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Wide crosses of durum wheat (*Triticum durum* Desf.) reveal good disease resistance, yield stability, and industrial quality across Mediterranean sites

Meryem Zaïm[a,b,1], Khaoula El Hassouni[a,b,1], Fernanda Gamba[c], Abdelkarim Filali-Maltouf[a], Bouchra Belkadi[a], Ayed Sourour[d], Ahmed Amri[b], Miloudi Nachit[b], Mouna Taghouti[e], Filippo M. Bassi[b,*]

[a] Laboratory of Microbiology and Molecular Biology, Faculty of Sciences, University Mohammed V, Agdal avenue S Al Oumam Al Mouttahida-ex N. Uni, B.P. 554 - 10000, Rabat, Morocco
[b] ICARDA, Biodiversity and Integrated Gene Management, P.O. Box 6299, Rabat Instituts, Rabat, Morocco
[c] Department of Plant Protection, Faculty of Agronomy, UDELAR, Route 3 k 363, Paysandú, Uruguay
[d] Department of Agronomy and Plant Biotechnology, National Institute of Agriculture of Tunis, 43, Avenue Charles Nicole, 1082 Tunis, Tunisia
[e] Laboratory of Agro-Food Technology and Quality, National Institute of Agronomic Research, Avenue Mohamed Belarbi Alaoui B.P: 6356, Rabat-Instituts, 10101, Rabat, Morocco

A R T I C L E I N F O

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A B S T R A C T

Durum wheat (*Triticum durum* Desf.) breeders over the past century have increased the productivity and resilience of this crop via strong selection applied to genes controlling agronomically important traits. Along this process, some of the primitive genetic diversity of this species was lost. A debate exists on whether or not some of the original primitive diversity should be re-introgress into modern germplasm in order to facilitate new improvements. Here, the possible negative effects of re-introducing primitive diversity were assessed by comparing the performances of three ICARDA elites and four commercial cultivars against seventeen durum wheat wide crosses, generated by hybridization of elites and *Triticum dicoccoides, T. araraticum,* and *Aegilops speltoides*. The material was grown in Lebanon, Algeria and 10 environments in Morocco. Tested under natural inoculation against *Lr14a* virulent strains of leaf rust as well as tan spot races 4 and 6, revealed that wide crosses had significantly higher levels of resistance. Further, the use of a selection index that combined selection for grain yield potential and stability revealed that 14 wide crosses performed better than any of the elites or cultivars. Finally, testing quality traits at four sites revealed that wide crosses had significantly higher grain size and protein content than the other two germplasm classes, while no significant difference could be observed for gluten strength. Only in the case of yellow pigment, an industrially important trait for durum wheat, one variety ('Tomouh') outperformed all other classes, even though wide crosses lines also achieved good scores. Hence, it was not possible to identify any negative drag in the use of wide crosses for improving durum wheat modern germplasm, with the partial exception of yellow pigment.

1. Introduction

Durum wheat (*Triticum durum* Desf., 2n = 4x = 28, AABB) is a tetraploid cereal crop grown in a range of climatic zones varying from warm and dry to cool and wet environments (Giraldo et al., 2016). Its global acreage is estimated at 17 million hectares (ha) and the most important growing areas are situated in the Mediterranean Basin, North America, and South West Asia (Maccaferri et al., 2014). However, durum wheat is an economically important crop because of its unique rheological characteristics and the varieties of industrial end-products that can be derived from it (Gonzalez-Segura et al., 2014).These include mostly pasta, couscous, and bourghul, but also several dishes of the tradition such as frike, gofio, and several types of flat breads.

Durum wheat growing environments are mostly located in areas subject to alternating favorable and stressed conditions (Nachit and Elouafi, 2004). Therefore, genetic improvement via breeding for tolerance to biotic and abiotic stresses remains a strategic practice to improve its productivity and stability (Rajaram and Hettel, 1994; Nsarellah et al., 2000). In the last decades, many durum wheat varieties have been developed based on field assessment for higher yield, disease

* Corresponding author.
E-mail address: f.bassi@cgiar.org (F.M. Bassi).
[1] These authors contributed equally to this article.

