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Tritordeum, wheat and triticale yield components under multi-local mediterranean drought conditions

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ABSTRACT

The species × location interaction was of great importance in explaining the behaviour of genetic material. The study presented here shows, for the first time, the performance, under field conditions of the new tritordeum species, compared to wheat and triticale in a wide range of Mediterranean countries (Spain, Lebanon and Tunisia). The results obtained revealed that despite the diversity of environmental conditions, the main differences in yield were due to genotypes, especially to differences between species.

The multi-local study with different growth conditions revealed important information about the water availability effect on yield. In the lowest yielding environments (Tunisia rainfed), Tritordeum and triticale yields were equivalent. However under better growth conditions (Spain), tritordeum yield was shown to be lower than wheat and triticale. Interestingly, when water limitation was extended during the pre-anthesis period, differences in tritordeum versus wheat-triticale yield rate were larger than when water stress occurred during anthesis. These variations were explained by the fact that kernel weight has been found as the limiting factor for yield determination in tritordeum, and a delay in the anthesis date may have been the cause for the low kernel weight and low yield under Mediterranean drought conditions. Such differences in yield between tritordeum and wheat or triticale could be explained by the fact that tritordeum is a relatively new species and far fewer resources have been devoted to its improvement when compared to wheat and triticale. Our results suggest that breeding efforts should be directed to an earlier anthesis date and a longer grain filling period.

Tritordeum proved to have possibilities to be grown under drought environments as a new crop, since its performance was quite close to wheat and triticale. Besides, it has qualitative added values that may improve farmers' income per unit land.

1. Introduction

According to the different scenarios predicted by the Intergovernmental Panel on Climate Change (IPCC, 2007) for the Mediterranean basin, a reduction in precipitation and rising evapotranspiration rates are expected. Drought is the main abiotic stress affecting cereal crops production in the Mediterranean area and is predicted to be intensified with climate change (Mannion, 1995; Araus et al., 2002).

Although water scarcity may affect plant growth during different phenological stages, as described by Edmeades et al. (1989), it is generally more relevant during anthesis and the grain filling period. Whereas harvest index (HI) is reaching a ceiling in favourable environments (Araus et al., 2003a,b), in Mediterranean conditions there is still room for yield improvement through changes in crop development. Thus drought stress at critical stages, relative proportions of pre- to post-anthesis biomass, mobilisation of pre-anthesis assimilates to reproductive organs and patterns of water supply during the vegetative cycle may all limit HI and thus final yield (Araus et al., 2002; Richards et al., 2002).

The progressive increase in drought during late spring coincides with grain filling in cereal crops in the Mediterranean basin (Acevedo et al., 1999; Araus et al., 2002). Reducing of crop duration (i.e. escape from the stress) has been a very successful strategy in plant breeding programmes applied to the Mediterranean region (Araus et al., 2002). Greater early vigour and/or faster phenological

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Table 1
Characteristics of the Mediterranean locations (three in Spain, one in Lebanon and one in Tunisia) where experiments were conducted in field conditions.

Zone	Coordinates				Agronomic characteristics	
	Location	Latitude	Longitude	Altitude (m)	Terminal stress	Productivity
Spain (Catalonia)	Gimenells	41°38′N	0°23′E	200	Moderate	Medium-High
Lebanon	Tal-Amara	33°51′N	35°59′E	902	Moderate	Medium
Spain (Andalusia)	Córdoba	37°51′N	4°48′W	120	Moderate	Medium
Spain (Andalusia)	Granada	37°10′N	3°40′W	650	High	Medium-low
Tunisia	Nabeul	36°38′N	10°45′E	10	Moderate	Low

development (earlier maturity) would allow more efficient consumption of water resources, ensuring that more water could be available for plant growth during the grain filling period where drought is more severe (Araus et al., 2002, 2008). However, the suitability of adopting early vigour and phenological adjustment as breeding traits will strongly depend on the nature of water stress and its interaction with other environmental conditions (Araus et al., 2002).

