THE CROP JOURNAL 3 (2015) 423–433

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The Crop Journal

Field evaluation of durum wheat landraces for prevailing abiotic and biotic stresses in highland rainfed regions of Iran

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A R T I C L E I N F O

Article history:
Received 12 December 2014
Received in revised form 24 March 2015
Accepted 27 March 2015
Available online 15 May 2015

Keywords:
Durum wheat
Landraces
Biotic and abiotic stresses
Phenotypic diversity

A B S T R A C T

Biotic and abiotic stresses are major limiting factors for high crop productivity worldwide. A landrace collection consisting of 380 durum wheat (*Triticum turgidum* L. var. *durum*) entries originating in several countries along with four check varieties were evaluated for biotic stresses: yellow rust (*Puccinia striiformis* Westendorf f. sp. *tritici*) and wheat stem sawfly (WSS) *Cephus cinctus* Norton (Hymenoptera: Cephidae), and abiotic stresses: cold and drought. The main objectives were to (i) quantify phenotypic diversity and identify variation in the durum wheat landraces for the different stresses and (ii) characterize the agronomic profiles of landraces in reaction to the stresses. Significant changes in reactions of landraces to stresses were observed. Landraces resistant to each stress were identified and agronomically characterized. Percentage reduction due to the stresses varied from 11.4% (yellow rust) to 21.6% (cold stress) for 1000-kernel weight (TKW) and from 19.9 (yellow rust) to 91.9% (cold stress) for grain yield. Landraces from Asia and Europe showed enhanced genetic potential for both grain yield and cold tolerance under highland rainfed conditions of Iran. The findings showed that TKW and yield productivity could be used to assess the response of durum wheat landraces to different stresses. In conclusion, landraces showed high levels of resistance to both biotic and abiotic stresses, and selected landraces can serve in durum wheat breeding for adaptation to cold and drought-prone environments.

1. Introduction

Wheat landraces are variable, genetically dynamic, and in equilibrium with biotic and abiotic stresses in the environments where they evolve. The development of new varieties using wheat landraces is a practical strategy for improving yield and yield stability, especially under stresses and future climate change conditions. Wheat landraces adapt to changing climate

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Peer review under responsibility of Crop Science Society of China and Institute of Crop Science, CAAS.

http://dx.doi.org/10.1016/j.cj.2015.03.008
2214-5141/

conditions and to harsh environments, owing to their population genetic structure, buffering capacity, and combinations of agro-physiological traits conferring adaptability to stress environments [1]. Wheat landraces are still cultivated in western Asia and North Africa, with some also found in Ethiopia, China, the Indian subcontinent, and small areas of Latin America. The proportion of wheat area planted to landraces also varies by wheat type and environment. For example, in developing countries, 23% of the area planted to durum wheat and 12% of the area planted to winter bread wheat are sown to landraces, while only 3% of the spring bread wheat area is still planted to landraces [2].

There is growing interest in use of available genetic resources in the development of new durum wheat cultivars that tolerate major biotic and abiotic stresses and for the improvement of crop productivity and quality [3]. This development will require thorough understanding of the available genetic variation in landraces, primitive wheats, and wild relative species. The rate of progress, however, will depend on the presence of genetic variation for desired traits and the availability of reliable methods for the identification, selection, and transfer of superior genes [3].

Drought stress is a major problem for agricultural production in many parts of the world. Because drought is the single largest abiotic stress factor leading to reduced crop yields, varieties that yield well even in environmentally stressful conditions are essential [4,5]. Climate change is projected to have a large impact on temperature and precipitation profiles, increasing the incidence and severity of drought. The extension of durum wheat into areas with cold winters is limited by the cold susceptibility of existing landraces. Low temperature often affects plant growth and crop productivity and causes severe crop losses [6]. Plants differ in their tolerance to chilling (0–15 °C) and freezing (<0 °C) temperatures [7]. Besides abiotic stresses, wheat yellow rust, caused by *Puccinia striiformis* Westendorf f. sp. *tritici*, the most common and widely distributed wheat rust in the world [8], and wheat stem sawfly [*Cephus pygmaeus* (L.) Hym. Cephidae], which is a major problem in the Mediterranean basin [9], limit wheat production.

Deployment of genetic resistance to these stresses is likely to be the most economical and environmentally friendly control measure [9–12]. Characterization of the population structure of wheat landraces is critical for identifying and correctly interpreting the association between functional and molecular diversity. Such information is essential for using landraces as trait donors in wheat breeding, defining the areas of their adaptation, identifying priority areas for promoting their on-farm conservation, and evaluating the genetic consequences of the interaction between climate change, growing environment, and farmers' practice. Accordingly, the main objectives of this study were to (i) quantify phenotypic diversity and identify variation in the durum wheat landraces for major biotic and abiotic stresses, (ii) characterize the agronomic profiles of different subsets of landraces (as resistant, moderately resistant, moderately susceptible, or susceptible) to different stresses and (iii) investigate the potential of landraces to combine tolerance to biotic and abiotic stresses with good agronomic performance. This information could greatly assist in the conservation of durum landraces and their efficient deployment in durum breeding programs.

2. Materials and methods

2.1. Plant materials and experimental layout

A subset of 380 durum wheat landraces collected from a wide range of agricultural zones worldwide were selected from the landraces conserved in the Iranian gene bank. The subset collection consisted of landraces from 16 countries: Iran (307; collected from a wide geographic area across the country), Japan (16), Afghanistan (8), Australia (9), Bulgaria (5), Portugal (5), Turkey (5), United States (5), former Yugoslavia (2), Italy (3), Iraq (2), China (2), Argentina (2), France (1), Greece (1), and Austria (1) and six landraces of unknown origin. This subset was evaluated at three rainfed research stations of the Dryland Agricultural Research Institute (DARI), Iran, during the 2009–2011 cropping seasons. The three research stations represent cold rainfed regions (Maragheh station, 37°22' N, 46°15' E and 1400 m.a.s.l. and Qamloo station, 35°23' N, 47°14' E and 1850 m.a.s.l.) and moderately cold rainfed regions (Sararood station, 34°19' N, 47°17' E and 1351 m.a.s.l.) for durum wheat production in Iran.

