

Full Length Research Paper

Response of durum wheat varieties to water in semi-arid Algeria

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Irrigation and varietal improvement are two major ways of increasing and stabilizing durum wheat (*Triticum durum* Desf.) production in semi-arid Mediterranean countries. A 3-year study was conducted in Khemis-Miliana (Upper Chelif, Algeria) to evaluate the yield response of six durum wheat genotypes to deficit irrigation. Grain yield in the unirrigated treatment ranged from 2.0 t.ha⁻¹ (2008) to 2.8 t.ha⁻¹ (2009). In rainfed conditions, the local variety Mohammed Ben Bachir (MBB) was the least productive (yield < 2.0 t.ha⁻¹) but the most stable, being the most insensitive to early drought. Yields of Bousselem exceeded 3.0 t.ha⁻¹ whereas Mexicali and Vitron had more variable and lower yields. Rainwater productivity (RWPg, the ratio of grain yield to precipitation) ranged from 0.5 (MBB) to 1.1 kg.m⁻³ for Bousselem, Chen's, and Waha, three varieties known to be drought-tolerant. Deficit irrigation (140 mm) resulted in an increase in grain yield of 0.4 to 3.2 t.ha⁻¹ depending on weather conditions and variety, with a mean response of 1.1 t.ha⁻¹. Irrigating between shooting and booting increased straw production by 23% and grain production by 46% on average. The most explanatory components of final yield under rainfed management were the number of ears.m² and the number of grains per ear, while under irrigated management the number of grains per ear and the thousand grain weight were more critical for yield determination. The development of irrigation on durum wheat could help to close the gap between current and attainable grain yields in semi-arid Algeria, provided groundwater is available and the flowering period escapes desiccating hot winds. Wheat breeding should be focused on developing genotypes with stable behavior under drought but which respond well to irrigation.

Key words: Irrigation, drought, yield components.

INTRODUCTION

In Algeria, durum wheat (*Triticum durum* Desf.), grown on 47% of the cultivated area, constitutes the main small-grain cereal (Haddouche and Mekliche, 2008). Since the

70s cereal production has failed to meet the needs of the population. As a result, the country imports between 1 and 2 Mt of durum wheat a year as the staple to make

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bread and couscous (Smadhi and Zella, 2009). Although the area under cereal production fluctuates around 3 million hectares (FAOSTAT, 2014), 60% of this area has a semi-arid climate in regions where the farmers traditionally use a limited amount of inputs (seeds, fertilizers), resulting in a low attainable yield level. Effectively, in those areas where annual rainfall is below 450 mm on average and falling largely in winter, durum wheat yield ranges from 0.7 to 1 t.ha⁻¹ and in future the year-to-year variability in Algeria may become more extreme due to rainfall patterns becoming more erratic and unpredictable (Feliachi et al., 2001; Smadhi and Zella, 2009; Sahnoune et al., 2013).

It has been well established that drought is the major limiting factor of wheat yield in north Africa, the losses ranging from 10 to 80% of potential yield depending on the year (Nachit et al., 1998). In this environment, once the soil water present at planting in November has been exhausted, the amount of rainfall received in the spring determines the level of attainable yield in the absence of supplementary irrigation (Chennafi et al., 2006). Although water stress may occur at any time during crop life, terminal heat and drought stress are the rule (Baldy, 1993). However, one feature of the climate is also uncertain rainfall in the early stages of the winter wheat crop (El Hafid et al., 1998a). The effects on crop development, growth and grain yield depend on the timing and intensity of water stress (Mogensen et al., 1985; Musick and Porter, 1990; Debaeke et al., 1996). Thus, if drought occurs during the two weeks before heading, it can reduce the number of grains per spikelet (Fisher, 1973) while the lack of water at the end of the season reduces the individual grain weight (Kobata et al., 1992). The number of ears per m² will be reduced by drought occurring from crop tillering (Assem et al., 2006).

To fill the gap between domestic needs and national cereal production, Algeria needs to quadruple its local production either by increasing the sown area from 3 to 12 million hectares (that is, by reducing the area of fallow land) or by raising the average yield from 0.7 to 2.8 t.ha⁻¹ (Smadhi and Zella, 2009). This highlights the huge technical progress required. To increase and stabilize grain yield at this level, improved genotypes combined with appropriate crop management are strongly recommended (Bouthiba et al., 2008).

Improving drought tolerance of winter cereals has long been the main target for breeders in the Mediterranean region but substituting the local landraces by varieties selected for high yield potential is also an objective (Monneveux and Ben Salem, 1992; Rajaram and Hettel, 1994; Nachit et al., 1998; Hafsi et al., 2001; Richards et al., 2002). A relatively small number of durum varieties are grown in Algeria, either local or recently introduced (Benbelkacem and Kellou, 2001). Local genotypes are characterized by a low but relatively stable yield potential. Conversely, introduced varieties can give a high yield but only under favorable conditions of water supply and temperature. Adoption of short-term varieties was intended

in semi-arid Algeria for an effective use of limited soil water and to reduce the effects of terminal stress, but grain yield remains very low anyway (Annicchiarico et al., 2006).

Therefore, to achieve this potential and stabilize production in semi-arid Mediterranean regions, supplemental irrigation of wheat has been proposed in addition to varietal choice and zero tillage (Bouthiba et al., 2008; Karrou, 2013). However, faced with the scarcity of water resources, exacerbated by possible climate change, the use of irrigation has to be optimized and adapted to genotype and wheat crop management.

The generic response of durum wheat to irrigation has been studied extensively in north Africa and west Asia (Oweis et al., 1999; Zhang and Oweis, 1999; Chennafi et al., 2006; Oweis and Hachum, 2006; Bouthiba et al., 2008; Karam et al., 2009). However very few studies have compared the differential response (in terms of yield and water use efficiency) of a range of wheat genotypes to several water regimes (Bouthiba et al., 2008; Mohammadi et al., 2011). However, it is foreseeable that interactions between water availability and plant response may occur depending on the level of drought tolerance of a variety and its growth pattern.

To assess the significance of these interactions, a 3-year experimental study was conducted in semi-arid conditions of Algeria, involving a range of local and introduced genotypes and different water stress levels varying in timing and intensity. This range of constraints was achieved by combining different irrigation and rainfall patterns that were more or less deficient in terms of crop water requirements. The main objective of this study was to analyze the yield response of a range of durum wheat genotypes to deficit irrigation compared to rainfed management.

In cereal-livestock farming systems of north Africa and west Asia, the straw of durum wheat is frequently used for feeding animals during the dry season and may enhance the sustainability and the flexibility of farming in various respects (Annicchiarico et al., 2005). Therefore, our analysis will be extended to grain and straw response to genotype and irrigation.

MATERIALS AND METHODS

Permanent characteristics of the experimental site

The experimental site in Khemis-Miliana belongs to the 'Institut Technique des Grandes Cultures' (ITGC). It is located in the Upper Chelif, west of Algiers (36° 15'N, 02° 14'E, altitude 382 m) and is subjected to a semi-arid climate characterized by an average annual rainfall of 373 mm that occurs mostly in winter. This amount (recorded between November and February) accounts for 65% of the precipitation falling during the growing season.

