Chapter IV

Nitrogen and water use efficiencies in cereal crops under Mediterranean environments

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Nitrogen and water use efficiencies in cereal crops under Mediterranean environments

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Abstract

In Catalonia, as in other Mediterranean regions, farmers usually grow barley in drought-prone areas while wheat in higher-yielding areas. This implies the assumption of barley having higher water use efficiency (WUE) than wheat or less water requirements. However, information on the comparative performance of both crops under scarce resource availability is rudimentary. Recently, it was found that barley and wheat yields were rather similar in a wide range of Mediterranean conditions, that may be due to similarities in water (WUE) and nitrogen (N) use efficiency (NUE) between both species. Understanding the differences between wheat and barley in terms of WUE or NUE may be relevant to define management practices such as N fertilization for Mediterranean environments. The aim of the present work was to compare the performance of wheat (bread and durum) and barley in terms of water use, N uptake, WUE and NUE under Mediterranean environments. Four experiments were conducted on farmers' fields at Agramunt, province of Lleida (Catalonia, north-eastern Spain) during 2004/05, 2005/06 and 2006/07. Treatments consisted of sowing wheats (durum and bread) and barley under different combinations of water (rainfed or irrigated) and N fertilization. Water and N availabilities resulted in a wide range of variability in WUE (from 6.3 to 23 Kg grain ha-1 mm-1) and NUE (from 2.9 to 33.9 kg grain kg available N-1 in soil). N uptake was closely and positively related to grain yield and total biomass at maturity for the three species. N fertilization modified yield of the three species mainly through changes in WUE (r2=0.75) but also through those in NUE (r2=0.34). Relative differences between wheat and barley (analyzed as the ratio between grain yield of the species [illegible] of grain [illegible] explained by the relative differences between them in terms of NUE and WUE (analyzed as the ratio between WUE or NUE of the species). These relative differences between grain yields of the species were better explained by relative differences in WUE than by relative differences in NUE. It seemed that under the conditions of this study, barley did not outperform wheat under poor-yielding conditions, as both crops showed differences in WUE and NUE without a consistent pattern in favor of barley.

Introduction

Crop productivity for a particular region is the consequence of the breeding x management x weather interaction. As crop productivity is determined by the availability and the efficiency in the use of limiting resources, understanding the eco-physiological bases for improved resource management has been increasingly important (Araus et al., 2002; Turner, 2004; Veron et al., 2004; Turner and Asseng, 2005). Water is recognized as the most limiting factor in Mediterranean regions determining the land use (Cossani et al., 2007; Ryan et al., 2008), though nitrogen (N) shortages may be quite important as well (Passioura, 2002; Abeledo et al., 2008). Passioura (2002), suggested that the level of N availability could affect water use and its efficiency. Also N fertilization may be a tool to increase water use (WU) and water use efficiency (WUE). Abeledo et al. (2008) (using a simulation model) found that high N availability reduced the gap between potential and attainable yield in years with low and mild water shortages. Sadras (2004; 2005), suggested that against a background of available water, the gap between attainable and actual yield decrease with the degree of co-limitation between water and N. This lower yield gap resulted from a higher WUE as the co-limitation between water and N increased. However, in some cases, an excess in N availability could be negatively related to grain yield (van Herwaarden et al., 1998a and b).

French and Schultz (1984a and b; for South Australia), found that in most of the cases grain yield and biomass production of wheat crops were below the potential associated to a certain water use. The gap between actual and potential yield were related in some cases to nutrients availability (French and Schultz, 1984a) or to

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the effect of weeds and pest diseases (French and Schultz, 1984b). However, Mediterranean-type environment in Southern Australia is usually more humid than in Mediterranean Catalonia. Recently, Sadras and Angus (2006) reported for Mediterranean basin an attainable WUE $_{yield}$ value of 20.4 kg $_{grain}$ ha^{-1}mm^{-1} with a maximum of 22 kg $_{grain}$ ha^{-1}mm^{-1}. These values are well aligned with values reported by French and Schultz (1984a and b) and values suggested by Angus and van Herwaarden (2001) for wheat crops. Katerji et al. (2008a) reported certain variability in WUE $_{yield}$ for the Mediterranean region with values from different countries (Syria, Morocco, Israel, Italy and Turkey) for wheat ranging from 5 to 25 kg $_{grain}$ ha^{-1} mm^{-1}. The variability for barley seemed lower, ranging from 14.6 to 27.8 kg $_{grain}$ ha^{-1}mm^{-1}, although in this case their analysis was restricted to Italy.

Nitrogen use efficiency (NUE) decreases as the amounts of N available increases in crop production, although the result is reflected in terms of higher grain yield or higher WUE. Angás et al. (2006) found that NUE in barley ranged between 10 and 81 kg $_{grain}$ kg $_{fertilized\ N}$$^{-1}$ and a range for uptake (UpE) or recovery N efficiency of 18 to 53% for the Mediterranean region of Ebro River Valley. However, the values of NUE used in these experiments did not include the available N in the soil before N fertilization. Also Angás et al. (2006) reported values of N uptake for barley ranging from 46 to 154 kg N ha^{-1}. López-Bellido et al. (2005) [illegible], for southern Spain, values of [illegible] from 10 to 32 kg $_{grain}$ kg $_{available\ N}$$^{-1}$ and values of UpE between 0.60 and 0.81 kg N $_{uptaken}$ kg $_{available\ N}$$^{-1}$. In these experiments the N uptake of bread wheat exceeded 250 kg N ha^{-1}.

Comparisons of wheat and barley grain yield and resource use efficiencies are rather scarce (Cossani et al. 2007).). López-Castañeda and Richards (1994). reported a that barley yielded more than wheat, due to reducing the soil evaporation in barley in an environment characterized by water stress but not Mediterranean. Although information on WUE, NUE, water used, or N uptake is available for the Mediterranean region, as far as we are aware, there are only few cases reporting WUE and NUE comparisons between bread wheat, durum wheat and barley within the same experiment. From these few cases, only one dataset showed barley having higher WUE $_{yield}$ than wheat in Western Australia (Simpson and Siddique, 1994). Recently, it was found that barley and wheat yields were rather similar in a wide range of growing conditions in the Mediterranean basin (Cossani et al., 2009 in Spain; Albrizio et al., 2010 in Italy), which implies similar WUE and NUE between both species.

This sort of comparisons may be relevant as there is a generalized assumption that barley (in NE Catalonia) and durum wheat (in southern Mediterranean basin) do behave better than bread wheat when subjected to water shortages: in other words that barley (and durum wheat) may be more efficient in the scarce resource conditions than bread wheat.

In this paper we aimed to compare the performance of barley, bread and durum wheat in terms of WUE and NUE in different water and N levels under Mediterranean conditions and how is N and water availability related to grain yield in the three species.

Materials and Methods

The experimental site was located in Agramunt (lat. 41° 47´17´´ N, long. 1° 5´59´´ E, altitude 337 m), province of Lleida (Catalonia, north-eastern Spain) on a Fluvisol calcari soil (FAO, 1990). Four experiments were sown with wheat and barley (experiment I: barley and bread wheat; experiments II, III, and IV: barley, bread wheat and durum wheat) in three consecutive growing seasons (2004/05, 2005/06, and 2006/07) in a factorial combination of N and water availabilities. Previous crop was bread wheat in all the experiments.

Cultivars for barley (*cv.* Sunrise), bread wheat (*cv.* Soissons) and durum wheat (*cv.* Claudio) were the same in the four experiments and were chosen to represent successful and well adapted modern cultivars sown in the region as explained in Cossani et al. (2007). In addition, the cultivars were used as standard controls in [illegible] GENVCE [illegible] group (Group for the Evaluation of the New Cereals Varieties [illegible] 2004).

In experiment I, bread wheat and barley were sown on November 16, 2004, and consisted of a factorial combination of the two species with two water regimes and with two N fertilizer rates. The irrigated treatment consisted of a weekly (twice weekly on few occasion) frequency, starting at the beginning of stem elongation (DC 3.1, Zadoks *et al.*, 1974). Crops received 17 mm of water in each irrigation time. It was carried out with a drip irrigation system with drip lines separated at 25 cm at right angle to the crops rows. N was applied splitting the dose in two, in order to minimize possible losses, at DC 1.2 and DC 3.1 as ammonium nitrate (34.4-0-0). Flowering date was recorded on May 3 and May 10, 2005 for barley and bread wheat respectively. Harvest date for wheat and barley was similar under rainfed conditions (June 20, 2005) while under irrigated conditions wheat was harvested a week later than barley (June 28, 2005).

Experiment II was sown on November 28, 2005, and consisted of a factorial combination of the three species (barley, bread wheat and durum wheat) with two water regimes, and with four N fertilizer rates. N was applied splitting the dose as in experiment I. Irrigated treatment was performed through a drip irrigation system with a weekly (twice weekly on few occasion) as in the experiment I, but this time with the drip tube's lines placed in between crop rows (only due to facilitate the

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III and IV.

(*cv.* Soissons) did not reach anthesis (probably because

efficiency ($WUE_{\text{Biomass or yield}}$) was then calculated as the

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Results

Weather conditions

Environmental conditions differed between experiments and growing seasons. Both the amount and the distribution of precipitations during the growing season differed between experiments (Fig. 1). The wettest season and also that with precipitations relatively well distributed, occurred during experiment III with at least c. 10 mm of rainfall in each month. Contrarily, during experiments I and II precipitations were not uniform during the growing season. While in experiment I precipitations occurred mostly during the period between jointing and flowering, in experiment II the highest amount of precipitations occurred during the period between sowing and jointing, without any precipitation higher than 10 mm from jointing to maturity.

Reference evapotranspiration (ET_0) increased from February to July in all years. Higher values of ET_0 were observed in experiments I and II than in experiment III during April. In experiment II, high values of ET_0 coincided with a period with almost no precipitations, therefore increasing water stress for the crops. In contrast, in experiment III the period of higher precipitations coincided with the increasing atmospheric water demand (Fig. 1).

Water [illegible]

A wide range (120 to 693 mm) of water use (evapotranspiration) by [illegible] three experimental years mainly generated by the differences in total rainfall, water content at crop emergence and the amount of irrigated water (Table 1; Fig. 2a, b).

Naturally, crops under rainfed treatments used less water (136, 236, 357 and 311 mm for experiments I, II, III and IV respectively) than under irrigation (348, 299 and 634 mm during the growing season for I, II and III respectively; Fig. 2a).

Grain yield was positively related to water used from emergence to maturity (Fig. 2a). Most experimental data were close to WUE limits reported by Sadras and Angus (2006) with only few exceptions of durum wheat and barley.

There were no significant differences in water use from emergence to flowering ($p<0.05$) for wheat (bread or durum) and barley in two of the four experiments (exps I and IV). Barley crops used slightly less water from emergence to flowering than wheat in the other two experiments (exp. II and III); and these minor differences in water use were minimized when expressed in terms of mean water use per day (Fig. 3).

Nitrogen uptake

It was explored a wide range of total N uptake for bread wheat (49 to 220 kg N ha^{-1}), durum wheat (100 to 280 kg N ha^{-1}) and barley (46 to 290 kg N ha^{-1}) across the three growing seasons and resource availabilities due to treatments (Fig. 4). Bread wheat and barley explored [illegible] mainly because the extremely poor conditions during the [illegible] rimental year (in which durum wheat was not grown). Barley tended to have higher N uptake than bread wheat in experiments II and III ($p<0.05$; Fig. 4).

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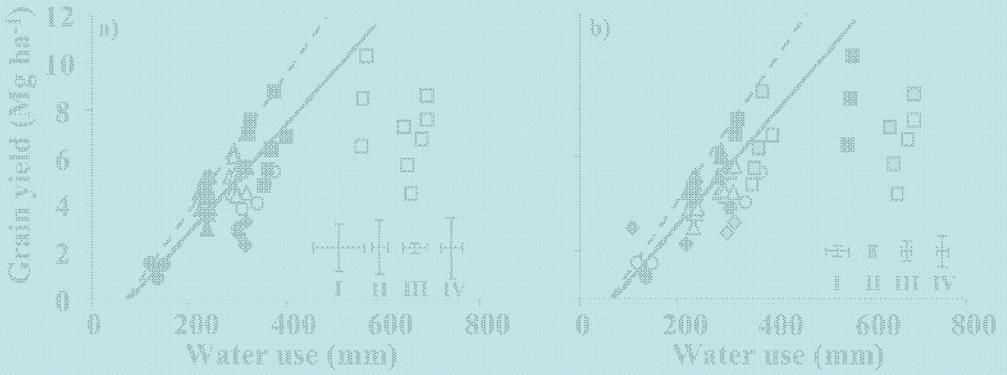

Figure 2. Grain yield as a function of water use from emergence to maturity. a) showing the inter-annual variation (○exp I, △ exp II, □ exp III, and ◇ exp IV) and water regime (open and closed symbols represent irrigated and rainfed conditions respectively) and b) sowing species variability (barley, bread wheat and durum wheat are represented by black, white and grey symbols respectively) for each experimental year (○exp I, △ exp II, □ exp III, and ◇ exp IV). LSD (P=0.05) values for water regime (a) and species (b) treatments of each experiment are represented as vertical and horizontal bars. Continuous lines represent the attainable transpiration efficiency limit for Mediterranean regions (0.022 Mg ha^{-1} mm^{-1}) found by Sadras and Angus (2006), and dotted lines represent maximum values of transpiration use efficiency obtained in the present experiments (0.029 Mg ha^{-1} mm^{-1}).

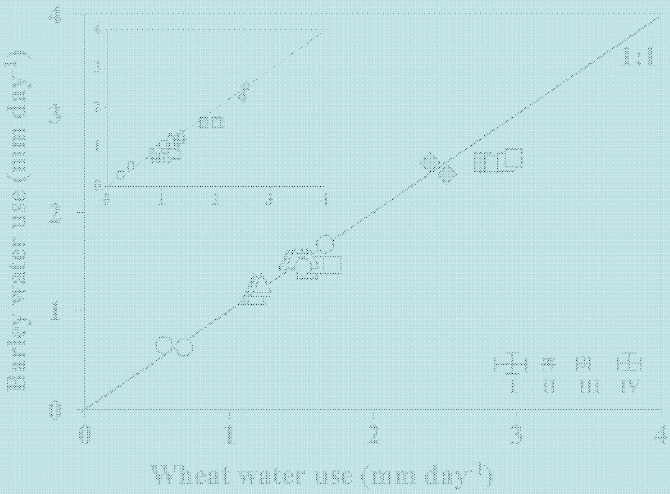

Figure 3. Relationship between mean water use per day (mm day^{-1}) from emergence to maturity (and from emergence to flowering- inset Figure -) for bread wheat (open symbols) or durum wheat (grey symbols) and mean water use per day for barley. Experiments are represented using different symbols (○ exp I, △ exp II, □ exp III, and ◇ exp IV). LSD (P=0.05) values for species treatments of each experiment are represented as vertical and horizontal bars.

However, in the poorest yielding condition (experiment I) barley presented higher N uptake than bread wheat only under irrigation. In contrast durum wheat and barley had similar N uptake in all the experiments ($p<0.05$; Fig. 4).

N uptake was significantly higher in the fertilized treatments than in the unfertilized controls in all the experiments, except in the out-of-season experiment (exp IV), where differences follow the same trend (205 vs. [illegible] Intermediate fertilized treatments across experiments (lower than 100 kg N [illegible] than unfertilized treatments while fertilized treatments equal or higher than 100 kg N ha^{-1} absorbed *c.* 80% more N than the unfertilized control. Therefore, disregarding the source of variation (growing seasons, nitrogen levels and species) grain yield was related to nitrogen uptake ($r^2=0.67$; $p<0.001$).

Grain and biomass water use efficiencies

In general WUE $_{yield}$ and WUE $_{biomass}$ were linearly and closely related in all experiments ($r^2=0.84$ ($P<0.001$)). Thus, only results for WUE $_{yield}$ is reported in Table 2. Across all the experiments barley had higher or similar WUE $_{yield}$ than both wheats (Table 2). Under the poorest [illegible] barley had similar WUE $_{yield}$ to bread wheat (experiment I) and to [illegible] IV; Table 2). As expected, nitrogen fertilization tended to increase WUE $_{yield}$, although these trends were statistically significant only in experiment III (Table 2).