Each landrace was sown in two rows 2.5 m long with 20.0 cm row spacing in an unreplicated trial with four checks repeated every 20 entries at each research station. The checks consisted of two durum genotypes including Dena (a newly released durum variety originating from CIMMYT germplasm having high yielding performance, high pasta quality, and adaptation to favorable conditions) and Zardak (an old durum variety with high grain weight and average yield productivity and adaptation to unfavorable conditions) and two bread wheats including Saison (a winter variety from France having high yield and tolerance to terminal drought) and Verinak (a spring cultivar from CIMMYT with earliness and tolerance to terminal drought and heat stresses). Standard crop cultural practices were used at all test locations. Weeds were controlled manually as required. Fertilizer rate was 50 kg N ha^{-1} and 50 kg P_2O_5 ha^{-1} applied at planting.

The landraces were evaluated for several drought-adaptive traits: days to heading (DTH), days to maturity (DTM), plant height (PLH), thousand-kernel weight (TKW), and grain yield (YLD) under rainfed conditions in each location and scored for cold stress, yellow rust and wheat stem sawfly (Table 1).

2.2. Statistical analysis

Data were statistically analyzed to identify landraces that were genetically different or similar based on the environmental stresses and agronomic traits measured. The grain yield data and other measured traits (DTH, DTM, PLH, and TKW) were analyzed separately with GenStat [14] for spatial analysis of un-replicated trials in which the responses of the repeated checks provide the basis for modeling the spatial variation in the field for adjusting genotype performance [15]. For each trait, the best linear unbiased predictions (BLUPs) from the best-fitting model were used as adjusted data.

To display the relationships among the landrace groups and measured traits, a graphical biplot, the genotype-by-trait (GT) biplot described by Yan and Rajcan [16] was constructed, for each of the environments differing in stress conditions, by

Table 1 – Measured or evaluated traits, their descriptions, and approaches to statistical analysis of phenotypic data.

Traits measured/evaluated	Description	Statistical analysis
Days to heading (DTH)	DTH was scored as the number of days from sowing until half of the plants in the plot showed at least one emerged spike.	The phenotypic data of measured traits separately were analyzed with GenStat for spatial analysis of unreplicated trials, in which the responses of the repeated checks provide the basis for modeling the spatial variation in the field for adjusting the genotypes' performance. The adjusted phenotypic data for each measured trait from the best linear unbiased prediction (BLUP) model in each environment were used to describe and evaluate the landraces.
Plant height (PLH)	PLH was measured at physiological maturity stage.	
Days to maturity (DTM)	DTM was recorded when half of the plants in a plot had yellow leaves.	
1000-kernel weight (TKW)	TKW was measured using 1000 grains for each landrace.	
Grain yield (YLD)	YLD was measured per plot and converted to kg ha^{-1} for each landrace.	
Cold tolerance	The proportion of foliage damage due to frost was scored in early April using the visual scores R, resistant (plants with normal leaf color and no signs of frost damage); MR, moderately resistant (plant with yellow symptoms on leaf tips and recovering after frost period); MS, moderately susceptible (plants with 50% of the leaves with yellow color); S, susceptible (plants with full frost damage symptoms on leaves and up to 50% of plants per plot dead); and VS, very susceptible (plants with all leaves yellow, overall growth affected and >50% of plants per plot dead).	For each group of landraces (R, MR, MS, S, VS), mean values were calculated and used to compare the agronomic performance of each group. The parentage of landraces based on their scores for biotic and abiotic stresses were identified. The measured traits as described above were used to identify the characteristics of each group. To display the relationships of landrace groups under each of the environmental stresses and to characterize the agronomic performance of each group, a genotype-by-trait (GT) biplot method was applied.
Yellow rust	At the crop growth stage after heading, two parameters were considered when scoring the rust: host reaction and rust severity, and recorded for the most heavily infected flag leaves of each entry. Estimates of disease severity were based on the modified Cobb scale [13], which estimates the percentage of rusted tissue. The coefficient of infection was calculated by multiplying the severity value by 0.10, 0.25, 0.50, 0.75, or 1.00 for host response ratings of resistant (R), moderately resistant (MR), moderately resistant-susceptible (M), moderately susceptible (MS), and susceptible (S), respectively.	
Wheat stem sawfly	At physiological maturity stage, in each plot 0.5 m^2 was used to estimate the percentage of damage by wheat stem sawfly (WSS). Total numbers of stems (tillers) and stems infested (characteristic cut stems) were recorded and percentage of infestation by WSS was measured for each landrace. The landraces were classified into four groups using the percentage of infestation: landraces with no infestation were scored as R, infestation of 1–5% as MR, infestation of 6–10% as MS, and infestation > 10% as S.	

