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Stability Analysis of Durum Wheat (*Triticum durum* Desf.) Grain Yield

[1]A. Adjabi, [2]H. Bouzerzour and [2]A. Benmahammed
[1]Department of Agronomy,
[2]Department of Ecology and Plant Biology, Faculty of Life and Natural Sciences,
Sétif-1 University, Sétif, 19000, Algeria

Abstract: The results of the study of the genotype×environment interaction of durum wheat (*Triticum durum* Desf.) varieties tested during six consecutive cropping seasons (1997/98 to 2002/03), under semi-arid conditions, indicated the lack of reproducibility of the yield information because genotype rank changes from one year to another. During the six cropping seasons, except Beliouni, MBB and Semito which performed always poorly the remaining genotypes ranked among the top yielding at least once. The presence of genotype×year interaction is suggested by the combined analysis of variance which indicated that the treatment sum of squares consisted of 42.41, 8.43 and 49.15% due, respectively to cropping season, genotype and interaction effects. The AMMI model was appropriate, explaining 84.0% of the interaction sum of squares. The results showed that the interactions lead to different rankings of the tested genotypes across the cropping seasons with a diversification between genotypes groups. Cyprus1, Deraa and Bousselem exhibited low nominal grain yield under low yielding conditions and were more responsive to good growth conditions; while Mrb5, Heider and Waha, on the contrary, showed a high nominal yield under low yielding conditions and exhibited a minimal responsiveness to improved environmental conditions. Heider combined low interaction and above average yield, making it suitable for cultivation in the semi-arid region of the Eastern high plateaus of Algeria.

Key words: *Triticum durum*, interaction, grain yield, AMMI analysis, cropping seasons, adaptation

INTRODUCTION

Durum wheat (*Triticum durum* Desf.) is grown on more than 1.2 million hectares as a rainfed crop in Algeria. Its grain yield is low and variable, in space and time, due to erratic rainfall, low winter temperature, spring late frost hazard and high temperature during grain filling (Belaid, 2000; Annicchiarico *et al*., 2002; Nouar *et al*., 2012). Grain yield instability is among the main factors responsible of the gap between actual yield and the potential (Annicchiarico *et al*., 2005). Development of high yielding and yield stable cultivars with improved adaptation to the prevailing weather conditions is an important breeding goal. Yield stability has been described as yield consistency across years, while adaptation refers to the ability of a genotype to perform well across locations (Lin and Binns, 1988). Crop performance is a function of the genetic make-up of the variety and the nature of the environment where it is grown. As a consequence, genotype performances may vary in different environments, reflecting Genotype by Environment Interactions (GEI). GEI occurs and generates a crossover of reaction norms in which no genotype performs in a superior manner in all environments. It is a serious constraint to breeding and selection efforts, because large GEI affects heritability and inhibits genetic gain from selection (Yan and Kang, 2003). This can lead to selection of genetic material that is not truly superior. However, study of the GEI offers opportunities, to select genotypes showing positive interaction with specific locations (Ceccarelli, 1996). To manage the effects of genotype and environment on crop performances, multi-season and multi-site experimental trials are conducted throughout the target region, to generate data on grain yield and other traits of interest (Annicchiarico *et al.,* 2002). Effective interpretation of the collected data is important to insure selection efficiency. Several statistical procedures have been developed over time and are used in the multi-environment data analysis. These statistical methods include conventional analysis of variance, regression analysis, pattern analysis, factorial regression, additive main effect and multiplicative interaction and GGE-biplot analysis (Finlay and Wilkinson, 1963; Lin *et al*., 1986; Becker and Leon, 1988; Zobel *et al*., 1988; Crossa *et al*., 1990; Yau and Hamblin, 1994; Vargas *et al*., 1999; Yan *et al*., 2000; Voltas *et al*., 2005).

Corresponding Author: A. Adjabi, Department of Agronomy, Faculty of Life and Natural Sciences, Sétif-1 University, Sétif, 19000, Algeria

