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Research Article

Genetic Advance and Grain Yield Stability of Moroccan Durum Wheats Grown under Rainfed and Irrigated Conditions

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The development of high-yielding durum wheat genotypes requires the knowledge of the genetic variation for grain yield and its components. This study was performed to determine genetic gain and to evaluate the genotype × environment effect for grain yield and related traits in Moroccan durum wheat. A historical series of varieties developed during the last three decades was grown under two water regimes (rainfed and irrigated) during three growing seasons. Traits evaluated in the present work included grain yield, spikes per m^2, kernels per spike, spikelets per spike, kernels per spikelet, spike length, kernel weight, plant height, harvest index, and fertile tillering. Results from ANOVA analyses revealed that grain yield and related traits were controlled to a large extent by water regime and growing season. Grain yield advance per year was estimated in 78 kg ha^{-1} under irrigated conditions, with no significant change under rainfed ones. Overall, the results indicated that most of the yield components changed by breeding activities during the last three decades. AMMI and joint regression analyses revealed that intermediate varieties have a wide adaptation, and old varieties were specifically acclimated to water-limit environments, while modern varieties were performed only under favorable conditions.

1. Introduction

Durum wheat (*Triticum turgidum* L. var. *durum*) is grown on around 17 million hectares worldwide, with a total production of about 38 million tons [1]. It is cultivated mainly in North America, European Union, Northern Africa, and Australia. The Mediterranean basin is the most significant market and the large consumer of durum wheat products [2].

In Morocco, durum wheat is one of the leading cereal crops, appreciated by consumers, mainly used for the preparation of traditional foods [3]. It is sown annually on acreage of more than one million hectares, and the average grain yield during the last ten years (2008–2017) was estimated to be 1.74 $t\,ha^{-1}$ [4]. However, most durum wheat growing regions are characterized by drought and fluctuating seasonal precipitation resulting in stress during anthesis and the grain filling period. Under these environments, increasing yield stability represents the main component for agricultural improvement [5, 6]. In addition, it is difficult to develop high-yielding durum wheat genotypes for Mediterranean rainfed areas because of the high genotype × environment ($G \times E$) interaction.

Testing genotypes in different environments across many growing seasons is highly needed to assess the extent of $G \times E$ interaction and to identify varieties with stable yield and wide adaptation. Several statistical methods have been developed for the analysis of yield stability and adaptation. These methods range from univariate parametric based on linear regression [7] to multivariate methods such as the

AMMI analysis (additive main effects and multiplicative interaction) [8]. The models based on linear regression explained a small part of the sum of squares of $G \times E$ interaction and are unable to estimate the nonlinear response to environments [5]. In contrast, the AMMI model based on ANOVA and principal component analysis is able to characterize the main effect of genotype and environment and seems to be able to predict a large part of their interactions [9].

Genetic improvement in durum wheat grain yield has been associated with changes in plant characteristics [10]. Grain yield is often dissected in final kernel weight and the number of grains per square meter resulting from the number of spikes per unit area and the number of kernels per spike [11, 12]. These two yield components, determined successively from double ridge to anthesis, are agronomic traits that provide an opportunity to improve grain yield under water-limited conditions [11]. Historical yield studies indicate that improving grain yield is accompanied by a rise in kernel number by unit area [13–16]. In addition, the increase in yield related to the introduction of semidwarf genes is responsible of a decrease in plant height and, hence, reduced competition between growing stems and spikes, giving larger spikes with more kernels per spike, while increasing the harvest index [17].

From 1960s onwards, wheat production has increased noticeably worldwide [18]. Evaluation of the annual rate of genetic gain within many breeding programs gives a benchmark for progress in plant breeding [19]. Previous estimates from several countries for genetic gain in durum wheat have been reported [10, 13, 20–23].

The beginning of durum wheat breeding in Morocco dates back to 1920. By 1970s, the partnership with CIMMYT and ICARDA provided opportunities to have access to a wide range of germplasm with earliness characteristics and semidwarf genes. It has helped with the development of a set of durum wheat varieties with high yield, good quality, early maturity, and drought tolerance. Therefore, it is important to perform a retrospective study in order to assess the genetic advance for Moroccan varieties as well as analyzing their stability. The current study aims to (i) investigate the water regimes effect, (ii) to quantify the genetic change in grain yield and related traits, and (iii) to analyze yield stability and adaptation for six representative Moroccan durum wheat varieties developed during the last three decades.

2. Materials and Methods

2.1. Experimental Site and Design. The trials were carried out under two water regimes (irrigated and rainfed) during 2017, 2018, and 2019 growing seasons in the experimental station of the Polydisciplinary Faculty of Taza, northern Morocco. Experimental conditions and agronomic details are given in Table 1. The total rainfall and average temperatures recorded during the three growing seasons are shown in Figure 1. The study region is characterized by a Mediterranean climate with humid winters and semiarid summers. Six durum wheat varieties were selected to represent the germplasm developed in Morocco between 1984 and 2007 (Table 2). Three periods were considered, and two varieties for each period were selected: old (developed from 1980 to 1990), intermediate (developed from 1990 to 2000), and modern (developed from 2000 to 2010). The trials were arranged in a completely randomized block design with three replicates. The varieties were planted manually in plots of three rows 2 m long and spaced 0.2 m apart. Irrigated plots were watered biweekly, and the volume of required water was determined based on the daily meteorological data and calculated as the difference between crop evapotranspiration and precipitation to replace evapotranspiration loss. On the other hand, the rainfed plots were exposed only to natural precipitation.

