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Using Path Analysis to evaluate Breeding Progress in Grain Yield and Related Characters of Durum Wheat in Morocco

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ABSTRACT: This study evaluates yield formation and breeding efforts in durum wheat grown in Morocco by the mean of path coefficient techniques based on plant ontogeny. A field experiment was conducted during 2008-2009 growing season with six Moroccan durum wheat varieties released between 1984 and 2007. Results obtained showed an increased grain yield from old to moderns varieties that was mainly due to longer vegetative period and heavy grains. Path coefficient analysis elucidates the correlation studies, and showed that grain yield was dependent on their three main components from old to modern varieties. Absolute and relative genetic gains in grain yield was 23 kg ha^{-1} $year^{-1}$ and 0.5% $year^{-1}$ indicating an important breeding progress in durum wheat made in Morocco since last two decades as compared to other countries with more pronounced breeding programs.

KEYWORDS: Path analysis, breeding, genetic gain, durum wheat, Morocco.

1 INTRODUCTION

Cereals are of paramount importance in Morocco and their consumption is one of the highest in the world, and cereal demand is almost synonymous with demand for food. The area planted annually with cereals in Morocco is about 5 million hectares. The national production contributes 43% of total consumption [1]. Among cereals, durum wheat, *Triticum turgidum* var. L. *durum* is sown annually over 1.2 million hectares, with an average consumption of around 65 kg/person/year [2]. Morocco is ranked third in the Mediterranean region and first in the North Africa and Middle East region in term of durum wheat acreage. Arid and semi arid regions (60% of the cropped Moroccan lands) are characterized mainly by drought and poor rainfall distribution within seasons [3]. Due to these reasons, the average yield is low and variable ranging from 0.5 to 1.2 t ha^{-1} [4]. The new durum wheat varieties released since 1972 in Morocco have allowed a grain yield gain of at least 25% over the landraces, but their productivity and grain quality are highly affected by the environmental factors [5]. The improvement of grain yield of durum wheat and its quality are the major objectives of the research conducted by the National Agricultural Research Institute (INRA) and the collaborating International Centers, CIMMYT and ICARDA [6].

Morocco and all countries belonging to the Mediterranean basin suffer from low and erratic distribution of rainfall, which has explained as much as 75% of the variation in wheat yield [7]. Under these conditions, most rain falls during autumn and winter and water deficit emerges in the spring, resulting in a moderate stress for rainfed wheat around anthesis, which increases in severity throughout grain filling [8]. Grain yield of wheat can be analyzed in terms of three yield components (number of spikes m^{-2}, number of grains $spike^{-1}$, and grain weight) that appear sequentially with later-developing components under control of earlier-developing ones [9], [10]. Understanding the effect of water stress and temperature regimes on yield formation becomes an essential step in the development of higher-yielding and more stable varieties [11].

Numerous studies on cereals include correlations between grain yield and its components. Although these are helpful in determining which components is influencing final grain yield, they may not provide a clear picture of the importance of each component in determining grain yield. Path coefficient analysis divides the correlation coefficients into direct and indirect effects. It allows, then, the separation of the direct influence of each yield component on grain yield from the indirect effects caused by the mutual relationships among yield components themselves [11].

Evaluation of breeding advances was undertaken in several works on bread wheat (*T. aestivum* L.) and other cereals [12], [13], [14], [15], but durum wheat has been analyzed in only a few studies. In fact, , McCaig and Clarke [16] reported yield increases in Canada of 0.81% year^{-1} over the period 1947-1992, while the genetic gain in durum wheat yield among CIMMYT germplasm between 1960 and 1984 was 3% year^{-1} [17]. Recently, Royo et al. [18] showed a relative genetic gain of 0.61% year^{-1} in grain yield across Spain and Italy from 1945 to 2000.

This study aims: (i) to evaluate yield formation in six durum wheat varieties released between 1984 and 2006 by using the path coefficient analysis; and (ii) to estimate the genetic gain in grain yield among these varieties over 20 years of breeding efforts in Morocco.

2 MATERIAL AND METHODS

A field trial was conducted during 2008-2009 growing season under rainfed conditions at the INRA Experimental Station of Jemâa Shaim (110 km west of Marrakech). The experiment consisted of a randomized complete block design with three replications and plots of 3 m^2 (six rows 0.15 m apart and 3 m length). Experimental details are given in Table 1. The seeding rate was adjusted for a density of 200 viable seeds m^{-2} according to the standard practices in the zone.