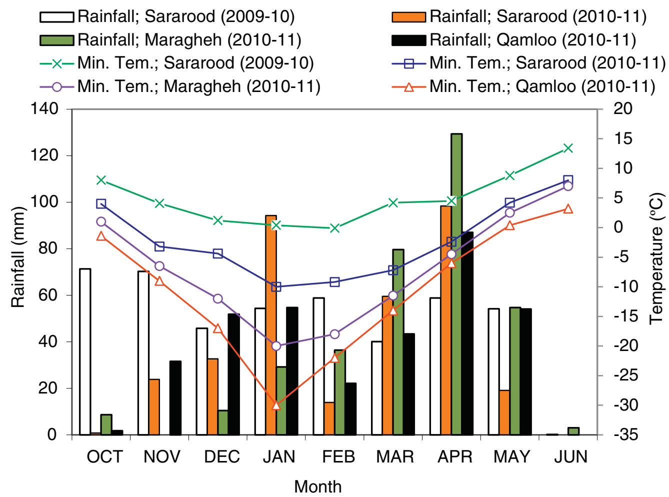

Fig. 1 – Monthly distribution of rainfall and minimum temperatures at three research stations during the 2009–2011 cropping seasons.

plotting the first principal component (PC1) scores of the landrace groups and the traits against their respective scores for the second principal component (PC2) resulting from singular-value decomposition (SVD) of trait-standardized data in each environment. In the GT biplot, vectors are drawn from the biplot origin to the trait markers to facilitate visualization of the relationships among the traits. The correlation coefficient between any two traits is approximated by the cosine of the angle between their vectors. Acute angles indicate positive correlations, obtuse angles negative correlations, and right angles no correlation. A short vector may indicate that the trait is not related to other traits. All biplots were generated with the GGEbiplot software [17].

To characterize the agronomic performance of each landrace group, the "which-for-what" pattern of the GT biplot was used. This operation is performed by connecting the furthest groups from the origin with straight lines to form a polygon. The polygon view of a biplot is the best way to visualize the interaction patterns between landrace groups and traits and to interpret effectively the results of the biplot [16].

Table 2 – List of outstanding entries among 380 durum wheat landraces with resistance/tolerance to biotic (yellow rust and wheat stem sawfly) and abiotic (cold stress) stresses along with the check cultivars.

Entry	Landrace	Origin	Yellow rust	Wheat stem sawfly	Cold stress
1	Wc-378	Iran	MR	MR	R
3	Wc-908	Iran	MR	MR	R
16	Wc-3711	Iran	MR	MR	MR
40	Wc-4151	Iran	MR	MR	R
41	Wc-4154	Iran	R	R	MR
49	Wc-4341	Iran	MR	MR	MR
52	Wc-4353	Iran	R	MR	R
78	Wc-46198	Iran	MR	MR	MR
83	Wc-46078	Japan	R	R	R
84	Wc-46061	Japan	R	MR	MR
85	Wc-46048	Japan	MR	MR	MR
87	Wc-46046	Japan	R	MR	MR
102	Wc-45704	Afghanistan	R	MR	MR
105	Wc-45666	Unknown	R	MR	MR
106	Wc-45648	Yugoslavia	MR	MR	MR
110	Wc-45588	Iran	MR	MR	MR
114	Wc-45425	Portugal	R	MR	R
140	Wc-47340	USA	MR	R	MR
159	Kc-647	Iran	R	R	MR
204	Kc-1179	Iran	MR	MR	MR
266	Kc-3081	Iran	MR	R	R
342	TN-12490	Iran	MR	MR	MR
347	TN-12571	Iran	R	MR	MR
365	TN-12713	Iran	MR	R	MR
Check cultivars	Verinak	CIMMYT	S	MR	MR
	Saison	France	MR	MR	MS
	Dena	Iran	MR	MR	MS
	Zardak	Iran	S	MR	MR

R: resistant; MR: moderately resistant; MS: moderately susceptible; S: susceptible.

3. Results

3.1. Climatic condition of test locations

No large differences in total amount of rainfall were observed among the three locations in 2010–2011, although the locations differed in their monthly rainfall distribution (Fig. 1). Total rainfall amounts were 342.5, 351.4, and 346.6 mm at Sararood, Maragheh, and Qamloo, respectively. Rainfall at the cold stations (Maragheh and Qamloo) was around the long-term average, but at the moderately cold station (Sararood) was significantly less than the long-term average (445 mm). The locations differed in temperature. The absolute minimum temperature during the cropping season was –30 °C at Qamloo, –20 °C at Maragheh, and –9 °C at Sararood. Average minimum temperatures at Qamloo, Maragheh and Sararood were –10.6, –6.9, and –2.2 °C, respectively. The number of freezing days at Qamloo was 132, at Maragheh 130, and at Sararood 75. In conclusion, rainfall distribution and temperature were contrasting at the locations, showing that the landraces experienced both cold and drought stresses during the season. In Sararood, the 2009–2010 cropping season was optimum for crop growth; the precipitation was

453.9 mm, slightly higher than the long-term average (445 mm) for Sararood research station, and the crop growth experienced minimum and maximum temperatures of –8.6 and 38.3 °C, respectively. In contrast, the next cropping season, 2010–2011 experienced severe drought, with a marked decrease in rainfall by 111.4 mm relative to the optimum year (2009–2010). However, no large changes in temperature were observed over the two cropping seasons at this location (Fig. 1).

3.2. Data description

The mean grain yields for each location reflect the relative severity of the stresses experienced. Mean yields were 3644, 2610, 1627, and 2534 kg ha^{-1} at Sararood (2009–2010), Sararood (2010–2011), Maragheh (2010–2011), and Qamloo (2010–2011), respectively (data not shown), giving a mean yield reduction from the moderately cold to cold locations. In contrast, a mean reduction in TKW from 35 to 25 g among the landraces was observed from cold to moderately cold locations, indicating a negative correlation between yield and TKW among the landraces. A mean reduction in plant stature was observed for the landraces from moderately cold (102–115 cm) to cold (62–88 cm) stations. For days to heading and maturity, the landraces tended to be earlier in the moderately cold than the cold locations.

The percentage reduction due to yellow rust varied from 7.7% to 11.4% for TKW and from 0.54% to 19.90% for grain yield, while the percentage reduction due to WSS varied from 7.1% to 17.9% for TKW and 2.7% to 25.5% for grain yield. The percentage reduction due to cold stress varied from 2.7% to 21.6% for TKW and 17.6% to 79.5% for grain yield at Maragheh and from 8.1 to 21.6 for TKW and 22.2% to 91.9% for grain yield at Qamloo.