2.2. Measurements. At ripening before harvest, spikes per m^2 were counted for each plot. Five plants were randomly chosen, and the following yield components were determined: kernels per spike, spikelets per spike, and spike length (cm). Plant height (cm) was measured from the soil to the base of the spike. The number of kernels per spikelet was calculated as the kernels per spike divided by spikelets per spike. Harvest index was computed as the ratio of kernel weight to the total above-ground plant weight. The whole plots were harvested manually, and grain yield (kg h^{-1}) was determined at 10% moisture content. Fertile tillering (%) was calculated by dividing the number of spikes containing grains by the maximum stems number, expressed as a percentage. Kernel weight (mg) was also assessed in three samples of 100 g of harvested grains.

2.3. Statistical Analyses. The responses of the period of release, water regimes, growing seasons, and their interactions were tested with ANOVA. Least significant difference (LSD) values were calculated at the 5% probability level. Principal component analyses (PCA) and correlation studies were performed on the matrix from the mean data across replicates and growing seasons. Genetic gain was computed as the slope of the linear regression between the trait and the year of release. All statistical analyses were carried out by using the Statgraphics Centurion XVII package (StatPoint Technologies, Inc., Virginia, USA).

2.4. $G \times E$ Interaction Studies. Data from growing seasons and water regimes were combined as environments ($3 \times 2 = 6$) to test the effect of variety, environment, and their interaction on grain yield. Each combination was considered as a specific environment and was performed based on the joint regression analysis (JRA) and the additive main effects and multiplicative interaction (AMMI) model to analyze the $G \times E$ interaction effects and estimate the adaptation pattern of our durum wheat varieties.

2.5. Joint Regression Analysis (JRA). JRA was suggested by Finlay and Wilkinson [7]. This method quantifies the interactions by modelling individual grain yield as a linear function of a continuous variable representing the effect of

Table 1: Experimental conditions of the trials.

	2016-2017	2017-2018	2018-2019
Coordinates		34°12′ N 4°00′ W	
Altitude		550 m	
Sowing date	14 Dec 2016	18 Dec 2017	19 Dec 2018
Harvest date	21 June 2017	26 June 2018	23 June 2019
Soil characteristics			
Classification		Typic Xerofluvent	
Texture		Silty clay loam	
pH		7.14	
P		20 mg kg^{-1}	
K		16 mg kg^{-1}	
Organic matter		2.85%	
Sowing density		350 kernels m^{-2}	
Fertilization			
1st application		350 kg ha^{-1} NPK (15 : 15 : 15)	
2nd application		200 kg ha^{-1} ANS 26% N	

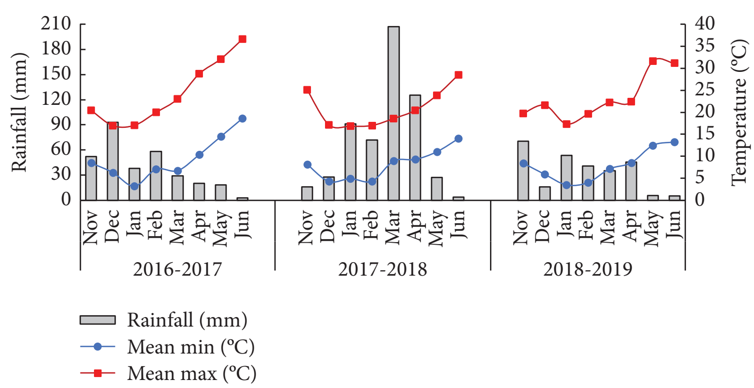

Figure 1: Rainfall distribution and average air temperatures during 2017, 2018, and 2019.

Table 2: Year of release and pedigree of six durum wheat varieties used in the current study.

Variety	Year of release	Pedigree	Breeding program
Marzak	1984	INRA EII, 12 selection in CIMMYT germplasm	INRA
Karim	1985	Bittern ‘S‘ or sel in « JO‘S‘.AA”:S‘//FG”S‘ »	INRA
Ourgh	1995	NRA 1769 “Unk”	INRA
Tarek	1995	INRA 1768 “Unk”	INRA
Marouane	2003	Sebou/BT40//Sarif #CF4(1896–1904)	INRA
Faraj	2007	Cross between Nassira, Qarmal, and Lahn (ICARDA)	INRA

the environment. Stability parameter calculated was the regression coefficient (b_i):

$$\left(ge_{ij}\right) = b_i e_j + d_{ij}, \qquad (1)$$

where ge_{ij} is the effect of the interaction between the i^{th} variety and j^{th} environment (e_j), b_i is the linear regression coefficient for the i^{th} variety, and d_{ij} is the deviation associated with the i^{th} variety in the j^{th} environment. According to Finlay and Wilkinson [7], regression coefficient (b_i) close to 1.0 indicates the variety is well adapted to all environments. A regression coefficient above 1.0 indicates a variety specifically adapted to high performing environments. However, the value of regression coefficient below 1.0 indicates a variety specifically adapted to unfavorable environments.

The joint regression for grain yield was calculated as follows:

$$gy_{ij} = \mu + v_i + b_i e_j + \varepsilon_{ij}, \qquad (2)$$

where gy_{ij} is the grain yield of variety i in the environment j, v_i is the main effect of the i^{th} variety, μ is the grand mean, b_i is the linear regression coefficient of the i^{th} variety, e_j is the main effect of the j^{th} environment, and ε_{ij} is the residual.