Table 1. Site localization, agronomical details, and climatic data

Site	Jemâa Shaim (rainfed)
Coordinates	
Latitude	32°24'09''
Longitude	08°46'55''
Altitude, m	176
Soil characteristics	
Classification	*Vertisol*.
Texture	*Tirs (calcareous clay)*
pH:	6.8 to 7
P	not available
K	abundant
Organic matter, %	1.1 to 2.8
Climatic data	
Seasonal rainfall, mm	171
Average temperatures,°C	
Tmax	23
Tmean	16.5
Tmin	10
Agronomic practices	
Fertilizers, kg ha^{-1}	
N	204
P_2O_5	404
K_2O	0
Sowing date	13 Nov. 2008

Six durum wheat varieties were selected to represent the germplasm grown in Morocco during the second half of the 20th century. Based on the year of release (Table 2), varieties were assigned to three periods, namely old (released before 1990), intermediate (released between 1990 and 2000), and modern (released after 2000).

Table 2. Description of the six durum wheat varieties used in this study

Varieties	Origin	Registration date	Adaptation zone
Olds			
Marzak	INRA Morocco	1984	Large, high yield potential
Karim	INRA Morocco	1985	Large, Irrigated, High yield potential
Intermediates			
Yasmine	INRA Morocco	1993	Large
Ourgh	INRA Morocco	1995	Large
Moderns			
Nassira	INRA Morocco	2003	Semi arid, drought tolerant
Faraj	INRA Morocco	2007	Semi arid, drought tolerant

The length of vegetative period was calculated as days from sowing to anthesis (growth stage 65 according to [19]. Duration of grain filling was considered to be the days from anthesis to physiological maturity (growth stage 87). The number of spikes m^{-2} was calculated by counting the spikes contained in 1 m of one of the central rows in each plot. The number of grains $spike^{-1}$ was determined by counting grains on every spike from a subsample of 10 plants selected from 1 m of row taken completely at random in each plot before harvest. Thousand grain weight (TGW) was calculated from the weight of three sets of 100 grain per plot. Grain yield was determined on the basis of the harvested plot and corrected to 120 g kg^{-1} moisture level.

Combined ANOVA over periods and varieties were performed with the Statgraphics package [20]. Means were compared by Duncan's test at $P < 0.05$. Correlation coefficients among all characters were computed from the mean values of the three replications. Genetic gain was calculated for grain yield as the slope of the linear regression between the mean value of grain yield of each variety and its corresponding year of release.

Path coefficient analysis was performed to partition the correlation coefficient, r_{ij}, into direct and indirect effects. The following four sets of simultaneous equations were solved to determine the path coefficient, P_{ij}, with subscripts indicating the six characters: vegetative period (1), number of spikes m^{-2} (2), grain filling duration (3), number of grains $spike^{-1}$ (4), TGW (5), and grain yield (6).

$$\begin{cases} r_{26} = P_{26} + r_{24}P_{46} + r_{25}P_{56} \\ r_{46} = r_{24}P_{26} + P_{46} + r_{45}P_{56} \\ r_{56} = r_{25}P_{26} + r_{45}P_{46} + P_{56} \end{cases} \qquad \begin{cases} r_{25} = P_{25} + r_{23}P_{35} + r_{24}P_{45} \\ r_{35} = r_{23}P_{25} + P_{35} + r_{34}P_{45} \\ r_{45} = r_{24}P_{25} + r_{34}P_{35} + P_{45} \end{cases}$$

$$\begin{cases} r_{14} = P_{14} + r_{12}P_{24} + r_{13}P_{34} \\ r_{24} = r_{12}P_{14} + P_{24} + r_{23}P_{34} \\ r_{34} = r_{13}P_{14} + r_{23}P_{24} + P_{34} \end{cases} \qquad \begin{cases} r_{13} = P_{13} + r_{12}P_{23} \\ r_{23} = r_{12}P_{13} + P_{23} \end{cases}$$

In the equation $r_{13} = P_{13} + r_{12}P_{23}$, P_{13} is the direct effect of character 1 on 3 (the path coefficient) while $r_{12}P_{23}$ is the indirect effect of character 1 on 3 via 2. Similar definitions apply to the other equations. The causal system assumed (as described in [10], [11]) was based on the ontogeny of the cereal plant, and it is shown in Fig. 1.