A decrease of the genetic variability in major crops (i.e. wheat, maize, rice) is increasing the vulnerability of agriculture to predicted climate change scenarios (IPCC, 2007; Kotschi, 2007). Plant genetic resources for agriculture might be one of the biological bases of world food security. Thus, obtaining drought tolerant crops for Mediterranean environments is a strategic goal for the future of breeding programmes. Compared with temperate regions, conventional plant breeding programmes carried out in water-limiting regions only increased the yield of crops grown by about half (Turner, 2004). To increase yield under drought in Mediterranean environments, it is necessary to improve the yield of crops by farm management practices and plant breeding (Hatfield et al., 2001; Richards et al., 2002), the second approach being the most promising in the long term (Miflin, 2000; Araus et al., 2002).

Tritordeum (×Tritordeum Ascherson et Graebner) is a fertile amphiploid derived from the crosses between Hordeum chilense Roem. et Schultz. as the maternal parent, and either tetraploid or hexaploid wheat (Martin and Chapman, 1977; Martín and Sánchez-Monge Laguna, 1982). Tritordeum has been subject of a breeding programme to become a new crop, and it has also been used as a genetic bridge for transferring useful barley traits like storage proteins or carotene content to wheat (Martín et al., 1999; Ballesteros et al., 2005). Tritordeum is known to have high levels of seed carotenoid content (Ballesteros et al., 2005; Atienza et al., 2007a), high protein content (Millán et al., 1988) and adaptation to Mediterranean environments. Its parental species, H. chilense, shows different traits that may be potentially useful for wheat breeding including resistance to different diseases or tolerance against drought or salinity, and a high variability for endosperm storage proteins with influence in breadmaking (Martín and Cabrera, 2005). Tritordeum has been found to have a delayed anthesis date, lower yield and lower kernel weight than wheat (Millán et al., 1988). The new tritordeum genotypes from the current breeding programme have not been extensively tested at field level in a set of environments with different yield potentials.

The objective of this study was to analyse yield and yield components to determine the potential of tritordeum as a new crop in a range of field conditions in several Mediterranean locations and environments.

2. Materials and methods

Six field experiments were conducted during the 2007/2008 season in five Mediterranean regions located in Spain (Gimenells, Córdoba and Granada), Lebanon (Tal-Amara) and Tunisia (Nabeul), see Table 1 for details. Genetic material comprised four genotypes of hexaploid tritordeum (HT621, HT374, HT376, HTC2078), obtained at the CSIC of Córdoba, Spain, by Antonio Martín. HT621 is a doubled haploid deposited at the USDA National Plant Germplasm System (PI 636334) (USDA, 2004). This line shows a high yellow pigment content, between 18 and 20 ppm, and was obtained by the maize method from HT263, a secondary hexaploid tritordeum (Ballesteros et al., 2005). Both HT374 and HT376 were selected as free-threshing tritordeums. These lines were derived from crosses between tritordeum and bread wheat as a result of an extensive search for free-threshing. Both lines carry a chromosome substitution 5D/(5H^{ch}) as demonstrated using both molecular and cytological tools (Atienza et al., 2007b). Finally, HTC2078 was obtained by the genealogical method and selected for yield.

The field trials also included two varieties of wheat (Bancal and Califa Sur) and two varieties of triticale (Imperioso and Titania), all these varieties being relatively new, and grown in Spain. The experiments consisted on a randomised complete block design with three replications and plots of 6 m^2, with 6 rows, 0.2 m apart.

Experiments were planted between November the 15th and December the 15th, these dates being within the usual planting date in each location. Seed rate was adjusted to 400 viable seeds m^{-2}. Agronomic practices were the ones common for each location, in order to maintain the crop free from diseases and pests. Meteorological conditions experienced during the season are shown in Fig. 1. All experiments were conducted under rainfed conditions, except of the Nabeul irrigated one, which received 30 mm of irrigation (Fig. 1).

The date of anthesis was recorded when at least half of the main heads in each plot reached stage Z65 (Zadoks et al., 1974). The physiological maturity date was recorded as the day when spikes completely lost their green colour. Grain filling duration was calculated as the difference between the number of days to anthesis and the number of days to physiological maturity. At maturity, a sample was taken consisting of plants contained in a 1-m-long portion of a central row. From this sample, the number of spikes per m^2, and the number of grains per spike were obtained. Plots were harvested at commercial ripening, and kernel weight (mg) was calculated from a randomly chosen sample of 200 grains. Grain filling rate (mg/day) was estimated from the ratio between kernel weight and grain filling duration. Plots were mechanically harvested and yield (g/m^2) was calculated from a plot basis.