A weather station on the experimental site provided the basic daily climatic data (Table 1): maximum and minimum temperatures, sunshine duration, wind speed, relative humidity, and precipitation. Over the period 1990 to 2008, cumulative rainfall from October to June averaged 351 mm; the corresponding ETo (Penman) was 737 mm, and the rainfall deficit (P-ETo) was 386 mm.

Table 1. Monthly precipitation (P, mm), Penman potential evapotranspiration (Eo, mm) and mean air temperature (°C) for the 3 growing seasons : 2007, 2008 and 2009.

Year	Parameters	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total Oct - Jun
1990 - 2009	Precipitation (mm)	33	54	57	56	46	44	38	25	6	359
	ETo (mm)	83	39	23	26	41	78	103	153	194	740
2006 - 2007	Precipitation (mm)	2	12	69	15	48	127	78	1	0	352
	ETo (mm)	97	48	21	26	45	70	85	150	194	736
	Mean temperature (°C)	22.8	17	11.4	10.5	13.3	11.6	16	20	25	16.4
2007 - 2008	Precipitation (mm)	58	110	39	26	18	63	7	25	8	354
	ETo (mm)	75	32	24	26	49	80	118	127	137	668
	Mean temperature (°C)	19.2	12.8	10.4	10.4	12.2	12.8	16.3	19.9	24.3	15.4
2008 - 2009	Precipitation (mm)	43	77	105	89	32	73	75	19	0	513
	ETo (mm)	76	40	21	32	47	89	96	166	205	772
	Mean temperature (°C)	20.6	13.1	9.9	10.2	10.9	14.2	14.4	23.4	28.2	16.1

Table 2. Main soil characteristics in Khemis-Miliana experimental station.

Soil characteristics	Soil layers (cm)			
	0-25	25-45	45-70	70-100
Clay (%)	30.3	31.0	30.5	43.0
Fine silt (%)	24.1	25.2	24.3	20.2
Silt (%)	24.4	24.7	24.5	18.8
Fine sand (%)	10.3	9.8	10.0	6.0
Sand (%)	10.9	9.3	10.7	12.0
Organic matter (%)	2.0	1.3	1.3	1.3
CaCO ₃ (%)	7.7	7.7	7.3	10.4
pH	7.7	7.5	7.6	8.1
EC (dS.m ⁻¹)	0.31	0.37	0.28	0.57
Bulk density	1.34	1.40	1.37	1.48
Soil moisture at field capacity (Pf 2.5), (%)	25.2	24.6	24.8	25.4
Soil moisture at wilting point (Pf 4.2), (%)	11.9	11.8	11.9	12.0

The physical and chemical soil properties are summarized in Table 2. Soil characteristics were determined by the Soil Science Department of the 'Ecole Nationale Supérieure d'Agronomie' in Algiers, using routine methods. The soil is a chalky silty clay. As its electrical conductivity (EC) is less than 4 mmhos.cm⁻¹, it is not considered as a saline soil. The cation exchange capacity (CEC) is high, and sodium represents less than 10% of the total CEC. Soil organic matter in the top layer is at 2%, but is very poor at depth. The available soil water content (ASWC) to 1 m depth is 183 mm. The saturated hydraulic conductivity is 1.2 cm h⁻¹ (Ollier and Poirée, 1981).

The quality of irrigation water was assessed by the following variables: Ca⁺⁺ (6.93 meq.l⁻¹), Mg⁺⁺ (5.67 meq.l⁻¹), Na⁺ (6.43 meq.l⁻¹), HCO₃⁻ (3.75 meq.l⁻¹), EC (2.5 dS.m⁻¹) and pH (7.5). SAR (Sodium Adsorption Ratio) was 2.62, which presents no risk for soil degradation. Although this water salinity level is considered to be high, it should not affect the yield potential of durum wheat (Ayers and Westcot, 1985; Bauder et al., 2007).

Treatments and experimental design

Three field experiments comparing the response of six durum wheat varieties to irrigation were conducted between 2007 and 2009 to take advantage of the natural high variability of rainfall. The experimental layout was a split-plot design with irrigation as the main plot treatment (irrigated vs non irrigated) and the varieties as sub-plots, each being replicated three times within each main plot. The area of each basic plot was 6 m². The crop was planted in 6 rows, 5 m long, with 20 cm between rows.

Plant material

Six durum wheat genotypes were selected for this study: Bousselem (B), Chen's (C), Mohammed Ben Bachir (MBB), Mexicali (M), Vitron (V), and Waha (W). They are among the genotypes most commonly grown in Algeria (Annicchiarico et al., 2006).

Table 3. Main aspects of wheat crop management.

Year	Sowing date	Harvest date	Water regimes	Irrigation amounts (mm)				
				Tillering	Shooting	Heading	Maturation	Total
2007	17/12/06	08/06/07	Rainfed	0	0	0	0	0
			Irrigated	50	0	0	0	50
2008	12/12/07	08/06/08	Rainfed	0	0	0	0	0
			Irrigated	50	0	50	80	180
2009	28/12/08	07/06/09	Rainfed	0	0	0	0	0
			Irrigated	50	0	50	80	180

Only MBB is derived from breeding in a local population. Other varieties are accessions from CIMMYT (Chen's, Mexicali), ICARDA (Bousselem, Waha) or Spain (Vitron). In terms of earliness at heading, the varieties rank from the earliest to the latest as follows: C = M = W > V > B > MBB. The difference in maturity between C, M, W group and MBB is 10 days at heading (Mekhlouf et al., 2006).

Crop management

After an application of 69 kg ha⁻¹ of P as super phosphate (46% P), the soil was ploughed to 30 cm depth soon after the first fall of rain with a disc plough, thereafter shallow tilled with a disk harrow, then with a tine harrow equipped with a roller cage. Wheat was sown after fallow in December using an experimental planter at a density of 350 seeds m⁻² (Table 3). Total nitrogen fertilization was 100 kg N ha⁻¹ as urea (46% N) split between three-leaf stage (40 kg N ha⁻¹) and early heading (60 kg N ha⁻¹). Depending on the years, the crop was harvested from late May to early June at grain moisture of 12 to 14% (Table 3). Every year, all the varieties were sown and harvested at the same time.

Irrigation

The optimal management of irrigation was determined previously, during seasons with roughly average precipitation. It became a guideline for the application of irrigation from 2007 to 2009, but with an adjustment for the earliness and intensity of annual rainfall deficit. Water was supplied by sprinklers across each plot.

The average rainfall deficit over the period from January to May during which irrigation takes place was 195 mm (105 to 300 mm depending on the year) (Table 1). The contribution of soil water due to the previous fallow was very variable from year to year. Moreover, the depth of the rooting zone did not exceed 60 cm in general due to the initial soil dryness and/or the low rainfall in autumn.