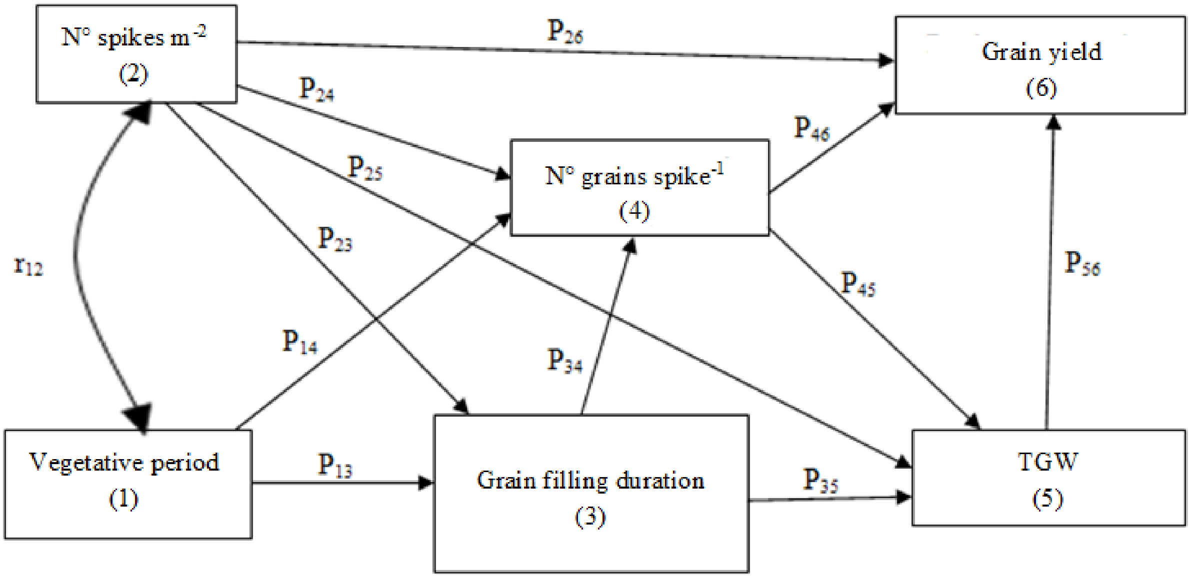

Fig. 1. Path coefficient diagram showing the interrelationships among the six characters studied. The single-headed arrows indicate path coefficients, and the double-headed arrows indicate simple correlation coefficients.

3 RESULTS

3.1 CHANGES IN GRAIN YIELD AND RELATED CHARACTERS OVER PERIODS OF RELEASE

Results presented in Table 3 indicate that modern varieties showed the highest grain yield with an increased number of spikes m^{-2} but mainly because of their high grain weight. Old and intermediate varieties revealed low grain yields in spite of high number of grains spike^{-1}. This was caused by their lower grain weight that negatively influenced final grain yield. In relation to plant cycle duration, modern varieties had flowered later in comparison to old and intermediate ones while grain filling duration was relatively the same for the three groups of varieties.

Table 3. Mean values of grain yield and related characters for the three categories of varieties

Period of release	Grain yield (kg ha^{-1})	Spikes m^{-2}	Grains spike^{-1}	TGW (g)	Vegetative period (days)	Grain filling duration (days)
Olds	880b†	228b	42.1a	34.0b	120b	36a
Intermediates	650b	269a	44.0a	31.4b	119b	37a
Moderns	1320a	279a	31.9b	41.1a	132a	36a

† Values followed by the same letter in a column are not significantly different according to Duncan's test ($p < 0.05$).

3.2 CORRELATION STUDIES

Correlation analyses (Table 4) revealed that yield components (number of spikes m^{-2}, number of grain spike^{-1}, and TGW) had low but; in general, positive associations with grain yield in old varieties. In this group, the length of vegetative period was significantly and negatively related to grain yield ($r = -0.947$**). For intermediates varieties, grain yield was moderately but no significantly dependent on number of spikes m^{-2} ($r = 0.742$). Among yield components, grain weight was positively associated to number of spikes m^{-2} but negatively and significantly affected by number of grains spike^{-1} ($r = -0.830$*). Regarding modern varieties, grain yield was highly dependent on its three main components with particular significant and positive correlation to number of spikes m^{-2} ($r = 0.817$*) and grain weight ($r = 0.854$*). This latter component was highly and significantly affected by number of spikes m^{-2} ($r = 0.920$**) and number of grains spike^{-1} ($r = 0.833$*). In addition, grain filling duration was negatively and significantly affected by the length of vegetative period ($r = -0.965$**).