They can be classified into two major groups, based on the nature of the data available and the objectives of the analysis. The classical analysis of GEI involves evaluating genotypic performances across trials. Alternatively, it is often desirable to describe the reaction of genotypes to environments relative to the biophysical variables that directly affect crop yield to get meaningful biological interpretation of the observed GEI (Voltas *et al*., 2005; Annicchiarico *et al*., 2005; Kadi *et al*., 2010) tested thirteen barley (*Hordeum vulgare* L.) genotypes, over 5 growing seasons, under semi-arid conditions and found significant GEI, 26.8% of which was explained by the joint regression while the AMMI model accounted for 84.7%. The GEI pattern revealed by the AMMI analysis indicated that the set of barley genotypes had narrow adaptability as no one genotype was found to have high performances in all environments (Kadi *et al*., 2010; Meziani *et al*., 2011) tested twelve barley (*Hordeum vulgare* L.) genotypes at 6 locations and found significant GEI which accounted for 29.3% of the treatments sum square. The AMMI first two IPC absorbed 82.6% of the GEI sum square. Plant traits acting as major sources of interaction were plant height, straw yield, number of days to heading, number of spikes m^{-2} and number of grains per spike. Variations in accumulated winter and June rainfall, as well as the mean winter temperature, were among the environmental co-variables causal of the interaction (Meziani *et al*., 2011; Nouar *et al*., 2012) tested twelve durum wheat (*Triticum durum* Desf.) genotypes over 5 locations and found a significant GEI. AMMI model explained 90.8% of the GEI sum of square. Selection for specific adaptation allowed 10.5% genetic gain over selection for large adaptation. This study evaluates the temporal stability of 15 durum wheat breeding lines and cultivars evaluated during 6 consecutive cropping seasons (1997/98 to 2002/03) under rain fed conditions.

MATERIALS AND METHODS

Plant material, experimental design and measured variables: Fifteen durum wheat genotypes from different origins (Algeria, Italy, Cyprus, Jordan and Icarda) were evaluated during six consecutive cropping seasons, from 1997/98-2002/03, at the Agricultural Experimental Station (1081 m.a.s.l. 5°21'E, 36°9'N) of the Field Crop Institute (ITGC) of Setif (Algeria). The targeted zone represented by the experimental site is a semi-arid area characterized by a Mediterranean continental climate, with most of the accumulated rainfall recorded during the cold winter months. The plant material was evaluated in a randomized complete block design with three replications. Plot dimensions were 5 m long by 1.2 m wide, covering an area of 6 m^2. Trials were fertilized with one hundreded kg ha^{-1} of 45% triple superphosphate at sowing, in November and one hundred kg ha^{-1} of 35% urea at jointing, in March. Weeds were controlled chemically by application of Grandstar 75DF (*Methyl tribenuron*) herbicide, at a rate of 12 g ha^{-1}. Among the measured variables, reported by Adjabi *et al*. (2007), only grain yield was analyzed herein.

Data analysis: An analysis of variance of grain yield was conducted per season to test significant differences among genotypes. The homogeneity of error variances was tested with F max prior to perform the combined analysis of variance, according to the following model:

$$Y_{ijk} = \mu+G_i+Y_j+B_k(Y_j)+(G\times Y)_{ik}+e_{ijk}$$

where, Y_{ijk} is the grain yield of the ith genotype, in the jth year, in the kth replication. μ is the grain mean yield. G and Y are the main effects and G×Y is the interaction effect. Blocks are nested into years (Annicchiarico *et al*., 2002). In this model, the genotypes were regarded as fixed effects while years and blocks were regarded as random effects. Year main effects were tested against the blocks within years ($B_k(Y_j)$). Genotype main effect was tested against the genotype×year interaction (G×Y) and the G×Y interaction was tested against the pooled residual (Annichiarico, 2002). Clustering of both genotypes and cropping seasons, based on grain yield data, was carried out using an agglomerative hierarchical clustering procedure with squared Euclidean distance as a measure of dissimilarity and incremental sums of squares as a grouping strategy (DeLacy *et al*., 1996). The free software Past (Hammer *et al*., 2001) was used to obtain dendrograms. To describe the genotype×year interaction for grain yield, the additive main effect and multiplication interaction (AMMI) analysis were performed on the $(G\times Y)_{ij}$ terms, according to the following model proposed by Gauch (1992):

$$(G\times Y)_{ij} = \Sigma\iota_n,u_{ni},v_{nj}+r_{ij}$$

where, Σ is the sum of the n = 1, 2… n PC axes included in the model, ι_n is the eigen value of the nth PC axis, u_{ni} is the scaled eigenvector of the ith genotype for the nth axis, v_{nj} is the scaled eigenvector of the jth year for the nth axis and r_{ij} is the residual of the G×Y interaction. The nominal grain yield of each genotype was estimated as the genotypic main effect plus the product of genotype and location IPCA1 scores. Nominal yield was plotted against location IPCA1 scores, to identify the environments shearing the same highest yielding cultivars. The AMMI Stability Value (ASV) was calculated, according to Purchase *et al*. (2000), as follows:

$$\text{ASV} = \sqrt{\left\{\left[\frac{\text{SSIPCA1}}{\text{SSIPCA2}} \times \chi\text{GIPCA1}\right]^2 + \text{GIPCA2}^2\right\}}$$

where, SSIPCA1/SSIPCA2 is the weight given to the IPCA1 value by dividing the IPCA1 sum of squares (SS) by the IPCA2SS, GIPCA1 and GIPCA2 are scores of the considered genotype on the IPCA1 and IPCA2 axes. Spearman rank correlation coefficients and significance levels were determined using Past software version 2.03 (Hammer *et al*., 2001). AMMI analyses were performed with Cropstat 7.2. software package (CropStat, 2008) using the balanced analysis of variance and cross-site analysis subroutines (Annicchiarico, 2002).