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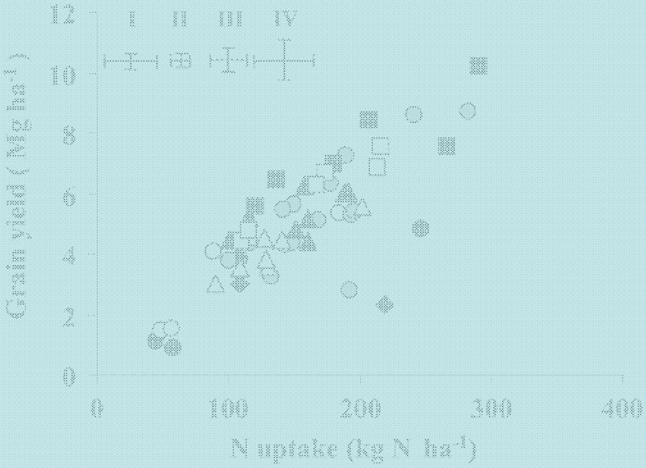

Figure 4. Grain yield as a function of nitrogen uptake at maturity during the three experimental years (○ exp I, △ exp II, □ exp III, and ◇ exp IV) for the three species (barley, bread wheat and durum wheat are represented by black, white and grey symbols respectively) at Agramunt (NE Spain). LSD (P=0.05) values for species treatments of each experiment are represented as vertical and horizontal bars.

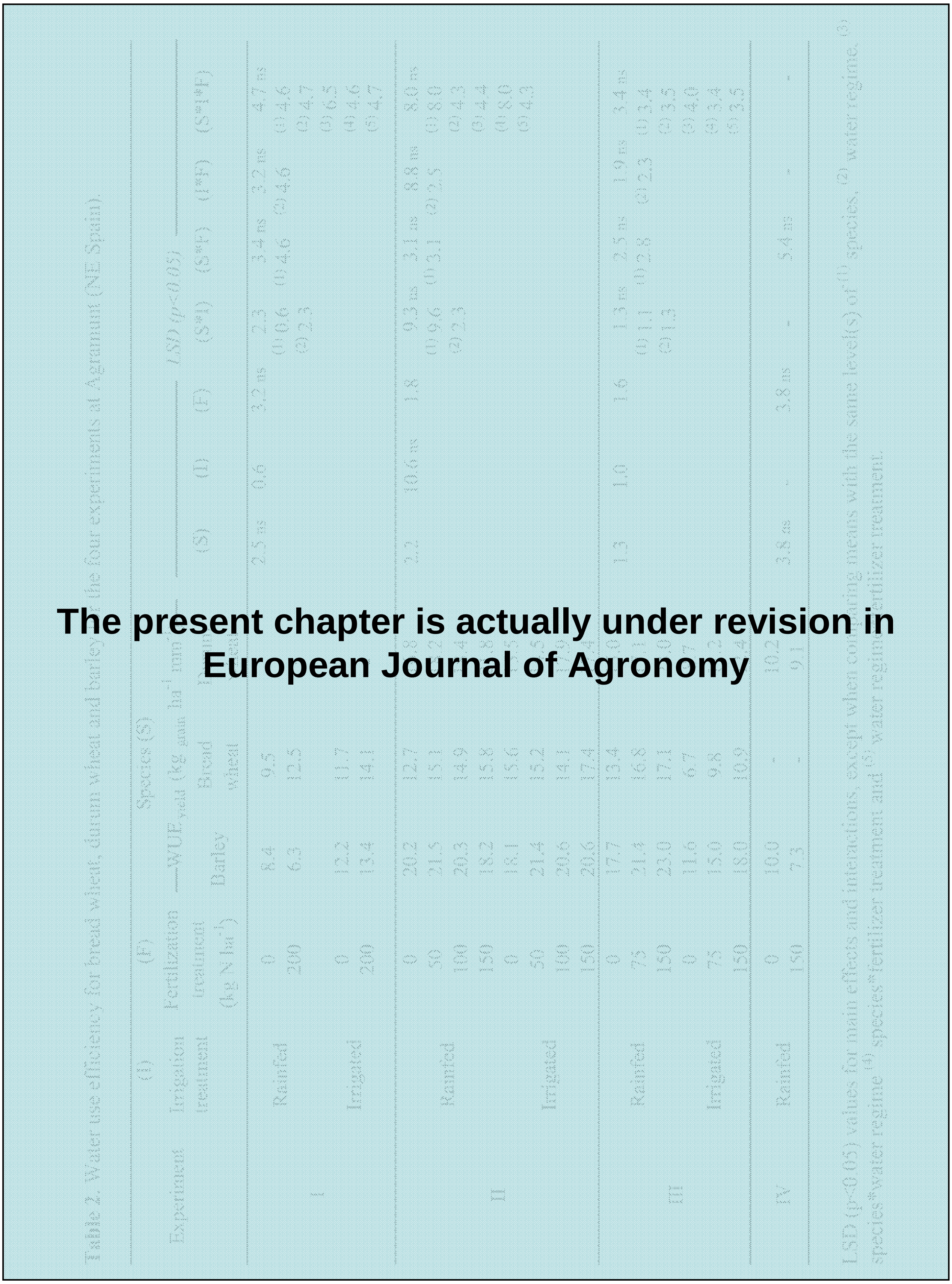

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Table 2. Water use efficiency for bread wheat, durum wheat and barley for the four experiments at Agramunt (NE Spain).

Experiment	(I) Irrigation treatment	(F) Fertilization treatment (kg N ha^{-1})	Species (S) WUE$_{yield}$ (kg $_{grain}$ ha^{-1} mm^{-1})			LSD ($p<0.05$)						
			Barley	Bread wheat	Durum wheat	(S)	(I)	(F)	(S*I)	(S*F)	(I*F)	(S*I*F)
I	Rainfed	0	8.4	9.5	[illegible]	2.5 ns	0.6	3.2 ns	2.3 (1) 0.6 (2) 2.3	3.4 ns (1) 4.6	3.2 ns (2) 4.6	4.7 ns (1) 4.6 (2) 4.7 (3) 6.5 (4) 4.6 (5) 4.7
		200	6.3	12.5	[illegible]							
	Irrigated	0	12.2	11.7	[illegible]							
		200	13.4	14.1	[illegible]							
II	Rainfed	0	20.2	12.7	[illegible]	2.2	10.6 ns	1.8	9.3 ns (1) 9.6 (2) 2.3	3.1 ns (1) 3.1	8.8 ns (2) 2.5	8.0 ns (1) 8.0 (2) 4.3 (3) 4.4 (4) 8.0 (5) 4.3
		50	21.5	15.1	[illegible]							
		100	20.3	14.9	[illegible]							
		150	18.2	15.8	[illegible]							
	Irrigated	0	18.1	15.6	[illegible]							
		50	21.4	15.2	[illegible]							
		100	20.6	14.1	[illegible]							
		150	20.6	17.4	[illegible]							
III	Rainfed	0	17.7	13.4	[illegible]	1.3	1.0	1.6	1.3 ns (1) 1.1 (2) 1.3	2.5 ns (1) 2.8	1.9 ns (2) 2.3	3.4 ns (1) 3.4 (2) 3.5 (3) 4.0 (4) 3.4 (5) 3.5
		75	21.4	16.8	[illegible]							
		150	23.0	17.1	[illegible]							
	Irrigated	0	11.6	6.7	[illegible]							
		75	15.0	9.8	[illegible]							
		150	18.0	10.9	[illegible]							
IV	Rainfed	0	10.0	-	10.2	3.8 ns	-	3.8 ns	-	5.4 ns	-	-
		150	7.3	-	9.1							

LSD ($p<0.05$) values for main effects and interactions, except when comparing means with the same level(s) of (1) species, (2) water regime, (3) species*water regime (4) species*fertilizer treatment and (5) water regime*fertilizer treatment.

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Table 3. Nitrogen use efficiency for bread wheat, durum wheat and barley for the four experiments at Agramunt (NE Spain).

Exp.	(I) Irrigation treatment	(F) Fertilization treatment (kg N ha^{-1})	(S) Nitrogen use Efficiency (kg $_{grain}$ kg $_{available\ N}^{-1}$ in soil)			LSD (p<0.05)						
			Barley	Bread wheat	Durum wheat	(S)	(I)	(F)	(S*I)	(S*F)	(I*F)	(S*I*F)
I	Rainfed	0	11.4	13.5	-	5.5 ns	9.1	2.4	8.0 ns (1) 8.5 (2) 2.9	3.0 (1) 3.4	7.5 (2) 4.6	7.0 ns (1) 7.0 (2) 3.8 (3) 4.8 (4) 7.0 (5) 3.8
		200	2.9	4.7	-							
	Irrigated	0	24.4	33.9	-							
		200	11.7	11.8	-							
II	Rainfed	0	29.4	22.1	24.7	6.7 ns	5.1 ns	2.7	6.8ns (1) 4.8 (2) 6.7	6.9 ns (1) 4.6	4.3 ns (2) 3.8	8.2 ns (1) 6.9 (2) 8.2 (3) 6.5 (4) 6.9 (5) 8.2
		50	23.6	17.2	17.4							
		100	17.0	19.7	15.6							
		150	11.4	11.3	17.5							
	Irrigated	0	28.8	27.3	27.6							
		50	27.0	27.8	18.1							
		100	22.2	18.9	17.3							
		150	22.0	18.6	15.5							
III	Rainfed	0	33.2	30.3	28.1	5.1 ns	1.3 ns	2.3	5.0 ns (1) 2.2 (2) 5.0	5.3 ns (1) 3.9	2.7 ns (2) 3.2	6.1 ns (1) 4.8 (2) 6.1 (3) 5.5 (4) 4.8 (5) 6.1
		75	30.4	30.3	25.7							
		150	23.8	26.9	24.8							
	Irrigated	0	31.8	27.8	27.1							
		75	31.6	29.9	29.2							
		150	29.3	26.7	27.8							
IV	Rainfed	0	18.4	-	16.2	4.7 ns	-	4.7 ns	-	6.6 ns	-	-
		150	6.9	-	7.0							

LSD (p<0.05) values for main effects and interactions, except when comparing means with the same level(s) of (1) species, (2) water regime, (3) species*water regime (4) species*fertilizer treatment and (5) water regime*fertilizer treatment.

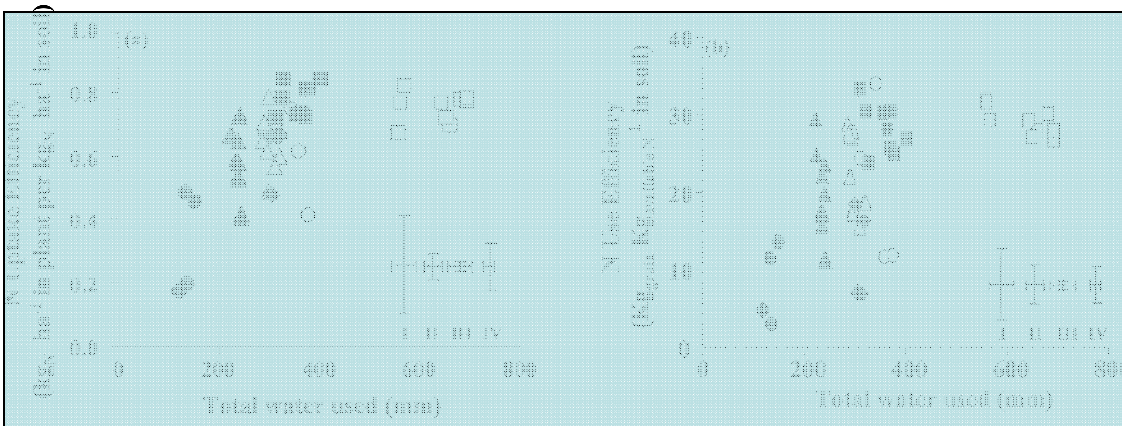

Figure 5. Nitrogen uptake efficiency (a) and nitrogen use efficiency (b) as a function of total water used from sowing to maturity (mm) for barley bread wheat, and durum wheat under rainfed (closed symbols) and irrigated (open symbols) conditions in all experiments sown at Agramunt (NE Spain).). LSD (P=0.05) values for water regime treatment of each experiment (○exp I, △ exp II, □ exp III, and ◇ exp IV) are represented as vertical and horizontal bars.

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Nitrogen uptake efficiency

A wide range of N uptake efficiency (UpE) was observed from 0.15 to 0.84 (kg N ha^{-1} in plant per kg $_{available N}$ ha^{-1} in soil) in the three experimental years. In most of the cases, the species did not differ in UpE. N fertilization decreased UpE in three of the four experiments [illegible] and maximum N fertilizer rate were 17%, 16% and 14% in experiments I, [illegible] but increased UpE in experiment III (14% higher). UpE increased hyperbolically with water availability with a threshold value of *c*. 400 mm (Fig. 5a).

Nitrogen utilization efficiency

There were significant differences between wheat and barley in N utilization efficiency (UtE) depending on the yield level determined by the year. Under the lowest yielding conditions (experiments I and IV), barley had lower or similar UtE than wheat (bread or durum) (23.3 *vs*. 32.8 kg $_{grain}$ kg $_N$$^{-1}$ for barley and bread wheat in experiment I; and 19.2 *vs*. 19.3 kg $_{grain}$ kg $_N$$^{-1}$ for barley and durum wheat in experiment IV). In experiment II, barley had higher UtE than bread and durum wheat (35.6, 32.2 and 32.3 kg $_{grain}$ kg $_N$$^{-1}$ for barley, bread wheat and durum wheat, respectively) while there were not significant differences between durum or bread wheat.

Although the main effects for species did not showed significant differences in UtE for the conditions explored in experiment III. (39.6, 37.4, 36.0 for barley, bread wheat and durum wheat, respectively) a significant species x N fertilizer treatment interaction was observed indicating in this case a higher UtE for barley (46.8 kg $_{grain}$ kg $_N$$^{-1}$) than bread wheat (40.9 kg $_{grain}$ kg $_N$$^{-1}$) and durum wheat (38.0 kg $_{grain}$ kg $_N$$^{-1}$) only under unfertilized treatments. N fertilization produced a high significant effect in UtE in all experiments [illegible] control.

Nitrogen use efficiency

NUE was the result of the combination of both sub-components UtE (r^2 = 0.64) and UpE (r^2= 0.68). The range of variability was higher in UpE (0.15 to 0.84 kg N ha^{-1} in plant per kg $_{available N}$$^{-1}$ in soil) than in UtE (10.6 to 49 kg $_{grain}$ kg $_N$$^{-1}$). Wheat (bread and durum) and barley did not differ in total NUE except in experiment I where bread wheat presented slightly higher values (23.7 kg $_{grain}$ kg $_{available N}$$^{-1}$ in soil) than barley (17.9 kg $_{grain}$ kg $_{available N}$$^{-1}$ in soil) under unfertilized conditions (Table 3).

As generally reported, N fertilization decreased significantly NUE in all the experiments, except in experiment III. Treatments with a low water availability and high level of N fertilization had the lowest NUE (3.8 kg $_{grain}$ kg $_{available N}$$^{-1}$ in soil) in experiment I. The increase in water availability due to irrigation resulted in a significant higher NUE in experiment I, but not in experiments II and III (Table 3). As observed in UpE, NUE increased hyperbolically with water availability with a threshold value of *c*. 400 mm (Fig. 5b).

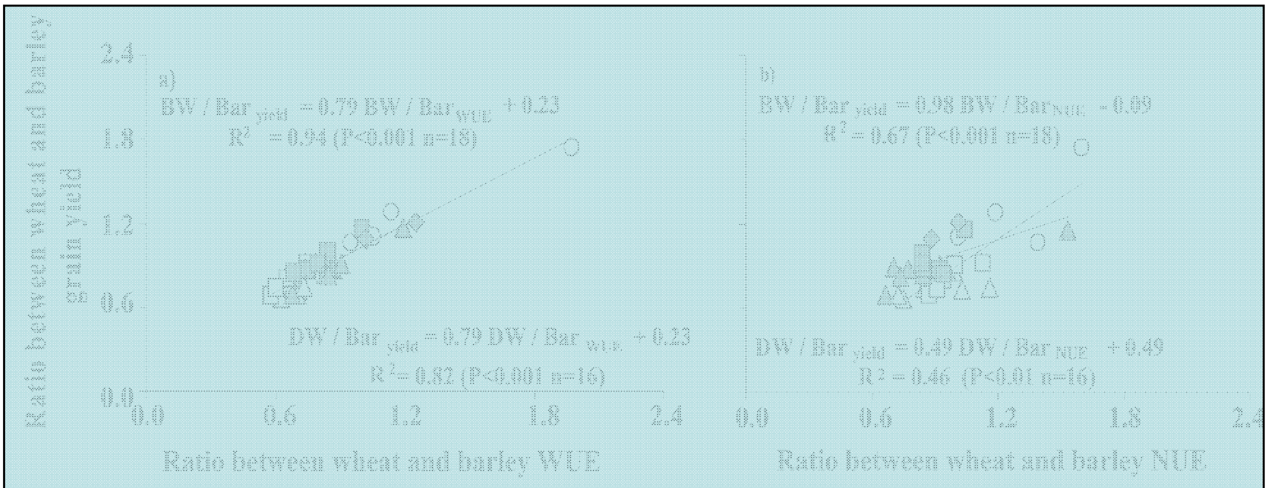

Figure 6. Ratio between wheat and barley grain yield (bread wheat or durum wheat $_{GY}$/ barley $_{GY}$) as a function of the ratio (bread wheat or durum wheat $_{WUE}$/ barley $_{WUE}$) between wheat and barley water use efficiency (WUE $_{yield}$) (a) and nitrogen use efficiency (NUE) (bread wheat or durum wheat $_{NUE}$/ barley $_{NUE}$) (b). Differences across all the experiments (○ exp I, △ exp II, □ exp III, and ◇ exp IV) are represented using open symbols and grey symbols for bread wheat and durum wheat, respectively.