Analyses of variance for yield, yield components and phenology traits (days to anthesis and grain filling duration) were carried out considering location, species and genotypes as fixed factors. The genotype sum of squares percentage over the total modelled was divided into variation due to species, and differences attributable to genotypes within species. When factors were significant at $P < 0.05$, mean values were calculated and separated according to the Duncan's Multi-range Test. Forward multiple regression analysis with yield as the dependent variable and yield components as independent variables was carried out, any variable being included in the model if it was significant at $P < 0.05$, and Pearson correlation coefficients were calculated from the means of the three blocks in each experiment. All statistical analyses were carried out with the SAS package (SAS Inc, Cary 2000).

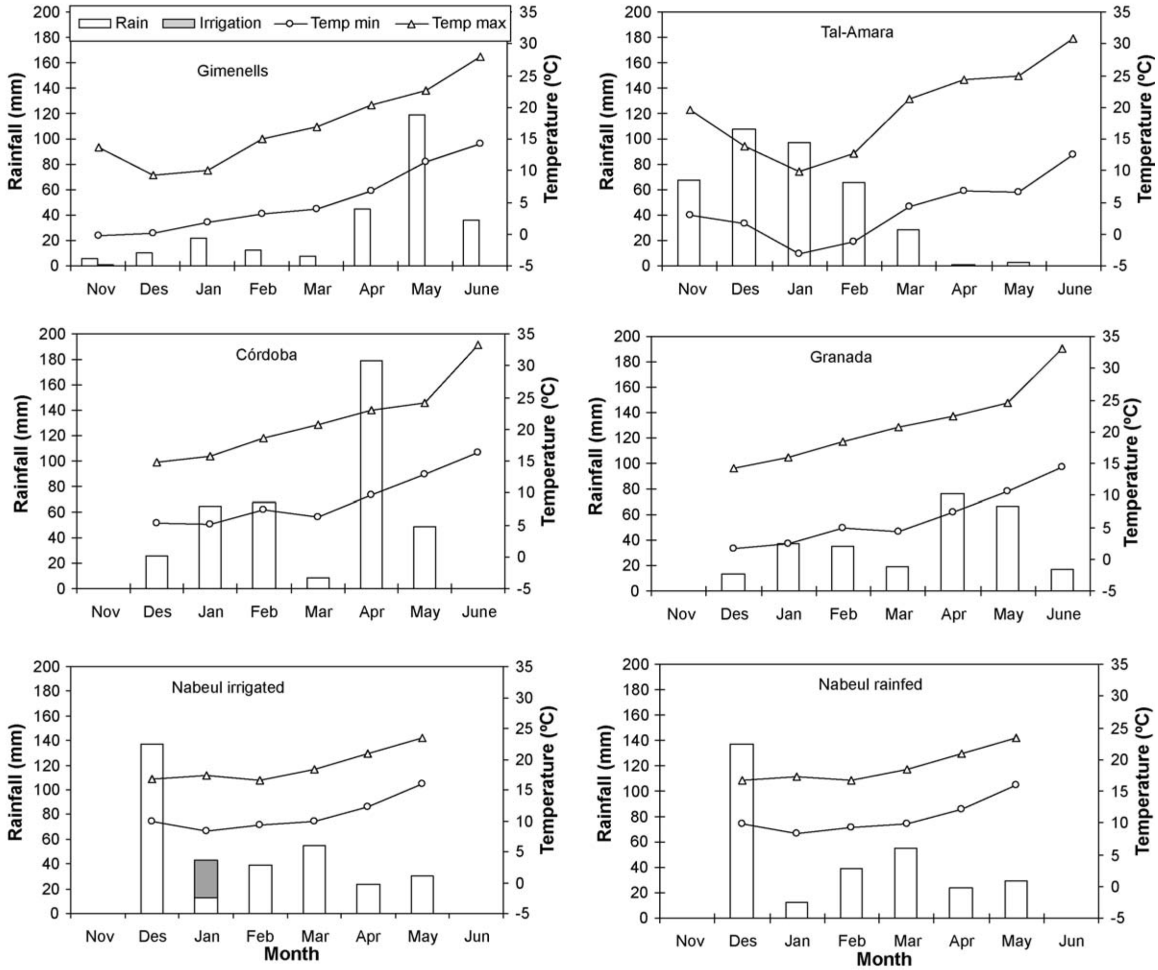

Fig. 1. Rainfall, irrigation, minimum and maximum temperatures during the 2007–2008 cropping season in the five locations studied.