The outstanding entries among 380 landraces with resistance or tolerance to both biotic and abiotic stresses are presented in Table 2. None of the checks appeared resistant to any of the stresses, indicating the presence of some potential in landraces for improving resistance to yellow rust, WSS, and cold stresses. For yellow rust, 12.1% of landraces were resistant, 8.7% were resistant to WSS, and 0.8–12.9% were found to be cold-resistant.

3.3. Comparison and selection for different environmental stresses

3.3.1. Yellow rust

At Sararood, the 2009–2010 cropping season was optimum for crop growth; the precipitation was 453.9 mm, slightly higher than the long-term average (445 mm) for the station, and the crop experienced minimum and maximum temperatures of –8.6 °C and 38.3 °C, respectively. Of the total rainfall, 113 mm was received during booting to anthesis stage with increasing temperature. These conditions provided an opportunity for screening for yellow rust, with the landraces scoring from R to 100S under natural infection. Based on the results, the landraces differed in their responses to yellow rust. Only 12.1% of the landraces were found to be resistant to yellow rust, 9.5% moderately resistant, 10.5% moderately susceptible, and 67.9% susceptible. Decreasing trends were found in grain yield, TKW, and earliness from resistant to susceptible landrace groups (Table 3). Those resistant to yellow rust had higher grain yield and TKW and earlier heading date. Among the checks, Verinak and Zardak were scored as susceptible and Saison and Dena as moderately resistant to yellow rust.

3.3.2. Wheat stem sawfly

Of the landraces, 8.7% were found to be resistant to WSS, 68.2% moderately resistant, 20.5% moderately susceptible, and 2.6% susceptible (Table 3). Decreasing trends in yield and TKW were observed from resistant to susceptible landraces, but no clear trends were found between other traits in different subsets of landraces.

3.3.3. Cold stress

Among the landraces, 12.9% at Maragheh and 0.8% at Qamloo were resistant to cold stress and 25.0% and 23.7%, respectively, were moderately resistant. At Maragheh, 31.1%, 28.4%, and 2.4% of the landraces were moderately susceptible, susceptible, and very susceptible, respectively (Table 3). At Qamloo, 50.8%, 17.4%, and 7.4% of landraces were moderately susceptible, susceptible and very susceptible. The landraces showed relatively weak responses to cold stress, as expressed by decreases in grain yield, TKW, and plant height, and some did not complete their growth cycle.

3.4. Characterization of landraces resistant or tolerant to environmental stresses

3.4.1. Yellow rust

The foreign landraces produced higher yield productivity with higher TKW and were shorter in stature than the Iranian ones (Table 4). No difference was found between the foreign and Iranian landraces in heading and maturity dates. The foreign landraces were from Japan, Afghanistan, France, Portugal, and Yugoslavia. Among the foreign landraces, grain yield varied from 5625 (Portugal) to 8813 kg ha^{-1} (Japan), and TKW varied between 29 (Portugal) and 44 g (Yugoslavia). The shortest were from Japan (94 cm) and the tallest from Yugoslavia (141 cm).

Compared to Iranian landraces, the foreign ones produced higher yields and TKW and were shorter in plant stature. The landraces from Japan were characterized as the highest yielding with the highest TKW and the lowest plant stature, while those from Austria had the lowest yields and latest maturity. The landraces from Bulgaria had the lowest TKW and were the earliest in heading. The tallest landraces were from the U.S. and had medium yield and low TKW.

3.4.2. Wheat stem sawfly

The Iranian landraces were superior to foreign ones in yield productivity, TKW, earliness and plant stature (Table 5). The foreign landraces were from Japan, Turkey and America. Those with the origin of Japan produced the highest yield and tend to earliness and were the shortest among foreign ones. Foreign landraces with moderate resistance produced higher yield and were shorter than the Iranian ones. The landraces from Iraq (4250 kg ha^{-1}) and Austria (1125 kg ha^{-1}) produced the highest and the lowest grain yield among the foreign landraces. In case of TKW, the highest value was observed for Greek landraces (33 g), while the lowest value was found in those from Bulgaria (21 g). Landraces from Japan and China

Table 3 – Agronomic characteristics of different subsets of 380 durum wheat landraces in reaction to different environmental stresses.

Subset	Trait				
	DTH (day)	PLH (cm)	DTM (day)	TKW (g)	YLD (kg ha^{-1})
Yellow rust (2009–2010)					
R (12.1%)	172	112	213	35	6646
MR (9.5%)	172	110	213	33	6610
MS (10.5%)	172	111	213	33	6092
S (67.9%)	178	113	215	31	5318
Wheat stem sawfly (2010–2011)					
R (8.7%)	198	100	238	28	2758
MR (68.2%)	197	101	237	26	2683
MS (20.5%)	197	105	238	23	2610
S (2.6%)	197	115	239	23	2056
Cold stress, Maragheh (2010–2011)					
R (12.9%)	218	88	250	37	1781
MR (25.0%)	220	87	251	36	1450
MS (31.3%)	220	84	252	37	1240
S (28.4%)	222	78	256	33	829
VS (2.4%)	230	62	268	29	365
Cold stress, Qamloo (2010–2011)					
R (0.8)	220	77	251	39.7	4533
MR (23.7%)	217	80	248	33.7	3526
MS (50.8%)	217	77	248	35.1	2366
S (17.4%)	218	78	249	34.9	1577
VS (7.4%)	–	–	–	–	–

DTH: days to heading; PLH: plant height; DTM: days to maturity; TKW: 1000-kernel weight; YLD: grain yield; R: resistant; MR: moderately resistant; MS: moderately susceptible; S: susceptible; VS: very susceptible.

were the shortest (76 cm) and the tallest (120 cm) among the foreign ones, respectively. The landraces from France, Greece and Iraq were early in heading (193 days) and those from Austria (206 days) were late. In the case of maturity, the earliest ones belonged to Yugoslavia (236 days), while the latest ones were from Turkey (240 days).