2.6. AMMI Analysis. Each environment was performed based on the AMMI model [8] to explain the $G \times E$ interaction effects. The following statistical model was used:

$$gy_{ij} = \mu + \alpha_v + \beta_e + \sum \lambda_n \cdot \Upsilon_{in} \cdot \delta_{jn} \cdot \rho_{ij}, \qquad (3)$$

where gy_{ij} is the grain yield of variety i in the environment j, α_v is the variety deviation from the grand mean, μ is the grand mean, β_e is the environment deviation, λ_n is the eigenvalue for interaction principal component n, Υ_{in} is the eigenvalue for variety i and principal component n, δ_{jn} is the eigenvalue for environment j and principal component n, and ρ_{ij} is the residual error.

The AMMI stability value (ASV) described by Purchase et al. [24] was calculated using the following formula:

$$\mathrm{ASV} = \sqrt{\left[\frac{\text{PC1 sum of squares}}{\text{PC2 sum of squares}}(\text{score PC1})\right]^2 + (\text{score PC2})^2}, \tag{4}$$

where PC1 and PC2 are the interaction principal components 1 and 2, respectively, and score PC1 and score PC2 are respective scores from the principal component analysis of the AMMI model. The yield stability index (YSI) was calculated as $\mathrm{YSI} = \mathrm{R_{ASV}} + R_{\mathrm{Y}},$ where $\mathrm{R_{ASV}}$ is the rank of the AMMI stability value, and RY is the rank of the mean grain yield of each variety across environments. The AMMI analysis, AMMI stability value, yield stability index, joint regression, and rank stability index were performed by using *R* software (R Core Team, 2018) with agricolae package [25].

3. Results

3.1. Data Variability. The combined analyses of variance revealed highly significant effects of water regime, growing season, and period of release on all evaluated traits (Table 3). Grain yield and related traits were controlled to a large extent by water regime. The growing season effect was mainly noticed on plant height and spike length, accounting about 57 and 47% of total variance, respectively. In contrast, the magnitude of period of release was of minor importance (less than 13% of total variance), except for kernels per spikelet and spike length where it explained 25 and 35%, respectively. The variance of kernels per spike, kernel weight, and fertile tillering was assigned in equal proportion to water regime and growing season. Moreover, spikelets per spike were equally affected by the period of release and growing season. Interactions among the three factors were in general of lower importance, and only water regime × period of release explained around 18% of the variability for kernels per spikelet.

3.2. Water Regime and Growing Season Effects. Mean values of the grain yield and related traits for two water regimes and three growing seasons are given in Table 4. The results revealed that the values of all traits were significantly reduced under rainfed conditions compared with the irrigated ones. The decrease generated by water deficit was 30% in grain yield and spikes per m^2, 15% in harvest index, and lower than 10% in the remaining traits. In addition, grain yield and related traits varied significantly among the three growing seasons. 2018 was the wettest season for this study (570 mm) (Figure 1), and then, the average grain yield was 4702 kg ha^{-1} with the highest values for kernel weight (47.2 mg), harvest index (0.40), kernels per spikelet (2.5), fertile tillering (67.2%), and plant height (88.1 cm). 2017 and 2019 were drier growing seasons (312 mm and 273 mm of total rainfall, respectively) as compared to 2018. Consequently, the average grain yield decreased significantly (3274 and 3418 kg ha^{-1}, respectively). 2018 has received an important amount of precipitation (570 mm), which resulted in the greatest average grain yield (4702 kg ha^{-1}).

3.3. Genetic Progress. Mean comparisons among the release periods for the considered traits are given in Table 4. When combining the two-trial data, high values of grain yield, harvest index, spikelets per spike, fertile tillering, and spike length were found in modern varieties, while kernel weight, kernels per spikelet, and plant height exhibited good values in old varieties. For spikes per m^2 and kernels per spike, means values were unchangeable from old to modern varieties.

Absolute and relative genetic changes in grain yield and related traits under irrigated and rainfed conditions for six durum wheat varieties are presented in Table 5. Considering all experiments (irrigated and rainfed trials), grain yield progress increased significantly between 1984 and 2007, with an annual genetic gain of 23.5 kg ha^{-1} (data not shown). Within the irrigated trial, grain yield increased over the period between 1987 and 2007, representing a genetic gain of 1.75% $year^{-1}$ (or 78 kg ha^{-1} $year^{-1}$). Most of the yield components were positively correlated with year of release, representing a genetic advance of 0.51% $year^{-1}$ (or 2.19 spike $year^{-1}$) for spikes per m^2, 1.05% $year^{-1}$ (or 0.01% $year^{-1}$) for harvest index, 0.6% $year^{-1}$ (or 0.10 spikelet $year^{-1}$) for spikelets per spike, 0.51% $year^{-1}$ (or 0.33 fertile tillers $year^{-1}$) for fertile tillering, and 0.47% $year^{-1}$ (or 0.03 cm $year^{-1}$) for spike length. In contrast, significant genetic loss was observed for kernels per spike with a decrease of −0.23% $year^{-1}$ (or −0.09 kernel $year^{-1}$) and kernels per spikelet with loss of −0.79% $year^{-1}$ (or −0.02 kernel $year^{-1}$). No significant change was observed for the kernel weight and plant height with year of release. Regarding the rainfed conditions, no significant variation for grain yield occurred between 1984 and 2007. From all yield components, three traits changed significantly over time exhibiting a genetic gain of 0.44% $year^{-1}$ (or 0.066 spikelet $year^{-1}$) for spikelets per spike and 0.14% $year^{-1}$ (or 0.082 fertile tillers $year^{-1}$) for fertile tillering, 0.33% $year^{-1}$ (or 0.021 cm $year^{-1}$) for spike length. The rest of traits did not differ between 1984 and 2007.