RESULTS AND DISCUSSION

Grain yield variability per cropping season: Analysis of variance of grain yield measured per cropping season showed a significant genotype effect (Table 1), suggesting the presence of exploitable genotypic variability. Averaged over genotypes, grain yield per season ranged from 179.6-333.5 g m^{-2} with a coefficient of variation changing from 6.0 to 9.9%. Mohamed Ben Bachir, Beliouni and Semito were, during the six cropping seasons, the least performing genotypes, while the remaining entries ranked, at least once, among the top grain yielding (Table 2). Cropping seasons were clustered, at 50% dissimilarity, into three groups which exhibited different yielding capacities: 333.5, 287.4 and 257.5 g m^{-2}, respectively (Fig. 1). Genotype clustering showed three groups of entries which differed in yield potential, averaged over cropping seasons: 307.0, 284.1 and 250.3 g m^{-2}, for G1, G2 and G3, respectively (Fig. 2). Changes in genotype ranking, from one season to another, differential yielding ability of the evaluated entries and variation in environmental yield potential are suggestive of the presence of genotype×season interaction. The presence of the interaction is also suggested by the size of the ratio of the inter-season variances ($\sigma_{max}^{-2}/\sigma_{min}^{-2}$) which varies from 1 to 12.1 (data not shown). Over cropping seasons mean grain yield was positively and significantly correlated with the inter-season variance ($r = 0.5770$, $p<0.05$, $n-2 = 13$), suggesting that the best performing genotypes were the least stable.

These results stress the difficulty to select stable and adapted genotypes, to seasonal variation, to harness maximum yield gain. The combined analysis of variance indicated the presence of a significant genotype×cropping season interaction, a highly significant cropping season effect and a non-significant genotype effect. This later effect had been tested against

Table 1: Mean of squares of grain yield analysis of variation per cropping season

Source of variation	df	CS1	CS2	CS3	CS4	CS5	CS6
Total	44	2102.61	6626.65	15408.8	2256.39	855.33	1401.77
Block	2	2014.87	400.56	482.45	1670.56	151.09	1077.96
Genotype	14	4859.77**	20271.50**	47808.80**	6065.79**	2506.42**	3780.61**
Error	28	730.29	248.96	275.06	393.53	80.08	235.48

CS1-CS6: 1997/98, 1998/99, 1999/2000, 2000/2001, 2001/2002, 2002/2003 cropping seasons, respectively, **Genotypic effect significant at 1% probability

Table 2: Mean grain yield of the different genotypes observed per season, averaged over seasons (Yi.) and over entries (Y.j), least significant difference and coefficient of variation values

Genotype	CS1	CS2	CS3	CS4	CS5	CS6	Yi.
Adamillo/Duillio//Semito	360.7^a	253.3	392.7	359.0	160.7	146.7	278.8
Belikh2	266.7	305.0	288.0	306.7	188.7	255.7^a	268.4
Cyprus1	354.3^a	227.3	557.3	307.0	257.7^a	211.3	319.0
Bicre	283.7	273.3	219.7	397.7	161.3	247.0^a	263.8
Daki	349.7^a	178.3	344.7	318.3	169.0	246.7^a	267.8
Deraa	283.3	200.0	593.0^a	284.3	179.3	215.7	292.6
Heider	300.0	385.0	306.3	359.3	204.3	234.3^a	298.2
Bousselem	254.3	338.3	500.0	332.7	197.0	234.3^a	309.4
Massara1	336.3^a	308.3	190.7	255.3	178.0	241.3^a	251.7
Mrb16/Ente//Mario	342.3^a	243.3	335.3	327.0	200.7	240.3^a	281.5
Mrb5	325.0^a	426.6^a	240.7	321.7	163.3	258.3^a	289.3
Waha	331.7^a	333.3	308.3	431.7^a	149.0	180.3	289.1
Mohamed ben bachir	288.0	328.3	202.0	326.0	147.0	162.7	242.3
Beliouni	256.7	374.3	287.0	291.0	152.7	176.3	256.3
Semito	241.3	136.6	236.3	294.0	186.7	219.7	219.1
Y.j	304.9	287.4	333.5	327.4	179.6	218.0	275.2
LSD 5%	45.2	29.3	27.73	33.1	15.0	25.7	
CV%	9.9	6.5	6.2	7.2	6	8	