From local studies carried out in 2001 and 2003 where the yield responses of cv. Chen's and cv. Waha to increasing irrigation amounts were studied, the irrigation target for durum wheat was fixed at 180 mm as a compromise between the different cultivar responses. The intention was to meet the crop water needs during critical phases without consideration of varietal differences. Actual irrigation amounts and schedules were reported in Table 3.

Estimation of water use from a simple water balance model

As soil water content was not measured with probes or gravi-

metrically, a simple spreadsheet water balance model was built to calculate actual evapotranspiration (ET_c) or consumptive water use for each year x water regime combination. Possible varietal differences were ignored. The water required to fully satisfy the crop requirement (ET_{max}) was calculated as usual as the product of ET_o and K_c. The phasic crop coefficients (K_c) came from the FAO review of Doorenbos and Kassam (1979) but specific K_c values were not available to distinguish the six wheat genotypes (Bouthiba et al., 2008). We assumed that the crop reduced its transpiration linearly from ET_{max} once soil water content (SWC) fell below 2/3 ASW (that is, 121 mm), and ceased when ASW was exhausted (at a soil-water matric potential of -1.5 MPa) which is the norm in agro-climatic models (Brisson et al., 1992; Allen et al., 1998) as well as in irrigation scheduling methods (Bouthiba et al., 2008). Assuming a wheat root elongation of 1.2 mm per day after sowing (Paillard et al., 1992), the size of the reservoir accessible to roots increases steadily until heading. Assuming ASW to be zero at the end of summer in this region, SWC at wheat sowing was initialized by taking into account the P-ET_o difference in October and November as this period has a direct influence on the water recharge of the profile.

Plant measurements

All the plant samplings and the organ counting were done at harvest on a microplot of 1.2 m² (6 rows) in the middle of the 6 m² sub-plot. The number of plants was determined after emergence and the number of ears (NE) at harvest. The number of grains per ear (NGE) was counted on a random sample of 15 ears for each sub-plot rather than by calculation from yield and individual grain weight. Grain yield (GY) was determined after mechanical threshing of wheat ears at plot harvest. From this grain bulk, the thousand grain weight (TGW) was determined. Grain number.m⁻² was derived from NE and NGE and not from GY and TGW. Straw dry yield (SY) was determined after weighing the fresh non-grain fraction (leaves, stems and empty ears) and correcting by the moisture content of vegetative parts. Harvest index (HI) was calculated as the ratio of grain yield to total above-ground biomass at harvest.

Indicators of water productivity

We used here the terminology proposed by Oweis and Hachum (2006) to compare the efficiency of water for grain production between years, irrigation schemes and varieties. Thus, we speak of RWP_g (Rain Water Productivity, kg of grain per m³) for water efficiency resulting only from rainfall, of TWP_g (Total Productivity Water, kg.m⁻³) for water efficiency based on rain plus irrigation, and IWP_g (Irrigation Water Productivity, kg.m⁻³) for the marginal yield

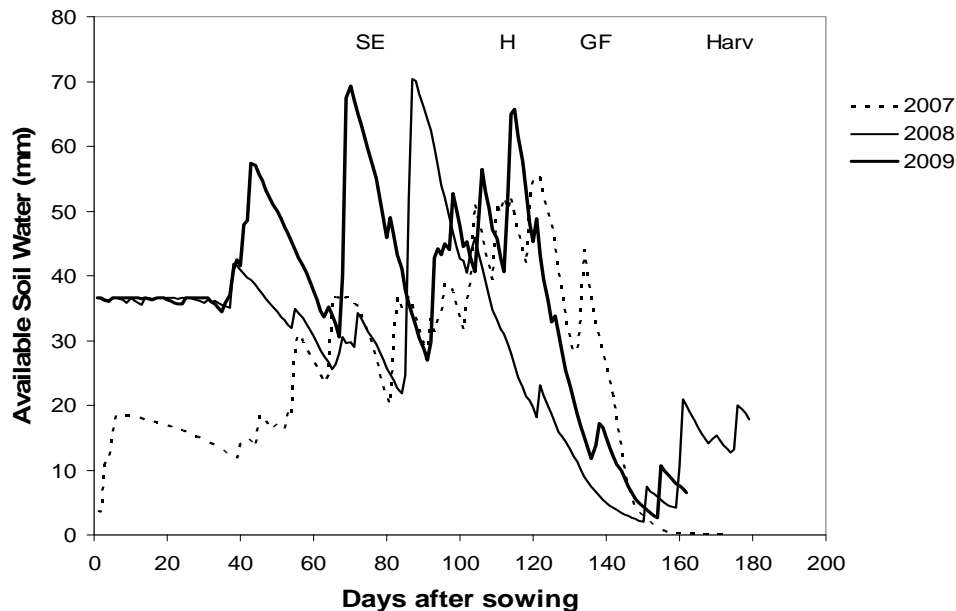


Figure 1. Time-course of the available soil water content (mm) during the 3 years (2007 to 2009) using a simplified soil water balance model. SE: onset of stem elongation; H: heading; GF: early grain filling; Harv: harvest.

gain allowed by irrigation alone.

Water use efficiency is generally calculated with an evapotranspiration term, either measured or simulated. As ET_c did not result from soil water content measurements but from simulations, and because evapotranspiration was not estimated at variety level, we decided to use the previous ratios for comparing the performance of the wheat genotypes.

So, RWP was taken as the ratio of rainfed yield (grain or biomass) to rainwater, TWP was taken as the ratio of irrigated yield (grain or biomass) to total water supply (rain + irrigation), IWP was taken as the ratio of increase in yield (grain or biomass) to the amount of irrigation water applied.

Using the same assumptions, we calculated similar efficiency ratios for the production of straw: RWPs, TWPs and IWPs respectively.

Statistical analysis

Analyses of variance, stepwise and simple linear regressions and correlation analysis were all performed using the software Statistix 9.0 (Analytical Software, Tallahassee, FL, USA), and means were compared using the Least Significance Difference (LSD) method at $P < 0.05$. A split-split-plot design with three replications was used to analyze the combined effects of year, water regime and variety and their corresponding interactions. The main plot was 'year', the subplot was 'water regime' and the sub-subplot was 'variety'. This design confers to the 'variety' factor the highest degree of precision.

RESULTS

Characterization of water stress patterns

The intensity and timing of water deficit was analyzed

using weather data (precipitation, evapotranspiration), simulated soil water content (obtained from a water balance sheet model) and yield component patterns in non-irrigated conditions.

Climatic and soil water deficit

During the two seasons 2006-2007 and 2007-2008 (October to June), the wheat crop received about the same amounts of rainfall (352 and 354 mm, respectively) as the 18-year average for that period (359 mm) (Table 1). However, the 2008 to 2009 season received 43% more rainfall than the average (513 mm).