3.4. Associations among Grain Yield and Related Traits. Correlations among grain yield and related traits are presented in Table 6 for the two trials, separately. The irrigated and rainfed conditions impacted differently the relationships among traits. In fact, under irrigated conditions, grain yield was significantly and positively related to spikes per m^2 ($r = 0.832^*$), harvest index ($r = 0.818^*$), spikelets per spike ($r = 0.814^*$), fertile tillering ($r = 0.912^*$), and spike length ($r = 0.839^*$), while negatively associated with kernels per spikelet ($r = -0.815^*$) and plant height ($r = -0.812^*$). Under

Table 3: Mean squares of the combined analyses of variance for grain yield, spikes per m^2, kernels per spike, kernel weight, harvest index, spikelets per spike, kernels per spikelet, fertile tillering, plant height, and spike length in six durum wheat varieties released in different periods (old, intermediate, and modern) grown under two water regimes (irrigated and rainfed) during three growing seasons (2017, 2018, and 2019).

	Df	Grain yield		Spikes per m^2		Kernels per spike		Kernel weight		Harvest index		Spikelets per spike		Kernels per spikelet		Fertile tillering		Plant height		Spike length	
Water regime, WR	1	46444800	***	534252	***	442.6	***	355.3	***	0.0985	***	19.57	***	0.428	***	647.8	***	1059.1	***	0.683	*
Period of release, PR	2	1995140	***	2077	***	5.5	*	62.1	***	0.0270	***	26.32	***	0.521	***	145.6	***	516.2	***	2.811	***
Growing season, GS	2	22263400	***	54329	***	355.538	***	457.1	***	0.0596	***	32.27	***	0.167	***	800.7	***	2202.8	***	3.861	***
Replicate (GS)	6	64922	—	52	—	3.0	—	0.6	—	0.0002	—	0.39	—	0.064	—	4.9	—	0.7	—	0.149	—
WR × PR	2	10964400	***	9969	***	50.5	***	157.3	***	0.0090	***	2.02	*	0.380	***	66.3	***	1.5	—	0.110	—
WR × GS	2	2926040	***	23617	***	46.0	***	93.6	***	0.0221	***	3.20	**	0.137	***	55.5	***	106.7	***	0.388	**
PR × GS	4	607930	*	3906	***	20.7	***	12.4	***	0.0003	—	2.65	**	0.185	***	51.8	***	22.8	*	0.131	*
WR × PR × GS	4	20468900	***	2144	***	10.8	***	3.0	—	0.0012	—	3.02	**	0.222	***	10.1	—	6.3	—	0.026	—
Residual	84	233093	—	164	—	1.6	—	2.3	—	0.0084		0.60	—	0.018	—	7.0	—	5.0	—	0.062	—
Total (corrected)	107	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

*Significant at 0.05 probability level. **Significant at 0.01 probability level. ***Significant at 0.001 probability level.

Table 4: Mean values of grain yield, spikes per m^2, kernels per spike, kernel weight, harvest index, spikelets per spike, kernels per spikelet, fertile tillering, plant height, and spike length in six durum wheat varieties released in different periods (old, intermediate, and modern) grown under two water regimes (irrigated and rainfed) during three growing seasons (2017, 2018, and 2019).

	Grain yield (kg h^{-1})	Spikes per m^2	Kernels per spike	Kernel weight (mg)	Harvest index (%)	Spikelets per spike	Kernels per spikelet	Fertile tillering (%)	Plant height (cm)	Spike length (cm)
Trials										
Irrigated	4453^{a}	426^{a}	40^{a}	45.3^{a}	0.39^{a}	16.0^{a}	2.5^{a}	64.4^{a}	80.8^{a}	6.65^{a}
Rainfed	3142^{b}	285^{b}	36^{b}	42.7^{b}	0.32^{b}	15.1^{b}	2.3^{b}	59.5^{b}	74.8^{b}	6.48^{b}
Period of release										
Old	3526^{b}	347^{a}	38^{a}	44.4^{a}	0.34^{b}	15.0^{b}	2.6^{a}	59.8^{c}	79.8^{a}	6.32^{c}
Intermediate	3933^{a}	356^{a}	37^{b}	44.1^{a}	0.35^{b}	15.3^{b}	2.5^{b}	62.1^{b}	76.6^{b}	6.48^{b}
Modern	3934^{a}	362^{a}	38^{a}	42.0^{b}	0.38^{a}	16.6^{a}	2.3^{c}	63.8^{a}	77.1^{b}	6.87^{a}
Growing season										
2017	3418^{b}	360^{a}	39^{a}	43.4^{b}	0.32^{c}	16.3^{a}	2.4^{c}	58.1^{c}	74.0^{b}	6.75^{a}
2018	4702^{a}	391^{a}	40^{a}	47.2^{a}	0.40^{a}	16.0^{a}	2.5^{a}	67.2^{a}	89.4^{a}	6.74^{a}
2019	3274^{b}	314^{b}	34^{b}	40.1^{c}	0.34^{b}	14.5^{b}	2.3^{b}	60.5^{b}	70.1^{c}	6.18^{b}

Means for each character followed by the same letter are not significantly different according to the LSD test at $P < 0.05$.