3.4.3. Cold stress

Agronomic characteristics of the resistant and moderately resistant landraces to cold stress at Maragheh location are presented in Table 6. Compared to Iranian, the foreign resistant landraces produced higher yield and higher TKW, and were shorter in plant height and slightly earlier in heading and maturity. The foreign resistant landraces were from Japan, Afghanistan and Portugal, and those from Japan were amongst the highest yield and TKW with short stature. The Iranian landraces were the best in grain yield among the moderately resistant ones. Those with unknown origin had the lowest yields and were late in heading and maturity than others. Foreign landraces with moderate resistance to cold stress were from Argentina, Australia, Bulgaria, China, Iraq, Turkey and the U.S. The landraces from China and America produced the highest and the lowest yield among moderately resistant foreign landraces, respectively. The landraces from China and Australia had the highest (39 g) and the lowest (31 g) TKW, respectively. The shortest and the tallest landraces belonged to Iraq (81 cm) and China (95 cm), respectively. The landraces from Iraq tended to be early in heading, while those from Turkey were late in heading. The landraces from Bulgaria were early in maturity and those from Iraq tended to be late in maturity.

At Qamloo, only three landraces from Iran showed adequate resistance to cold stress. Compared to the foreign landraces, the Iranian ones produced higher yield, had slightly higher TKW, and were taller and earlier in heading and maturity. One landrace of unknown origin produced higher grain yield and was taller than the Iranian ones (Table 7). The foreign landraces with moderate resistance to cold stress were from Afghanistan, Australia, Iraq, Italy, Japan, Turkey, the U.S., and Yugoslavia. Those from Japan had the highest grain yield and TKW with early heading and

Table 4 – Agronomic characteristics of landraces resistant or tolerant to yellow rust in relation to their origin.

Landrace group		DTH (day)	PLH (cm)	DTM (day)	TKW (g)	YLD (kg ha^{-1})
Resistant	Total (46)	172	114	213	35	6646
	Iran (33)	172	118	213	33	6431
	Foreign (11)	172	103	212	39	7682
Moderately resistant	Total (36)	172	110	213	33	6610
	Iran (26)	173	112	212	31	6129
	Foreign (10)	171	105	213	36	7813
Check cultivars	Reaction to disease					
Verinak	S	172	90	213	30.1	6938
Saison	MR	172	91	213	29.9	6946
Dena	MR	172	91	213	29.9	6985
Zardak	S	172	91	213	30.0	7065

DTH: days to heading; PLH: plant height; DTM: days to maturity; TKW: 1000-kernel weight; YLD: grain yield; R: resistant; MR: moderately resistant; S: susceptible.

Table 5 – Agronomic characteristics of landraces resistant/tolerant to wheat stem sawfly in relation to their origin.

Landrace group		Trait				
		DTH (day)	PLH (cm)	DTM (day)	TKW (g)	YLD (kg ha^{-1})
Resistant	Total (33)	198	100	238	28	2021
	Iran (28)	183	93	221	26	1877
	Foreign (5)	195	87	238	25	1625
Moderately Resistant	Total (259)	197	101	237	26	2683
	Iran (207)	197	104	237	26	2626
	Foreign (48)	197	91	238	26	2920
Check cultivars	Reaction to pest					
Verinak	MR	195	79	235	21	2597
Saison	MR	195	79	235	21	2583
Dena	MR	195	79	235	21	2600
Zardak	MR	195	80	235	21	2629

DTH: days to heading; PLH: plant height; DTM: days to maturity; TKW: 1000-kernel weight; YLD: grain yield; R: resistant; MR: moderately resistant.

maturity, while those from Yugoslavia had the lowest yield and TKW with late heading and maturity dates. The landraces from Afghanistan were shortest and those from Iraq and Italy were tallest.

3.5. *Visual characterization of landrace groups for environmental stresses*

Fig. 2 shows a polygon view of a GT biplot generated from data for five agronomic traits of different landrace groups for each environmental stresses. The GT biplots explained 94.0% to 98.9% of the total variation (Fig. 2). Under yellow rust conditions, the resistant (R) group had the highest values for grain yield and TKW, whereas the susceptible (S) group was tallest in stature and tended to flower and mature later than the other groups. The MR and MS groups with no traits in their sectors were not the best for any of the traits. Under wheat stem sawfly (WSS) infestation (Fig. 2), the R group had the highest values for TKW and yield and tended to be late in flowering. The S group, with high plant stature, tended to mature later than the other groups.

Under cold stress at Maragheh (Fig. 2), the R and MR groups had the highest values for yield, TKW, and PLH, whereas the VS group, with the highest DTH and DTM, tended to flower and mature later than the other groups. Similarly, under severe cold stress at Qamloo (Fig. 2), the R group had the highest yield and TKW and was later in flowering and maturity, while the MR group was the tallest among the landrace groups.

Under yellow rust infestation (Fig. 3), a close relationship was found between phenological traits (DTH and DTM). These traits were positively associated with plant height and negatively associated with grain yield and TKW, indicating that selection for earliness directly enhanced grain yield and productivity. The R group, with earlier flowering and maturity, had higher grain weight and productivity, while the S group was later in flowering and maturity and poor in yield productivity.

Under WSS% infestation (Fig. 3), yield, TKW and DTH had positive correlations and were negatively associated with PLH and DTM. In comparison to the others, the R and MR groups had higher DTH and grain weight and tended to be earlier in maturity and shorter in stature.

Table 6 – Agronomic characteristics of cold stress resistant/tolerant landraces in relation to their origin at Maragheh location.

