheat genotypes released for drought stress conditions owe part of their superior performance to their high grain yield potential. The contribution of high grain yield potential in marginal environments has been postulated by several researchers because of a positive association between grain yield under non-stress and stress conditions (Bramel-Cox *et al.*, 1991; Zavala-Garcia *et al.*, 1992; van Ginkel *et al.*, 1998). In addition, high grain yield potential, as expressed by a genotype's ability to respond to improved moisture conditions, is particularly important. In one or two out of every five years, the precipitation in drought-stressed environments tends to significantly exceed the long-term mean. In those years, farmers need to be able to benefit from the weather's unpredictable nature (van Ginkel *et al.*, 1998). In contrast, in the Mediterranean regions, particularly Iran, environmental conditions are prone to severe drought every 5 to 7 years (Mohammadi *et al.*, 2010, 2011). Under such conditions, rainfall tends to be significantly lower than the long-term average; for this reason, farmers in those regions need genotypes with good performance and improved response to drought stress.

The effect of plant breeding on durum wheat grain yield potential and its physiological determinants has been widely studied (Pecetti and Annichiarico, 1998; Motzo *et al.*, 2005; García del Moral *et al.*, 2003; Royo, 2005; Giunta *et al.*, 2007, 2008; Royo *et al.*, 2008). Genetic gains from 10 to 50 kg $ha^{-1}yr^{-1}$ have been recorded over the last century in most countries; they are often associated with a few key genes affecting morpho-phenological traits (Slafer *et al.*, 1994; De Vita *et al.*, 2010). Similar genetic gain was found for cv. Saji relative to durum wheat landraces in Iran's durum wheat breeding program. The higher grain yield of cv. Saji under both stress and non-stress environments indicated that this cultivar had been selected for improved environmental stress tolerance under both stress and non-stress conditions. Results also showed that more recently developed materials were highly responsive for grain yield and associated attributes, and also resistant to lodging, disease and pests.

Breeders have selected cultivars that are earlier, shorter in stature, have higher grain weight and produce more yield than landraces. These findings of this study are in agreement with previously reported results (Feyerherm *et al.*, 1984; Cox *et al.*, 1988; Donmez *et al.*, 2001; Fufa *et al.*, 2005; Pswarayi *et al.*, 2008).

Variability for most of the measured agro-physiological traits was observed in the test breeding lines and landraces under different growing conditions. Differences in performance of various genotypes in each cropping season may be due to the higher amount of rainfall and better rainfall distribution in 2009-10, which resulted in adequate moisture and also favorable temperatures during flowering. Improved cultivar Saji was high yielding and had more genotypic stability across stress and non-stress environments. The landraces showed low potential for increasing grain yield under both stress and non-stress conditions.

Among the studied traits, grain yield and PL were highly variable among genotypes under both stress and non-stress conditions, suggesting selection options for these two traits under both conditions. In contrast, the lowest variability was observed for DH and DM under both conditions. Selection for one trait can reduce the chance of successfully selecting for other traits due to competition for the same source of nutrients. However, the combination of traits contributing to the improvement of grain yield in various ways can result in maximum gain for each trait individually (Quarrie *et al.*, 1999).

Breeders are continuously looking for new indirect selection parameters for screening genotypes, detecting yield differences and finding strong associations with grain yield (van Ginkel *et al.*, 1998; Fufa *et al.*, 2005; Gutierrez *et al.*, 2012). This study could contribute to a better understanding of the associations among important rainfed durum wheat breeding objectives in Iran. Positive association of YLD and PL under stress conditions and negative strong association of these two traits with DH, DM and FL are desirable, suggesting that it is relatively easy to develop high yielding durum genotypes with increased PL, and decreased DH, DM and FL. There was no correlation between yield and TKW, SPAD, SL, CT, and PH, which suggests that grain yield could potentially be improved without decreasing these traits under terminal drought stress conditions. The negative association of YLD, SPAD and TKW with phenological traits DH and DM, as well as with PH, FL and PH, showed that genotypes with high grain yield, high grain weight and high SPAD reading values tended to flower earlier than other genotypes and were short in stature under non-terminal drought stress conditions.

There were considerable responses to the environment for all pair-wise trait associations, including those that were relatively stable, reinforcing the common understanding that the correlation between two quantitative traits is not fixed, but rather depends on the genotypes tested and the environments in which they are tested (Yan and Wallace, 1995). This introduces considerable uncertainty into indirect selection in terms of selecting for another trait in the same environment or selecting for the same trait in different environments. This also suggests that direct selection for multiple breeding objectives in multiple environments is essential for identifying adapted genotypes with superior trait combinations. The finding that most associations were only of moderate magnitude indicated that there are opportunities for selecting superior genotypes with desirable trait combinations, and also points up the need to directly select for multiple traits (Yan *et al.*, 2007).