Table 5: Absolute and relative genetic changes in grain yield, spikes per m^2, kernels per spike, kernel weight, harvest index, spikelets per spike, kernels per spikelet, fertile tillering, plant height, and spike length in six durum wheat varieties grown under two water regimes (irrigated and rainfed) during three growing seasons (2017, 2018, and 2019).

	Grain yield (kg h^{--1})	Spikes per m^2	Kernels per spike	Kernel weight (mg)	Harvest index (%)	Spikelets per spike	Kernels per spikelet	Fertile tillering (%)	Plant height (cm)	Spike length (cm)
Irrigated										
Absolute changes ($year^{-1}$)	78.08	2.19	−0.09	0.07	0.01	0.10	−0.02	0.33	−0.04	0.03
Relative changes % ($year^{-1}$)	1.75	0.51	−0.23	0.16	1.05	0.60	−0.79	0.51	−0.05	0.47
r^2	0.85^{**}	0.93^{**}	0.81^{*}	0.60	0.92^{**}	0.79^{*}	0.86^{**}	0.93^{**}	0.03	0.87^{**}
Rainfed										
Absolute changes ($year^{-1}$)	−31.08	−0.69	0.10	−0.26	0.01	0.07	−0.01	0.08	−0.18	0.02
Relative changes % ($year^{-1}$)	−0.99	−0.24	0.23	−0.62	0.34	0.44	−0.18	0.14	−0.25	0.33
r^2	0.63	0.39	0.45	0.64	0.53	0.77^{*}	0.18	0.29^{*}	0.56	0.78^{*}

*Significant at 0.05 probability level. **Significant at 0.01 probability level.

rainfed conditions, correlation coefficients were in general less important, although some interesting associations can be highlighted. Grain yield was positively related only to spikes per m^2 ($r = 0.960^{**}$) and kernel weight ($r = 0.960^{**}$) but negatively associated to kernels per spike ($r = -0.934^{**}$) and plant height ($r = -0.858^{*}$). In both trials, significant correlations were found among yield component, and kernels per spike were negatively related to spikes per m^2 ($r_{\text{irrigated}} = -0.946^{**}$; $r_{\text{rainfed}} = -0.960^{**}$) and kernel weight ($r_{\text{irrigated}} = -0.954^{**}$; $r_{\text{rainfed}} = -0.907^{*}$). In addition, a negative association was scored between plant height and harvest index ($r_{\text{irrigated}} = -0.931^{**}$; $r_{\text{rainfed}} = -0.825^{*}$).

Principal component analysis (PCA) was applied as a second tool to establish the characteristics of each group of varieties and the particularity of each trial with regard to yield components expression (Figures 2 and 3). Results showed that 84% of the total variability was accounted by the first two PCs: the PC1 explained 60% of the total variance, while PC2 accounted for 24%. The first PC separated kernels per spikelet appearing in the negative direction from all other traits positioned in the positive one. The variability along the second PC was mainly due to grain yield, plant height, spikes per m^2, kernels per spike, kernel weight, and kernels per spikelet located towards the upper direction, while fertile tillering, harvest index, spikelets per spike, and spike length were observed downwards. Variety means plotted on the plan determined by the two PC axes are arranged in clusters related to three groups of varieties (Figure 2) and to two trials (Figure 3). PC1 separated clearly between the both water regimes and irrigated trial located on the right side with significant scores for all traits as revealed by mean comparison. The observation of Figure 3 showed some discrimination along PC2 between groups of varieties. The cluster corresponding to old varieties was located on the positive side with higher values of kernels per spikelet and plant height, while the modern varieties were clustered in the negative side, close to the eigenvectors for grain yield, fertile tillering, harvest index, spikelets per spike, and spike length. Intermediate varieties occupied an intermediate position; this location suggests an association with better kernel weight, spikes per m^2, and kernels per spike.

3.5. G × E Interactions for Grain Yield. The relationship between variety mean grain yield and regression coefficient (b_i) is shown in Figure 4. The varieties are distributed according to their specific adaptability. The values of b_i across varieties ranged from 0.89 to 1.82. Utilizing the joint regression method, "Ourgh" and "Tarek" were the most stable varieties with b_i values closer to 1, "Karim" and "Marzak" were specifically adapted to low-yielding environments with the lowest b_i values, whereas the varieties "Faraj" and "Marouane" with the highest values were adapted only to high performing environments.

The additive and interaction effects of both variety and environment on grain yield are shown in Figure 5. IPCA1 of the AMMI model justify 86% of the total variation. The biplot of the IPCA1 against grain yield clustered "Ourgh" and "Tarek" near to the origin of the axes, indicating that intermediate varieties have a small grain yield variation between environments. Old varieties "Karim" and "Marzak" were located in the upper part of figure, close to the vectors representing rainfed 2019 and 2017 environments. The points corresponding to modern varieties "Faraj" and "Marouane" were placed in negative direction of the IPCA1 axis and closer to the vectors symbolizing irrigated in 2017, 2018, and 2019 environments.

The AMMI model and joint regression analysis provided no quantitative measures. AMMI stability indices were applied as an additional tool to quantify and rank varieties in terms of grain yield stability (Table 7). Based on the ASV

Table 6: Correlations between analyzed traits in six durum wheat varieties released in different periods (old, intermediate, and modern) grown under two water regimes: irrigated (upper right diagonal) and rainfed (lower left diagonal) during three growing seasons (2017, 2018, and 2019).