To assess the year-to-year variation in water deficit, the dynamics of soil water content were simulated under non-irrigated conditions for the 3 growing seasons under study (Figure 1). A significant drought occurred in autumn 2006, characterized by a late start to the rains in 2007, which fell mainly from February to April (253 mm, Table 1).

The 2007-2008 season was characterized by high rainfall in autumn, a moderate water shortage in winter and spring and a rapid soil water depletion before heading. In contrast, the 2008-2009 season was characterized by uniform but moderate water availability throughout the growing season. During the period of establishment of the number of grains per ear, the 2009 conditions were obviously the most favorable for the yield. In May and June, rainfall was extremely deficient whatever the season (< 35 mm) but the largest water deficit was observed in 2008.

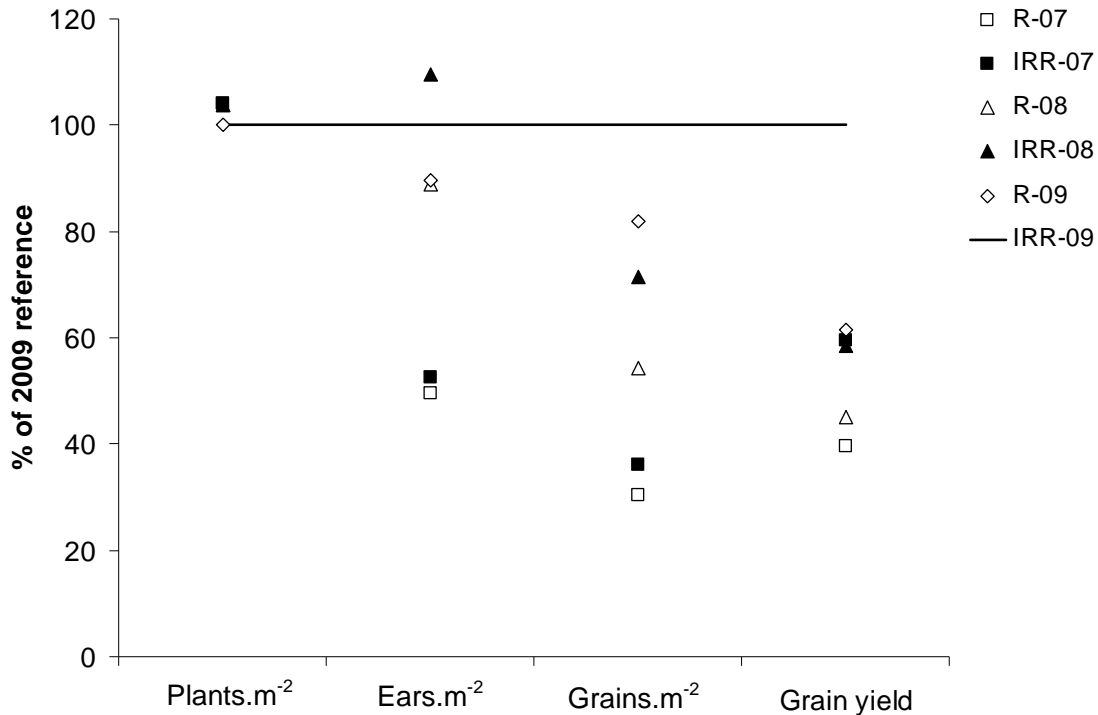


Figure 2. Annual pattern of yield build-up under rainfed (R) and irrigated (IRR) wheat management; the yield component values are expressed as relative values of 2009 irrigated reference (average data on 6 durum wheat cultivars) – 07, 08 and 09 refer to 2007, 2008 and 2009 growing seasons.

Yield components' patterns

According to the seasonal rainfall, the year-to-year variability of wheat yield was pronounced in the semi-arid conditions of Upper Chelif, resulting in rainfed grain yields ranging from 1.8 t.ha⁻¹ (2007) to 2.8 t.ha⁻¹ (2009) for the mean of all varieties, and from 0.7 to 3.4 t.ha⁻¹ when considering all the variety x season combinations.

It is generally agreed that wheat yield results from four successive steps: (i) the establishment of the plant population (NP), (ii) the establishment of the number of ears per m² (NE) achieved at heading, (iii) the establishment of the number of grains per m² (NG) completed in early grain filling, (iv) grain filling, established at physiological maturity (GY). To identify the phenological phases that were affected by water shortage, we broke down the elaboration of wheat yield in the form of a chronological pattern, expressing each yield component (plants.m⁻², ears.m⁻², grains.m⁻², grain yield) relative to its reference value measured under fully irrigated conditions. The yield build-up pattern with time is shown in Figure 2 for unirrigated wheat by averaging the data of the six wheat genotypes. The component reference was given by the yield components under irrigated conditions in 2009, the season considered to express the yield potential.

In 2007, drought was severe during shooting, which resulted in a small number of ears.m⁻² (49% of the reference). In 2008 and 2009, water stress was less

pronounced and occurred later during the formation of the number of grains per ear (NE at 89-90% of the reference, but NG at 71 and 82% of the reference in 2008 and 2009, respectively). Thus, under a rainfed regime, yield establishment gradually diverged from the optimum, with water stress increasing during the season. The final GY was 40 to 61% of the reference value (IRR-09).

Response of durum wheat yield to water

In irrigated conditions, the maximum yield (4.5 t.ha⁻¹) was observed in 2009, associated with maximal water use (380 mm). In rainfed conditions, maximum yield was 2.8 t.ha⁻¹ in 2009 and water use did not exceed 250 mm. Corresponding values for above-ground biomass (grain + straw) at harvest were 11.4 t.ha⁻¹ (irrigated) and 8.1 t.ha⁻¹ (rainfed).

The average annual yield (GY, t.ha⁻¹) of durum wheat, all varieties averaged, increased linearly with actual evapotranspiration (ETa, mm) whatever the origin of water, either rainfall or irrigation (Figure 3a). The relationship obtained was: $GY = 0.0118 ETa - 0.21$ ($r^2 = 0.89$, $n = 6$, $P < 0.01$). From Figure 3a, a mean crop water productivity value (GY/ETa) of 1.10 kg.m⁻³ was determined for durum wheat.