Variation in canopy temperature under water stress conditions was evident in differences in grain yield. Significant positive correlations between canopy temperature and DRI, as well as significant negative correlations between PH and DRI under non-stress conditions, indicated the potential for screening durum wheat genotypes for non-terminal drought stress conditions. In contrast, the significant positive correlations between PH and DRI, as well as the significant negative correlations between FL, DH and DM and DRI indicated the potential for screening wheat genotypes for drought response.

The breeding lines showed considerable variability for grain yield and agro-physiological traits as well as drought tolerance that could be used for crop improvement. Data analysis suggests that the breeding lines could be grouped. Such groupings are useful to breeders when identifying genotypes that could be used as parents when breeding for any morphological trait of interest.

The traits measured in three field experiments (two rainfed and one irrigated) showed few consistent significant associations with grain yield. Apparently, the lack of association may be due to other environmental factors that affected grain yield performance, and/or to the fact that few genotypes were better adapted to growing conditions in each experiment (Gutierrez *et al*., 2012). Results showed that adaptive traits also contributed significantly to performance under drought stress conditions. The studied germplasm showed its potential for genetically improving most characteristics using applied breeding methods. Therefore, it was easy to identify genotypes that possess characteristics different from those of other genotypes for earliness, grain weight, grain yield performance and drought tolerance. However, the relationships among agronomic characteristics made it possible to identify the best genotypes for the studied traits. The development and release of high yielding genotypes with good agronomic attributes and adaptation to drought-prone environments could support the expansion of the durum wheat area in Iran.

REFERENCES

Abebe, A., M. A. Brick, and R. A. Kirkby. 1998. Comparison of selection indices to identify productive dry bean lines under diverse environmental conditions. Field Crops Res. 58: 15–23.

Acevedo, E., and S. Ceccarelli. 1989. Role of physiologist-breeder in a breeding program for drought resistance conditions. Pp. 117–139 In: P. W. G. Baker (ed.). Drought Resistance in Cereals. Commonwealth Agricultural Bureaux (CAB), Wallingford.

Ball, S. T., and C. F. Konzak. 1993. Relationship between grain yield and remotely sensed data in wheat breeding experiments. Plant Breed. 110: 277–282.

Bidinger, F. R., V. Mahalakshmi, and G. D. P. Rao. 1987. Assessment of drought resistance in pearl millet [*Pennisetum americanum* (L.) Leeke]. II. Estimation of genotype response to stress. Aust. J. Agric. Res. 38: 49–59.

Borrel, A. K., G. L. Hammer, and R. G. Henzell. 2000. Does maintaining green leaf area in sorghum improve yield under drought? II. Dry matter production and yield. Crop Sci. 40: 1037–1048.

Bramel-Cox, P. J., T. Barker, F. Zavala-Garcia, and J. D. Eastin. 1991. Selection and testing environments for improved performance under reduced-input conditions. Pp. 29-56. In: D. A. Slepper, T. C. Barker and P. J. Bramel-Cox (eds.). Plant breeding and sustainable agriculture: Considerations for objectives and methods. CSSA Special Publication No. 18. CSSA and ASA, Madison, WI, USA.

Brennan, J. P., A. Aw-Hassan, K. J. Quade, and T. L. Nordblom. 2002. Impact of ICARDA Research on Australian Agriculture. Economic Research Report No. 11. NSW Agriculture. 96 pp.

Ceccarelli, S., M. M. Nachit, G. O. Ferrara, M. S. Mekni, M. Tahir, J. Van Leur, and J. P. Srivastava. 1987. Breeding strategies for improving cereal yield and stability under drought. Pp. 101-114. In: J. P. Srivastava, E. Porceddu, E. Acevedo and S. Varma (eds.). Drought tolerance in winter cereals. John Wiley & Sons, New York.

Cooper, M., and G. L. Hammer. 1996. Plant adaptation and crop improvement. CAB International, Wallingford, UK, ICRISAT, Patancheru, India, and IRRI, Manila, Philippines. 636 pp.

Cox, T. S., J. P. Shroyer, L. Ben-Hui, R. G. Sears, and T. J. Martin. 1988. Genetic improvement in agronomic traits of hard red winter wheat cultivars from 1919 to 1987. Crop Sci. 28: 756–760.

De Vita, P., A. M. Mastrangelo, L. Matteu, E. Mazzucotelli, N. Virzì, M. Palumbo, M. L. Storto, F. Rizza, and L. Cattivelli. 2010. Genetic improvement effects on yield stability in durum wheat genotypes grown in Italy. Field Crops Res. 119: 68–77.

Donmez, E., R. G. Sears, J. P. Shroyer, and G. M. Paulsen. 2001. Genetic gain in yield attributes of winter wheat in the Great Plains. Crop Sci. 41: 1412–1419.