	Grain yield	Spikes per m^2	Kernels per spike	Kernel weight	Harvest index	Spikelets per spike	Kernels per spikelet	Fertile tillering	Plant height	Spike length
Grain yield	— —	0.832 *	−0.714 —	0.583 —	0.818 *	0.814 *	−0.815 *	0.912 *	−0.812 *	0.839 *
Spikes per m^2	0.960 **	— —	−0.946 **	0.811 —	0.993 ***	0.943 **	−0.978 ***	0.907 *	−0.898 *	0.945 **
Kernels per spike	−0.934 **	−0.960 **	— —	−0.954 **	−0.924 **	−0.865 *	0.941 **	−0.849 *	0.834 *	−0.971 **
Kernel weight	0.960 **	0.880 *	−0.907 *	— —	0.781 —	0.730 —	−0.830 *	0.731 —	−0.729 —	0.920 **
Harvest index	−0.770 —	−0.653 —	0.774 —	0.897 *	— —	0.953 *	−0.976 ***	0.874 *	−0.931 **	0.918 **
Spikelets per spike	−0.612 —	−0.489 —	0.606 —	−0.602 —	0.663 —	— —	−0.984 **	0.768 —	−0.861 *	0.898 *
Kernels per spikelet	−0.126 —	−0.293 —	0.178 —	−0.105 —	−0.136 —	−0.665 —	— —	−0.832 *	0.881 *	−0.955 **
Fertile tillering	−0.159 —	−0.102 —	0.122 —	−0.015 —	−0.075 —	0.682 —	−0.660 —	— —	−0.828 *	0.892 *
Plant height	0.705 —	0.503 —	−0.573 —	0.764 *	−0.825 *	−0.867 *	0.536 —	0.372 —	— —	−0.844 *
Spike length	−0.858 *	−0.787 —	0.774 —	−0.760 —	0.625 —	0.862 *	−0.331 —	0.585 —	−0.810 —	— —

*Significant at 0.05 probability level. **Significant at 0.01 probability level. ***Significant at 0.001 probability level.

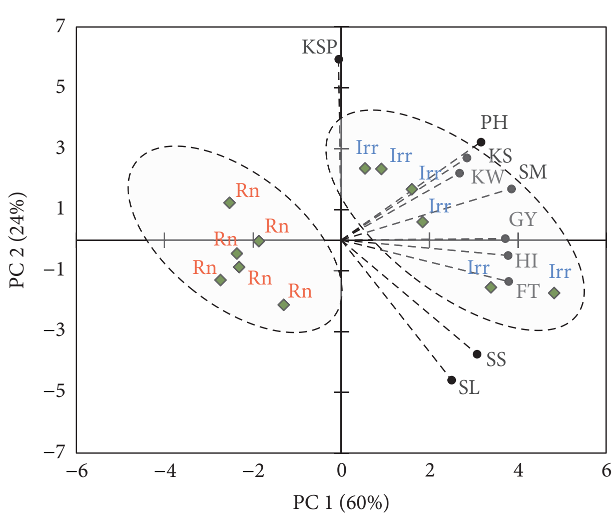

Figure 2: PCA projections on axes 1 and 2 accounting for 84% of total variance. Eigenvalues of the correlation matrix are symbolized as vectors representing traits that most influence each axis. The 12 points representing traits means for each water regime (rainfed (Rn) and irrigated (Irr)) are plotted on the plane determined by axes 1 and 2. Grain yield (GY), spikes per m^2 (SM), kernels per spike (KS), kernel weight (KW), harvest index (HI), spikelets per spike (SS), kernels per spikelet (KSP), fertile tillering (FT), plant height (PH), and spike length (SL).

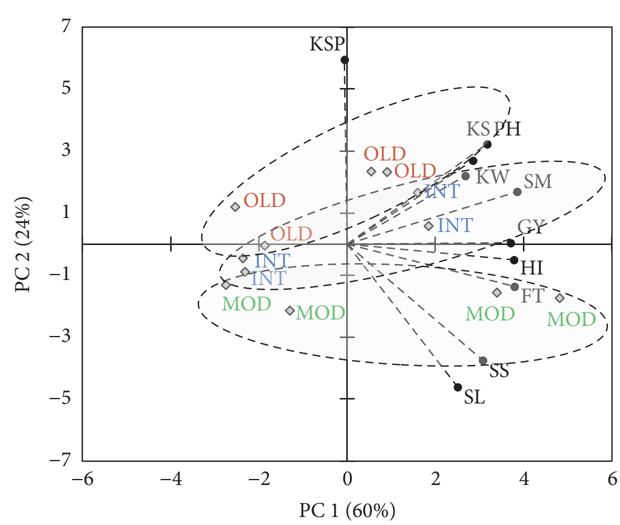

Figure 3: PCA projections on axes 1 and 2 accounting for 84% of total variance. Eigenvalues of the correlation matrix are symbolized as vectors representing traits that most influence each axis. The 12 points representing traits means for each period of release (old (OLD), intermediate (INT), and modern (MOD)) are plotted on the plane determined by axes 1 and 2. Grain yield (GY), spikes per m^2 (SM), kernels per spike (KS), kernel weight (KW), harvest index (HI), spikelets per spike (SS), kernels per spikelet (KSP), fertile tillering (FT), plant height (PH), and spike length (SL).

method, a variety with the lowest ASV value is the most stable. Consequently, "Ourgh" was the most stable variety followed by "Tarek." In addition, yield stability index, which combined both grain yield across environments and AMMI stability value, showed "Ourgh" and "Tarek" as the best and "Marzak" as the worst among the tested varieties.