Table 4. Correlation coefficients among the characters studied for the three categories of varieties

	Spikes m^{-2}	Grains $spike^{-1}$	TGW	Vegetative period	Grain filling duration
Olds					
Grain yield.	0.379	0.581	0.471	–0.947**	0.099
Spikes m^{-2}		0.221	–0.339	–0.297	0.522
Grains $spike^{-1}$			0.182	–0.386	–0.307
TGW				–0.521	–0.531
Vegetative period					–0.262
Intermediates					
Grain yield.	0.742	–0.122	0.566	0.094	0.064
Spikes m^{-2}		–0.363	0.780	0.212	0.449
Grains $spike^{-1}$			–0.830*	0.216	–0.285
TGW				–0.079	0.522
Vegetative period					0.042
Moderns					
Grain yield.	0.817*	0.786	0.854*	0.657	–0.518
Spikes m^{-2}		0.665	0.920**	0.462	–0.358
Grains $spike^{-1}$			0.833*	0.530	–0.319
TGW				0.492	–0.306
Vegetative period					–0.965**

3.3 PATH COEFFICIENT ANALYSIS

Path coefficient analysis was performed to obtain further information on the interrelationships among traits and their effects on grain yield. For this purpose, a cause–effect system (as shown in Fig. 1) was constructed and based on the ontogeny of the durum wheat plant. Hence, the number of spikes m^{-2} and length of vegetative period are shown to have a mutual relationship (double-headed arrow). Both traits could have a reciprocal influence at early stages of wheat growth. Duration of vegetative period was believed to affect both number of grains $spike^{-1}$ and the duration of GFP. Tiller production (which determines the number of spikes m^{-2}) is known to be the first developmental process in cereals, and then it may exercise a direct influence on all other traits that are developed later. The duration of GFP could modify number of grains $spike^{-1}$ by reducing abortion of pollinated florets after anthesis [10], [11].

Path coefficients presented in Fig. 2 revealed a direct and positive effect of the three main components on grain yield for all groups of varieties. In fact and for old varieties (Diagram a, Fig. 2), a non-significant direct effect of number of spikes m^{-2}, number of grain $spike^{-1}$ and grain weight was observed on grain yield. Number of spikes m^{-2} had a direct positive effect on number of grains $spike^{-1}$ but a direct negative effect on grain weight; it had also a positive direct effect on grain filling duration. The length of vegetative period had a direct negative effect on number of grains $spike^{-1}$ while grain filling duration affected negatively grain weight. Direct effects calculated for intermediate varieties (Diagram b, Fig. 2) showed that main yield components were non-significantly but positively associated to grain yield. Number of spikes m^{-2} had a direct negative effect on number of grains $spike^{-1}$ but a direct positive effect on both grain weight and grain filling duration. In addition, number of grains $spike^{-1}$ had a direct negative effect on grain weight. Finally, path analyses for modern varieties (Diagram c, Fig. 2) revealed that number of spikes m^{-2} and grain weight had a significant direct and positive effect on grain yield. Number of grains $spike^{-1}$ had a positive although non-significant direct effect on grain yield. Number of spikes m^{-2} had a positive direct effect on the two remaining yield components. Grain weight was positively affected by number of grains $spike^{-1}$ but negatively influenced by grain filling duration. The length of vegetative period had a marked but non-significant positive effect on number of grains $spike^{-1}$.