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resistance and technological seed qualities. However, the strong selection pressure imposed through genetic improvement has eroded a large part of the genetic diversity available to breeders (Jing et al., 2013). This genetic narrowing has led to a reduction in allelic plasticity, hence to a germplasm less prone to adapt to new environmental stresses, diseases and pests (Makai et al., 2016; Tanksley and McCouch, 1997). Compared with domesticated varieties, crop wild relatives and primitive wheats have been challenged in natural environments for thousands of years and maintain a much higher level of diversity (Zhang et al., 2016). Hence, interspecific hybridization between durum elite lines and wild relatives of the *Gramineae* family is a promising method to restore variability to the modern breeding germplasm (Rajaram and Hettel, 1994). Several useful traits have been identified in species related to durum wheat, for instance about half of the leaf rust genes listed in the Catalogue of Gene Symbols for Wheat (McIntosh et al., 2003) and 20 of the known genes for stem rust resistance are derived from species other than the cultivated ones (Mcintosh et al., 1991; Mcintosh et al., 1998; Monneveux et al., 2000). In fact, wild species have been identified as a potential source of resistance to leaf rust (Anikster et al., 2005; Cherukuri et al., 2005; Kassem et al., 2011; Lalkova et al., 2004; Marais et al., 2005) and tan spot (Tadesse et al., 2006), two diseases that cause significant losses in wheat production worldwide (Goyeau et al., 2012; Martinez et al., 2005). For scale, Singh et al. (2010) reported that yield losses in durum wheat by tan spot can exceed 50% of the production, and Herrera-Foessel et al. (2006) indicated that leaf rust can be even more devastating. Likewise, *Aegilops sharonensis*, *Triticum dicoccoides, A. speltoides, A. tauschii* have all been identified as holder of resistance to powdery mildew (Gill et al., 1985; Ji et al., 2007; Jia et al., 1996; Miranda et al., 2007), stem rust (Anikster et al., 2005; Babaiants et al., 2012; Mago et al., 2009), stripe rust (Gerechter-Amitai and Stubbs, 1970; Knaggs et al., 2000; Marais et al., 2010; Valkoun et al., 1985; Yildirim et al., 1995) and to other diseases and insect pests (Ghannoum et al., 2016; El Haddoury et al., 2005).Furthermore, it has been found that members of the *Aegilops (A. tauschii, A. umbellulata, A. speltoides)*, *Triticum (T. dicoccum* and *T. dicoccoides)* and *Haynaldia* have useful traits for adaptation to drought, cold and salinity stresses (Feldman and Millet, 1993; Monneveux et al., 2000; Nachit et al., 2015; Plamenov, 2003; Trethowan and Mujeeb-Kazi, 2008; Trethowan, 2014). Also, the potential of using *T. dicoccoides* as a source of genetic variation to improve the baking quality of durum wheat was suggested (Feldman and Millet, 1993; LeClerc et al., 1918).

Regardless of the proven usefulness of wild relatives for trait discovery and deployment in pre-breeding, wheat breeders have often regarded to this type of crosses as a “last resource” that will inevitably require several years and multiple recurrent cycles before delivering a promising candidate for variety release (Brown and Marshall, 2015). This was mostly due to the risk indicated by several authors that undesirable linkage drag exist between useful wild traits and negative yield or quality alleles (Mondal et al., 2016). One of the exception to this breeding trend has been the ICARDA durum wheat program that broadly utilized wild relatives and landraces into their hybridization (Nachit and Elouafi, 2004).This is demonstrated by the release in 1981 of the first ICARDA mega cultivar ‘Om Rabi’, derived by the simple cross between the elite ‘Jori’ and the landrace ‘Haurani’ (Nachit, 1992). This cultivar is still cultivated today in 21 countries, mostly in the driest environments by smallholder farmers (Latican et al., 2016). Further, ‘Om Rabi’ proved to be an excellent parent, with several recent releases derived from its hybridization (Nachit et al., 2016). To further this knowledge, this article utilizes top-crosses between wild relatives of durum wheat and elite lines of the ICARDA breeding programs to assess their possible demerits for yield drags, to identify their biotic stress response, and to quantify the negative effect of wild alleles on rheological quality.

Table 1
List of 24 durum wheat genotypes used in this study and their simplified code.