4. Discussion

In the Mediterranean basin, year-to-year climatic variation and abiotic factors are the main constraints to grain yield formation. The data from our experiments revealed that

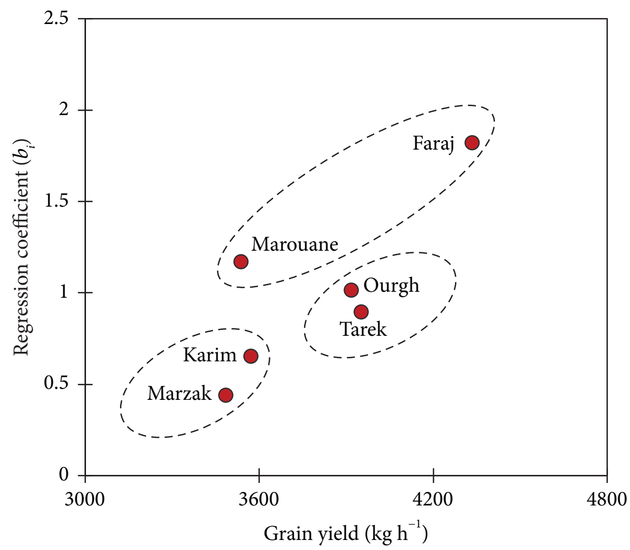

Figure 4: Relationship between regression coefficient (b_i) and average grain yield of six Moroccan durum wheat varieties grown under two water regimes during three growing seasons.

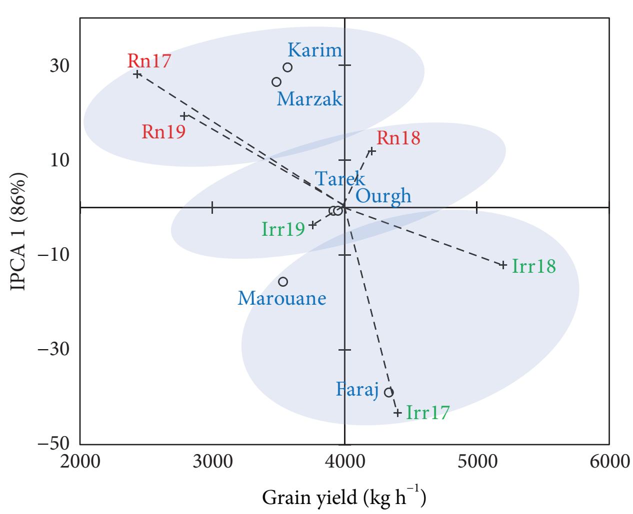

Figure 5: AMMI biplot for grain yield (kg h^{-1}) of the six Moroccan durum wheat varieties evaluated in six test environments (combination of the growing season and water regime). Rn17, rainfed 2016-17; Rn18, rainfed 2017-18; Rn19, rainfed 2018-19; Irr17, irrigated 2016-17; Irr18, irrigated 2017-18; Irr19, irrigated 2018-19.

Table 7: Mean yield across the studies environments, AMMI stability value, and yield stability index for the studied Moroccan durum wheat varieties.

Variety	Mean grain yield across all environments (kg h^{--1})	AMMI stability value (ASV)	Rank ASV	Yield stability index (YSI)	Rank YSI
Ourgh	3917	7	1	4	1
Tarek	3950	9	2	4	2
Marouane	3536	156	3	8	4
Marzak	3483	263	4	10	6
Karim	3569	294	5	9	5
Faraj	4333	387	6	7	3

Rank YSI = RASV + RY.

grain yield and associated traits were essentially affected by water regime and growing season. In our study, the environmental effects, considering both water regimes and growing seasons, accounted for the largest percentages of variability for grain yield. This observation was reported in other studies on durum wheat under Mediterranean environments [26–30]. The nonirrigated plots had 30% lower grain yield than irrigated ones. Pampana et al. [30] reported a significant reduction in grain yield only when waterlogging was prolonged to more than 20 days and highlighted that 40 and 60 days of waterlogging reduced grain yield by 19% and 30%, respectively. Reduction in grain yield and related traits under stress are caused by pollen abortion [31], production of sterile tillers [32], and variation in resource accumulation [33]. The number of spikes per m^2 was the yield component most affected by drought conditions. This trait is developed from the double ridge to anthesis, the period most sensitive to drought [34]. Giunta et al. [35] also demonstrated that severe water deficit during anthesis influenced seriously wheat grain yield by reducing the number of spikes and, therefore, decreasing plant fertility. García del Moral et al. [36] also demonstrated that water supply favored tillering and number of spikes. In addition, clear differences were observed in grain yield and related traits among the three growing seasons. The highest values were recorded in the second growing season characterized by abundant rainfall and its good distribution during crop growth.

The genetic advance in grain yield between 1984 and 2007 was 23.5 kg ha^{-1}. A similar result (23.3 kg ha^{-1} per year) was reported in a study conducted on Moroccan varieties by Rharrabti and Elhani [37]. This value was also similar to the genetic yield gain of 23.6 kg ha^{-1} per year found in Spain [23] and 19.9 kg ha^{-1} per year reported in Italy [10]. Analogous results were also reported in similar investigations carried on bread wheat [15, 38]. Considering each water regime separately, the genetic changes in grain yield and different traits depended on the conditions under which the durum wheat varieties were tested. The present study reported an annual genetic gain of 78 kg ha^{-1} under irrigated conditions, and no significant change was under rainfed conditions. Similar results were reported by other researchers [21, 39–41] who worked on wheat genotypes under different climatic conditions and found a very high dependence of the genetic gain on environmental conditions. In fact, Chairi et al. [21] worked on a set of Spanish durum wheat genotypes in different sites embracing a wide range of water regimes and growing temperatures and reported that genetic gains are associated with the average mean and maximum daily temperatures of the testing site. These results indicate that there are interactions between genetic changes in grain yield and the environment in which improvement is studied. Thus, breeding effects measured on a trait in one agroecological condition are not necessarily similar in other conditions. Therefore, when similar experiments are performed by breeders, particular attention should be paid to environmental conditions.