Evans, L. T. 1998. Feeding the ten billion: plants and population growth. Cambridge University Press: Cambridge. 267 pp.

Feyerherm, A., G. M. Paulsen, and J. L. Sebaugh. 1984. Contribution of genetic improvement to recent wheat yield increases in the U.S.A. Agron. J. 76: 985–990.

Fischer, R. A., and R. Maurer. 1978. Drought resistance in spring wheat cultivars 1. Grain yield responses. Aust. J. Agric. Res. 29: 897–912.

Fufa, H., P. S. Baenziger, B. S. Beecher, R. A. Graybosch, K. M. Eskridge, and L. A. Nelson. 2005. Genetic improvement trends in agronomic performances and end-use quality characteristics among hard red winter wheat cultivars in Nebraska. Euphytica 144: 187–198.

García del Moral, L. F., Y. Rharrabti, D. Villegas, and C. Royo. 2003. Evaluation of grain yield and its components in durum wheat under Mediterranean conditions: an ontogenic approach. Agron. J. 95: 266–274.

Garrity, D. P., and J. C. O'Toole. 1994. Screening rice for drought resistance at the reproductive phase. Field Crops Res. 39: 99–110.

Giunta, F., R. Motzo, and G. Pruneddu. 2008. Has long term selection for yield in durum wheat also induced changes in leaf and canopy traits? Field Crops Res. 106: 68–76.

Giunta, F., R. Motzo, and G. Pruneddu. 2007. Trends since 1900 in the yield potential of Italian-bred durum wheat cultivars. Eur. J. Agron. 27: 12–24.

Gutierrez, M., M. P. Reynolds, W. R. Raun, M. L. Stone, and A. R. Klatt. 2012. Indirect selection for grain yield in spring bread wheat in diverse nurseries worldwide using parameters locally determined in north-west Mexico. J. Agric. Sci. 150: 23–43.

Kroonenberg, P. M. 1995. Introduction to biplots for G × E tables. Research Report 51. Centre for Statistics, University of Queensland, Brisbane, Australia. 22 pp.

Lopes, M. S., M. P. Reynolds, M. R. Jalal-Kamali, M. Moussa, Y. Feltaous, I. S. A. Tahir, N. Barma, M. Vargas, Y. Mannes, and M. Baum. 2012. The yield correlations of selectable physiological traits in a population of advanced spring wheat lines grown in warm and drought environments. Field Crops Res. 128: 129–136.

Lopes, M. S., and M. P. Reynolds. 2010. Partitioning of assimilates to deeper roots is associated with cooler canopies and increased yield under drought in wheat. Funct. Plant Biol. 37:147–156.

Ludlow, M. M., and R. C. Muchow. 1990. A critical evaluation of traits for improving crop yields in water-limited environments. Adv. Agron. 43: 107–153.

Marti, J., J. Bort, G. A. Slafer, and J. L. Araus. 2007. Can wheat yield be assessed by early measurements of normalized difference vegetation index? Ann. Appl. Bio. 150: 253 –257.

Mohammadi, R., and A. Amri. 2011. Graphic analysis of trait relations and genotype evaluation in durum wheat. J. Crop Improv. 25: 680–696.

Mohammadi, R., R. Haghparast, A. Amri, and S. Ceccarelli. 2010. Yield stability of rainfed durum wheat and GGE biplot analysis of multi-environment trials. Crop Pasture Sci. 61: 92–101.

Mohammadi, R., D. Sadeghzadeh, M. Armion, and A Amri. 2011. Evaluation of durum wheat experimental lines under different climate and water regime conditions of Iran. Crop Pasture Sci. 62: 137–151.

Mohammadi, R., and R. Haghparast. 2011. Evaluation of rainfed promising wheat breeding lines on farmers' fields in west of Iran. Int. J. Plant Breed. 5: 30–36.

Motzo, R., S. Fois, and F. Giunta. 2005. Relationship between grain yield and quality of durum wheats from different eras of breeding. Euphytica 140: 147–154.

Mutava, R. N., P. V. V. Prasad, M. R. Tuinstra, K. D. Kofoid, and J. Yu. 2011. Characterization of sorghum genotypes for traits related to drought tolerance. Field Crops Res. 123: 10–18.

Olivares-Villegas, J. J., M. P. Reynolds, and G. K. McDonald. 2007. Drought-adaptive attributes in the Seri/Babax hexaploid wheat population. Funct. Plant Biol. 34: 189–203.

Ouk, M., J. Basnayake, M. Tsubo, S. Fukai, K.S. Fischer, M. Cooper, and H. Nesbitt. 2006. Use of drought response index for identification of drought tolerant genotypes in rainfed lowland rice. Field Crops Res. 99: 48–58

Pantuwan, G., S. Fukai, M. Cooper, S. Rajatasereekul, and J. C. O'Toole. 2002. Yield response of rice (*Oryza sativa* L.) genotypes to different types of drought under rainfed lowlands. 2. Selection of drought resistant genotypes. Field Crops Res. 73: 169–180.