Code	Type	Cross
WC1	Wide cross	Amedakul1/TdicoSyrCol//Cham1
WC2	Wide cross	Omrabi5/TdicoAlpCol//Cham1
WC3	Wide cross	Younes/TdicoAlpCol//Korifla
WC4	Wide cross	Korifla/AegSpeltoidesSyr//Amedakul
WC5	Wide cross	Amedakul1/TdicoSyrCol//Loukos
WC6	Wide cross	Korifla/AegSpeltoidesSyr//Heider
WC7	Wide cross	Omrabi5/TdicoAlpCol//Cham1
WC8	Wide cross	Korifla/AegSpeltoidesSyr//Omrabi5
WC9	Wide cross	Amedakul1/TdicoSyrCol//Cham1
WC10	Wide cross	Korifla/AegSpeltoidesSyr//Loukos
WC11	Wide cross	Korifla/AegSpeltoidesSyr//Omrabi5
WC12	Wide cross	Korifla/AegSpeltoidesSyr/Amedakul
WC13	Wide cross	Amedakul1/TdicoJCol//Cham1
WC14	Wide cross	Younes/TdicoAlpCol//Korifla
WC15	Wide cross	Heider/TAraticumMA//Omrabi5
WC16	Wide cross	Korifla/AegSpeltoidesSyr//Omrabi5
WC17	Wide cross	Korifla/AegSpeltoidesSyr//Lahn
Louiza	Cultivar	Rascon_39/Tilo1
Faraj	Cultivar	F413J.S/3/Arthur71/Lahn//Blk2/Lahn/4/Quarmal
Waha	Cultivar	Plc/Ruff//Gta/Rtte
Tomouh	Cultivar	Joric69/Hau
Icakassem1	Elite	Geromtel1/Icasyr1
Secondroue	Elite	Stj3//Bcr/Lks4/3/Ter3/4/Bcr/Gro1//Mgnl1
Icarnada	Elite	Src2/Azn1/3/Bcr/Gro1//Mgnl1

2. Materials and methods

2.1. Plant material

Twenty-four durum wheat genotypes were selected for this study. Seventeen wide crosses (WC) F_{12} derived by top crosses involving ICARDA parents with *T. dicoccoides, T. araraticum* and *A. speltoides,* were selected on the basis of leaf rust (LR, *Puccinia triticina*) and tan spot (TS, *Pyrenophora tritici-repentis*) response in one season and one environment in Morocco (data not shown). In addition, three new commercial varieties released in Morocco; ‘Tomouh’, ‘Faraj’, ‘Louiza’ and one Algerian variety ‘Waha’ (syn. ‘Cham1’) were used as checks. Finally, three elite lines were included from the ICARDA program derived by top crosses of “best-by-best” selected from the international nursery 37th IDYT on the basis of their good performances in Moroccan environmental conditions (data not shown). The full list of pedigrees is reported in Table 1.

2.2. Locations, experimental design and management practices

The genotypes were assessed in ten different agro-climatic conditions (environments) as described in Table 2, eight where located in Morocco: Sidi Allal Tazi (ALT), Jemhâa Shaim (JS), Marchouch (MCH), Melk Zhar (MKZ), Sidi el Aydi (SAD), Tessaout (TES), Laarache (LRC) and Guich (GCH), one in Lebanon: Terbol (TER), and one in Algeria: El Khroub (ELK). The experiments were run during the 2013-14 (14) and the 2014-15 (15) seasons. The experimental design used at all stations was alpha-lattice with two replications and six incomplete blocks of size four. Each entry was planted in plots of 6 rows of 5 m in length, row spacing was 0.2m, for a total sown surface of 6 m^2at a seeding rate of 120 kg ha^{-1}. Agronomic practices varied based on the station, but followed the general guidelines of sowing between 15th of November and 15th of December with a base pre-sowing fertilizer application of 50 kg ha^{-1} of N, P, and K. Planting always occurred after a fallow season, with the exception of the Lebanese site where the precedent crop was lentil. At stage 14 on Zadok's scale (Z) herbicide was applied in a tank mixture to provide protection against both monocots and dicots. A week after herbicide application, ammonium nitrate was provided to add 36 kg ha^{-1} of N. In MCH15, TER15 and TES15 a final