Landrace group		Trait				
		DTH (day)	PLH (cm)	DTM (day)	TKW (g)	YLD (kg ha^{-1})
Resistant	Total (49)	218	86	250	38	1747
	Iran (44)	219	86	250	38	1679
	Foreign (4)	216	78	249	41	2315
Moderately Resistant	Total (72)	220	87	251	36	1450
	Iran (56)	219	87	251	36	1469
	Foreign (14)	220	88	251	34	1341
Check cultivars	Reaction to cold stress					
Verinak	MR	159	65	191	33	1463
Saison	MR	159	65	191	33	1476
Dena	MS	159	65	191	33	1489
Zardak	MR	159	66	191	33	1496

DTH: days to heading; PLH: plant height; DTM: days to maturity; TKW: 1000-kernel weight; YLD: grain yield; MR: moderately resistant; MS: moderately susceptible.

Table 7 – Characteristics of cold stress resistant/tolerant landraces in relation to their origin at the Qamloo location.

Landrace group		Trait				
		DTH (day)	PLH (cm)	DTM (day)	TKW (g)	YLD (kg ha^{-1})
Resistant	Total (3)	220	77	251	40	4533
	Iran (3)	220	77	251	40	4533
Moderately resistant	Total (90)	217	80	248	34	3526
	Iran (79)	217	80	248	34	3592
	Foreign (10)	218	75	249	33	2988
Check cultivars	Reaction to cold stress					
Verinak	MR	217	66	248	33	2727
Saison	MS	217	66	248	33	2715
Dena	MS	217	67	248	33	2705
Zardak	MR	217	67	248	34	2758

DTH: days to heading; PLH: plant height; DTM: days to maturity; TKW: 1000-kernel weight; YLD: grain yield; MR: moderately resistant; MS: moderately susceptible.

Under cold stress at Maragheh (Fig. 3), TKW and PLH were closely correlated with grain yield. These traits were negatively associated with phenological traits, as indicated by the obtuse angle between their vectors. In comparison to other groups, the R and MR groups had higher grain yield, and were earlier in flowering and maturity and tallest in stature, whereas the VS group tended to be later in flowering and shorter in stature.

Under severe cold stress at Qamloo (Fig. 3), TKW, DTH, and DTM were closely correlated. These traits were positively associated with grain yield and negatively with plant height. The R group had higher grain weight and later flowering and maturity with high yield productivity, while the MR group was tallest in stature early in flowering and maturity, lower in grain weight, and relatively high in yield productivity. These results indicated that the grouping of traits under different environmental stresses was not consistent and that the performance of genotypes was influenced by environmental stresses.

Phenotypic correlations among agronomic traits across locations are presented in Table 8. Positive correlations were observed between days to heading and plant height (r = 0.481, P < 0.01), days to maturity (r = 0.690, P < 0.01) and 1000-kernel weight (r = 0.352; P < 0.01). Plant height was also significantly correlated with days to maturity (r = 0.704; P < 0.01) and 1000-kernel weight (r = 0.365, P < 0.01). The 1000-kernel weight had the highest correlation with days to maturity (r = 0.544; P < 0.01), while the highest correlation with grain yield was found for 1000-kernel weight (r = 0.260; P < 0.01) followed by days to maturity (r = 0.201; P < 0.01). No significant correlation with days to heading and plant height was found for grain yield.

4. Discussion

The climatic conditions that prevailed during the 2009–2011 cropping seasons showed that the planted landraces are subjected to varying degrees of cold stress combined with drought stress, yellow rust, and wheat stem sawfly stress at different rainfed locations. The phenotypic diversity encountered in durum landraces indicates that there is a large potential for the improvement of durum wheat in cold rainfed areas of Iran. This wide variation is probably only a proportion of the variation present in durum wheat worldwide [18–23], and further evaluation to use and conserve this potentially valuable genetic resource appears warranted. Breeding strategies need to exploit existing variation to broaden the genetic base of durum wheat landraces. Future mining of wheat collections for resistance or tolerance to biotic and abiotic stresses will be based on the choice of resistant and tolerant landraces using the focused identification of germplasm strategy (FIGS) [24].

The phenotypic diversity and variation in the durum landraces indicated high potential for durum breeding for agronomic traits and for common biotic and abiotic stresses under Mediterranean conditions, particularly in Iran. With respect to yield productivity under environmental stresses, we found many landraces with high grain yield in the three locations. Another example is plant height, where we found superior landraces under rainfed conditions in the three locations. This finding indicates the potential of genetic materials to produce tall cultivars, a trait important for adaptation in dry areas, given that one of the main effects of a dry spell during the growing season is a drastic reduction of stem elongation with a reduction in straw yield. This reduction also makes combine harvesting difficult or impossible. Our study showed the potential of some landraces to produce tall plants under drought and cold conditions, and such landraces will be useful for improving plant height in cultivated durum. However, our results showed that tall landraces were susceptible to wheat stem sawfly, which causes reduction in yield and TKW. Based on the results, for environments under biotic stresses such as wheat stem sawfly the cultivation of taller plants should not be practiced. Gregoire [25] reported that most cultivars are susceptible, whereas other sources indicated that much variation exists for wheat stem sawfly susceptibility in durum [26,27]. Our results, in which the landraces differed for infestation by WSS and few sources of resistance to WSS were found, are in agreement with these findings.

Similarly, reductions in grain yield and TKW from subsets of resistant to susceptible landraces to yellow rust disease