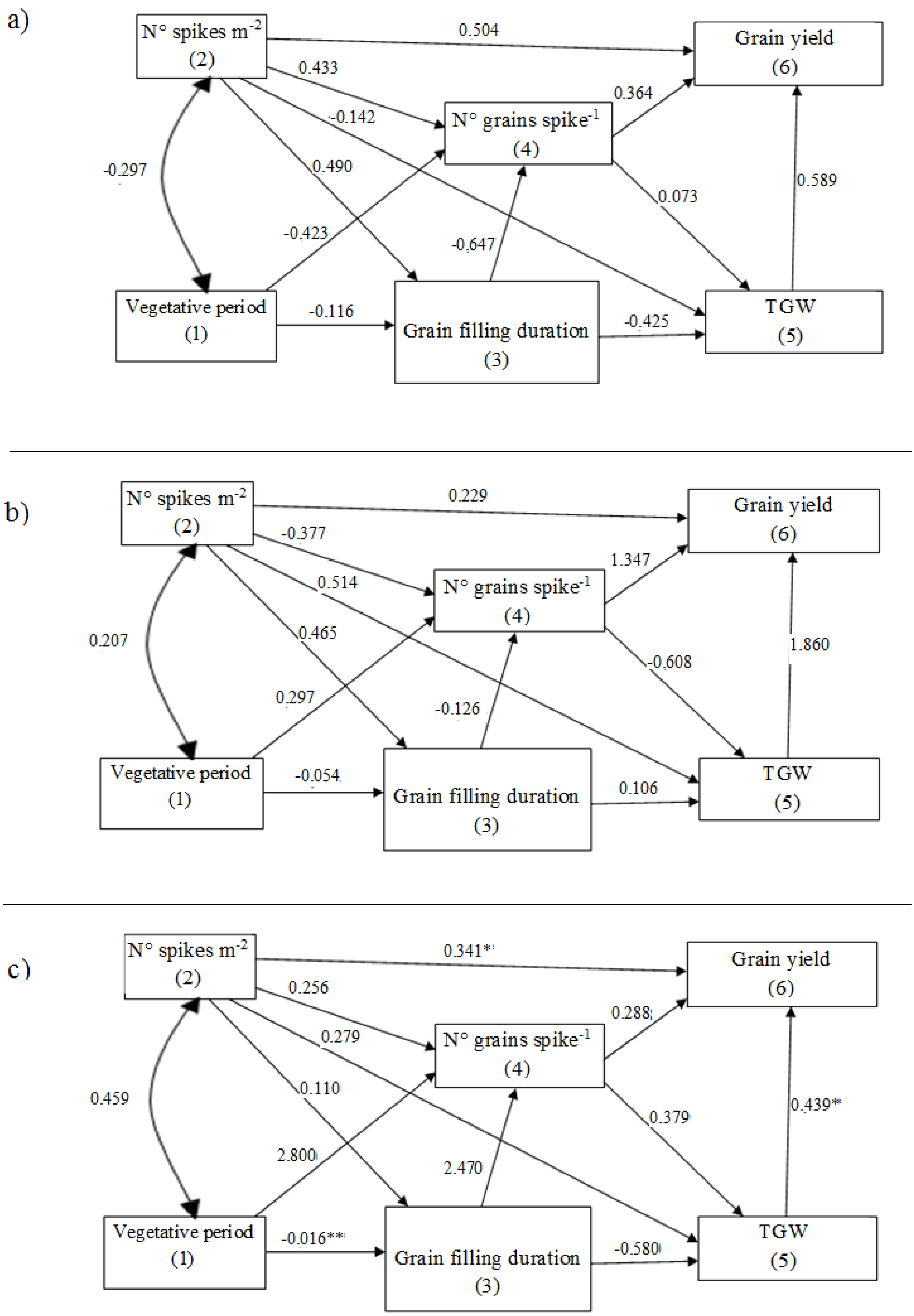

Fig 2. Path coefficient diagrams showing direct effects among the six studied characters for the three categories of varieties: olds (a), intermediates (b), and moderns (c). The single-headed arrows indicate path coefficients, and the double-headed arrows indicate simple correlation coefficients.

GENETIC GAIN IN GRAIN YIELD

Regression of mean grain yield of the six studied varieties over its year of release are displayed in Fig. 3. A marked evolution in grain yield could be observed from 1984 to 2007. Absolute changes in grain yield from old to modern varieties used in the present work had leaded to an absolute genetic gain (regression slope) of 23 kg ha^{-1} $year^{-1}$ that correspond to a relative genetic gain of 0.5% year¯1.