^{a}Top grain yielding genotypes per cropping season

Table 3: Combined analysis of variance, joint regression and additive main effect and multiplicative interaction analysis for grain yield of 15 durum wheat genotypes evaluated during six cropping seasons under semi-arid conditions

Source of variation	df	Sum squares (SS)	Mean squares (MS)	F-test	SS (%)
Treatments	89	207.32	3.04	9.21**	100.00
Seasons (S)	5	87.92	17.58	18.12**	42.41
Block/S	12	1.16	0.97	2.46**	-
Genotype (G)	14	17.49	1.25	0.86^{ns}	8.43
GxS	70	101.91	1.46	4.42**	49.15
IPCA1	18	67.23	3.74	8.31**	65.97
IPCA2	16	18.35	1.14	2.53**	18.01
Residual	36	16.34	0.45	1.16ns	16.02
Pooled error	168	5.50	0.33		
Total	269	213.99			

*, **Significant effect at the 5 and 1% threshold, respectively, ns: Not significant

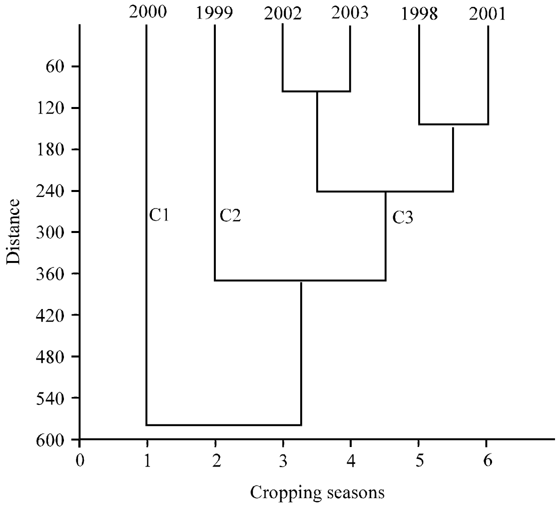

Fig. 1: Clustering pattern of the 6 cropping seasons based on grain yield data of 15 durum wheat genotypes

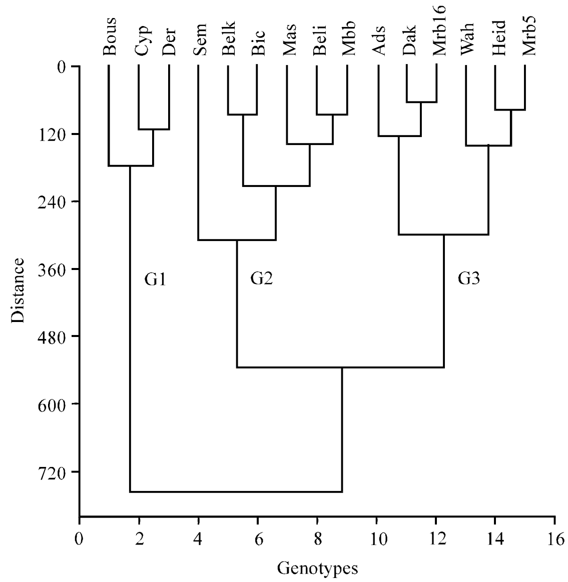

Fig. 2: Clustering pattern of 15 durum wheat genotypes based on grain yield data of 6 cropping seasons

the genotype×cropping season interaction mean of squares as suggested by McIntosh (1983) and Annicchiarico (2002) (Table 3). Cropping season, an unpredictable component of source of variation, explained 42.41% of the treatment sum of squares (Table 3). The genotype×cropping season interaction explained 49.15% of the treatment sum of squares, which was six times larger than the genotype sum of squares, reflecting sizeable differences in genotypes response across cropping seasons.

Groups of seasons C1 and C2 discriminated relatively well between the evaluated genotypes and ranked them differently, while C3 group of seasons was less discriminating (Fig. 3). Deraa, Cyprus1 and Bousselem were the top yielding in the C1 group of seasons; while Mrb5, Heider, Beliouni and Bousselem were among the top yielding genotypes in the C2 group of seasons (Fig. 3). Samonte *et al.* (2005) reported that when the GEI is significant, the analysis of variance based on the additive model is not suitable to explore the GEI pattern. The presence of significant interaction, in the present study, justified the use of AMMI analysis to explore the interaction pattern and to identify relatively high yielding and stable genotypes.