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Discussion

Impact on relative grain yield performance

The [illegible] barley in terms of WUE (Table 2) or NUE (Table 3) did not seem to show clear [illegible] yielding conditions (experiment I and IV). Albrizio et al. (2010) also reported similar WUE $_{yield}$ for durum wheat and barley under different N and water availabilities in other Mediterranean environment (Bari, Italy). Results reported for grain yield by Cossani et al. (2009) showed no differences between wheat (bread or durum) and barley in low yielding conditions. If it is analyzed together the performance in grain yield with the reported in the present study for WUE and NUE, it can be observed that the relative differences in grain yield between wheat an barley (analyzed as the ratio between grain yield of the species) were directly related to the relative differences in efficiency in using water or N between wheat and barley (analyzed as the ratio between WUE or NUE of the species) (Fig 6). Some of these little differences in water use efficiency, when in favor of barley, could be based from the variation in the evaporative loss of water from the soil surface, differences in soil water extraction, or differences in net carbon assimilation between the species, as reported by Lopez-Castañeda and Richards (1994). In the case reported in the present study, differences between wheat and barley seem to be related to better conditions during critical period for grain number determination (Cossani et al., 2009) rather than to total water extraction. The impact of the relative differences between wheat and barley in WUE $_{yield}$ on relative differences between them on grain yield (Fig. 6) had lower variability than the impact produced by relative differences in NUE (WUE [illegible] $R^2 = 0.94$ vs NUE $R^2 = 0.67$ for differences between bread wheat and barley and WUE $_{yield}$ $R^2 = 0.82$ vs. NUE $R^2 = 0.46$ for differences between durum wheat and barley). This may be indicating that, when WUE or NUE are modified by some environmental factor or management practice, this modification is directly translated to differences in grain yield as reported above, more markedly so for water- than for N-use efficiency.

N fertilization produced a positive effect on WUE $_{yield}$. Differences in grain yield between fertilized and unfertilized treatments were higher when WUE $_{yield}$ was increased respect to the non-fertilized treatment due to N fertilization (Fig. 7a). However, it has an opposite effect in NUE. In most of the cases, it was observed a reduction in NUE due to higher N fertilization, although this reduction in NUE was translated (Fig. 7b) to higher grain yields. Yields tended to be higher when this reduction was closer to 0. On the other hand, probably due to the high level of N availability at sowing, the response of NUE to N fertilization had higher variability than WUE $_{yield}$.

The higher water availability increased grain yield while reducing WUE $_{yield}$ in experiments with high water availability (Fig. 7c), and increased yield in line with increased WUE $_{yield}$ in the most water-stressed conditions (experiment I). In general, the effect of water availability on NUE per mm of water irrigated presented higher variability than in WUE (Figs. 7c and d). Changes in grain yields were mediated by changes in the crops resources use efficiency in wheat as well as in barley. However, the differences observed in WUE (due to N fertilization) produced differences in grain yield with a lower variability than changes in NUE. It indicates that the most important trait behind the yielding differences among these crops has been WUE rather than NUE. Increases in grain yields, together with increases in WUE and decreases in NUE (due to higher N availabilities), were previously reported as a consequence of higher degree of water-nitrogen co-limitation (Sadras, 2005). The higher variability observed for NUE than for WUE in the response could be due to a high N availability at sowing for the unfertilized treatments during the second and third experimental year, that exposed the crops to an expectedly lower response to N than in experiment I. It seems that increases in resource use efficiency by affecting the resources availabilities had a limit in the response. It can be observed from the limits observed in the maximum NUE and UpE shown in Fig. 5. As NUE is the result of the combination of the both sub-components (UpE and UtE) limits of the NUE found for the 400 mm of water use could be think to be related to a maximum UpE (0.85 kg N ha^{-1} in plant per kg $_{available\ N}$ ha^{-1} in soil) and maximum UtE (48 c. kg $_{grain}$ kg $_{N}^{-1}$). Maximum UtE found for the present experiments were similar to the limits for UtE reported by Savin et al. (2006) for the Mediterranean region.

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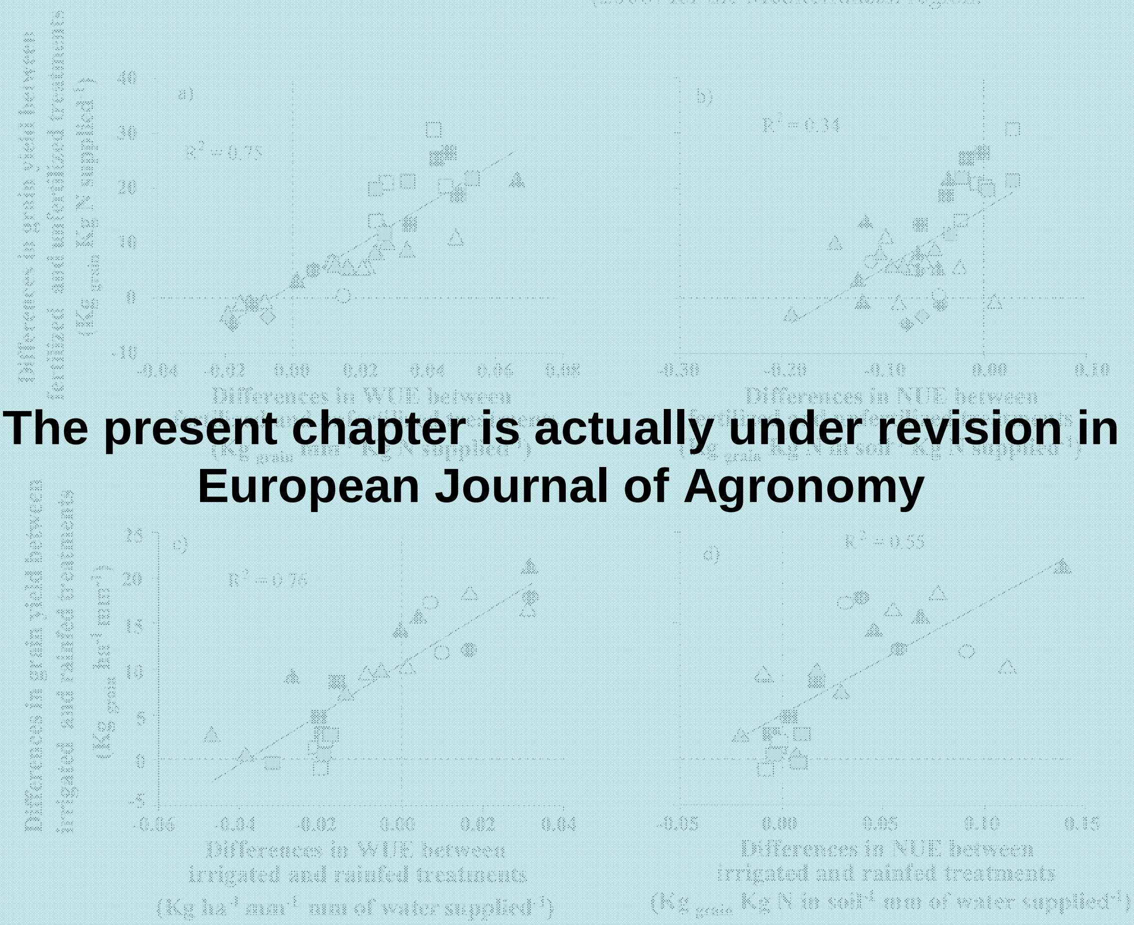

Figure 7. Differences in grain yield between fertilized and unfertilized treatments (grain yield N_x- grain yield N_0) per Kg N ha^{-1} supplied as a function of the (a), differences in water use efficiency between fertilized and unfertilized treatments (WUE N_x- WUE N_0) per Kg N ha^{-1} supplied and (b) differences in nitrogen use efficiency between fertilized and unfertilized treatments (NUE N_x- NUE N_0) per Kg N ha^{-1} supplied (upper panels); And differences in grain yield between irrigated and rainfed treatments (grain yield irrigated- grain yield rainfed) per mm of water irrigated function of the (c) and differences in water use efficiency between irrigated and rainfed treatments (WUE Irrigated-WUE rainfed) per mm of water supplied and (d) differences in nitrogen use efficiency between irrigated and rainfed treatments (NUE Irrigated-NUE rainfed) per mm of water supplied. Black, white and grey symbols represent barley, bread wheat and durum wheat, respectively for each experiment (○exp I, △ exp II, ☐ exp III, and ◇ exp IV) irrigated and rainfed treatments per mm of water irrigated and (d) differences in nitrogen use efficiency between irrigated and rainfed treatments per mm of water irrigated (lower panels).

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Barley and wheat resource use and resource use efficiency performance

Opposite to what is generally accepted, we did not find that barley had any higher efficiency than wheat to use limited resources under stress and had overall similar WUE than bread and durum wheat in the lowest-yielding environment. This is in line with previous finding in which barley did not clearly out-yield wheat under stressful Mediterranean conditions (Simpson and Siddique, 1994 in Australia; Cossani et al., 2007, Cossani et al., 2009 in Catalonia; Albrizio et al., 2010 in Italy).

Across the four experiments wheat and barley did not markedly differ in total water used except in experiment III where barley used 85 and 75 mm less than bread and durum wheat, respectively ($p<0.05$; Fig. 2b). The similar water use (evapotranspired water) found in experiment I, II, and IV between wheat and barley may not necessarily indicates an advantage of barley over wheat in terms of lower water requirements. Nevertheless, in the case of experiment II at the beginning of stem elongation barley crops had a higher proportion of photosynthetic active radiation intercepted than wheat (78 % *vs* 59% and 53% as an average of the different treatments for barley, durum wheat and bread wheat, respectively). This could be interpreted as a higher [illegible] translated into higher grain yield, for barley than for wheat. As we did not [illegible] evapotranspired water, we may only speculate here a lower evaporation in barley than in wheat. In turn, the higher amount of transpired water (as indicated earlier by Richards, 1992), would determine a higher WUE, with similar WU. This speculated improved water use partitioning, together with lower temperatures during the critical period for grain yield determination, as reported in Cossani et al. (2009), would has allowed sustaining a higher post-flowering growth in barley than in wheat in experiment II. On the other hand, in experiment III, the higher water use of wheat over barley could be attributed to a late irrigation that increased available water that was not used by barley but evapotranspired by wheat (Table 1). In this case, the lower amount of water used by barley was translated in a higher proportion of water that remained in the soil at harvest (data not shown). In fact, there were no significant differences in the proportion of photosynthetic active radiation intercepted by the species at the beginning of stem elongation in this experiment.

Although the use of only one cultivar for each species could be interpreted as a weakness of the present approach, the carefully and objective criteria of selection of each cultivar to represent current farmers' preference support the validity of the results. Genotypic variability in the response of grain yield or WUE to salt concentration in soil has been recently reported by Katerji et al. (2008b) for bread wheat, barley or durum wheat. However, it was not reported a barley higher WUE stability than durum or bread wheat in the mentioned report between maximum or minimum salt concentration.

Regrettably, direct comparisons of the WUE values obtained by Katerji et al. (2008b) can not be done due to different water availability for the species and not exactly the same salinity level for wheat and barley except for the lowest one. Also, the analysis was not performed on field plots and results could slightly differ from the reality. Katerji et al. (2009) using lisimeters reported a similar reduction (37%) in grain yield for durum wheat and barley caused by drought at three salinity levels. However, a higher sensitivity of durum wheat yield to soil salinity was reported (Katerji et al., 2009).

In terms of NUE there were no clear either differences between wheat (bread or durum) and barley throughout the environmental conditions explored. In some occasions of the present study one of the NUE-components (UpE or UtE) showed significant differences between species, but these differences in one component tended to be compensated by the opposite [illegible] poor environmental conditions of experiments I and IV, [illegible] wheat. In contrast under higher yielding environments, in line with results by Delogu et al. (1998) and Albrizio et al. (2010) barley had higher UtE than wheat.

Conclusion

Considering the data from the four experiments in the three contrasting growing seasons barley did not present a clear pattern of advantage in terms of water or nitrogen use efficiency over wheat, either bread or durum. Therefore, differences in WUE and NUE do not explain the popularity of barley over wheat. This may change the present general view on best pattern of land use in the Mediterranean region defined by López-Bellido (1992) and Ryan et al. (2008). Thus wheat cropping could be expanded avoiding problems associated with barley monocultures, such as control of specific weeds (e.g. Bromus sp.) which is a common weed in Catalonia and many other regions.

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References

Abeledo, L.G., Savin, R., Slafer, G.A., 2008. Wheat productivity in the Mediterranean Ebro Valley: Analyzing the gap between attainable and potential yield with a simulation model. Eur. J. Agron. 28, 541-550.

Albrizio, R., Todorovic, M., Matich, T., Stellacci, A.M., 2010. Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. Field Crops Res. 115, 179-190.

Anonymous (Group for the Evaluation of New Cereals Varieties in Spain). 1999-2004. Report of new varieties of wheat and barley evaluated during the growing season 1999-2000, 2000-2001, 2001-2002, 2002-2003 and 2003-2004.

Angás, P., Lampurlanés, J., Cantero-Martínez, C., 2006. Tillage and N fertilization Effects on N dynamics and Barley yield under semiarid Mediterranean conditions. [illegible]

Angus, J.F., van Herwaarden F., 2001. Increasing Water Use and Water Use [illegible] Agrono. J. 93, 290-298.

Araus, J.L., Slafer G.A., Reynolds M.P., Royo, C., 2002. Plant breeding and drought in C3 cereals: what should we breed for? Ann. Bot. 89, 925–940.

Cossani, C.M., Savin, R., Slafer, G.A., 2007. Contrasting performance of barley and wheat in a wide range of conditions in Mediterranean Catalonia (Spain). Ann. App. Biol. 151, 167-173.

Cossani, C.M., Slafer, G.A., Savin, R., 2009. Yield and biomass in wheat and barley under a range of conditions in a Mediterranean site. Field Crops Res. 112, 205-213.

Delogu, G., Cattivelli, L., Pecchioni, N., De Falcis, D., Maggiore, T., Stanca, M.A.,1998. Uptake and agronomic efficiency of nitrogen in winter barley and winter wheat. Eur. J. Agron. 9, 11-20.

F.A.O., 1990. F.A.O. UNESCO soil map of the world: revised legend. World Soil Resources Report 60. Rome, Italy: FAO.

Fischer, R.A., 1993. Irrigated spring wheat and timing and amount of nitrogen fertilizer. II. Physiology of grain yield response. Field Crops Res. 33, 57-80.

French R.J., Schultz, J.E., 1984a. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and Climate. Austr. J. Agr. Res. 35, 743-764

French R.J., Schultz, J.E., 1984b. Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. Austr. J. Agr. Res. 35, 765-775.

Katerji, N., Mastrorilli, M., Rana, G., 2008a. Water use efficiency of crops cultivated in the Mediterranean region: Review and analysis. Eur. J. Agron. 28, 493-507.

Katerji, N., Mastrorilli, M. Nachit, M.M., van Hoorn, J.W., Hamdy, A., Oweis, T., Abdalla, O., Grando, S., 2008b. Salt tolerance classification of winter cereal varieties according to grain yield performance and water use efficiency. 105-114. In: Sustainable Irrigation Management, Technologies and Policies II. Eds. Villacampa Esteve Y., Brebbia, C.A., Prats Rico, D. Witpress, Southampton, Boston, UK. 381pp.

Katerji, N., Mastrorilli, M., van Hoorn, J.W., Lahmer, F.Z., Hamdy, A., Oweis, T., 2009. Durum wheat and barley productivity in saline-drought environments. Eur. J. Agron. 31, 1-9.