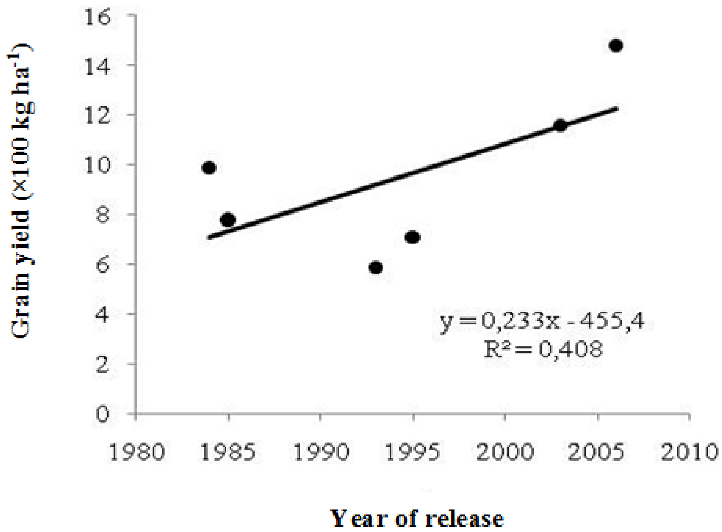

Fig. 3. Absolute changes in grain yield of six durum wheat varieties released between 1984 and 2007 in Morocco.

4 DISCUSSION

Results of the present work showed that grain yield increased in Moroccan durum wheat by about 50% from 1984 to 2007. This was mainly due to a long vegetative period allowing more accumulation of assimilates which resulted in heavier grains and higher grain yield. The positive effect of lengthening vegetative period on grain yield had been previously reported [11], [21], [22]. Evans and Wardlaw [23] indicated that variation in the duration of vegetative period accounted for 5 to 10% of the variation in grain yield.

The interrelationships among the studied characters revealed a high dependency of grain yield on its three main components particularly number of spike m^{-2} and grain weight. This was true specifically in modern varieties. Importance of number of spike m^{-2} in determining grain yield was previously reported in barley [10], [24], [25] and wheat [11], [26], [27], [28], [29], [30]. Path coefficient analysis elucidates some associations obtained by correlation coefficients. In fact, grain weight was weakly related to grain yield in intermediate varieties. This was a misleading because the direct positive effect on grain yield was masked partially by the direct negative influence that exercised number of grain $spike^{-1}$ on grain weight. This agrees with results of [26] in durum wheat and may indicate a compensatory effect between apical development, and grain growth in wheat, presumably deriving from the negative allometry between these traits during plant development [9]. Moreover, yield component compensation in cereals, arising from the fact that these components develop sequentially with later-developing components under control of earlier-developing ones [10]. One interesting point from the results is the evolution of the relationship between the length of vegetative period and grain $spike^{-1}$ and grain weight (influencing consenquently grain yield) from old to modern varieties as demonstrated by correlations and path analyses. While length of vegetative period influenced negatively number of grain $spike^{-1}$ and grain weight resulting in lower grain yield in old varieties, it was positively associated with number of grain $spike^{-1}$ and grain weight in modern varieties. The negative effect of lengthening vegetative period on number of grain $spike^{-1}$ was reported in several works under water-limited conditions [10], [26], [31]. Moreover, Giunta et al. [32] also indicated that severe water deficit around anthesis produces serious effects on wheat yield, reducing the number of spikes and spikelets and therefore causing a decrease in plant fertility.

Total absolute genetic gain in grain yield found in our study was 23 kg ha^{-1} $year^{-1}$ (50% of increase), which amounts to a relative genetic gain of 0.5% $year^{-1}$. These values are similar to the genetic yield gain of 20 kg ha^{-1} $year^{-1}$ recently reported for durum wheat in Spain [18] and 19.9 kg ha^{-1} $year^{-1}$ in Italy [33], and values of 0.4 to 0.6% $year^{-1}$ reported for bread wheat [34], [35], [36]. However, evaluations of genetic gains by the durum wheat breeding program of International Maize and

Wheat Improvement Center (CIMMYT) reached much higher values due to experiments conducted under optimal conditions [37]. In fact, Pfeiffer et al. [38] found that the gain in yield increase in durum wheat between 1967 and 1994 was 1.7% year^{-1}.

5 CONCLUSION

It could be concluded that grain yield increases in Moroccan durum wheat varieties was mainly due to lengthening the period from sowing to anthesis and a high remobilization of assimilates during grain filling that increased grain weight. Grain yield was positively affected mainly by number of spikes m^{-2} and grain weight as was showed by correlation studies, and elucidated by path analysis particularly in modern varieties. Compensatory effects among yield components was also observed in the three group of varieties. Genetic gain in grain yield within durum wheat varieties released between 1984 and 2007 in Morocco was similar to what is reported in other countries with pronounced breeding programs like Spain and Italy.

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