AMMI analysis of grain yield: The AMMI analysis captured a sizeable part of the interaction sum of squares, the first two components retained 85.58% of the interaction sum of squares (67.23% for IPCA1 and 18.35% for IPCA2), leaving 16.02% as residual (Table 3). The AMMI1-biplot shows the overall average grain yield achieved by a genotype and how this was achieved, as far as cropping seasons are concerned. The AMMI1-biplot showed that, among the cropping seasons, CS5 expressed a low grain yield while CS3 had a high grain yield average; the other cropping seasons were intermediate. Similarly, among the genotypes Semito, Mohamed Ben Bachir and Massara1 expressed a low grain yield, while Bousselem and Cyprus1 presented a high grain yield average (Fig. 4). Based on the information brought by the IPCA1 scores, Semito, Ads, Mrb16/Ente//Mario, Daki and Belikh2,

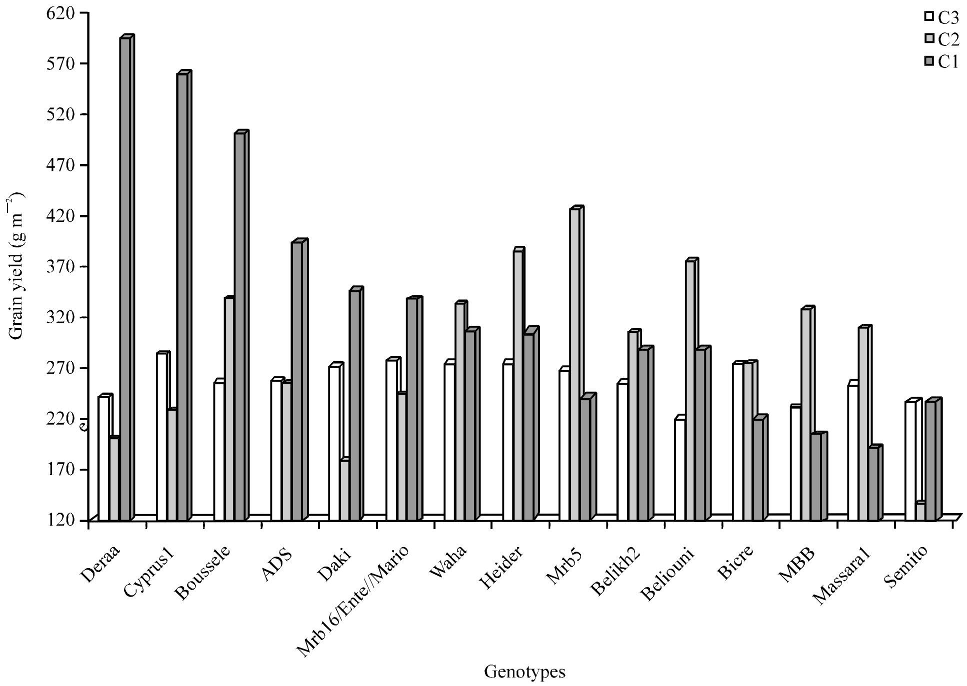

Fig. 3: Mean grain yield variation of 15 durum wheat genotypes during the different groups of cropping seasons