Lopez-Bellido, L., 1992. Mediterranean cropping systems. In Ecosystems of the World. Field Crop Ecosystems, 14, pp. 311-356. Ed C.J. Pearson. Netherlands: Elsevier.

López-Bellido, L., López-Bellido, R.J., Redondo, R., 2005. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split [illegible] 97.

López-Castañeda, C., Richards, R.A., 1994. Variation in [illegible] environments III. Water use and water-use efficiency. Field Crops Res. 39, 85-98.

Passioura, J.B. 2002. Environmental biology and crop improvement. Funct.l Plant Biol. 29, 537–546.

Payne, W.R., Harding, S.A., Murray, D.A., Soutar, D.M., Baird, D.B., Glaser, A.I., Channing, I.C., Welham, S.J., Gilmour, A.R., Thompson, R., Webster, R. 2008. GenStat® Release 11, Reference Manual. VSN International, Hemel Hempstead, Herttfordshire, UK, pp. 405.

Richards, R.A., 1992. The effect of dwarfing genes in spring wheat in dry environments. II. Growth, water use and water use efficiency. Austr. J. Agr. Res. 43,529-539.

Ryan, J., Singh, M., Pala, M., 2008. Long-Term Cereal-Based Rotation Trials in the Mediterranean Region: Implications for Cropping Sustainability. In: Adv. in Agron. 97, 273-319.

Sadras, V.O., 2004. Yield and water-use efficiency of water-and nitrogen-stressed wheat crops increase with degree of co-limitation. Eur. J. Agron. 21, 455-464.

Sadras, V.O., 2005. A quantitative top-down view of interactions between stresses: theory and analysis of nitrogen –water co-limitations in Mediterranean agro-ecosystems. Austr. J. Agr. Res. 56, 1151-1157.

The present chapter is actually under revision in European Journal of Agronomy

Sadras, V.O., Angus, J.F., 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. Austr. J. Agr. Res. 57, 847-856.

Savin, R., Sadras, V.O., Slafer, G.A., 2006. Do Mediterranean environments set up an upper limit in wheat nitrogen use efficiency?. In: Bibliotheca Fragmenta Agronomica. IX ESA CONGRESS. Book of proceedings Part I. Division 2, 339.

Simpson, P.G., Siddique, K.H.M.,1994. Soil type influences relative yield of barley and wheat in a Mediterranean-type environment. J. Agron. Crop. Sci. 172, 147–160.

Turner, N.C., 2004. Agronomic options for improving rainfall-use efficiency of crops in dryland farming systems. J. Exp. Bot. 55, 2413–2425.

Turner, N.C., Asseng, S., 2005. Productivity, sustainability, and rainfall-use efficiency in Australian rainfed Mediterranean agricultural systems. Austr. J. Agr. Res. 56, 1123–1136.

van Herwaarden, A.F., Angus, J.F., Richards, R.A., Farquhar, G.D., 1998a. "Haying-off" the negative grain yield response of dryland wheat to nitrogen fertilizer. I. Biomass, grain yield and water use. Austr. J. Agr. Res. 49, 1067-1082.

van Herwaarden, A.F., Richards, R.A, Farquhar, G.D., Angus, J.F., 1998b. "Haying-off" the negative grain yield response of dryland wheat to nitrogen fertilizer. III. The influence of water deficit and heat shock. Austr. J. Agr. Res. 49, 1095-1110.

Veron, S.R., Paruelo, J.M., Slafer, G.A., 2004. Interannual variability of wheat yield in the Argentine Pampas during the 20th century. Agr. Ecosys. Environ. 103, 177-190.

Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stage of cereals. Weed Res., 14, 415-421.

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Chapter V

Do cereals differ in grain weight stability under Mediterranean conditions?

Submitted to Field Crops Research

Do cereals differ in grain weight stability under Mediterranean conditions?

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Keywords: grain growth, grain filling duration, wheat, barley, Mediterranean environment

Abstract
Under Mediterranean environments, barley is usually preferred to sow than bread wheat by the farmers as it is believed to yield more under stressful conditions. As high temperature and water stress are two common constraints, especially during grain filling period, higher grain weight stability under these environments may confer a great advantage in order to maintain or increase yield. The objective of the present study was to compare the stability in terms of grain weight and its components for barley, bread wheat, and durum wheat, exploring a wide range of nitrogen and water availabilities under a Mediterranean environment. Grain weight ranged from 23.8 to 47.7 mg grain^{-1}, being higher for durum wheat than barley and bread wheat. Durum wheat presented higher variability both in maximum grain filling rate and duration of grain filling period than bread wheat or barley. The three species responded similarly in terms of grain nitrogen content to changes in the environmental conditions explored. It is concluded that in terms of grain weight barley is as stable as bread wheat. However, Durum wheat presented a lower stability than barley and bread wheat.

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1. Introduction

The large variability in grain yields that frequently occurs under Mediterranean environments often determines conservative strategies by farmers (Sadras et al. 2002). Many of the strategies used by farmers to avoid risks are related to efficient input managements in order to reduce crop costs, to cho[illegible] higher grain yield stability or to apply site specific management practices. In rainfed agricultural systems of Catalonia (NE Spain), as well as in many other Mediterranean regions, farmers usually grow barley continuously in drought-prone areas generating monoculture regions. This is based on the assumption that barley's yield is more stable than other cereals (see arguments in Cossani et al. 2007) or better barley yielding than durum and bread wheat in drought prone areas (Anderson and Impiglia, 2002; Ryan et al. 2008). Although grain number dominates grain weight in yield determination (e.g. Peltonen-Sainio et al. 2007), grain weight still varies and, in conditions prone to terminal stresses, yield stability might be associated to a more stable grain weight (Khanna-Chopra and Viswanathan, 1999; Royo et al. 2006). Even though the better performance of barley over wheat under stressed Mediterranean conditions has not been found in some comparative studies (Simpson and Siddique, 1994; Palumbo and Boggini, 1994; Cossani et al. 2009), it has been indeed confirmed by other authors (e.g. López-Castañeda and Richards, 1994; Josephides, 1993). Based on these evidences it can be hypothesized that barley grain weight would be more stable than grain weight of other cereals under Mediterranean environments.

The effect of high temperatures and/or water stress during grain filling period in small cereals has been well documented (e.g. Stone and Nicolas 1994 in bread wheat; Savin and Nicolas 1996 and Voltas et al. 1999 in barley, and Bharrabi et al 2003 in durum wheat). Grain [illegible] of grain filling parameters (duration and rate of grain filling) of different cereals, has not been widely compared, particularly under Mediterranean conditions. Fischer and Wood (1979), in a study conducted in Mexico, found that grain weight sensitivity to drought was only 4 % higher in bread and durum wheat than in barley. Simpson and Siddique (1994) showed a similar response of wheat and barley in grain weight to changes in soil type (fine textured vs. coarse textured soil) in Western Australia.

The main objective of the present work was to compare grain weight stability and its components in bread wheat, barley and durum wheat under a wide range of conditions in a Mediterranean region thus testing the hypothesis that barley grain weight is more stable than that of bread or durum wheat. To actually fulfill the aim of having a wide range of condition we had to restrict the genotypes analysed to only one per species. To compensate for this limitation we chose carefully these cultivars to actually represent the expected behavior of these species.

2. Materials and Methods

2.1 Experimental details

Five field experiments were sown from 2003 to 2007 in Agramunt (lat. 41° 47´17´´ N, long. 1° 5´59´´ E, altitude 337 m), a characteristic location of Mediterranean cereal production in Catalonia, Spain. The soils were classified as Arenosol calcari (experiment I) and Fluvisol calcari (experiments II, III, IV and V) (FAO 1990). Bread wheat (*cv.* Soissons), barley (*cv.* Sunrise) and durum wheat (*cv.* Claudio) were sown in all experiments under different water and N availabilities at sowing. As mentioned above, cultivars were chosen carefully to represent well adapted genotypes which in fat are those of commonly sown in the region (Cossani et al. 2007 and 2009). Details of each experiment are given briefly in Table 1. More details accounting for experimental design, weather conditions and growing stages for each species are given in Cossani et al. (2009).

A fertilizer combining P and K (0-7-14) was applied before sowing in all experiments to avoid P and K deficiencies. The average dose was of *c.* 60 kg P ha^{-1} and 120 kg K ha^{-1}. Weeds and diseases were controlled as required using conventional herbicides and fungicides as recommended by the manufacturers.

2.2 Observation and sampling methodology

Flowering date was recorded when 50% of the plants in each plot had spikes with the anthers extruded (anthesis) in the case of durum and bread wheat, and when 50% of the plants in each plot reached heading in the case of barley. Weekly sampling from anthesis to harvest was performed in experiments II, III, and IV, while in experiments I and V only one sample at maturity was harvest[illegible] dried at 65 °C and then counted, weighted and mean individual grain weight was deter[illegible]

Canopy temperature depression (CTD) was calculated as the difference between mean air temperature and the canopy temperature, measured with an infrared thermometer (Flashpoint FT 8000, Jules Richard Instruments) weekly during grain filling in experiments III and IV.

Grain nitrogen (N) percentage was determined using Near Infra Red Technology, calibrated for each species against Dumas combustion in experiment II, Dumas combustion in experiment III, and Kjeldahl methodology in experiments IV and V.

2.3 Data Analysis

Physiological maturity, final grain weight and its components were estimated by fitting the grain weight data over time with a sigmoidal model:

$AGW= a/(1 + \exp (-b^{(Ta - Ta\ MGFR)})$

where "a" is the 95% of maximum average grain weight, "b" is a parameter directly related to the rate of change in average grain weight, and MGFR (maximum grain filling rate) is calculated as [MGFR = ¼ a b] expressed in mg day^{-1}. Ta is the time from anthesis (days) and Ta $_{MGFR}$ is time from anthesis to the onset of the maximum grain growth rate (Loss et al., 1989). Parameters of the curve for each treatment were estimated iteratively using TBL curve software (Jandel, 1991). Data of MGFR and duration of grain filling (DGF) from experiment I, from rainfed treatment for bread wheat in experiment III, and from experiment V could not be included in the analysis due to insufficient sampling during grain filling (experiment I and V) and lack of enough number of points during grain filling (rainfed treatment for bread wheat in experiment III). In [illegible] model fitted the data reasonably well (r^2=0.76-0.99; P<0.01). [illegible] growing season and treatment, the environmental index (Finlay and Wilkinson, 1963) was calculated for grain weight and grain N content to determinate the stability of each species. A T-Test was used to compare regression slopes (*b* coefficient) between wheat and barley using SAS Software.

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Table 1. Experimental details for the five field experiments conducted in Agramunt (NE Spain).

Experiment	Species	Sowing date	Flowering date	Nitrogen treatment (Kg N ha^{-1})	Water regime
I	Barley Bread wheat	21-Nov-03	11 May 04 31 May 04	0-40-80-120-160 and 200	Rainfed
II	Barley Bread wheat	16-Nov-04	03 May 05 10 May 05	0 and 200	Rainfed and irrigated
III	Barley Durum wheat Bread wheat	28-Nov-05	03 May 06 09 May 06 16 May 06	0-50-100 and 150	Rainfed and irrigated
IV	Barley Durum wheat Bread wheat	06-Nov-06	30 Apr 07 07 May 07 15 May 07	0-75 and 150	Rainfed and irrigated
V	Barley Durum wheat	22-Feb-07	21 May 07 27 May 07	0 and 150	Rainfed

Table 2. Total rainfall (PP) and average for mean, maximum and minimum temperatures during grain filling for the five experiments at Agramunt (NE Spain)

Experiment	Water condition	Species	Environmental conditions from flowering to maturity			
			T mean (°C)	T max (°C)	T min (°C)	∑ PP (mm)
Exp I	Rainfed	Barley	20.1	27.5	12.6	14.1
2003/2004		Bread wheat	22.5	29.7	15.4	29.0
Exp II	Rainfed	Barley	20.7	27.8	13.6	78.2
(2004/2005)		Bread wheat	21.1	28.2	14.0	75.2
	Irrigated	Barley	20.7	27.8	13.6	78.2
		Bread wheat	22.0	29.1	14.9	84.3
Exp III	Rainfed	Barley	19.5	27.1	12.0	6.8
(2005/2006)		Durum wheat	20.7	28.5	12.9	4.8
		Bread wheat	20.9	28.8	13.0	0.0
	Irrigated	Barley	19.5	27.1	12.0	6.8
		Durum wheat	23.0	29.0	13.7	8.0
		Bread wheat	23.7	29.4	13.9	3.2
Exp IV	Rainfed	Barley	19.0	25.9	12.1	110.6
(2006/2007)		Durum wheat	20.0	27.5	13.3	73.7
		Bread wheat	21.0	27.6	13.7	72.5
	Irrigated	Barley	19.0	25.9	12.1	110.6
		Durum wheat	20.0	27.5	13.3	73.7
		Bread wheat	21.0	27.6	13.7	72.5
Exp V	Rainfed	Barley	21.1	28.0	14.1	69.7
(2007/2008)		Durum wheat	21.0	28.1	14.0	58.9

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3. Results

3.1 Weather conditions

Crops were exposed to a wide range of environmental conditions during the four growing seasons (2003/04, 2004/05, 2005/06, 2006/07), especially in total rainfall and its distribution. A range of 110 mm of variability in total rainfall was observed during the period from flowering to harvest between the different treatments and experiments. Experiment III had the driest condition while experiment II and IV received more than 70 mm of rainfall within the post-flowering period.

Mean minimum and maximum temperatures during the post-flowering period differed between species and years (Table 2). In general, barley grain growth occurred under lower mean temperatures compared to bread and durum wheat (Table 2). Bread wheat filled its grains with 2.4, 0.8, 2.7, and 2.0 °C higher mean temperatures than barley for experiments I, II, III, and IV, respectively, while mean temperatures for durum wheat were 2.2 and 1.0 °C higher than barley for experiments III and IV, respectively (temperatures were similar for grain filling in exp. V).

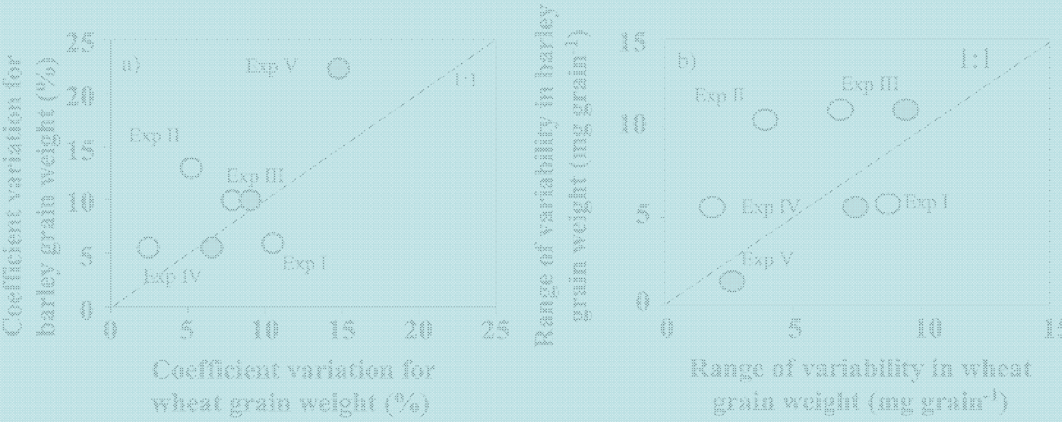

Figure 1: Coefficient of variation (a) and range of variation explored (b) for grain weight in barley against these parameters in bread (white symbols) and durum wheat (grey symbols) for experiments I, II, III, IV and V.

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3.2 *Grain weight and grain filling parameters*

Analysing firstly the coefficients and the range of variation of barley and wheat, it seemed rather difficult to establish any clear trend regarding stability of grain weight (Fig. 1). The magnitude of the variation explored, assessed in terms of environmental index, was from 28.1 to 39.3 mg grain^{-1}. Grain weight responsiveness to changes in environmental conditions were relatively small in bread wheat and barley (their slopes did not differ statistically; 0.67 and 0.83, respectively) while it was rather high in durum wheat (1.73) (Fig. 2). Final individual grain weight ranged from 23.8 to 35.9, 27.6 to 42.6 and 26.2 to 47.7 mg for bread wheat, barley and durum wheat, respectively (Fig. 2).

Even when barley grain weight was determined under lower temperatures and earlier than wheat, it did not show any higher stability than grain weight of bread wheat, and in both cereals it was significantly more stable than in durum wheat.

Grain filling parameters were affected by environmental conditions for the three species. Grain weight variation was equally explained by both MGFR and DGF (R^2=0.32 P<0.001 and R^2=0.16 P<0.01). That is, in some cases grain weight was more related to grain filling duration while in others to maximum grain growth rate. Regarding the variability of grain filling parameters, durum wheat presented the highest range explored for both of them (Fig. 3).