3. Results and discussion

Meteorological events during the 2007/08 season gave a high contrast to the experiments (Fig. 1), especially for the amount and distribution of rainfall. Some experiments were carried out under drought during the first part of the cycle (Gimenells, Granada); in others, drought occurred during grain filling (Tal-Amara, Nabeul), and the remainder had a constant but low amount of rainfall (Granada). Temperature data (Fig. 1) revealed that both Andalusian regions (Córdoba and Granada) reached the highest maximum temperature values, whereas the region in Tunisia (Nabeul) had the lowest temperature values.

The analyses of variance for yield (Table 2) showed that genotype was the main factor determining the differences in yield between treatments (44%), and due largely by differences between species (43.7%). Location explained 31.4% of yield total variability. The interaction location × genotype explained 18.3% of total variability, a great proportion of which was due to the location × species interaction. The location × genotype factor within species was even more important than genotype alone to explain yield. The variability of spikes/m^2, days to anthesis and grain filling duration was mainly due to location (71.7, 96.7 and 85.2% of total variability, respectively), while grains per spike was mainly explained by the location × genotype interaction. Finally, kernel weight was mainly explained by the genotype factor, and differences were mainly due to the species factor (Table 2).

3.1. Differences between locations

Despite the particular conditions of the year, location mean yields were in accordance with the yield potential of the location (Table 1). Thus, Gimenells and Tal-Amara were the highest yielding locations, followed by Cordoba and Granada, with Nabeul being the most limiting environment. As described in more detail below, the water availability and ambient temperature (Fig. 1) determined production in the different species.

Gimenells was the highest yielding location but the number of spikes/m^2 was the third in the rank, which can be explained by the low water availability in the first part of the growth cycle (Table 3). The relatively late anthesis of the crops grown in Gimenells was compensated by a sufficient period of grain filling that enabled the crop to maximise its yielding capacity.

Tal Amara was also a high-potential environment, but yield was somehow lower than in Gimenells. The water distribution was completely different, thus having a superior number of spikes per unit land that was enabled by a large amount of water during the first part of the cycle (Table 3). Our data suggest that water limitation during post-anthesis limited crop yield to a larger extent than water limitation during pre-anthesis water stress.

Despite having more water available, crops in *Córdoba* and *Granada* had a lower yield than crops in Gimenells and Tal-Amara. This fact may have been due to higher temperatures on those locations (Fig. 1). Differences between the yields in Cordoba and Granada could be explained by a different number of spikes/m^2,

Table 2
Mean squares (percentage of the sum of squares between parenthesis) explained by the ANOVA model for yield, yield components and phenology measured in experiments carried out in 2008. The genotype sum of squares was divided into differences attributable to species and to genotype within species.

Source of variation	d.f.	Yield	Spikes/m^2	Grains/Spike	Kernel Weight	Days sowing-anthesis	Grain filling duration
Location	5	210937 (31.4) ***	358773 (71.7) ***	115 (11.6) ***	516 (22.0) ***	9707 (96.7) ***	1447(85.2) ***
Genotype	7	211467 (44.0) ***	28073 (7.9) ***	223(31.6) ***	1115 (66.6) ***	155 (2.2) ***	87 (7.2) ***
Species	2	**734761 (43.7)** ***	**57239 (4.6)** ***	**624** (25.2) ***	**3011 (51.4)** ***	**438** (1.7) ***	**280** (6.6) ***
Genotype within tritordeum	*3*	*1273 (0.1) ns*	*18606 (2.2) ****	*74 (4.5) ***	*302 (7.7) ****	*65 (0.4) ****	*13 (0.5) ****
Genotype within wheat	*1*	*1179 (0.0) ns*	*26208 (1.0) ***	*83 (1.7) **	*836 (7.1) ****	*4 (0.0) ***	*8 (0.1) ***
Genotype within triticale	*1*	*5750 (0.2) ns*	*5 (0.0) ns*	*7 (0.1) ns*	*38(0.1) ***	*9 (0.0) **	*5 (0.1) ns*
Location × Genotype	35	17580 (18.3) ***	13232 (18.5) ***	72 (50.9) ***	35 (10.3) ***	16 (1.1) ***	18 (7.5) ***
Location × Species	**10**	**45194 (13.4)** ***	**30009 (12.0)** ***	**122** (24.7) ***	**76 (6.5)** ***	**41** (0.8) ***	**49 (5.8)** ***
Location × Genotype within tritordeum	*15*	*3935 (1.8) **	*8036 (4.8) ****	*48 (14.6) ***	*20 (2.5) ****	*5 (0.1) ***	*6 (1.0) ****
Location × Genotype within wheat	*5*	*10690 (1.6) ****	*1244 (0.2) ns*	*23 (2.3) ns*	*23 (1.0) ****	*5 (0.0) ****	*6 (0.4) ****
Location × Genotype within triticale	*5*	*101731 (1.5) ****	*7255 (1.4) **	*92 (9.3) ***	*8 (0.3) ns*	*10 (0.1) ***	*5 (0.3) **
Replication within location	12	6731 (2.4) ***	4018 (1.9) ns	24 (5.9) ns	10 (1.0) **	1 (0.0) ns	1 (0.1) ns