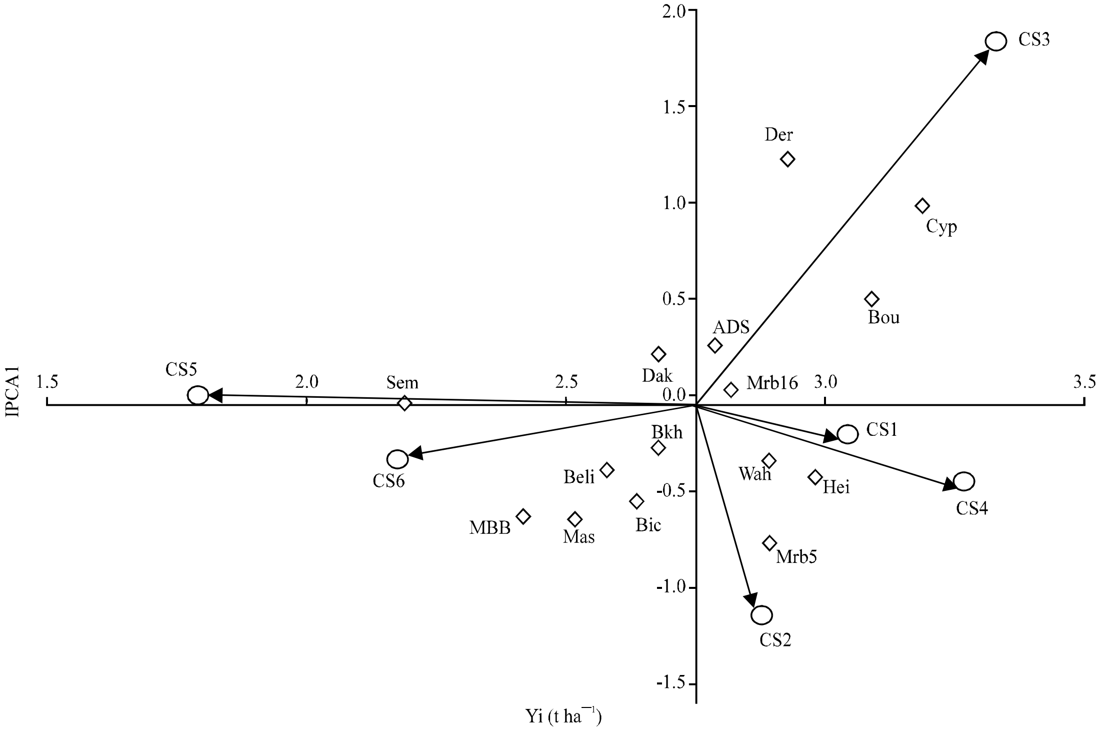

Fig. 4: AMMI1 biplot showing the main and interaction (IPCA1) effects of both genotypes and environments on grain yield. CS1-CS6: Cropping seasons, ADS: Adamilo/Duillio//Semito, Bkh: Belikh2, Bic: Bicre, Beli: Beliouni, Cyp: Cyprus1, Der: Deraa, Dak: Daki, Bou: Bousselem, Hei: Heider, Mas: Massara1, Mrb16: Mrb16/Ente//Mario, MBB: Mohammed Ben Bachir, Sem: Semito, Wah: Waha