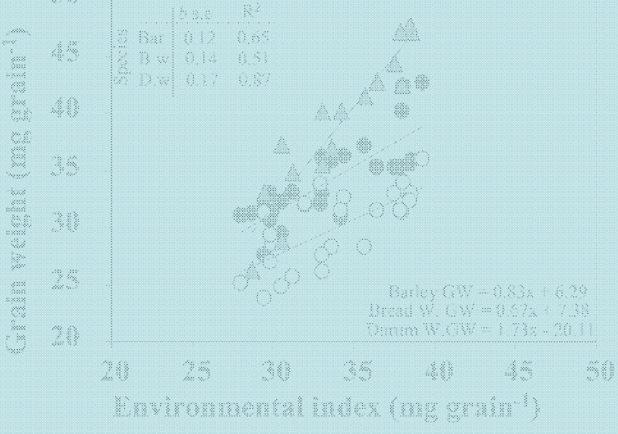

Figure 2: Grain weight of bread wheat, barley and durum wheat (white, black and grey symbols, respectively) as a function of the environmental index for grain weight for species sown in a range of experiments with N x water treatments. Inset table include the standard error of the estimation of b coeffient (*b* s.e) and R square for each species.

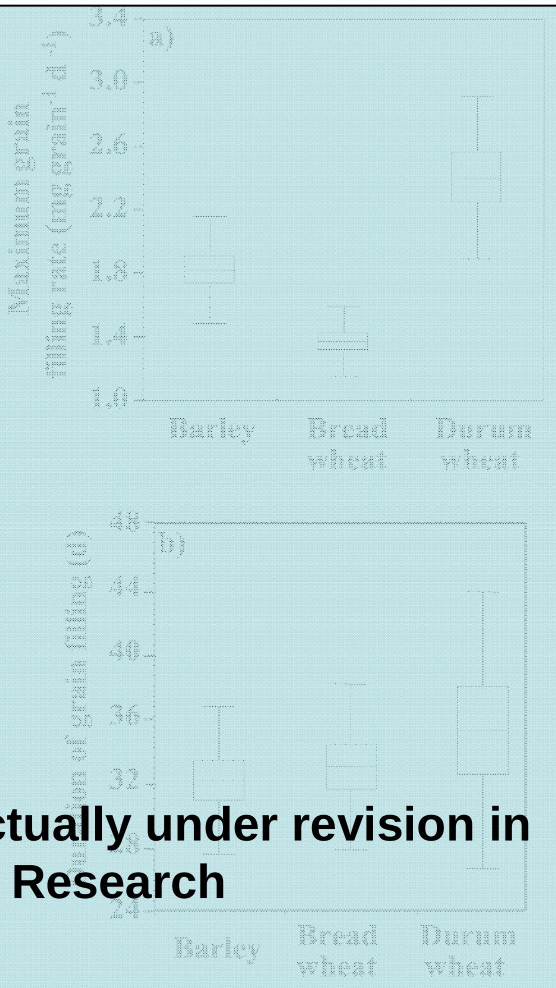

Figure 3: Variability explored in experiments II, III (irrigated treatments) and IV in maximum grain filling rate (a) and in duration of grain filling (b) for barley, bread wheat and durum wheat. Box lines, boxes and boxes plus bars represent mean, mean± standard error and mean± standard deviation, respectively.

On the other hand, bread wheat had similar or lower variability than barley in terms of MGFR (range from 0.93 to 1.69 mg d^{-1} and from 1.29 to 2.41 mg d^{-1} for bread wheat and barley, respectively) and DGF (range from 23.1 to 39.9 and 23.2 to 38.9 d for bread wheat and barley, respectively).

Grain weight (r^2=0.71) and MGFR (r^2=0.53) were positively related to average CTD during grain filling in experiment III (Fig. 4), but CTD did not explain differences in grain weight, MGFR or DGF in experiment IV. CTD only explained inter-annual variability differences in DGF due to environmental conditions (r^2=0.74).

3.3 *Grain N content*

Durum wheat exhibited the highest values of grain N percentage in all the experiments (2.2, 2.0 and 2.9% for experiments III, IV, and V, respectively) (Fig. 5a). Bread wheat presented intermediate values (2.4, 2.1 and 1.9 % for experiments II, III and IV, respectively), while barley always showed the lowest values (1.8, 1.8, 1.7 and 2.4 % for experiments II, III, IV and V, respectively) (Fig. 5a). Barley had similar stability in grain N percentage to that of bread wheat and durum wheat (Fig 5a) (P>0.05).

As the trends in stability of grain weight and grain N percentage were not in the same direction, grain N content, in absolute terms per grain for bread wheat, barley and durum wheat responded with similar sensitivity to the changes in environmental conditions (Fig 5b). In all cases, barley has the lowest N content in grains followed by bread wheat while durum wheat showed the highest values. The two data-points of durum wheat below the trend given by the other data correspond to experiment V (sown far away from the normal date for the region) (Fig. 5b).

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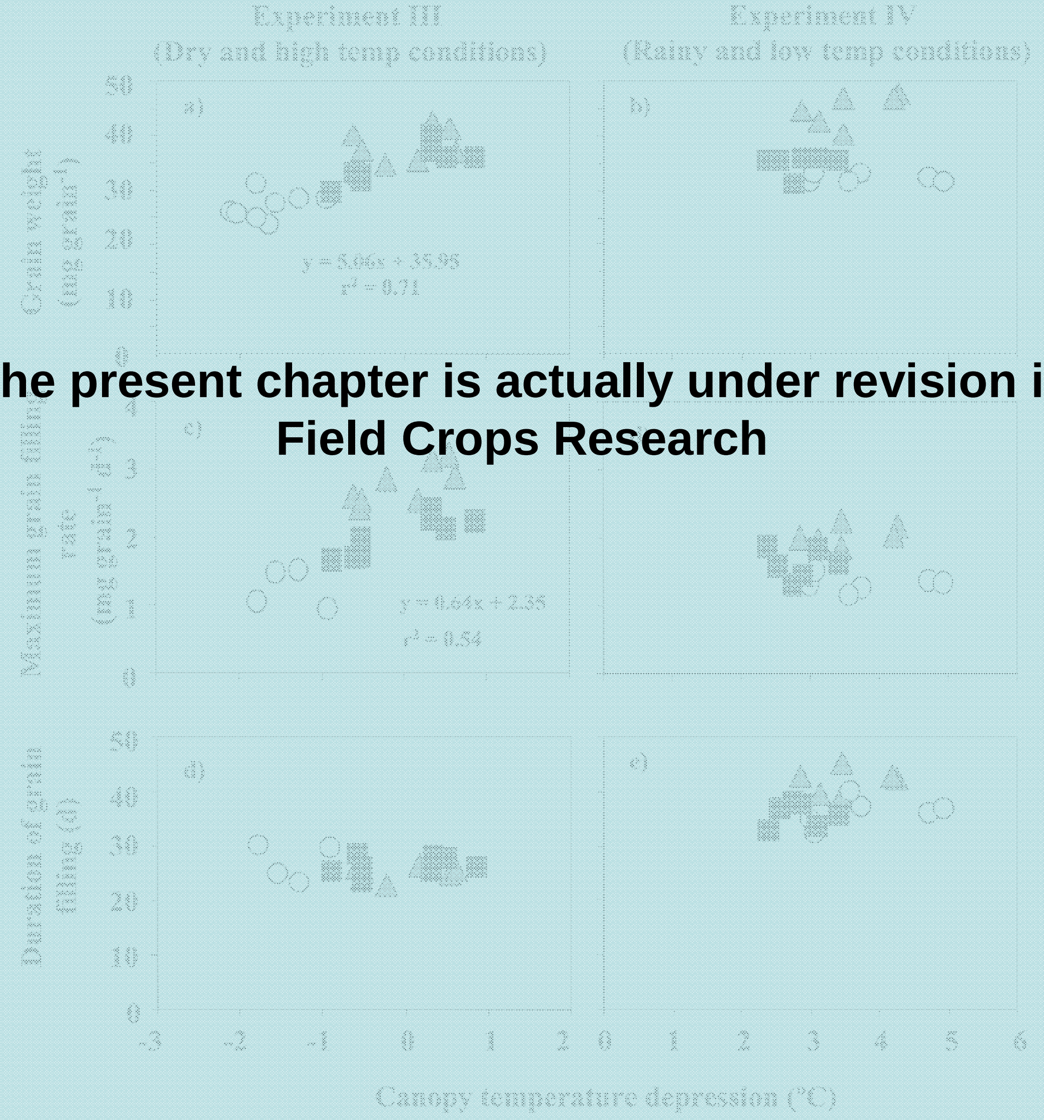

Figure 4: Grain weight (a and b), maximum grain filling rate (c and d) and duration of grain filling in experiments III (left panels) and IV (right panels) as a function of average canopy temperature depression during grain filling period for barley (black squares), bread wheat (white circles) and durum wheat (grey triangles). Equations and determination coefficient were only included in panels with significant relationships.

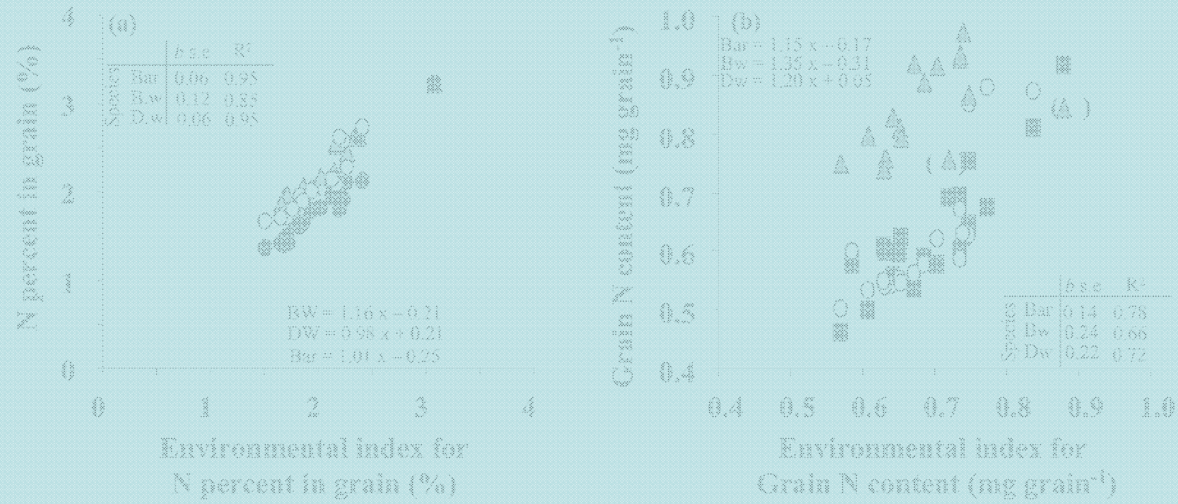

Figure 5: Grain N concentration (a) and content (b) as a function of their environmental indices for barley (black squares), bread wheat (open circles) and durum wheat (grey triangles) in experiments II, III, IV and V. Grey triangles between parenthesis correspond to experiment V (an out of season sowing) and were not included in the regression. Inset table include the standard error of the estimation of b coeffient (*b* s.e) and R square for each species.

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4.0 Discussion

In this study, because of experimental limitations (number of treatments, destructive sampling, methodology in each experimental [illegible] only one cultivar of each species could be used. However, they were carefully chosen to represent the farmer reality and those cultivars not only are well adapted but also are representatives of the farmer preference in the region (as indicated in Cossani et al., 2009). Therefore, although intra-specific genotypic variability in grain weight and grain filling parameters naturally exists (e.g. for bread wheat, Wardlaw and Moncur 1995,; for barley, Savin and Nicolas 1996 and for durum wheat, Alvaro et al. 2008) the differences reported in this paper can be extrapolable to what can be considered "average" well-adapted cultivars of each species.

In the present analysis, the development rate of these species followed the pattern that is most usually reported under Mediterranean conditions: barley crops flowered earlier than bread and durum wheat, and therefore were exposed to relatively more moderate temperatures during grain filling than those to which the wheats were exposed. All species were exposed to negative CTD values that caused the lowest DGF. This is consistent with the literature, that is, the duration of grain filling period is reduced when high temperatures occur (Sofield et al.1977; Slafer and Savin, 1991; Wardlaw and Moncur; 1995, Tewolde et al. 2006). Maximum grain filling rate and grain weight were higher when grains were exposed to lower stress conditions, which produced higher CTD values in experiment III (Fig. 4), where crops explored the driest [illegible] in this experiment a higher stress was observed for bread wheat than for barley, they did not differ in MGFR stability. CTD did not explain grain weight or MGFR in experiment IV, where less stressful conditions were explored by the crops. As previously reported, the generally higher MGFR observed under the most stressful conditions did not compensate the reduction in grain filling duration (Sofield et al., 1977; Wardlaw, 2002).

In terms of grain N content, the three species responded similarly: grain N percentage increased with higher N availabilities at sowing. Barley had the lowest grain N percentages, bread wheat intermediate and durum wheat the highest, which is in line with expectations from the objectives of their breeding. Differences in grain N percent *per se* between the species are not reflecting the differences in their stability for this attribute. However, the slopes of the relationship between grain N percentage and the explored environments reflected a similar stability for bread wheat, barley and durum wheat. The three species tended to decrease grain N percentage with increases in grain weight although the effect was more notorious in durum wheat, maybe due to the fact that its grain weight stability was lower than in the other two cereals. Grain N content also presented similar stability for bread wheat, barley and durum wheat.

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As the results observed in the present analysis are quite different when barley is compared to wheat depending whether the latter is bread or durum, conclusions do depend on the type of wheat. In regions where the alternative to barley is bread wheat, the general assumption of a higher stability of barley seems to be unjustified. This is the case of Mediterranean Catalonia, among other Mediterranean regions of the world. However, when the main alternative to barley is durum wheat (as it is the case in much of the Mediterranean basin), a higher stability of barley seems to be supported by the empirical data.

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References

Alvaro, F., [illegible] del Moral, L.F., Royo, C. (2008). Breeding [illegible] grain filling, biomass partitioning, and [illegible] in Mediterranean durum wheat. Agronomy Journal, 100:361–370.

Anderson, W.K., Impiglia, A. (2002). Management of dryland wheat. In: Curtis, B.C., Rajaram S., and Gómez Macpherson, H. (Eds.), Wheat: Improvement and production. Plant Production and Protection Series. No. 30, FAO, Rome, pp. 567.

Cossani, C.M., Savin, R., Slafer, G.A. (2007). Contrasting performance of barley and wheat in a wide range of conditions in Mediterranean Catalonia (Spain). Annals of Applied Biology, 151, 167-173.

Cossani, C.M., Slafer, G.A., Savin, R. (2009). Yield and biomass in wheat and barley under a range of conditions in a Mediterranean site. Field Crops Research. 112, 205-213.

Finlay, W.K., and Wilkinson, G.N. (1963). The analysis of adaptation in plant-breeding programme. Australian Journal of Agricultural Research, 14, 742-754.

Fischer, R.A., Wood, J.T. (1979). Drought resistance in spring wheat Cultivars. III*. Yield associations with morpho-physiological traits. Australian Journal of Agricultural Research, 30, 1001-1020.

Jandel. (1991). Table Curve v. 3.0. User's Manual Version 3.0. AISN Software, Jandel Scientific, Corte Madera, CA.

Josephides, C.M. (1993). Analysis of adaptation of barley, triticale, durum and bread wheat under Mediterranean conditions. Euphytica 65, 1–8.

Khanna-Chopra, R., Viswanathan, C. (1999). Evaluation of heat stress tolerance in irrigated environment of T. aestivum and related species. I. Stability in yield and yield components. Euphytica, 106, 169-180.

López-Castañeda, C., Richards, R.A. (1994). Variation in temperate cereals in rainfed environments I. Grain yield, biomass and agronomic characteristics. Field Crops Res. 37, 51–62

Loss, S.P., Kirby, E.J.M., Siddique, K.H.M., Perry, M.W. (1989). Grain growth and development of old and modern Australian wheats. Field Crops Research, 21, 131-146.

Palumbo, M., Boggini, G. (1994). Comparison of durum-wheat bread wheat and barley in a Mediterranean environment. Cereal Research Communications, 22, 113–120.

Peltonen-Sainio, P., Kangas, A., Salo, Y., Jauhiainen, L. (2007). Grain number dominates grain weight in temperate cereal yield determination: Evidence based on 30 years of multi-location trials. Field Crops Research, 100,179-188.