ns: non-significant at $P < 0.05$; *: $0.05 < P < 0.01$; **: $0.01 < P < 0.001$;***: significant at $P < 0.001$.

given that the rest of the components were not significantly different. It has been reported that in Granada the number of spikes/m^2 was the limiting factor for yield (García del Moral et al., 2003).

The *Nabeul* experiments showed that the extremely low water availability throughout the entire experiment and especially during grain filling, together with the lower ambient temperature conditions (Fig. 1), could have limited the yield. As a consequence of the stressful growth conditions compared with the other locations, crops grown in Nabeul reached anthesis sooner and grain filling was reduced. The irrigation at the beginning of the cycle was very effective to mitigate drought, but the harsh conditions of the location had as a consequence the lowest yield of the experimental set.

3.2. Differences between species

Wheat and triticale were found to yield similarly, while, generally, tritordeum showed a lower yield (Table 4). On average, compared to wheat and triticale, tritordeum reached anthesis about 8 days later. The grain filling duration was longest in triticale, followed by wheat, with tritordeum being the species with the shortest grain filling period. Given that under Mediterranean conditions the date of anthesis is an important trait of drought tolerance (Araus et al., 2002, 2008; Bruns, 2009; Loss and Siddique, 1994), the delay of more than a week in tritordeum during the more stressful growing period (especially in Córdoba and Granada) may have been crucial in the decrease of the final yield. The number of spikes/m^2 was similar for tritordeum and wheat, but lower for triticale. Grains per spike were different in all species, with triticale being the most favoured and tritordeum being the species with a lower value. Kernel weight was similar for wheat and triticale, while tritordeum had a significantly lower value. Two of the three yield components were lower in tritordeum (grains per spike and kernel weight), and they could not be compensated by a higher number of spikes per unit land, which was similar to wheat (Table 4). In tritordeum, a certain delay in anthesis date and low kernel weight had already been reported (Millán et al., 1988).

3.3. Location × species interaction

According to Table 2, the location × genotype interaction was significant for all traits studied, but its percentage of explained variation was mainly due to the location × species interaction. Despite being highly significant, the interaction for phenological

Table 3
Mean values by location of variables measured in field experiments carried out during the 2007/2008 season.

Location	Yield (g/m^2)	Spikes/m^2	Grains/spike	Kernel weight	Days sowing-anthesis	Grain filling duration
Gimenells	430a	428.3c	22.9a	43.77a	162a	43.7b
Tal-Amara	402ab	634.2a	18.2b	35.26c	158b	34.9d
Cordoba	387b	462.9b	24.5a	36.76b	119d	48.5a
Granada	326c	367.8d	23.5a	37.52b	142c	37.2c
Nabeul irrigated	258d	358.8d	22.8a	31.43d	118d	29.9e
Nabeul rainfed	170e	260.2e	21.9a	30.36d	118d	27.7f

Different letters within a column indicate significant differences at $P < 0.05$ according to the Duncan criterion.

Table 4
Mean values by species of variables measured in field experiments carried out during the 2007/2008 season.