The relationship was also linear when total above-ground biomass (or total dry matter, TDM) was used as

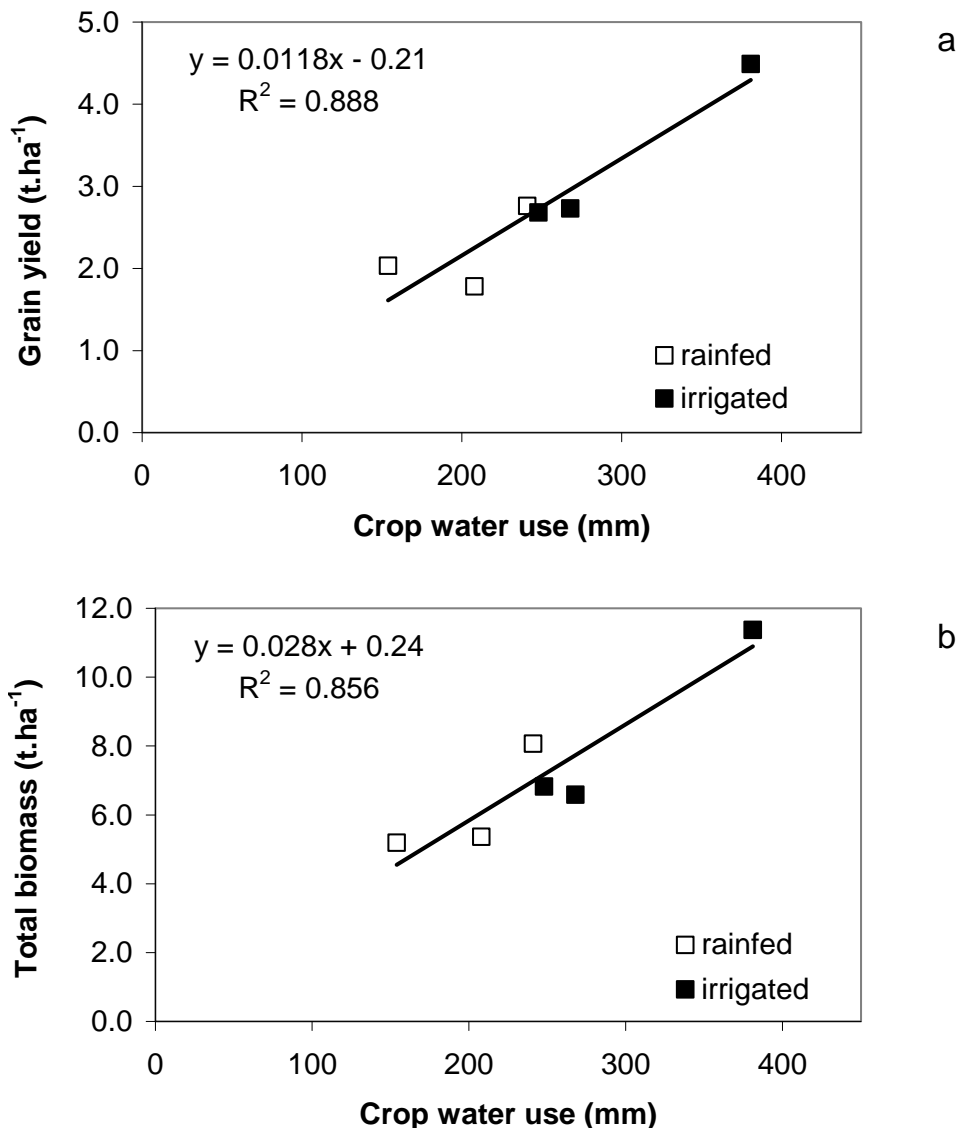


Figure 3. Relationship between average (a) grain yield (t.ha^{-1}) or (b) total above-ground biomass (t.ha^{-1}) and crop water use (mm) calculated by a simple water balance model; the 6 varieties under test are averaged; each point corresponds to a year \times water regime combination.

an indicator of crop growth (Figure 3b). The relationship obtained was: $\text{TDM} = 0.028 \text{ ETa} + 0.24$ ($r^2 = 0.86$, $n = 6$, $P < 0.01$). From Figure 3b, the mean crop water productivity value (TDM/ETa) was 2.89 kg.m^{-3} .

Wheat response to irrigation according to year and strategy

Grain yield

Grain yield differed significantly ($P < 0.001$) between years, water regimes and varieties. Significant interact-

tions were found between irrigation response and year ($P = 0.014$), and between variety and year ($P < 0.001$). The irrigation and variety main effects were both significant at $P < 0.05$ for the three years under test, but no irrigation \times variety interaction was found.

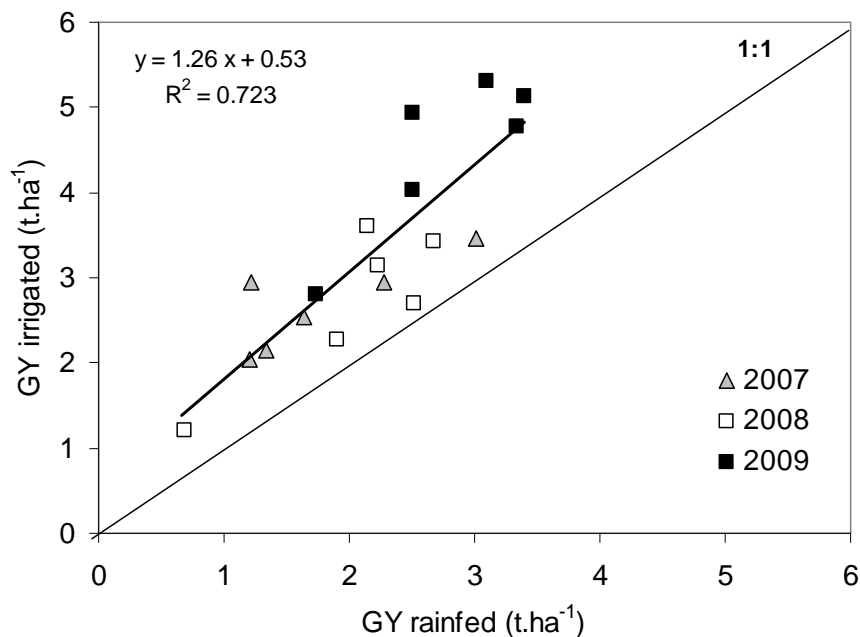
Irrigation gave a yield increase of 0.7 to 1.7 t.ha^{-1} according to year and scheduling strategy (Table 4). The extra yield obtained by irrigation (50 mm in 2007, 180 mm in 2008 and 2009) was generally less than 1.0 t.ha^{-1} except in 2009 when 1.5 to 2.5 t.ha^{-1} was obtained, depending on genotype.

The interaction between water regime (irrigation) and variety for yield was not statistically significant in 2007,

Table 4. Response of grain yield ($\text{kg}\cdot\text{ha}^{-1}$) to variety for the three growing seasons 2007, 2008, and 2009 and the two water regimes (rainfed, irrigated).

Water regimes	Bousselem	Chen's	Mexicali	Mohammed Ben Bachir	Vitron	Waha
Rainfed						
2007	3017 ^a	2283 ^b	1200 ^c	1633 ^c	1317 ^c	1217 ^c
2008	1904 ^b	2670 ^a	2234 ^{ab}	690 ^c	2144 ^b	2140 ^b
2009	3400 ^a	2500 ^{bc}	3333 ^a	1733 ^c	2500 ^{bc}	3100 ^{ab}
3 years	2774 ^a	2485 ^{ab}	2256 ^{ab}	1352 ^c	2113 ^b	2152 ^b
Irrigated						
2007	3460 ^a	3132 ^{ab}	2033 ^c	2532 ^{abc}	2150 ^{bc}	2951 ^{abc}
2008	2268 ^b	3425 ^a	3142 ^a	1210 ^c	3085 ^a	3052 ^a
2009	5133 ^a	4933 ^{ab}	4767 ^{ab}	2800 ^c	4033 ^b	5300 ^a
3 years	3620 ^{ab}	3767 ^a	3314 ^{ab}	2181 ^c	2963 ^b	3767 ^a

Data followed by the same letters in lines are not significant at $P < 0.05$.