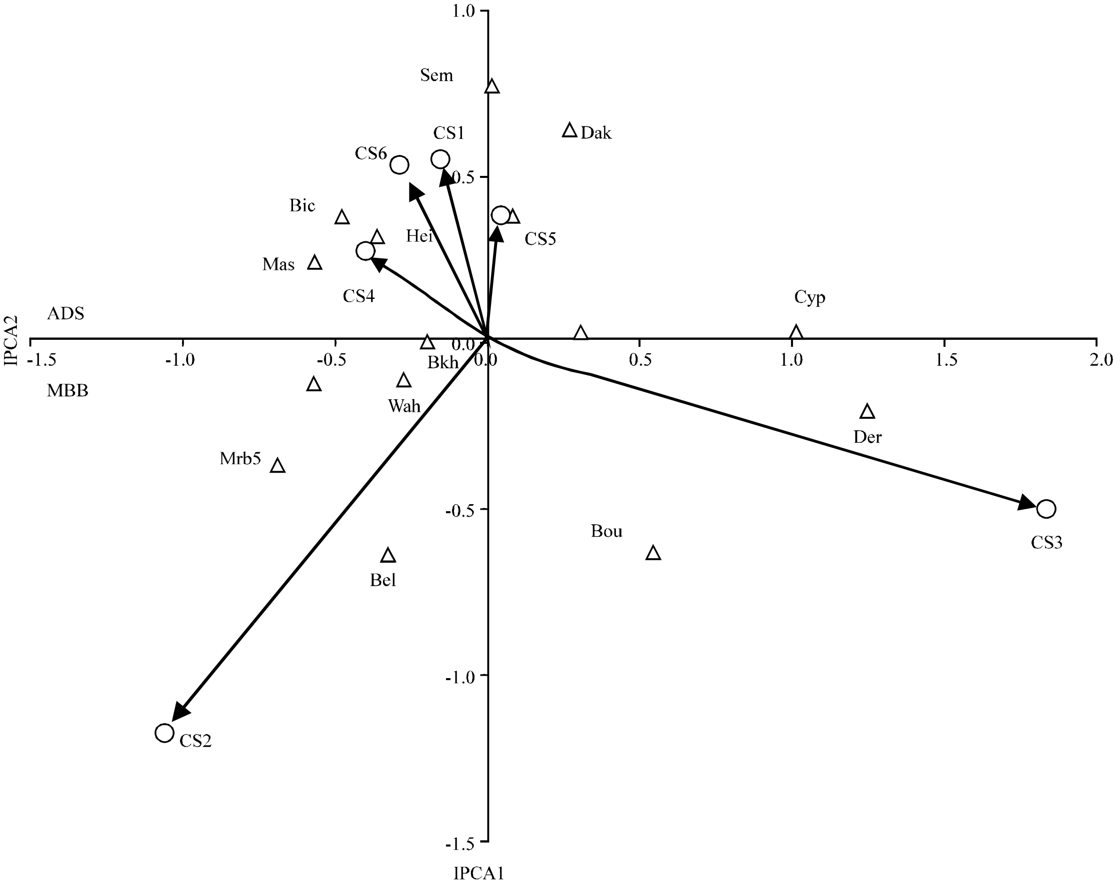

Fig. 5: Genotype×cropping season AMMI2 biplot based on the yield data for 15 durum wheat genotypes evaluated during 6 cropping seasons under semi-arid conditions. CS1-CS6: Cropping seasons, ADS: Adamilo/Duillio// Semito, Bkh: Belikh2, Bic: Bicre, Beli: Beliouni, Cyp: Cyprus1, Der: Deraa, Dak: Daki, Bou: Bousselem, Hei: Heider, Mas: Massara1, Mrb16: Mrb16/Ente//Mario, MBB: Mohammed Ben Bachir, Sem: Semito, Wah: Waha

having scores close to nil, expressed general adaptation whereas Deraa, Cyprus1 and Bousselem, having relatively larger positive scores, expressed specific adaptation to the CS3 cropping season. Mrb5 had a negative score was best expressed during the CS2 cropping season (Fig. 4).

Since, the best genotype would be the one combining high grain yield and stable performances across the cropping seasons, AMMI1-biplot suggested Heider as the best compromise. This genotype presented a low score and an above grain yield average (Fig. 4). Informations brought by the AMMI2-biplot suggested that CS2 and CS3 cropping seasons expressed highly interactive behavior, whereas the CS1, CS4, CS5 and CS6 cropping seasons exhibited relatively low interaction (Fig. 5).

The interactive genotypes were Cyprus1, Deraa and Bousselem which were best expressed during the CS3 cropping season. Beliouni, Heider and Mrb5 were best expressed during the CS2 cropping season, whereas Massara1, Bicre and Heider were best expressed during the CS4 cropping season. ADS, Waha and Belikh2 exhibited a general adaptation to the tested set of cropping seasons, based on the informations brought by the AMMI2 biplot (Fig. 5).

Nominal grain yield and yield stability: The nominal grain yield helps to apprehend the general adaptability of each cultivar and to identify genotypes that yielded best at specific group of cropping seasons IPCA1 scores. In the present study, no genotype showed a high nominal yield over the entire set of cropping seasons tested, suggesting that different germplasm type was specifically adapted to the extremes environments represented by the C1 and C2 groups of seasons (Fig. 6). Mrb5, Heider and Waha showed specific adaptation to low yielding environments while Cyprus1, Bousselem and Deraa were specifically

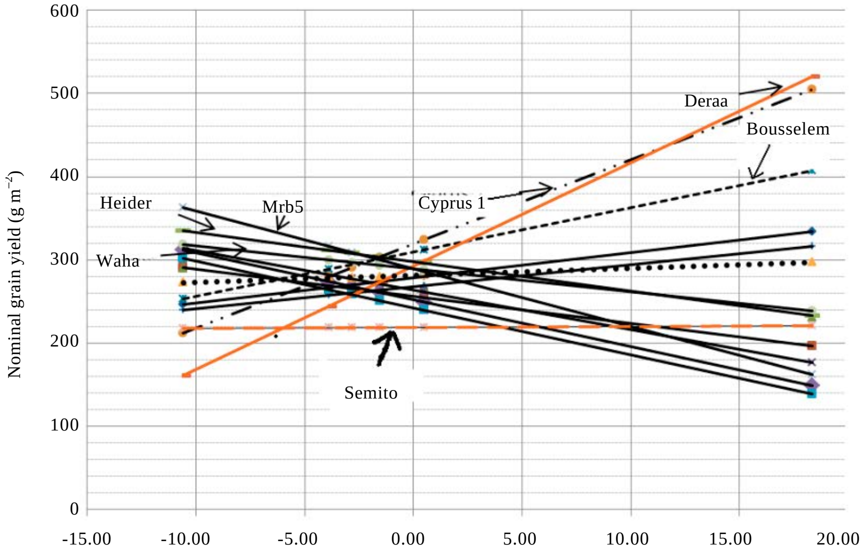

Fig. 6: Nominal grain yield of the 15 durum wheat genotypes tested across 6 cropping seasons