Species	Yield (g/m^2)	Spikes/m^2	Grains/spike	Kernel weight (mg)	Days sowing-anthesis	Grain filling duration
Tritordeum	234b	443a	19.4c	29.5b	141a	36.0c
Wheat	419a	447a	23.2b	41.0a	133b	37.3b
Triticale	434a	372b	26.6a	43.1a	134b	39.9a

Different letters within a column indicate significant differences at $P < 0.05$ according to the Duncan criterion.

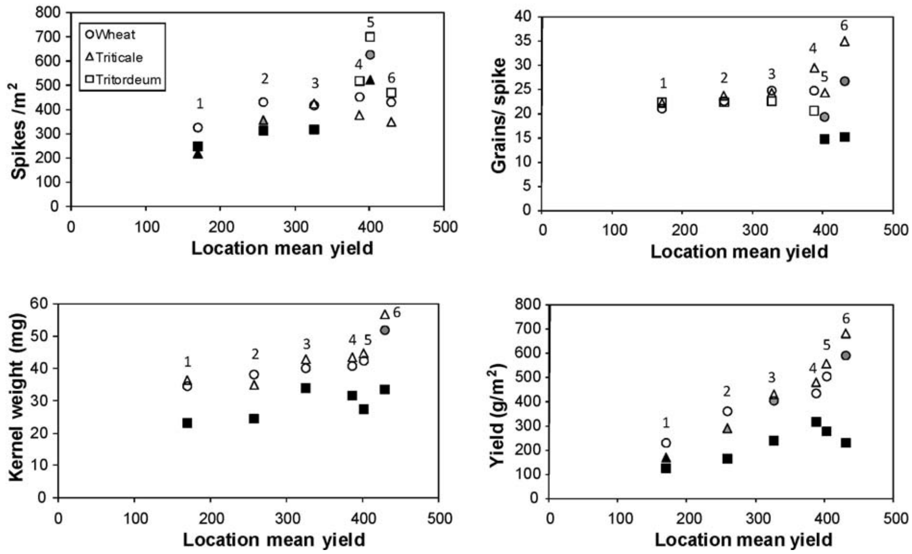

Fig. 2. Mean values by location and species of variables measured in field experiments carried out during the 2007/2008 season. Locations are indicated with a number over the vertical position of points (1: Nabeul rainfed; 2: Nabeul irrigated; 3: Granada; 4: Cordoba; 5: Tal-Amara; 6: Gimenells). Different colors within a location denote significant differences between species at $P < 0.01$.

traits was of minor importance in terms of percentage and is not further discussed. For yield and yield components, the mean values by species and location was plotted against the mean yield of each location (equivalent to yield potential, Fig. 2).

Fig. 2 shows that the three lowest yielding locations had a contrasting behaviour. The more specific analyses of the differences in crop production between the different species (Table 5) revealed important differences depending on the water limitation period. Our data revealed that the differences between yield of wheat and tritordeum (Fig. 2) were larger when water limitation took place during the pre-anthesis period (Gimenells) rather than when it occurred during the post-anthesis period (Tal-Amara). It was also remarkable that the differences in yield between tritordeum and wheat were lower in the location where water availability was more limiting (i.e. Nabeul; Turner et al., 1994). The fact that tritordeum had a lower biomass (data not shown) suggest that these plants transpired less water and that consequently, compared with the wheat and triticale, tritordeum could have extended the water availability period.

In locations with a mean yield below 350 g/m^2, the number of spikes/m^2 was steady, and tritordeum tended to have a low number of spikes/m^2 thus economising resources. The number of grains per spike was similar for all species under these drought environments, but kernel weight was significantly lower in

Table 5
Tritordeum genotype means for yield components on each location. Triticale and wheat means are also included for comparison.