Rharrabti, Y., Villegas, D., Royo, C., Martos-Nuñez, V., Garcia del Moral, L.F. (2003). Durum wheat quality [illegible] of climatic variables and relationships between quality [illegible] Crops Research, 80, 133–140.

Royo, C., Villegas, D., Rharrabti, Y., Blanco, R., Martos, V., Garcia del Moral. (2006). Grain growth and yield formation of durum wheat grown at contrasting latitudes and water regimes in a Mediterranean environment. Cereal Research Communications, 34, 1021-1028.

Ryan, J., Singh, M., Pala, M. (2008). Long-term cereal-based rotation trials in the Mediterranean region: implications for cropping sustainability. Advances in Agronomy, 97, 273-319.

Sadras, V.O., Roget, D., Krause, M. (2003). Dynamic cropping strategies for risk management in dry-land farming systems. Agricultural Systems, 76, 929-948.

Savin, R., Nicolas, M.E. (1996). Effects of short periods of drought and high temperature on grain growth and starch accumulation of two malting barley cultivars. Australian Journal of Plant Physiology, 23, 201-210.

Simpson, P.G., Siddique, K. H. M. (1994). Soil type influences relative yield of barley and wheat in a Mediterranean-type environment. Journal of Agronomy & Crop Science, 172, 147-160.

Slafer, G.A., Savin R. (1991). Developmental base temperature in different phenological phases of wheat (*Triticum aestivum*). Journal of Experimental Botany, 42:1077-1082.

Sofield, I., Evans, L.T., Cook, M.G., Wardlaw, I.F. (1977). Factors influencing the rate and duration of grain filling in wheat. Australian Journal of Plant Physiology, 4, 785-797.

Stone, P.J., Nicolas, M.E. (1994). Wheat cultivars vary widely in their responses of grain yield and quality to short periods of post anthesis heat stress. Australian Journal of Plant Physiology, 21, 887-900.

Tewolde, H., Fernandez, C.J., Erickson, C.A. (2006). Wheat cultivars adapted to post-heading high temperature stress. Journal of Agronomy & Crop Science, 192, 111-120.

Voltas, J., van Eeuwijkb, F.A., Sombrero, A., Lafargad, A., Igartua, E., Romagosa, I. (1999). Integrating statistical and ecophysiological analyses of genotype by environment interaction for grain filling of barley I. Individual grain weight. Field Crops Research, 62, 63-74.

Wardlaw, I.F. Moncur, L. (1995). The response of wheat to high temperature following anthesis. I. The rate and duration of kernel filling. Aust. J. Plant Physiol. 22, 391-397.

Wardlaw, I.F. (2002). Interaction between drought and chronic high temperature during kernel filling in wheat in a controlled environment. Annals of Botany, 90, 469-476.

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Chapter VI

Co-limitation of nitrogen and water on yield and resource-use efficiencies of wheat and barley

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For each experimental plot, WUE was calculated as the ratio between grain yield and water used (WU). Also UtE was calculated as the ratio between grain yield and N uptake. Finally, NUE was calculated as the ratio between grain yield and N availability for each experimental plot.

Due that the main objective of the present paper is to analyze the relationships between yield gap, WUE, NUE, UtE and limitation or co-limitation indices, Table 3 only shows the ranges of grain yield, NUE and WUE for each experimental year

2.2 *Assessment of yield gaps and stress levels*

Maximum attainable yield was assumed to be fixed in 9 Mg ha^{-1} (Savin et al. 2006; Abeledo et al. 2008) for bread wheat, as well as for durum wheat and barley. Yield gap was calculated following Sadras (2004) as the difference between actual yield and maximum attainable yield obtained in each treatment and experiment in the field.

Water and N stress indices were calculated for each treatment and specie in all the experiments using as reference the indices calculated by Sadras and Roget (2004). However, in this work the stress indices were calculated for the whole growing season. In addition, the relative differences between actual water used and water requirements for maximum yield determined for the re[illegible] requirements for maximum yield in the plot treatments were used to calculate stress indices.

Water stress-index (WSI) was calculated as the difference between evapotranspiration requirements for maximum yield (9 Mg ha^{-1}) using the boundary function proposed by Sadras and Angus (2006) for maximum attainable WUE (22 kg ha^{-1} mm^{-1}), and was defined as expressed in Equation 1.

Nitrogen stress-index (NSI), was calculated using the requirements to produce 9 Mg ha^{-1} using as reference a requirement of 30 kg N Mg $grain^{-1}$ which is equivalent to standard values of c. 12% protein concentration in grains and a NHI of 0.70 as expressed in Equation 2.

In this case, stress indices represent limitation in resources availability (water or nitrogen) during the growing period of the crops. The stress indices range from 0 (no stress) to 1 (maximum stress) for both water and N. As in Sadras (2004), NSI and WSI were used to calculate different stress indices to quantify the intensity of the stress. They were total stress index (T_{WN}) and maximum stress index (M_{WN}) expressed as Equations 3 and 4, respectively.

$$T_{WN} = NSI + WSI \qquad [\text{ Eq. } 3 \text{ }]$$

$$M_{WN} = \text{Max (NSI, WSI)} \qquad [\text{ Eq. } 4 \text{ }]$$

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$$WSI = 1 - \left(\frac{\text{Actual water used (mm)}}{9 \text{ Mg ha}^{-1} * (0.022 \text{ Mg}_{grain} \text{ ha}^{-1} \text{ mm}^{-1})^{-1} + 60 \text{ mm}} \right) = 1 - \left(\frac{\text{Actual water used (mm)}}{469.1 \text{ mm}} \right) \qquad [\text{ Eq. } 1 \text{ }]$$

$$NSI = 1 - \left(\frac{\text{Actual N uptake (Kg N ha}^{-1})}{9 \text{ Mg ha}^{-1} \text{ x } 30 \text{ (Kg N Mg}_{grain}{}^{-1})} \right) = 1 - \left(\frac{\text{Actual N uptake (Kg N ha}^{-1})}{270 \text{ (Kg N ha}^{-1})} \right) \qquad [\text{ Eq. } 2 \text{ }]$$

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A co-limitation index (C_{WN}) was calculated as Equation 5, tending to 1 when the magnitude of the limitation in water was similar to the limitation in N. However, as it was indicated in Sadras (2004) to account for the intensity of the stress with the degree of co-limitation two additional indices: co-limitation accounting for the total stress (CT_{WN}) and co-limitation accounting for the maximum stress (CM_{WN}) which were calculated as expressed in Equations 6 and 7, respectively.

$C_{WN} = 1 - |\,NSI - WSI\,|$ [Eq. 5]
$CT_{WN} = C_{WN}\,T_{WN}^{-1}$ [Eq. 6]
$CM_{WN} = C_{WN}\,M_{WN}^{-1}$ [Eq. 7]

After the calculation of the stress and co-limitation indices, a data screening was performed, in order to follow similar steps of the simulation model. In consequence only the cases that satisfy the following items were used:

(i) Both NSI and WSI estimations were higher than 0 and lower than 1 following the values reported by the APSIM model used by Sadras (2004).

(ii) Water availability (Initial content + rainfall + Precipitation) was lower than 400 mm following Sadras (2004).

Regression analysis was used to explore the relationship between [illegible] in Equations 1 to 8.

3. Results

3.1 Yield gap vs. limitation and co-limitation indices

Yield gap between actual and maximum attainable yields ranged from -3.8 to -8.1 Mg ha^{-1} across the different growing seasons and treatments analyzed (Fig. 2). During 2004/2005 growing season, the highest yield gap (more negative) was observed in rainfed treatment. Yield gap was lower (closer to 0) with the higher level of N input, and the trend was similar for bread wheat, barley and durum wheat (Fig. 2). Yield gap was negatively related to both T_{WN} (Fig. 3a) and M_{WN} (Fig. 3b), i.e. yield gap was more negative as the T_{WN} or M_{WN} increased. Yield gap tended to increase more markedly (be more negative) with the maximum stress index than with total stress index (rates: -10.32 Mg ha^{-1} per unit of M_{WN} vs -5.59 Mg ha^{-1} per unit of T_{WN}). On the other hand, there was a clear decrease in yield gap with increases in the degree of co-limitation expressed as CT_{WN} or CM_{WN} (Fig. 3c,d).

3.2 Water use and N use efficiencies vs. limitation and co-limitation indices

WUE was negatively related to total (T_{WN}) and maximum (M_{WN}) stresses indices (Fig. 4 a,b).

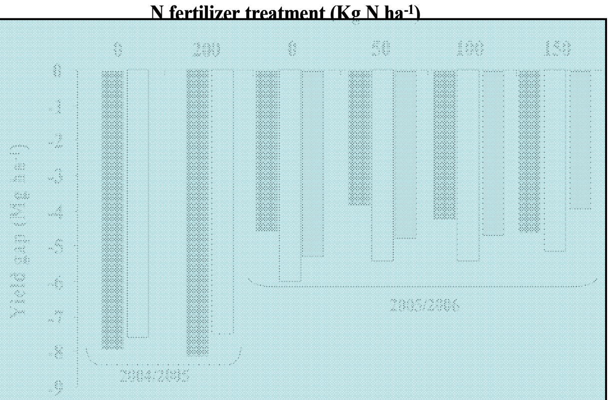

Figure 2. Yield gap (actual yield - maximum attainable yield) observed in rainfed treatments from 2004/05 and 2005/06 growing seasons for barley (black bars), bread wheat (white bars) and durum wheat (grey bars) under different fertilizers treatments.

The rate of decrease in WUE was approximately double when stress was expressed as M_{WN} (30.75 Kg $_{grain}$ ha^{-1} mm^{-1} [$M_{WN\ unit}$]$^{-1}$) than when expressed as T_{WN} (17.74 Kg $_{grain}$ ha^{-1} mm^{-1} [$T_{WN\ unit}$]$^{-1}$). Similarly to yield gap, WUE was positively related to the degree of co-limitation (CT_{WN} and CM_{WN}; Fig. 4 c,d). WUE reached its maximum values when the degree of co-limitation was [illegible] 1.7 for CM_{WN} [illegible] Although [illegible] general trends were similar to those of WUE [illegible] NUE or UtE were significantly related to water-nitrogen limitation or co-limitation indices. Regarding the independent effect of water or N stress, yield gap and WUE were closely and negatively related to WSI and NSI (yield gap was more negative, and WUE decreased, with higher stress) while NUE or UtE were not (Table 2). In general, slopes were stronger and coefficients of determination higher for the relationships with WSI than with NSI (Table 2).

4. Discussion

Yield gap, as well as WUE, was positively related to the degree of co-limitation for barley, bread wheat and durum wheat. Previous approaches analyzing the relationship between yield gap and co-limitation indices suggested their positive effects on yield and biomass production for wheat crops in the Mallee region of Australia (Sadras and Roget 2004; Sadras2004). However, these conclusions and the indices calculated in those works corresponded to stress indices derived from simulation models. In this study, similar relationships were found between yield gap and the co-limitation indices based on field data.

Results coincided with those reported by Sadras (2005) where yield gap is reduced, while WUE increased, with increase degree of co-limitation. However, in the present study, NUE and UtE were not significantly related to degree of water-nitrogen co-limitation.

Table 2. Determination coefficient and slope of the relationship between yield gap, water use efficiency stress

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Sinclair and Park (1993) also indicated that crop yield is

grain yield. This is like the fact that balanced N

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provision may avoid excess of water consumption during earlier stages in soils depending of the stored soil water (van Herwaarden et al. 1998a, c).

Also for other regions (India), Aggarwal and Kalra (1994) using simulation models indicated the importance of adjusting N availability depending on water availability indicating for wheat crops that the amount of N fertilizer applied should be closely linked to the amount of irrigation and considering climatic variation as well.

In this study, we suggest a positive effect of co-limitation on WUE and a negative effect on yield gap, coinciding with the previous reported results (Sadras and Roget 2004; Sadras, 2004) but differing with the temporal scale used. The co-limitation degree at which minimum yield gap is found, coincides with the highest levels of WUE for the experimental plots, actually achieving maximum attainable WUE values for Mediterranean region (Sadras and Angus 2006). Also, in the present study, the relationship between yield gap or WUE and degree of co-limitation is presented with an asymptotic response due to the fact that there is a limit in yield responses to WUE and in NUE.

Yield gaps obtained (3.8 to 8.1 Mg ha^{-1}) in the present analysis coincide with the yield gap calculated with data available at regional level for the county of Agramunt during th [illegible]. In this region, yield gaps (including irrigated and rainfed cultivated crops) ranged [illegible] for bread wheat and from 2.9 to 6.9 Mg ha^{-1} for barley corresponding the lower yield gaps to the irrigated crops. The minimum yield gap calculated under rainfed conditions was 5.5 Mg ha^{-1} during the period 1992-2004. For the analysis offered, we imposed a number of restrictions to facilitate the approach. We assumed a maximum yield in Mediterranean regions of 9 Mg ha^{-1}, from a particular study on wheat in Mediterranean regions, we limited the cases analyzed to those with available water ≤ 400 mm, and we assumed 60 mm of soil evaporation. All these restrictions might have influenced the outcome of the analysis. We tested this likely bias by doing the analysis with different retractions. For instance by using the maximum obtained yield for each species in this study as the specific maximum yield, and by rising fixed evaporation to 110 mm. Results of such analysis did not modify the conclusions of the study, as there was not a noteworthy change of the trends reported (Figure 5). Also a strong positive relationship (with intercept very close to zero and slope very close to 1 and $R^2=0.95$ $P<0.001$) between stress and co-limitation indices calculated as we did in the study and by using these alternatives limits (data not shown).

The analysis performed in this work allowed explaining the differences of actual with maximum attainable grain yield in terms of the resource availabilities and resource use efficiency with a combined effect of water and N [illegible] by Bloom et al. (1985) and the previously reported case for [illegible]estern Europe where N-P-K co-limitation were limiting the productivity (Venterink et al. 2001).

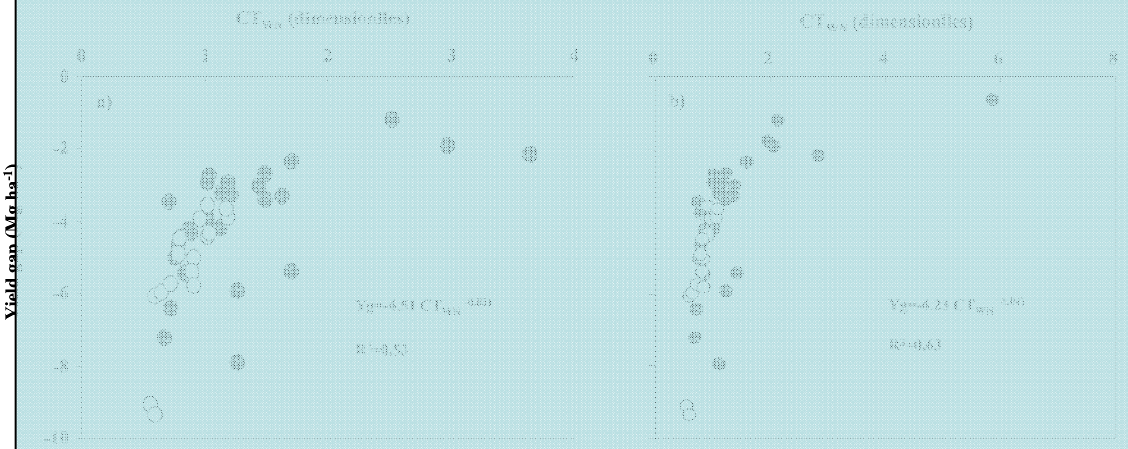

Figure 5. Yield gap as a function of the co-limitation index accounting for total stress for two possible alternatives. (a) Using maximum yields attained of each species at experimental conditions to estimate yield gaps. (b) Using maximum yields attained of each species at experimental conditions and raised fixed evaporation to 110 mm. In both cases, closed symbols represents all the experimental cases with limitations indices (NSI or WSI) between 0 and 1 and open symbols represents the previous data used with the yield gaps and co-limitation index re-calculated.

Although analyses of yield restrictions imposed by

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proceedings, part I. European Society for Agronomy. Polish Society for Agronomy. IX ESA Congress, 4-7 September 2006. Warsaw, Poland. 439pp

Sinclair, T.R., Park, W.I. (1993). Inadequacy of the Liebig limiting-factor paradigm for explaining varying crop yields. Agronomy Journal. 85, 742-746.

van Herwaarden, A.F., Farquhar, G.D., Angus, J.F., Richards, R.A., Howe, G.N. (1998)a. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser I. Biomass, grain yield, and water use. Australian Journal of Agricultural Research. 49, 1067-1081.

van Herwaarden, A.F., Angus, J.F., Richards, R.A., Farquhar, G.D. (1998)b. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser II. Carbohydrate and protein dynamics. Australian Journal of Agricultural Research. 49, 1083-1093.

van Herwaarden, A.F., Richards, R.A., Farquhar, G.D., Angus, J.F. (1998)c 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser III. The influence of water deficit and heat shock. Australian Journal of Agricultural Research. 49, 1095-1110.