**Figure 4.** Relationship between irrigated and rainfed grain yield (GY, $\text{t}\cdot\text{ha}^{-1}$) for a range of 6 durum wheat varieties and 3 growing seasons (2007, 2008, 2009).

2008 and 2009, when it was tested. No irrigation \times variety interaction was found at $P < 0.05$ when pooling all the seasons in the analysis of variance. However, the variety \times year interaction was significant, which suggests that genotype \times environment interactions may be observed as a result of differential water deficit patterns and genotype characteristics. Due to the absence of a variety \times irrigation interaction, yields of irrigated and rainfed wheat were strongly correlated when comparing the effect of water regime for the 6 varieties and 3 growing seasons ($r^2 = 0.73$, $n = 18$, $P < 0.001$) (Figure 4).

Yield components' responses to irrigation were

analyzed after averaging all the varieties under test as no variety \times irrigation interaction was observed for each of the yield components (Table 5). In 2007, the contribution of an early irrigation of 50 mm significantly increased the number of grains per ear (+13%) with positive effects on yield. However, the number of ears per m^2 was slightly increased on average, but leveled out at less than 200. In 2008, the positive effects of irrigation were apparent on the number of ears per m^2 (+25%). In 2009, irrigation had a positive but limited effect on the number of ears per m^2 (+11%) and the number of grains per ear (+9%). Due to the increased number of grains per m^2 with irrigation in

Table 5. Response of yield components to irrigation (the 6 varieties were pooled as no variety x irrigation interactions were observed for the yield components).

Yield components	2007		2008		2009	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Ears m ⁻²	184	195	325 ^b	408 ^a	334 ^b	372 ^a
Grains ear ⁻¹	33.6 ^b	37.8 ^a	33.1	35.5	49.6 ^b	54.3 ^a
Grains.m ⁻²	6177 ^b	7259 ^a	10724 ^b	14494 ^a	16561 ^b	20228 ^a
Thousand grain weight (g)	33.9	37.1	34.5	34.7	32.9	35.9

Within a year, the data followed by the same letters in lines are not significant at $P < 0.05$.

Table 6. Indicators of crop water productivity for grain (kg.m⁻³) as a function of variety and year : 2007, 2008, 2009.

Year	Bousselem	Chen's	Mexicali	Mohammed Ben Bachir	Vitron	Waha	Total
RWPg							
2007	0.96	0.72	0.38	0.52	0.42	1.09	0.68
2008	1.03	1.44	1.21	0.37	1.16	1.16	1.06
2009	1.17	0.86	1.14	0.59	0.86	1.06	0.95
3 years	1.05	1.01	0.91	0.49	0.81	1.10	0.90
TWPg							
2007	0.95	0.81	0.56	0.69	0.59	1.05	0.78
2008	0.62	0.94	0.86	0.33	0.84	0.84	0.74
2009	1.09	1.05	1.01	0.59	0.86	1.12	0.95
3 years	0.89	0.93	0.81	0.54	0.76	1.00	0.82
IWPg							
2007	0.89	1.32	1.67	1.80	1.63	0.81	1.35
2008	0.20	0.42	0.50	0.29	0.52	0.51	0.41
2009	0.96	1.35	0.80	0.59	0.85	1.22	0.96
3 years	0.68	1.03	0.99	0.89	1.00	0.85	0.91

RWP = Rain water productivity; TWP = total (rain + irrigation) water productivity; IWP = irrigation water productivity.

2007 (+17%), 2008 (+35%) and 2009 (+22%), the individual grain weight increased very little with irrigation, the differences in this component being non significant with rainfed management.

Thus, under irrigation, the yield formation patterns were relatively similar throughout the cycle, mainly because of irrigation schedules starting at heading (Figure 2). Grain number.m⁻² was the yield component systematically improved by deficit irrigation applied between shooting and booting (Table 5).

In 2007, because of early drought, the efficacy of irrigation at tillering (50 mm) was very high: IWPg increased to 1.35 kg.m⁻³ (Table 6). The same amount of water (180 mm) in 2008 and 2009 did not result in the same value of IWPg for the 2 contrasting seasons: 0.34 vs. 0.96 kg.m⁻³.

Straw yield and harvest index

Irrigation significantly increased straw yield (SY, $P <$

0.001) and harvest index (HI, $P < 0.05$). As in the case of grain yield, a year effect was clear for these two variables. SY and HI differences with irrigation were significant at $P < 0.05$ in 2007 and 2009 but not in 2008.

Irrigating between shooting and booting resulted in an increase in straw yield of between 16% (2007) and 30% (2009), and averaged over the 6 varieties. In 2007 and 2008, straw yield was about 4 t.ha⁻¹ while up to 7 t.ha⁻¹ was observed with irrigation in 2009. At the same time, harvest index (HI), which ranged from 0.34 to 0.38 under rainfed management, attained 0.40 to 0.42 with irrigation.

Similar to grain yield, no significant interaction between irrigation and variety was observed in the three experiments, but the interaction was significant between variety and year for straw yield and harvest index ($P < 0.001$).

Varietal response to available water

The performance of the six durum wheat varieties was

Table 7. Response of straw yield (kg.ha⁻¹) to variety for the two water regimes (rainfed, irrigated) – Average values over the 3 growing seasons.

Water regimes	Bousselem	Chen's	Mexicali	Mohammed Ben Bachir	Vitron	Waha	Average
Rainfed	3842 ^b	3755 ^b	3458 ^b	5724 ^a	3655 ^b	3656 ^b	4015
Irrigated	5173 ^b	4323 ^b	4583 ^b	6867 ^a	4227 ^b	4574 ^b	4958

Data followed by the same letters in lines are not significant at $P < 0.05$.

compared for 3 years (2007 to 2009) under rainfed and irrigated conditions.

Varietal response in rainfed management

Under rainfed management, the variety Mohammed Ben Bachir (MBB) was the least productive in 2008 and 2009 (Table 4) but with early drought (2007) MBB was less adversely affected than the other varieties, although its yield did not exceed 2.0 t.ha⁻¹. The Chen's variety had very stable yields, always above 2.0 t.ha⁻¹. Cv. Bousselem achieved its high potential yield (> 3.0 t.ha⁻¹) in 2007 and 2009. Cvs Mexicali, Waha and Vitron were characterized by higher yield variability under rainfed management, with yields similar to Chen's and Bousselem only in 2009, when water stress was moderately limiting.