Payne, R. W., D. A. Murray, S. A. Harding, D. B. Baird, and D. M. Soutar. 2009. GenStat for Windows 12th Edition. Introd. VSN Intern. Hemel Hempstead.

Pecetti, L., and P. Annichiarico. 1998. Agronomic value and plant type of Italian durum wheat cultivars from different eras of breeding. Euphytica 99: 9–15.

Pswarayi, P., F. A. Van Eeuwijk, S. Ceccarelli, S. Grando, J. Comadran, J. R. Russell, E. Francia, N. Pecchioni, O. Li Destri, T. Akar, A. Al-Yassin, A. Benbelkacem, W. Choumane, M. Karrou, H. Ouabbou, J. Bort, J. L. Araus, J. L. Molina-Cano, W. T. B. Thomas, and I. Romagosa. 2008. Barley adaptation and improvement in the Mediterranean basin. Plant Breed. 127: 554–560.

Quarrie, S. A., J. Stojanovic, and S. Pekic. 1999. Improving drought resistance in small grained cereals: a case study, progress and prospects. Plant Growth Regul. 29: 1–21.

Reynolds, M. P., S. Rajaram, and K. D. Sayre. 1999. Physiological and genetic changes of irrigated wheat in the post-green revolution period and approaches for meeting projected global demand. Crop Sci. 39: 1611–1621.

Royo, C. 2005. Durum wheat improvement in Spain. Pp. 883–906 in: Royo, C. and N. Di Fonzo (eds.). Durum Wheat Breeding: Current Approaches and Future Strategies. Food Products Press, New York.

Royo, C., V. Martos, A. Ramdani, D. Villegas, Y. Rharrabti, and L. F. García del Moral. 2008. Changes in yield and carbon isotope discrimination of Italian and Spanish durum wheat during the 20th century. Agron. J. 100: 352–360.

Salim, S. N., and M. C. Saxena. 1993. Adaptation of spring-sown chickpea to the Mediterranean basin. 2. Factors influencing yield under drought. Field Crops Res. 34: 137–146.

Simmonds, N. W., and M. Talbot. 1992. Analysis of on-farm rice yield data from India. Exp. Agric. 28: 325–329.

Singh, M., R. S. Malhotra, S. Ceccarelli, A. Sarker, S. Grando, and W. Erskine. 2003. Spatial variability models to improve dryland field trials. Exp. Agric. 39: 1–10.

Slafer, G. A., E. H. Satorre, and F. H. Andrade. 1994. Increases in grain yield in bread wheat from breeding and associated physiological changes. Pp. 1-68 in: Slafer, G.A. (ed.). Genetic improvement of field crops. Marcel Dekker, Inc., New York.

van Ginkel, M., D. S. Calhoun, G. Gebeyehu, A. Miranda, C. Tian-you, R. Pargas-Lara, R. M. Trethowan, K. Sayre, J. Crossa, and S. Rajaram. 1998. Plant traits related to yield of wheat in early, late, or continuous drought conditions. Euphytica 100: 109–121.

Yan, W. 2001. GGE biplot–A Windows application for graphical analysis of multi-environment trial data and other types of two-way data. Agron. J. 93: 1111–1118.

Yan, W., and J. Fregeau-Reid. 2008. Breeding line selection based on multiple traits. Crop Sci. 48: 417–423.

Yan, W., S. J. Molnar, J. Fregeau-Reid, A. McElroy, and N. A. Tinker. 2007. Associations among oat traits and their responses to the environment. J. Crop Improv. 20: 1–29.

Yan, W., and I. Rajcan. 2002. Biplot analysis of test sites and trait relations of soybean in Ontario. Crop Sci. 42: 11–20.

Yan, W., and D. H. Wallace. 1995. Breeding for negatively associated traits. Plant Breed. Rev. 13: 141–177.

Yue, B., L. Xiong, W. Xue, Y. Xing, L. Luo, and C. Xu. 2005. Genetic analysis for drought resistance of rice at reproductive stage in field with different types of soil. Theo. Appl. Genet. 111: 1127–1136.

Wright, G. C., and N. C. Rachaputi. 2004. Drought and drought resistance. Pp. 386–390 in: R. M. Goodman (ed.). Encyclopedia of plant and crop science. (Marcel Dekker, Inc.: New York.

Zavala-Garcia, F., P. J. Bramel-Cox, J. D. Eastin, M. D. Witt, and D. J. Andrews. 1992. Increasing the efficiency of crop selection for unpredictable environments. Crop Sci. 32: 51–57.