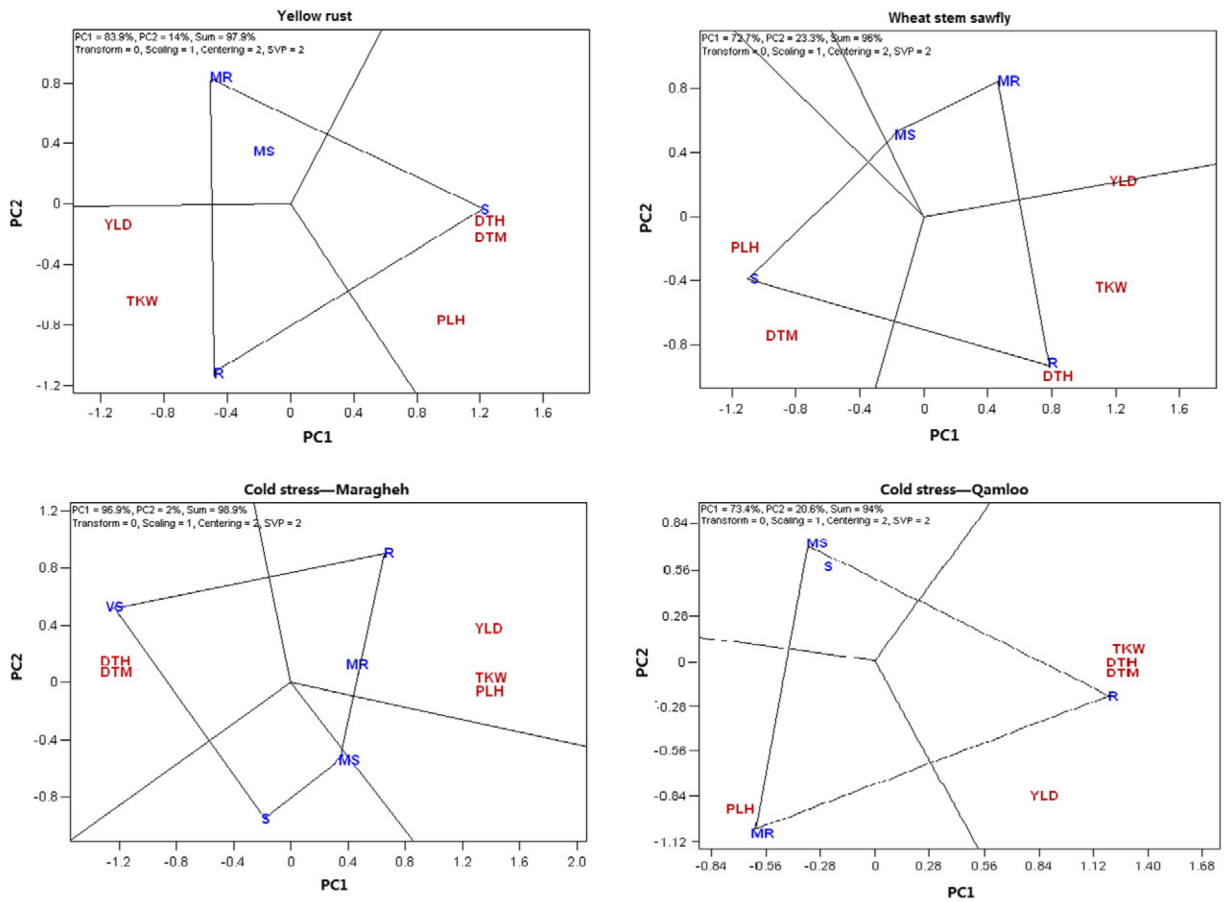

Fig. 2 – "Which-win-where" patterns of genotype-by-trait (GT) biplots of landrace groups for five traits under different environmental stresses. DTH: days to heading; DTM: days to maturity; PLH: plant height; TKW: 1000-kernel weight; YLD: grain yield. R: resistant; MR: moderately resistant; MS: moderately susceptible; S: susceptible; VS: very susceptible.

were observed, indicating that grain yield and TKW are substantially influenced by yellow rust. This result is in agreement with those of other reports [28,29] that yield losses from leaf rust are due mostly to reduction in kernel weight.

Climate and soil in the regions in which genotypes originate can influence their characteristics, especially in landraces, where environmental conditions can have substantial influence. High frequencies of landraces with early heading and early maturity in semiarid regions are considered [30] as indicators of increased tolerance to drought. Some landraces with earlier heading and maturity under rainfed conditions and with high levels of tolerance to biotic and abiotic stresses were found. This is another example of the potential of durum landraces to improve the adaptation of cultivated durum to drought-prone areas. Earliness is an important adaptive attribute as a drought escape mechanism under terminal drought conditions, and as a result, early lines will produce higher yields than late genotypes, particularly in very dry years [31]. Based on the above evidence, several landraces used in this study showed high levels of variation and desirable expression of tolerance or resistance to environmental stresses and the other important traits. Landraces with outstanding drought tolerance will be used as source of new diversity to develop new cultivars.

Cold tolerance is a desirable plant characteristic for autumn-sown cereals in continental and mountainous areas of the Mediterranean regions, which are characterized by winter and unpredictable late frosts in spring. However, landraces are a source of cold tolerance in cereal breeding, given that some possess high genetic variation for this character [32]. The evaluation of 380 landraces selected from the world collection conserved in Iran's gene bank indicated few sources of cold resistance when tested under cold-stressed locations, where only 0.8–12.7% of landraces were found to be resistant. Thus, to expand the cultivation of durum wheat to the highlands of Iran and other cold winter areas, special efforts are needed to develop durum wheat varieties with high cold tolerance and winter hardiness. This effort will need to use the landraces and available parental breeding landraces developed for cold areas. In addition, introgression of cold-tolerance and winter-hardiness genes (traits) from wild *Triticum* and *Aegilops* species that exhibit winter growth habit and cold tolerance can be performed. Further collection to target underrepresented agro-ecological zones such as Asian and European zones is generally suggested for maximum diversity sampling. New collecting missions targeting cold-tolerant landraces are needed to enrich gene bank holdings with durum wheat landraces and with primitive wheat and wild relatives with sufficient cold tolerance to survive under severe cold and drought stresses.