Water productivity in rainfed conditions (Table 6) was higher for Waha, Bousselem and Chen's (RWP between 1 and 1.1 kg.m⁻³) than for Mexicali and Vitron (0.8 to 0.9 kg.m⁻³) and the local variety Mohammed Ben Bachir (0.5 kg.m⁻³). Using the indicator TWPg, genotypes ranked the same but the values were lower except for the local variety.

In 2007, when drought occurred early, RWPg was low on average (0.68 kg.m⁻³). However, the two varieties Bousselem and Waha had an efficient use of rainwater in this situation (RWPg = 0.96 and 1.09 kg.m⁻³, respectively). In 2008, a late drought year, the best value was obtained for cv. Chen's under rainfed (RWPg = 1.44 kg.m⁻³), while the late-maturing variety MBB was strongly penalized (0.37 kg.m⁻³). In 2009, a year with well-distributed rainfall, RWPg was lower than in 2008, and the varieties Chen's, Vitron and MBB were the least efficient for rainfall use.

Varietal response to irrigation

Although varietal differences were rather small, we can nevertheless separate three types of response to wheat irrigation on the basis of water productivity indicators for grain (Table 6).

Cvs Bousselem and Waha, as early drought-tolerant varieties (RWPg₂₀₀₇ = 0.96 and 1.09 kg.m⁻³), did not respond well to early irrigation (IWPg₂₀₀₇ = 0.89 and 0.81

kg.m⁻³ respectively): this type of variety requires later irrigation, which is efficiently converted into yield.

Cv. Chen's variety is characterized by an average tolerance throughout its life, with a stable response to water, whether from rain or irrigation (RWPg = 1.01 kg.m⁻³, TWPg = 0.93 kg.m⁻³, IWPg = 1.03 kg.m⁻³). This variety responds well to a moderate water supply distributed evenly throughout growth. It responds best to regular irrigation regardless of drought patterns.

Cvs. Mexicali and Vitron are very sensitive to early drought (RWPg₂₀₀₇ = 0.38 and 0.42 kg.m⁻³, respectively), and require large water inputs as early as tillering if a drought begins then. The efficacy of such early irrigation is particularly high (IWPg₂₀₀₇ = 1.67 and 1.63 kg.m⁻³ respectively).

MBB, a late maturing variety with a low yield potential, responded poorly to irrigation except in the case of an early drought. But the good response in 2007 (IWPg₂₀₀₇ = 1.80 kg.m⁻³) did not result in a sufficient yield increase because of its low yield potential (Table 4). Indeed, its potential remained below 3.0 t.ha⁻¹ when the season was fully conducive to crop growth as in 2009.

The best overall response to available water (TWPg) was obtained for the variety Waha (1.00 kg.m⁻³) followed by Chen's (0.93 kg.m⁻³) and Bousselem (0.89 kg.m⁻³).

Straw production as affected by variety

The local variety MBB produced 50% (irrigated) and 56% (rainfed) more straw biomass than the 5 other introduced cultivars (Table 7). Among the latter, no significant difference in straw yield was observed, although more straw was obtained with irrigation: from 3.4 to 3.8 t.ha⁻¹ in non-irrigated treatments, from 4.2 to 5.2 t.ha⁻¹ with irrigation. This was in accordance with the plant height, which averaged 90 cm for MBB and ranged from 73 cm (Chen's) to 82 cm (Mexicali) for the other cultivars.

Consequently the local variety MBB was characterized by a very low harvest index: 0.19 vs 0.36 to 0.43 (5 varieties) in unirrigated plots, 0.25 vs 0.41 to 0.47 (5 varieties) in irrigated plots. Among the 5 varieties, no significant variety effect was observed for HI and there was no variety x irrigation interaction.

The best overall response to available water for straw production (TWPg) was clearly observed for MBB (2.15 kg.m⁻³), while the introduced varieties had much lower

Table 8. Significant coefficients at $P < 0.05$ of the stepwise linear regressions between grain yield and its main components.

Water regimes	R ²	Constant	Plants.m ⁻²	Ears.m ⁻²	Grains.ear ⁻¹	Thousand grain weight
Total	0.652	-17.21*	-0.057*	0.049***	0.448***	0.809***
Irrigated plots	0.703	-35.30***		0.036*	0.625***	0.871***
Rainfed plots	0.598	-2.19 ^{ns}		0.045*	0.301*	

ns: not significant ; * ($P < 0.05$) ; ** ($P < 0.01$) ; *** ($P < 0.001$). The missing cases correspond to variables not included in the model at $P < 0.05$.

values, ranging from 1.36 to 1.49 kg.m⁻³. The cultivar Mexicali had a balanced response to irrigation in terms of straw and grain as IWP was 0.83 kg.m⁻³ for straw and 0.99 kg.m⁻³ for grain while MBB was efficient for straw production and Chen's and Vitron were efficient for grain production.

Statistical model of grain yield formation

A stepwise linear regression was performed between grain yield and its main components (at $P < 0.05$) (Table 8). It is thus clear that under rainfed management, the yield components which are determined first, such as the number of ears per m² (NE) and the number of grains per ear (NGE), are the most explanatory of final grain yield. With irrigation, the components NGE and thousand grain weight (TGW), which is determined last, are more explanatory of the final yield. Moreover, the correlation coefficient of yield with plant density was higher in rainfed than in irrigated conditions, because partial compensation is possible by other components if water is available. Under a rainfed regime, the change in TGW had less impact on yield than under irrigation, because most of the yield variation was attributed to grains.m⁻².

DISCUSSION

Overall response of durum wheat to water use

The different weather scenarios and irrigation strategies were combined to examine the relationship between yield and water use for a wide range of yield and ETa values. The value of crop water productivity (GY/ETa) of 1.1 kg.m⁻³ that was derived from Figure 3a was in accordance with the average value given for wheat by Zwart and Bastianssen (2004). Their comprehensive review concealed however a wide variation in this indicator of water use efficiency. In previous literature reviews, Doorenbos and Kassam (1979) and Musick and Porter (1990) indicated common values between 0.8 and 1.2 kg.m⁻³. In Algeria and Tunisia respectively, Bouthiba et al. (2008) and Rezgui et al. (2005) mentioned values of 0.5 to 1.4 kg.m⁻³ depending on climatic zones, irrigation schedules and varieties. The good correlation between GY and ETa and the agreement of the crop water pro-

ductivity ratio with previous reports suggest that the simple water balance model we used to calculate crop evapotranspiration was reasonably realistic in these soil conditions.

Differential sensitivity of wheat to drought according to the physiological phases

The very contrasting drought scenarios under rainfed management made possible the appraisal of water deficit effects on the wheat crop. The early drought in 2007, which seriously reduced the number of plants and the number of ears per m², greatly reduced the final yield. According to El Hafid et al. (1998b), water stress at tillering stops tiller emission and reduces the growth of tillers already formed. In addition, severe water stress reduces the length and volume of seminal roots, mainly in the deeper layers of soil, reducing the available water for wheat during the second part of the growing season (Adda et al., 2005). All this leads to increased sensitivity of the wheat plants during later periods of water shortage and in reductions in the potential yield which are difficult to compensate for later by irrigation.