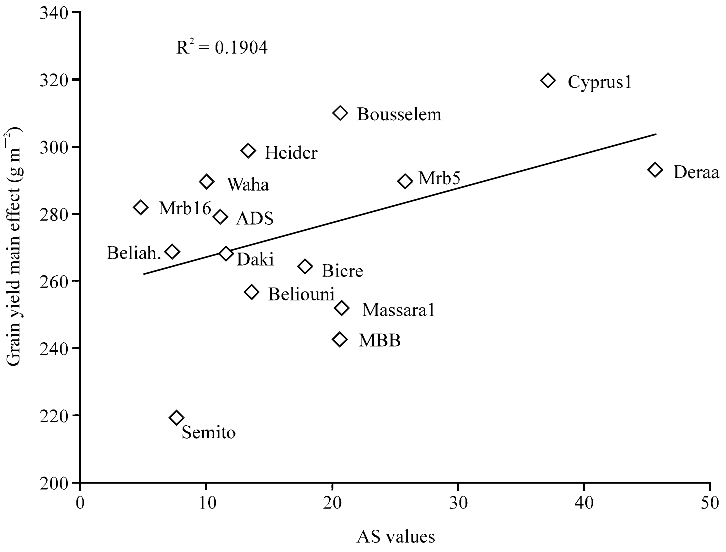

Fig. 7: Relationship between genotype grain yield main effect and AS values

adapted to high yielding environments. Intermediate environments (group of seasons C3) were not discriminating between genotypes (Fig. 1, 2, 3, 6).

Waha, Heider and Mrb5, which showed adaptation to low yielding environment, had AS values varying from 10.1-25.8, while Cyprus1, Bousselem and Deraa, which expressed adaptation to favorable environments, had AS values varying from 20.7-45.6 (Fig. 7), confirming that the former genotypes were less yielding and but relatively stable while the latter were high yielding and unstable. The rank correlation coefficient between genotype grain yield main effect and ASV is non-significant (rs = 0.3314, p = 0.2265), suggesting that stable genotypes were not necessarily high yielding across the tested cropping seasons, nor responsive to favorable growing conditions.

In the Mediterranean region, where a large part of the world durum wheat (*Triticum turgidum* var. *durum* L.) is grown, rainfall shows high spatial and temporal variation, especially in spring. Drought and heat stresses increase during grain filling and interact with genotype to produce large yield fluctuations. Genotype×environment interaction and yield-stability analyses are important to appreciate varietal stability and suitability for cultivation across seasons and ecological zones. Annicchiarico *et al.* (2005, 2006) reported an extensive study on the subject, focusing on the identification of stable genotypes, under Algerian cropping conditions. In the present study, AMMI analysis indicated that 49.15% of the treatment sum of squares was attributed to the genotype×cropping season interaction, 42.41% to cropping season and 8.43% to genotype main effect. The results showed that the interactions lead to different rankings of the tested genotypes across the cropping seasons with a diversification between genotypes belonging to Group G1 and those belonging to Group G3. Cyprus1, Deraa and Bousselem (group G1) exhibited the lowest nominal yield in cropping seasons with large negative IPCA1 scores and high nominal yield in cropping seasons with large positive IPCA1 scores. Mrb5, Heider, Waha; Daki and ADS (group G3), on the contrary, showed a high nominal yield in cropping seasons with large negative IPCA1 scores and low nominal yield in cropping seasons with large positive IPCA1 scores. Belikh2, Semito, Beliouni, MBB, Massara1 and Bicre, genotypes belonging to group G3, showed a different performance trend with significant low to intermediate nominal yield levels across the whole range of cropping seasons IPCA1 scores (Fig. 6). Genotypes of this group exhibited a minimal responsiveness to improved environmental conditions, expressing a fairly stable nominal yield regardless the environmental conditions in agreement with the concept of static stability (Lin *et al.*, 1986). Heider was identified as having a combination of low interaction and above average yield, making it suitable for cultivation across seasons in the semi-arid region of the eastern high plateaus. However, its low grain yield under fairly good season makes it less attractive even though it appears to be a drought tolerant genotype with low frequency of crop failure under stress. Pantuwan *et al.* (2002) suggested that genotypes with low yielding potential and high drought tolerance may be useful when drought stress is severe. However, Sinebo (2005) mentioned that breeding for low yielding conditions may result in cultivars that ensure yield stability and minimize risk, but force farmers to trade security for economic growth.

CONCLUSION

The results showed that the interactions lead to different rankings of the tested genotypes across the cropping seasons with a diversification between genotypes groups. Cyprus1, Deraa and Bousselem exhibited low nominal grain yield under stress and were more responsive to good growth conditions; while Mrb5, Heider and Waha, on the contrary, showed a high nominal yield under stress and exhibited a minimal responsiveness to improved environmental conditions. Heider combined low interaction and above average yield, making it suitable for cultivation in the semi-arid region of the eastern high plateaus.

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