Venterink, H.O., van der Vliet, R.E., Wassen, M.J. (2001). Nutrient limitation along a productive gradient in wet meadows. Plant and Soil, 234, 171-179

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Chapter VII

General discussion

General discussion

Brief introduction

The general discussion of the present thesis is written in three different sections in order to provide a global vision and its main contributions to crop-physiological knowledge.

The first section constitutes a global discussion *per se* of the thesis highlighting main results and findings. It integrates the results of all the experiments of each chapter previously reported, as well as their main conclusions, strengths and weaknesses. In turn, in this section I aimed to provide a global vision of the statements included in the objectives in terms of new findings or contributions and comparisons with the available research. Firstly, differences between wheat and barley performance are analyzed in terms of grain yields, and resource use and resource use efficiency for the Mediterranean region. Secondly, it is presented the main determinants of the variability in the grain yields, resource use and resource use efficiencies. Also, conditions allowing to reduce yield gaps between actual and maximum attainable grain yields are presented using jointly all the data available for the present thesis.

The second section titled "Future research" reports on likely opportunities for future research lines that, I believe, could be worthwhile pursuing based on the results provided in the thesis.

Finally, the third section titled "Conclusions" summarizes the main conclusions of the present thesis.

1. Integrated vision of the problematic in terms of species performance

There is a large amount of data available in the literature for wheat and for barley performance, in terms of grain yield in Mediterranean regions under a wide range of conditions. However, direct comparisons between cereals cannot be made rigorously without growing the different species in the same experiment. The present thesis contributes to the knowledge presenting reliable comparisons for wheat and barley that were not available for the region. Also, experimental data for it or other Mediterranean regions is not abundant except for the cases presented here (Chapter II, Figure 1) and some papers that appeared during the execution of the research for the present thesis (Katerji et al., 2008; Katerji et al. 2009; Ferrante et al. 2009; Albrizio, 2010). In the present thesis, both wheats (durum and bread) were compared to barley in terms of grain yield, resource use and resource use efficiency in different conditions mainly generated by water and nitrogen availabilities. The comparisons of grain yield (24 cases for bread wheat and barley and 16 cases for durum wheat and barley) allowed exploring a wide range of grain yields from 0.8 to 10 Mg ha^{-1}, although the main interest of the thesis was on stressed conditions (generally yielding conditions lower than 3-4 Mg ha^{-1}).

As some of the seasons were relatively wet (either more humid than usual throughout or at least during the spring), across all the experimental comparisons carried out in Western Catalonia for the present thesis, there were only four cases where the performances of bread or durum wheat and barley were actually compared under harsh drought conditions, severely limiting grain yields (see rainfed treatments of experiment II in Chapter II, Chapter III and Chapter IV for bread wheat, and experiment V of Chapter III for the case of durum wheat). In terms of grain yield, it can be concluded from the experimental data that is not clear at all that barley yield consistently more than wheat in stressed Mediterranean environments. At the worst environments, wheat (bread wheat or durum wheat) and barley did not differ significantly. Shillinger, (2003), for the Pacific Northwest region of the USA, did not find consistent differences between bread wheat and barley yields either (in one year differences were not significant, while in two other years barley yielded more than wheat, and in a fourth year bread wheat yielded more than barley). This lack of consistent differences in favour of barley is in line with what was observed for the Mediterranean regions reported in Chapters of the present thesis as well as in French and Ewing (1989), Simpson and Siddique (1994), Palumbo and Boggini (1994), and Albrizio et al. (2010), although conflicts with the results reported by other authors (Gregory et al. 1992; Josephides 1993; López-Castañeda and Richards 1994). Also some other papers the authors indicate better performance of barley, although such indication seemed most based in speculation than in robust evidences, as it is not unsupported by their own reported data on yield (Acevedo 1987; Austin et al. 1998). Recently, Katerji et al. (2009) using soil lisimeters reported a similar reduction (37%) in grain yield for durum wheat and barley caused by drought at three different salinity levels. In addition, some comparisons using simulation models were reported for the Mediterranean region (Wahbi and Sinclair 2005) indicating no or little differences between bread wheat and barley yields stressing the needs of more rigorous information being developed regarding both species performances. However, when environmental conditions become less stressful (yields higher than 3 Mg ha^{-1}) barley generally yielded more than durum wheat in one of the three experiments (and only under irrigated conditions of other experiment) of the present Thesis while it yielded lower or similar to bread wheat in two of the four comparisons and higher in the other two. It is indicating that barley seems to be as good as bread wheat under stressful conditions and under high yielding conditions.

Comparing the yield experimental performance with the regional data for Catalonia (Fig. 1) the same tendency can be observed (Chapter II; Figure 5). Although the analysis made with regional yields could be supposedly weak and biased (as farmers in the region would grow barley in poorer environmental conditions than those of wheat) I understand that a rather large database would preclude such a bias, and the regional database used was actually quite large (533 comparisons). Further supporting the incipient conclusion based on regional data, historical yields for bread wheat and barley during the (1820-1935) period also indicates similar performance at regional level for Catalonia (Garrabou et al. 1995).

This thesis contributes to this debate by having made the required comparisons of grain yield performance of wheat and barley through a wide range of conditions. The evidences that emerged corroborate the similitude in yield performance. The conclusion indicates that there is not a universal advantage in grain yield of barley over bread or durum wheat. It seems now not justified a continuous barley monoculture in arid or semi-arid Mediterranean zones based on that supposedly consistent better performance than wheat in particularly poor conditions. Likewise, it should be maintained the environmental limits defining the land use reported by other authors (López-Bellido 1992; Anderson and Impiglia 2002; Ryan et al. 2008), as those limits were based on empirical land use rather than in crop performance (they could be still maintained as a descriptive scenario of reality, whilst it stands, but not as a guide or recommendation). Although nowadays durum wheat is practically not cultivated in Catalonia, the present Thesis shows the potential for its cultivation, if the gross margin is adequate.

Analyzing the results of the performance of the cultivars used for each species in the Catalonian cultivars evaluation network (Xarxa d'Experimentió de Varietats de Cereal d' Hivern from Catalonia) during the same period of the experiment (DAAR 2005, 2006, 2007, 2008), it can be observed that differences between bread wheat and barley are similar to the observed in the experiments of the present Thesis without indicating a superiority of barley in the lowest-yielding conditions (Fig. 2). Similar results are observed for the nurseries from three sites of Syria (Acevedo 1987). However, in these networks, cultivars of each different species were not included within the same experimental design. Unfortunately there is no information available from the same network for durum wheat in Catalonia.

In all the cases, the differences between wheat (durum or bread) and barley as well as the differences between treatments within each experiment were mainly related to differences in resource use efficiency. Regarding the performance of barley and wheat in terms of resource use efficiency (in this case water and nitrogen), the present Thesis reported that under severe drought conditions barley did not present clear advantages over bread or durum wheat (Chapter IV). However, similarly to what was observed for grain yield, there were cases of higher WUE_{yield} or NUE of barley over wheat (durum or bread) under moderate and mild stress conditions. Albrizio et al. (2010) reported similar WUE_{yield} for durum wheat and barley under different N and water availabilities in other Mediterranean region (Bari, Italy). Also experimental data reported comparatively for bread wheat, barley or durum wheat indicates a similar WUE_{yield} stability for barley and durum or bread wheat in their response to different salt concentrations (Katerji et al. 2009).

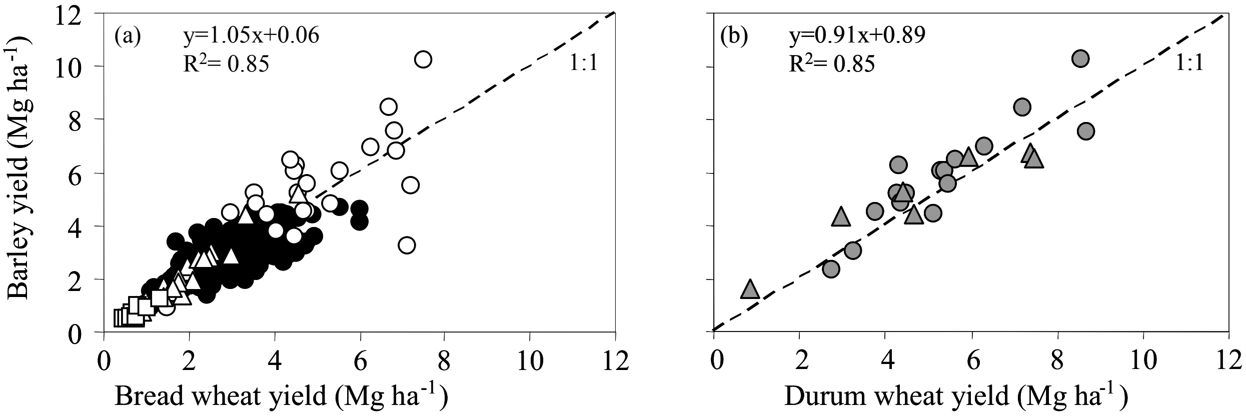

Figure 1: Bibliographic, regional and experimental data of barley grain yield as a function of the (a) bread wheat grain yield and (b) durum wheat grain yield. Black symbols represent regional data for Catalonia, circles represent experimental data from this thesis and triangles represent experimental data taken from other sources (Simpson and Siddique 1994; Palumbo and Boggini 1994 for bread wheat; and Katerji et al. 2009; Albrizio et al. 2010 for durum wheat) and squares represent historical data (Garrabou et al. 1995) for Catalonia

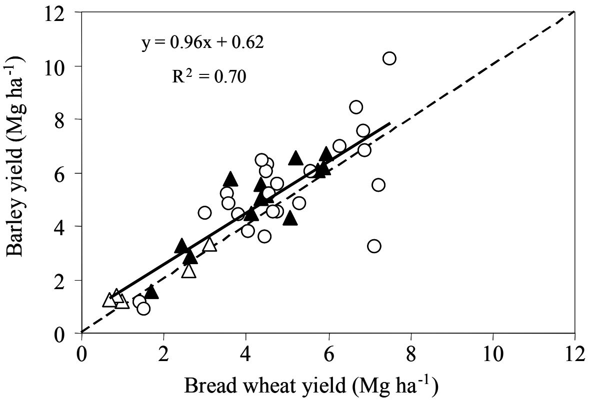

Figure 2: Relationship between bread wheat and barley grain yield for the experiments of the present thesis (open circles), Catalonian cultivars evaluation network (Xarxa d'Experimentió de Varietats de Cereal d' Hivern) (closed triangles) and from the nurseries results reported by Acevedo (1987) (open triangles). In the case of the networks, each data point is the average of all cultivars used for each species.

In contrast, a higher WUE $_{\text{yield}}$ in barley than in wheat was reported in two different low-yielding regions (one of typical Mediterranean climate) of Australia (Simpson and Siddique 1994; López-Castañeda and Richards, 1994b). These authors indicated the superiority of barley to be based on differences in early vigor (López-Castañeda and Richards, 1994b; López-Castañeda et al. 1995) or in intercepted radiation (Richards, 1992).

Regarding NUE, the differences between wheat and barley were even less clear than for WUE (Chapter IV). In terms of the sub-components that determine NUE (N uptake efficiency and N utilization efficiency) it was observed in the present thesis that differences between the species were in some cases in favor to barley whilst in others to wheat, or not significant (Fig. 3).

In the few published papers that include NUE data for the species studied in the present thesis, one of them (Arregui and Quemada 2008) used exactly the same cultivars of bread wheat (*Soissons cv.*) and barley (*Sunrise cv.*), and also reported a similar NUE for bread wheat and barley, supporting the results of the present thesis. However, the comparison of the mentioned reference was made in different years for bread wheat and barley and is not strictly correct to compare them. Delogu et al. (1998) reported higher N utilization efficiency in barley than in wheat for high-yielding environments. This is in line with what has been observed in the highest yielding years of the present thesis in which barley exhibited higher values for both sub-components of NUE in two of the three locations were observed. Murineen et al. (2006) reported a higher genetic gain in breeding for bread wheat than for barley, but a comparison with results of the present thesis can be hardly made, as that study was performed in Northern European conditions (Finland).

The three species presented similar amount of N uptake in the stressed conditions in concordance with the inconsistent differences in grain yield or N utilization. Also, in the highest yielding conditions the maximum values of N uptake observed for durum wheat and barley were similar. Neither barley nor wheat (durum or bread) exceeded the upper-limits estimated by Savin et al. (2006) for N utilization efficiency. The highest amount of N uptake, as well as the highest N uptake efficiency and NUE, was reached with approximately 400 mm of evapo-transpirated water by the crops.

Comparisons between wheat and barley in terms of WUE $_{\text{yield}}$ or NUE of other scientific experiences under Mediterranean regions are not abundant. The few studies reporting comparisons of wheat and barley in the literature (Simpson and Siddique 1994; Delogu et al. 1998; Arregui and Quemada 2008; Albrizio 2010) together with the experimental results of the present thesis, do not allow concluding on a higher NUE or WUE $_{\text{yield}}$ in barley than in wheat, supporting the results observed for grain yield.

When analyzing the values separately, values observed for the species in terms of WUE are acceptable and in concordance with the reported in the literature for the Mediterranean regions. Similarly to WUE $_{\text{yield}}$, the reported values for NUE in the present thesis are within the boundaries estimated for the region (Sadras and Angus, 2006; Savin et al. 2006).

Asseng et al. (2001), using simulation models, indicated that in the Mediterranean climatic region of Western Australia, WUE and NUE of wheat crops vary markedly depending on soil water-holding capacity, N management, rainfall amount, and in particular, seasonal rainfall distribution. Similarly, in the present thesis a wide range of variability of WUE as well as in NUE (and its sub-components) was observed across all the experiments.

Regarding to the weaknesses and strengths of the present thesis, fortunately it was generated a wide range of variability in WUE $_{\text{yield}}$ and NUE by the wide range of conditions explored (high/low rainfall during different developmental phases, high/low soil water availability at sowing, high/low N fertilization rates) that allowed reporting valuable information, so far not available, regarding the relative performance of wheat and barley WUE $_{\text{yield}}$ and NUE side by side within the same growing field conditions. The limited amount of information derived from severely-stressed conditions, and the fact that this work had to be done with only one cultivar of each species (although representative of the general mean) could be considered as weakness.

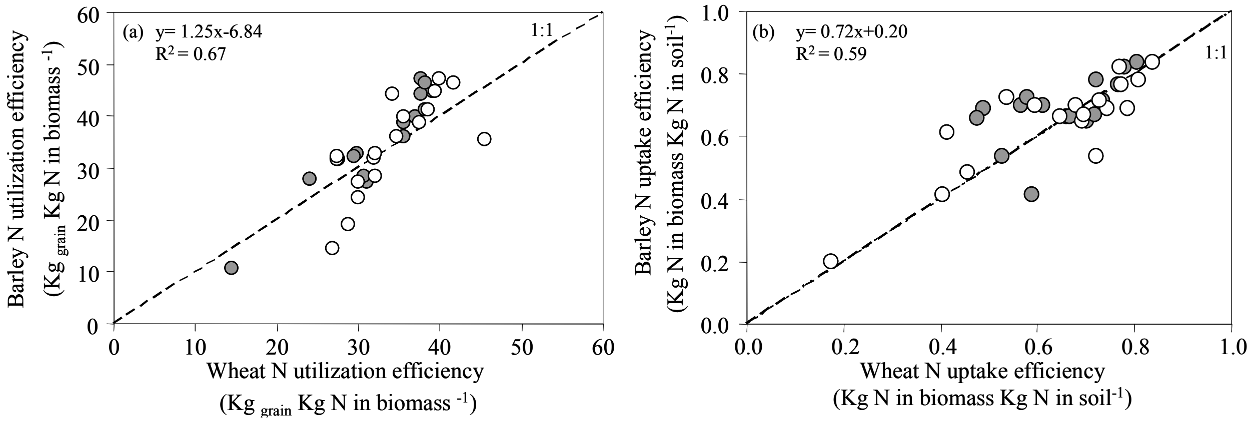

Figure 3: Relationship between wheat and barley sub-components of N use efficiency ((a) for N utilization efficiency and (b) for N uptake efficiency) under the experiments carried out in the present Thesis. White and grey symbols represent bread wheat and durum wheat, respectively.