Spikes per m^2, spikelet per spike, fertile tillering, and spike length were the traits that most changed during the last three decades. Spikes per m^2 exhibited a positive association with year of release under irrigated conditions, with rate of 2.2 spikes $year^{-1}$; this is similar to the increase noted for durum wheat grown under high-yielding conditions in Chile (2.6 spikes $year^{-1}$) from 1970 to 2010 [22]. In the case of Spanish durum wheats, Chairi et al. [21] noticed a nonsignificant increase in genetic gain for spikes per m^2 among cultivars released from 1980 to 2009. The number of spikes was improved in durum wheat by increasing the capacity of the plant to revert resources to additional tillers under favorable conditions [28]. The rise in the number of spikes per m^2 in our study could be explained by the significant genetic gain of fertile tillering (0.33% per year). Spikelet per spike significantly changed over time, increasing with year of release by 0.10 and 0.07 spikelet $year^{-1}$ under irrigated and rainfed conditions, respectively. Sanchez-Garcia et al. [40] detected also a significant association between spikelet per spike and year of release for Spanish bread wheat genotypes. In contrast, Royo et al. [42] found that the rate of genetic gain in the spikelets per spike was not significant for Italian and Spanish durum wheats obtained during the 20th century. The improvement in the number of spikelets per spike in the present work was proportional to increase in spike length (a genetic gain of 0.03 cm and 0.02 cm per year under irrigated and rainfed conditions, respectively). The greater spikes number and spikelet per spike of modern varieties suggest that Moroccan breeding program focused on improving spike size and decreasing the number of nonfertile tillers.

It is important to note that many studies have reported that plant height was reduced when comparing modern genotypes with old ones [15, 16, 41–44]. However, the varieties employed in our study were all semidwarf; therefore, plant height did not change significantly across year of release. A similar situation was reported by Chairi et al. [21] who worked on a set of 20 Spanish durum wheats fully semidwarf. In Australia, plant height declined with year of release, in bread wheats released between 1958 and 1973, but not in cultivars developed after 1973 [45].

In the present study, PCA and correlation studies showed the importance of environmental variation on the association among yield and its related traits similar to findings by García del Moral et al. [37]. Grain yield was positively associated to spike per m^2, and this association becomes more important under drought conditions. Previous studies have reported that grain yield in dry Mediterranean environments is determined mainly by spikes per unit area [43, 46, 47]. García del Moral et al. [11] noted that under rainfed conditions characterized by limited tiller formation, the spike number per meter square (developed during the early stages) was the best yield component in determining grain yield. Similarly, Ercoli et al. [47] found that the increase in grain yield was due to a higher number of spikes and greater spike size and suggested that good growing conditions during the initial stages of crop development favored the development of tillers and promoted the floret fecundation. A significant correlation between grain yield and kernel weight was found under rainfed conditions, but not under irrigated ones, which is consistent with previous studies [26, 48–50] which reported that kernel weight influences grain production mostly in rainfed areas. Similarly, Bányai et al. [50] found that thousand-kernel weight proved a high repeatability under drought stress during the three years of the experiment. On the other hand, the consistent relationships between this yield component and grain yield, under rainfed conditions, would suggest that probably breeding was performed for cultivars to be grown under rainfed conditions.

Grain yield is usually used to represent the impact of the environment because it is the principal agronomic output and also because no other trait integrates interacting factors that determine plant performance [51]. In our study, the environmental effects accounted for the largest percentages of variability for grain yield. The combination of two water regimes and three growing seasons created a range of six environments. The AMMI model [8], JRA [7], and AMMI stability value [24] were employed to test grain yield stability of the studied varieties in different environments. Similarly, these stability parameters were also performed to identify the performing durum wheat [20, 52, 53], bread wheat [54, 55], and barley [56, 57]. Our results indicated that old varieties were specifically adapted to low-yielding environments and modern varieties were more adapted to high-yielding environments, while intermediates varieties are well adapted to all environments. De Vita et al. [5] worked on a set of Italian durum wheat genotypes with Rht genes released from 1975 to 2003 and highlighted that "Tiziana" and "Giusto" developed in 2001 have high-yield stability across the tested environments. In agreement with previous studies [13, 43, 50, 52, 58, 59], our results indicate that modern durum wheat varieties were more responsive to changes in seasons and treatments. In fact, the most stable varieties would not necessarily give the best grain yield [60]; therefore, stability per se should not be the only selection parameter. In this regard, AMMI stability value and yield stability index were used to rank varieties in terms of grain yield stability. These two stability measurements identified the intermediates varieties "Tarek" and "Ourgh" as the most stable ones.

5. Conclusions

Moroccan durum wheat grain yield increased significantly between 1984 and 2007 under favorable conditions, with no clear genetic advance under rainfed ones. Moreover, our results showed that the most traits measured in our trials changed significantly over time. In addition, both JRA and AMMI revealed that intermediates varieties have a wide adaptation, and old varieties were specifically adapted to water-limit environments, while modern varieties performed only to favorable environments. Moreover, the intermediates varieties "Tarek" and "Ourgh" were identified as the most stable ones.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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