	Gimenells	Tal-Amara	Cordoba	Granada	Nabeul irrigated	Nabeul rainfed
Spikes/m^2						
HT621	515.6ab	676.6ab	563.3ab	306.7b	343.7b	279.7ab
HT374	497.8ab	736.7a	596.7a	312b	325.6b	249.4ab
HT376	537.8a	706.7ab	406.7c	320b	310.2bc	216.2b
HTC2078	320d	663.3ab	483.3abc	322.7b	263.5c	236.9b
Triticale	346.7cd	520c	375c	423a	352.3b	214.3b
Wheat	431.1bc	625b	451.7bc	417.7a	429.3a	325.7a
Grains/spike						
HT621	12.6c	15.5bc	16.5b	22.9abc	17.9b	18.4a
HT374	17.2c	11.3c	17.6b	26.8a	26.7a	27.1a
HT376	15.7c	14.9bc	33.3a	21.2bc	25.5a	21.9a
HTC2078	14.5c	16.7b	18.0b	19.3c	19.5b	22.2a
Triticale	34.9a	24.3a	30.6a	24.2abc	23.6ab	22.1a
Wheat	26.7b	19.3b	24.7ab	24.7ab	22.5ab	21.0a
Kernel weight (mg)						
HT621	29.7d	29.3b	32.9bc	33.8bc	22.0b	21.3c
HT374	29.9d	26.6bc	26.7c	30.7c	21.3b	22.8bc
HT376	32.9d	24.0c	28.2c	31.6bc	17.6b	17.5c
HTC2078	40.9c	28.8b	38.2ab	39.0abc	35.6a	30.0ab
Triticale	56.7a	44.6a	43.4a	42.8a	34.8a	36.3a
Wheat	51.7b	42.0a	40.6a	39.7ab	37.7a	34.3a
Yield (g/m^2)						
HT621	182.5b	306.7b	303.6c	234.4bc	135.6c	109.6bc
HT374	257.6b	222.2c	281.4c	254.1b	185.4c	154.3abc
HT376	277.2b	252.2bc	352.5bc	213.9c	139.5c	82.3c
HTC2078	187.5b	316.7b	331.8bc	243.4bc	184.5c	156.8abc
Triticale	681.5a	556.7a	480.2a	429.2a	287.6b	168.4ab
Wheat	587.2a	503.1a	431.7ab	401.5a	359.0a	230.0a

Table 6
Forward multiple regression analysis for the relationship between yield and its components for each location, where experiments were carried out during the 2007/08 season.

Location	Yield component	Partial R^2	Accumulated R^2	P
Gimenells	Grains/spike	0.968	0.968	<0.0001
Tal-Amara	Grain weight	0.979	0.979	<0.0001
	Grains/spike	0.007	0.986	0.002
	Spikes/m^2	0.006	0.992	0.0005
Cordoba	Grain weight	0.962	0.962	<0.0001
	Grains/spike	0.021	0.983	<0.0001
Granada	Spikes/m^2	0.968	0.968	<0.0001
	Grain weight	0.005	0.973	0.048
Nabeul irrigated	Grain weight	0.953	0.953	<0.0001
	Spikes/m^2	0.012	0.965	0.020
Nabeul rainfed	Grain weight	0.922	0.922	<0.0001
	Spikes/m^2	0.026	0.947	0.009

tritordeum than wheat and triticale. As a result, yield of tritordeum was lower than the other species in all cases. Nevertheless, in the lowest yielding environment, the yield of tritordeum was not statistically different from the triticale yield.

3.4. Variability for yield components within tritordeum

According to 2, within tritordeum the location × genotype factor was highly significant for spikes/m^2, grains/spike and kernel weight, explaining an important portion of the total location × genotype interaction. Means by genotype were calculated for tritordeum in each location, and compared among the genotypes using the Duncan criterion with the means for triticale and wheat as reference. Results are shown in Table 5.

In the higher yielding environments (Gimenells, Al-Amara and Córdoba), most genotypes of tritordeum had superior values of spikes/m^2 than wheat or triticale, except HTC2078. On the other hand, the number of spikes/m^2 was in general lower, this being also true for HTC2078, thus indicating that this genotype had a low number of spikes/plant and the possibility of devoting all resources to a few spikes instead of wasting carbohydrates on sterile tillers. The number of grains per spike reinforced this hypothesis, since values were not significantly different for most locations, except in Gimenells and partially in Tal-Amara (coinciding with the excessive number of spikes/m^2), where the number of grains/spike in tritordeum was lower than for wheat or triticale. tritordeum kernel weight was lower in many locations, except in one case, again for HTC2078, which had lower values but these were not significantly different from wheat or triticale under medium to low yielding environments.

Even though all yield components of HTC2078 did not differ from wheat or triticale in many environments, yield for this genotype was significantly equivalent only to wheat in Cordoba and rainfed triticale in Nabeul, being significantly lower in all other cases. This fact was possible because yield was the product of all components, and accumulated differences in all components resulted finally in yield being lower than any component alone. It was, however, noteworthy that the HTC2078 genotype was quite close to species bred for decades (such as triticale) or millennia (such as wheat) and its disadvantage was low in the most limiting environments.