The most common drought scenario was described as drought increasing during shooting with a consequent reduction in ear fertility and/or individual grain weight, depending on the earliness and intensity of water shortage. The regression of tillers during shooting can also affect greatly the number of ears (Debaeke et al., 1996). The representation of the yield formation pattern in Figure 2 illustrates clearly the gradual divergence of the yield component pattern from the potential production target defined in conditions with a regular precipitation distribution. We feel that this simple representation facilitates the comparison and analysis of the effect of water deficit between seasons, management options and varieties.

The varieties tested were differently affected by the drought scenarios according to their morphological, physiological and phenological traits and their potential pattern of yield formation. Among the tested varieties, previous studies have already discussed the importance of certain traits for conferring drought tolerance to durum wheat cultivars. In a 4-year study, Bouthiba et al. (2008) recommended cvs. Chen's and Waha in conditions of moderate stress, while cv Vitron performed better under

full irrigation. Comparing two cultivars under various water deficit treatments, Larbi et al. (2000) concluded that Waha was relatively drought-tolerant during shooting compared to Vitron. David (2009) estimated the osmotic adjustment capacity of several durum wheat cultivars grown in Algeria, based on pollen grain expression, and concluded that MBB, Bousselem and Chen's had high drought tolerance, Waha and Mexicali intermediate tolerance, and Vitron low tolerance. Among the varieties tested in this study, Mexicali and Vitron were inefficient in converting available water into grain (low RWPg) and Waha and Mexicali had low values of RWP for straw which is in agreement with the study of David (2009).

Response of wheat to irrigation

Irrigation increased the average rainfed yield of durum wheat by 1.1 t.ha⁻¹ (0.4 to 2.4 t.ha⁻¹ depending on the year, mean of all varieties). The mean yield achieved with irrigation was 3.3 t.ha⁻¹ compared with 2.2 t.ha⁻¹ for rainfed crops, an increase of 60%, using 140 mm irrigation on average.

Studies in the WANA region on durum wheat sometimes gave larger increases. Thus, in Algeria, Bouthiba et al. (2008) obtained a yield increase of 270% (rainfed yield : 1.3 t.ha⁻¹) with full irrigation (270 mm), 107% for irrigation prior to heading (130 mm) and 67% for post-heading irrigation (140 mm). In Syria, Oweis et al. (1999) observed increases of 45, 71 and 80% of rainfed yield (2.6 t.ha⁻¹) for irrigation programs covering 1/3, 2/3 and full water requirements of durum wheat (320 mm irrigation).

However, the irrigation program in this study covered only part of the water requirement of wheat, corresponding more to deficit irrigation than to supplementary irrigation *sensu stricto* (Geerts and Raes, 2009). By limiting water applications to drought-sensitive growth stages, this practice aims to maximize water productivity and to stabilize - rather than maximize - wheat yields (Khila et al., 2013). In Algeria, cereals are rarely grown under full irrigation, the common practice being to use small amounts at critical stages to prevent crop failure. Zhang and Oweis (1999) showed that the periods of maximum sensitivity of durum wheat to drought are between the onset of stem elongation to booting, and then from anthesis to dough grain, hence the importance of ensuring good water supply during these periods.

In 2007, the addition of 50 mm at tillering helped increase the yield by 52% in a situation where drought compromised wheat yield as early as the establishment phase. In Turkey, Ilbeyi et al. (2006) also obtained a 65% yield increase from early irrigation. This was related to the combined action of water deficit on early growth of roots and shoots, as well as the initiation of leaves and reproductive organs, the potential size or number of

which might be limited.

The different types of drought (early, late) characterizing the semi-arid Algerian area appear randomly and with varying intensities. The choice of varietal earliness at heading should result from a frequency analysis, and the use of simulation models might be of great help (e.g. Rezzoug et al., 2008). Among the varieties tested, Mohammed Ben Bachir matured the latest: although it may tend to escape early stress, it is likely to suffer towards maturity by the action of high temperatures that shorten the duration of filling. Thus, post-flowering photosynthesis can be severely reduced; therefore, delayed irrigation should benefit this kind of variety. A possible but partial compensation of grain growth could be achieved by the remobilization of sugars from the stem. Latiri et al. (2013) pointed out the buffering effect of this process for maintaining grain yield in water-limited conditions.

In rainfed conditions, the yield components determined early in the season - the number of ears (NE) and number of grains per ear (NGE) - are more explanatory of grain yield because they are more strongly affected by water deficit (Table 8). The individual grain weight is less depressed as it benefits from a reduction of the number of sinks, resulting in a high value of the source : sink ratio for carbon.

In irrigated conditions, the three yield components (NE, NGE, TGW) are all involved in the formation of yield. These observations confirm those of Garcia del Moral et al. (2005) from a 'path analysis' applied to the performance of 25 genotypes in irrigated and dry conditions. These authors showed that in irrigated conditions, grain yield depends equally on the three components NE, NGE and TGW, while in dry conditions, the variation in performance is mainly due to NE and to a lesser extent to NGE. In dry conditions, the production of tillers limits NE while in irrigated conditions the regression rate of tillers is the cause of lower NE. Overall, it was confirmed that irrigation increases all the yield components, with a consistent effect on NGE.

However, wheat irrigation could have some limitations in the conditions of semi-arid Algeria. Indeed, these areas are often subject to climatic hazards such as very dry air, hot winds and high temperatures that generate massive spikelet abortion and high rates of shriveling, exceeding 50% of the harvest. In our multi-year study, one year in four was subject to these problems. In these situations, the impact of irrigation could be negligible among the least drought-tolerant varieties.

Conclusion

From this 3-year study, it can be concluded that the varieties Mexicali and Vitron, which were very unreliable in rainfed conditions, should always be irrigated, while only varieties with a good yield potential and a fair

tolerance to drought, such as Bousselem and Chen's, can make full use of deficit irrigation, especially if it is applied between the end of shooting and the soft dough grain stage.

The development of deficit irrigation on durum wheat when adapted to variety choice and related crop management aspects could help to reduce the gap between actual and attainable grain yield and the minimization of the year-to-year variability in wheat yield in Algeria. Under experimental conditions over three years, a mean grain yield of 3.3 t.ha⁻¹ could be attained with irrigation in the Upper Chelif region (instead of 2.2 t.ha⁻¹ under rainfed conditions) with an irrigation efficacy of 0.79 kg.m⁻³.

However, the scarcity of water resources in north Africa and their priority for domestic uses and horticultural cash crops could limit the access to irrigation and climatic stresses could reduce its profitability on cereals. Therefore, Oweis et al. (1999) recommended irrigation to between one third and two thirds of total requirement of wheat, for reasons of efficiency and profitability. In addition, plant breeding should be focused to develop wheat genotypes with stable behavior under moderate drought but a good response to deficit irrigation when necessary.

Conflict of Interests

The authors have not declared any conflict of interests.

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