Landraces resistant to environmental stresses were found among both Iranian and foreign landraces. Iranian and foreign resistant landraces differed in their agronomic

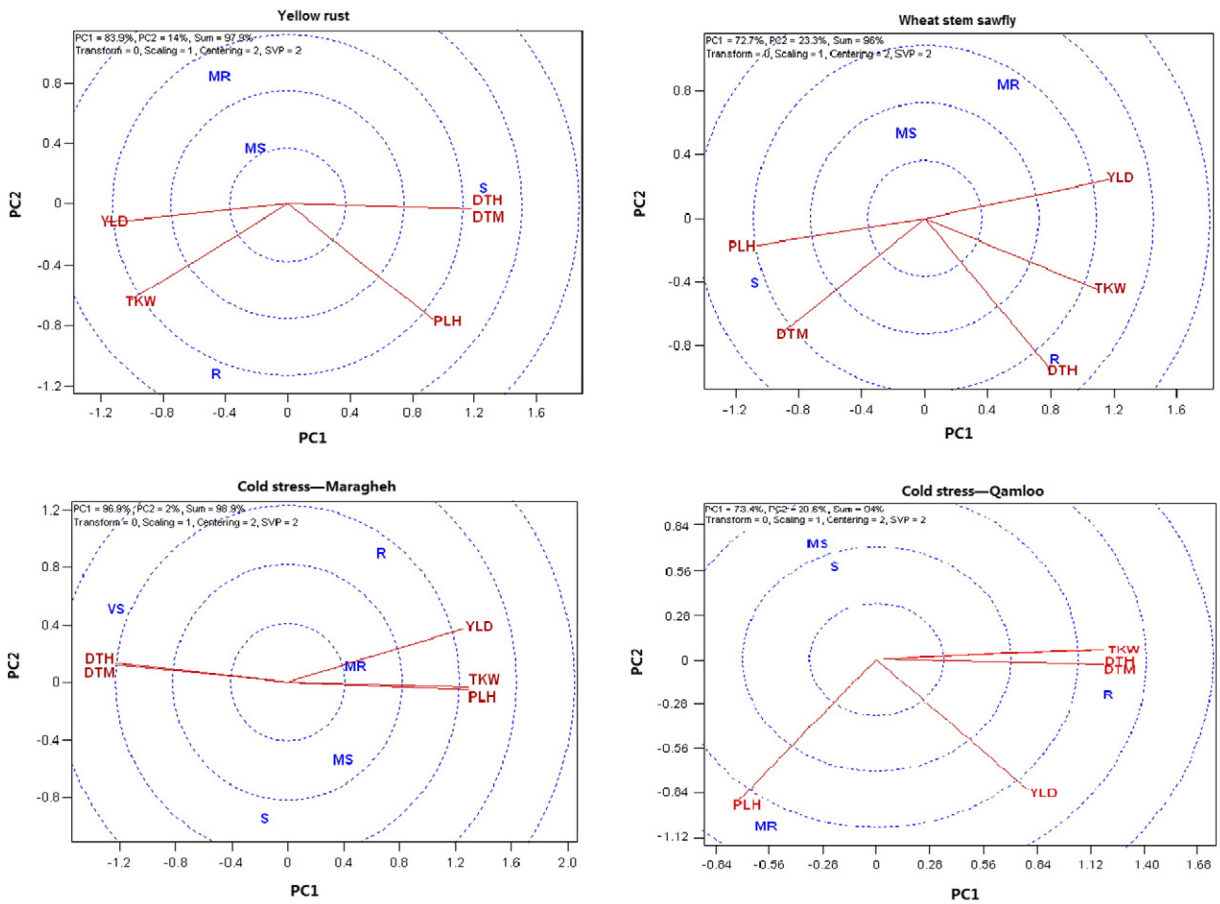

Fig. 3 – Genotype- by-trait (GT) biplot showing relationships among traits under different environmental stresses. DTH: days to heading; DTM: days to maturity; PLH: plant height; TKW: 1000-kernel weight; YLD: grain yield. R: resistant; MR: moderately resistant; MS: moderately susceptible; S: susceptible; VS: very susceptible.

performance depending on the kinds of stress. For example, under epidemic yellow rust infection, the foreign resistant landraces were characterized by higher yield productivity and TKW than the Iranian landraces. In contrast, under infestation by WSS, the Iranian resistant landraces were characterized by high yield, TKW, plant stature, and earliness in heading and maturity. Under cold stress, the Iranian resistant landraces had higher yield and TKW.

Resistance to environmental stresses and high yield are the key requirements for evaluating the success of durum wheat as an important cereal crop in highland rainfed areas of Iran. Landraces with high genetic diversity should be selected and crossed with locally adapted landraces and varieties to achieve breakthroughs in durum wheat genetic improvement. For higher yield under yellow rust epidemics, foreign landraces, particularly those from Japan, should be used, while under infestation by WSS the Iranian landraces and under cold stress the foreign landraces from Japan, Afghanistan, and Portugal should be given priority. Selection based on flowering, maturity, grain weight, and plant height, exploiting the variation among landraces, may enhance the genetic yield potential in cold and moderately cold rainfed areas of Iran. In conclusion, our results suggest that the early maturing, high yielding, and resistant durum wheat landraces held in the Iranian gene bank can adapt to the stressful environments of Iran and elsewhere and can be used for durum breeding targeting the development of improved varieties for cold and drought-prone environments.

Acknowledgment

This research was a part of the regional durum wheat research project of the Dryland Agricultural Research Institute (DARI) of Iran and was supported by the Agricultural Research and Education Organization (AREEO). The authors thank two

Table 8 – Phenotypic correlations among agronomic traits across locations (*n* = 384).

	DTH	PLH	DTM	TKW
PLH	0.481 **			
DTM	0.690 **	0.704 **		
TKW	0.352 **	0.365 **	0.544 **	
YLD	0.093	0.016	0.201 **	0.260 **

** Significant at the 0.01 probability level. DTH: days to heading; PLH: plant height; DTM: days to maturity; TKW: 1000-kernel weight; YLD: grain yield.

anonymous reviewers for their comments, discussions, and corrections on the manuscript. The authors also acknowledge the assistance of Professor James Nelson (Kansas State University) for valuable editorial and English improvements.

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