3.5. Relationship between yield and yield components

In order to ascertain which yield components were the most important to define yield, Forward multiple regression analyses were conducted considering yield as the dependent variable and yield components as independent variables. In Table 6, analyses were separated by locations, and the most important yield component was grain weight, with R^2 values above 90% of yield variations in all locations except Gimenells (where the most important was grains/spike) and Granada (the most important component was spikes/m^2). Even though in Gimenells it has been reported that yield was mostly explained by kernel weight (García del Moral et al., 2003), in this case yield was mostly related to grains/spike. This can be explained by the particular drought conditions during the 2007/08 season, in which the first part of the cycle was dry, up to the moment of determination of grains/spike, while the grain filling phase was not limiting because of the late rains that had fallen during spring. In Granada, with more steady water conditions, García del Moral et al. (2003) reported that the number of spikes/m^2 was the major factor explaining yield, as mentioned before.

Table 7
Forward multiple regression analysis for the relationship between yield and its components for each species, for experiments carried out during the 2007/08 season.

Species	Yield component	Partial R^2	Accumulated R^2	P
Tritordeum	Grain weight	0.918	0.981	<0.0001
	Spikes/m^2	0.033	0.951	<0.0001
	Grains/spike	0.009	0.960	0.0003
Wheat	Grain weight	0.947	0.947	<0.0001
	Grains/spike	0.012	0.959	0.0036
	Spikes/m^2	0.006	0.965	0.0281
Triticale	Grain weight	0.929	0.929	<0.0001

Table 7 shows the results of the multiple regression analyses when considering each species separately. In all cases kernel weight was the main yield component explaining yield, again with R^2 values above 90%. Given that kernel weight is the product of grain filling duration and its rate, Pearson correlation coefficients were calculate between kernel weight and grain-filling traits (Table 8). Results indicate that grain filling duration was the most important variable in defining both kernel weight and yield. For tritordeum, grain filling duration was highly significantly correlated with both yield and kernel weight, indicating that the 10-day delay of anthesis may be a limiting factor for grain filling and yield performance, especially under the Mediterranean conditions where late drought is a usual occurrence (Bruns, 2009; Loss and Siddique, 1994). In the case of triticale, grain weight was also a critical yield component (Tables 7 and 8), which had already been reported due to the fact that the high number of grains per spike of this species may put grain filling at risk under late drought (Ozkan et al., 1999).

3.6. Concluding remarks

This multi-local study carried out under a wide range of Mediterranean field conditions provided, for the first time,

Table 8
Pearson correlation coefficients between grain yield and thousand kernel weight, calculated from means by genotype and location.

	Correlation with kernel weight			Correlations with yield		
	Tritordeum	Wheat	Triticale	Tritordeum	Wheat	Triticale
Grain filling duration	0.56**	0.47	0.71*	0.67***	0.61*	0.78**
Grain filling rate	0.40	0.50	0.31	−0.20	−0.02	0.01

*: 0.05 > P > 0.01; **: 0.01 > P > 0.001; ***: P < 0.001.

information about the performance of new tritordeum genotypes compared with a sample of currently grown wheat and triticale varieties. Our data revealed that although the genotype factor was the main factor conditioning yield, performance was mediated by the amount of water and by the period when water limitation arose. In the location where water availability was more limiting throughout the year (Nabeul, Tunisia), the yield of tritordeum was closer to wheat and especially to triticale. However, under better growing conditions (locations in Spain and Lebanon) tritordeum yield was shown to be lower than in wheat and triticale. More studies will be needed to assure the potential of tritordeum under Mediterranean drought conditions.

This study also revealed that when water limitation was extended during the pre-anthesis period, differences in the tritordeum versus wheat-triticale yield rates were larger than when water stress was imposed during anthesis. These variations were explained by the fact that kernel weight has been found as the limiting factor for yield determination in tritordeum, and a delay in the anthesis date may be the cause for the low kernel weight and low yield under Mediterranean drought conditions.

Our results suggest that, although further studies and plant breeding programmes are required for tritordeum, this species may have interest as new crop under low water availability conditions. Furthermore, our results suggested that breeding efforts should be directed to an earlier anthesis date and extended grain filling period.

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