Despite of experimental data as well as, bibliographic, regional and historical data reports similar performance for the stressed Mediterranean environments, a strong justification to maintain a barley monoculture instead of a rotation including wheat seems not to be based on yield performance as it is frequently hypothesized in the region. Also, it has been reported a lack of evidences in genetic advances in barley in Mediterranean unfavorable conditions (Muñoz et al., 1998) that refuse the preference of farmers due to a supposed better breeding in barley than in wheat for the region. For the case of wheat, contradictory results are found for genetic advances in the Mediterranean Spain (Royo, et al. 2007; Acreche et al. 2008; Voltas et al. 2009). Calatayud (2006) reported that important changes in the Catalonian land use were occurred during the end of the XIX century together with the increasing cereal productivity. Between the years 1895 and 1935 the relative surface cultivated with barley respect to the that for all cereals increased from 23.5% to 38.3% and an opposite trend was observed for bread wheat (55.8% to 48.6%) indicating a preference of farmers to produce cereals for stock-feed. In Northern Catalonia, the changes were more significant (Calatayud 2006). Pujol (2006) reported that important innovations in cereal genetics were carried out during the same period (end of the XIX century and beginning of the XX century). At this period, new wheat cultivars from other regions were introduced to Catalonia mainly by large farmers and research institutes (*richella blanca de Nàpols, Rieti, l'herald del Rhin, Savoia, Bordeus, Vilmorin, Gallard, Dattel*, and others from Australia, Canada, USA and Italy). However, most of the cultivars introduced failed in their adaptation to the stress conditions of the region. The increased interest for the barley crops due to the changes in the agri-food production together with the failure of many of the then newly-introduced wheat cultivars, together with the fact that more of 40% of farmers are older than 65 years (e.g. for a typical agricultural rainfed zone as the Urgell county; Anonymous, 1999) seem to provide bases for the popular knowledge behind the pattern of land use with barley monocultures practiced in low-yielding, dryland Mediterranean conditions.

Limits reported by Ryan et al. (2008) to the land use based on the small grain productivity for the Mediterranean region could be reformulated as a wider region based on a barley/wheat rotation including wheat in the region of barley monoculture.

2. What is behind the wide range of variability of productivity, resource-use and resource-use efficiency?

Focusing on the variability of the grain yield, there were observed different factors determining it as it was reported by other authors for Mediterranean and non-Mediterranean conditions for the three species (Fischer 1985; Savin and Slafer 1991; Garcia del Moral et al. 2003 and 2005; Ugarte et al. 2007; Arisnabarreta and Miralles 2008). In all the experiments carried out during the present thesis, barley and wheat had a typical behavior in terms of crop development and growing cycle. Barley flowered at least a week earlier than durum wheat and in some occasions two weeks earlier than bread wheat being exposed to lower temperatures during critical period for grain yield determination. Regarding the two main numerical sub-components of grain yield, despite of the high stress conditions frequently observed under the Mediterranean conditions in the post-anthesis period, grain number per unit land area was the main numerical sub-component explaining the grain yield of wheat (bread or durum) as well as in barley. Therefore, even when it is commonly assumed that under Mediterranean conditions the average weight of the grains might be responsible of the differences in yield (as it is during grain filling when the stress occurs most frequently) another contribution of this study is the reinforcement of the fact that grain number pr m^2 is far more relevant as a yield determinant than average grain weight (Fischer 2008; and a plethora of references quoted in this article) even under Mediterranean conditions. Therefore, in the studies included in the present thesis, similarly to what was observed in grain yield, the range of grain number per unit land area explored was rather wide (from *c.* 2600 to 30000 grains per m^2). Disregarding the differences in the slope of the relationship between the species (due to an intrinsic different grain weight between them), grain number explained *c.* 80% of the variability observed in yield in each of the three species (Chapters II and III). Also the response of the number of grains per unit land area to treatments may have been the driving force behind responses in post-anthesis biomass accumulation by reinforcing post-flowering canopy photosynthesis, as suggested by Miralles and Slafer (1997) and Reynolds et al. (2005) who showed improved post-anthesis radiation-use-efficiency due to increased grain number through introgressing Rht or Lr19 genes, respectively, in isogenic lines. Also differences in the post-anthesis photosynthesis in modern vs. old cultivars of wheat would have been determined by sink strength (Calderini et al. 1997), which seemed to be true even in a Mediterranean region (Acreche and Slafer 2009).

Variability in grain number per unit land area was determined by the environmental conditions (water, nitrogen, radiation and temperature) explored by the crops. Water and nitrogen availabilities determined the crop growth generating the canopy structure that allowed intercepting more or less radiation at the critical period for grain number determination (during stem elongation, Fisher, 1985; Slafer and Savin, 2006). Ferrante et al., (2009) using the same cultivars of durum wheat and barley, reported that water and nitrogen availabilities increase the number of grains per unit land area in durum wheat and barley affecting different traits: (i) due to increases in grains per spike in wheat mainly in the distal positions of the spikelets (Miralles and Slafer 1995; Acreche and Slafer 2006) as a consequence of a diminished rate of floret abortion; (ii) associated with changes in tillering capacity in barley, finally producing changes in the number of spikes per m^2 (Prystupa et al. 2003). Photosynthetically active radiation intercepted by the crop canopy during stem elongation and the temperature affecting growth and developmental rates during that phase generate changes in photothermal quotient which ultimately determines the number of grains per m^2 (Fischer 1985; Savin and Slafer 1991; Arisnabarreta and Miralles 2008). Another original contribution of the work conducted for this thesis is the comparison between cereals in the capabilities of photothermal quotient for predicting the number of grains per m^2 than the crop will have, that to the best of my knowledge it has been never reported before. Although positive relationships were observed for the three species, the relationship was closer for bread wheat than for durum wheat or barley in all the experiments. Although the physiological bases of the higher variability in barley than in wheat have not been elucidated in this thesis (no experiments were designed to study this issue) it seems clear the message that extrapolating the behaviour of wheat to barley should be done with extreme care for this particular attribute.

The average weight of the grains did not explain grain yield significantly, except for the case of durum wheat, in which grain weight explaining around 40% of the variability observed across all experiments and years. Even in this case, although the proportion of yield explained by grain weight was significant it was much less than that explained by the number of grains per m^2. Despite grain weight was not the main grain yield determinant, as barley usually reaches flowering before durum and bread wheat, its variability could has been a factor determining a higher stability in grain yield. However, grain weight, as well as its parameters (grain filling rate and duration) and the protein percent did not show a higher stability in barley than in bread wheat, though in these two cereals the stability was noticeably higher than in durum wheat (Chapter V). These differences between the stability in grain weight could be behind the larger effect of grain weight on grain yield in durum wheat than in barley and bread wheat (see above).

In terms of resource use as determinants of the grain yield, N uptake across the whole growing season was positively related to grain yield. In all the cases the relationship observed was within the N utilization efficiency boundaries reported by Savin et al. (2006) for wheat grown Mediterranean conditions. Water used was positively related to grain yield as well as to N uptake. It seems that when N is available in the soil, the main effect of water used is to produce an increase in N uptake and, consequently, grain yield is increased as a result of a higher nutritional status of the crops.

Regarding the main determinants of resource use, across all the experiments of the present thesis, the amount of N absorbed and water used by the species tended to be higher when water availability and N in soil increased, in agreement with reports by other authors for wheat and barley (Delogu et al. 1998; Garabet et al. 1998; Sepaskhah et al. 2006). Angás et al. (2006) found differences in soil N dynamics (depending on the tillage system and N fertilization) and water availability for barley were responsible for yield differences in the same region of the Ebro Valley. Also the three species presented the potential capacity to absorb as much as 90% of the N available in soil during the growing season (Chapter IV). Also water used increased at the highest N availabilities as reported by Angus and van Herwaarden (2001) without a significant "haying-off" effect, as it sometimes occurs in dryland conditions of Eastern Australia (van Herwaarden, 1998). In Mediterranean Western Australia haying-off does not seem to be observed frequently either (Palta and Fillery 1995; Asseng et al. 1998; Asseng and van Herwaarden 2003).

The fact that N use efficiency across all experiments and species had been the result of the combination of the two sub-components (i) uptake efficiency and (ii) utilization efficiency reflects that both sub-components were limiting the efficient use of nitrogen in the three species. Uptake efficiency allowed absorbing N to produce growth and generate a crop canopy capable to absorb resources. N utilization efficiency depend on weather conditions (rainfall, radiation and temperature) to transform pre-flowering crop growth into grains to be filled after flowering, mainly by affecting the survival of different of reproductive structures depending on the species (chiefly spikes per m^2 and grains per spike in barley and wheat, respectively; as discussed above). Across all the experiments, it seemed that maximum values of N use efficiency can be achieved using an amount of water from emergence to harvest of approximately 400 mm. Also a reduction in NUE was observed with the increased level of N fertilization coinciding with the reported for the same region for other authors (Angás et al. 2006) and other Mediterranean or semi-arid regions (Delogu et al. 1998; Garabet et al. 1998;).

Regarding water use efficiency, it is known that N fertilization, as well as other management practices, such as weed control, allows increase $\mathrm{WUE}_{\mathrm{yield}}$ in wheat and barley under Mediterranean conditions (French and Shultz 1984a, 1984b; Cooper et al. 1987). In turn, it seems that N fertilization can actually be a management practice used by farmers in order to increase $\mathrm{WUE}_{\mathrm{yield}}$ (Sadras, 2005) matching N requirements to water availabilities. In the present thesis, $\mathrm{WUE}_{\mathrm{yield}}$ was higher at high N levels and when water used was matched to the N absorption by the crops. This is in concordance with reports by other authors using nitrogen limitation index as indicator of the level of N-limitation to WUE with simulation models (Sadras and Roget 2004; Sadras, 2005). In this context, another contribution of the present thesis is the evidence provided empirically for the first time that the degree of co-limitation of water and nitrogen conditions the yield penalty produced by stressful environments in both wheat and barley, (Chapter VI). $\mathrm{WUE}_{\mathrm{yield}}$ as well as grain yield of bread wheat, durum wheat and barley similarly to what had been previously reported for Australia (Sadras and Roget 2004; Sadras, 2005) was increased when nutritional conditions were balanced. In other words, given a certain level of stress for the three species, grain yield or $\mathrm{WUE}_{\mathrm{yield}}$ would be maximized when nutrients are co-limiting. Since water availability cannot be easily managed in rainfed zones (and most of the Mediterranean small cereal crops are grown in rainfed systems (as mentioned in Chapter I) the estimation of the feasibility of water availability to decide the N rates to be applied seems to be important in the region. Also, at least for the Catalonian rainfed zones (where the high level of N present in soils is frequent due to supply of animal manures), mineral N fertilization could be decided at least to the late tillering periods to have a more accuracy in the assessments of water availability for crop growth. Results of the Chapter VI and from the pilot experience with Tunisian farmers (Annex I) support this idea.

3. Future research

Through the different chapters of the present thesis several issues have been identified that could be investigated:

1) *Wheat and barley have similar productivity under stress condition. How should they be grown?* The main problematic evaluated in the present thesis was the actual monoculture of barley in dry zones of the Mediterranean region. Results of the present thesis have indicated that at least is not universally true that barley had a better performance than barley under stress conditions. The next step that I believe necessary is to have information regarding the most adequate combination(s) of these crops in the dryland Mediterranean region taking into account economic, as well as environmental, constraints. Although it does exist a national network of small cereals cultivars evaluation (GENVCE) data of wheat and barley cannot be easily used to compared between them due to different number of cultivars used and experimental design for each species. True comparisons between long and short cycle cultivars of bread wheat, durum wheat and barley across a wide range of Mediterranean environments could improve to find the more profitable combination of cultivars and species that improve the actual agro-ecosystem. Due to the land use is the consequence of the farmer decision I believe that it is really important the conduction of the field trials including some leading farmers on the region to improve the transference of the knowledge.
2) *Water and nitrogen are co-limiting the grain yield in wheat and barley. What is the most usual scenario for each agricultural rainfed zone in Catalonia fields? How much N should the farmers apply depending on the scenarios found until tillering?* Although the results of the present thesis allow deducing the importance of matching the N conditions to the water availabilities during the growing season to increase

grain yield by improving WUE. A regional characterization of the N availabilities together with the probabilities of rainfall within each cereal rainfed zone before the beginning of stem elongation phase could help to generate different scenarios of N fertilization rates recommended using simulation models for different rainfall scenarios.

3) *In the present thesis wheat and barley were compared in terms of two main environmental resources (water and nitrogen) resource use efficiency*. However, it was not compared neither analyzed the radiation use efficiency. Differences between the species were always related to their differences in water or N use efficiency. Also, differences in the transpiration/evaporation ratio seem to be behind the higher WUE. Abeledo et al. (2008) reported that for Mediterranean region of the Ebro Valley, variations between years in potential yield were positively associated with the length of the period from sowing to anthesis and the mean level of daily incident radiation. Analysis of the radiation use efficiency between wheat and barley as well as the effect of the different water and N availabilities on this attribute could be important to understand more fully the physiological determinants of grain yield and biomass in the region.
4) *How did breeding modify the WUE, NUE and RUE in wheat and barley?* In most of the literature regarding advances in productivity of small grain cereals is based on genetic gains in grain yield. Muurinen et al. (2006) found significant NUE improvements on wheat although no clear trend for cultivars of two-row spring barley under Northern Europe conditions. Under Mediterranean environments, during last years, several crop physiologists have suggested breeders to focus on resource use efficiency to further improve grain yield (Loss and Siddique 1994; Araus et al. 2002; Condon et al. 2002; Araus et al. 2003; Condon et al. 2004; Slafer et al. 2005; Richards et al. 2006, Witcombe et al. 2008). Araus and Buxo (1993) indicated changes in WUE of the small grain cereals for the past millennia based on carbon isotope discrimination. Although numerous papers has been published regarding eco-physiological traits to increase resource use efficiency (Ortiz-Monasterio et al. 1997; Araus et al. 2002; Araus et al. 2003; Slafer et al. 2005; Muurinen et al. 2006; Araus et al. 2008; Foulkes et al. 2009) available data on the literature regarding how much have been changed WUE, water use, or NUE for wheat and barley crops as a consequence of breeding is not abundant for the Mediterranean region of Southern Europe. Similarities or differences in genetic advances in the WUE or NUE and RUE could be addressed for wheat and barley under drought stress environments helping to understand the differences and similitude between the species. However, according to the recent paper published by Blum (2009) the analysis of the differences in effective use of water (EUW) should also be considered.
5) *Future scenario. Nowadays wheat and barley have similar productivity under stress conditions. However, what it is expected when the stress conditions will become more severe?* The influence of environmental conditions (rainfall amounts and distribution, radiation, temperatures) together with the N availabilities produced the wide range of grain yield explored in the present thesis. It is known (Lobell and Field 2007) that a more stressful scenario is expected for Mediterranean agricultural systems due to global warming. Experiments including wheat (bread and durum) and barley crops together with different expected effects of the global warming combined with different water availabilities at different growing stages under fertilized and un-fertilized conditions could be useful to understand (and attempt to mitigate) the effect of global warming on cereal production.

4. Conclusions

1- The actual preference of barley over bread wheat or durum wheat under severe stress conditions in the Mediterranean region is not justified by its supposedly universal better performance in low-yielding conditions. Bread wheat and barley presented similar yields and equivalent grain weight stability. Durum wheat also presented similar yields than barley but it seemed that the final weight of its grains was less stable.

2- Both water and N use efficiencies varied widely across years for wheat and barley depending on the N and water availabilities during the growing season. In line with the previous conclusion, it was also concluded that barley did not show consistent advantages over wheat in terms of resource use or resource use efficiency. However, whenever yield differences occurred between the species, or between treatments in a particular species, it seemed to be the consequence of differences in water and N use efficiency.

3- For the three species, grain number per unit land area was the main numerical component determining yield. Although this is not an original conclusion in a wide range of conditions in which cereals are grown worldwide, it is rather interesting to highlight that this has been proven to be true even in Mediterranean conditions in which terminal stress (mostly during grain filling) seem to dominate the outcome of the cropping season. It was also confirmed under these conditions that N uptake from sowing to maturity explained the differences in grain yield.

4- Naturally yields decreased in line with the magnitude of the water or N stress, but achievable yields (and WUE) for given level of stress under Mediterranean conditions are maximized with the degree of co-limitation between water and nitrogen.

5- All the previous conclusions concur with the evidences provided in Australia in that even under a rather severe water stressed conditions using N appropriately might help improving productivity in Mediterranean conditions. Although this tool may not be widely useful in the European part of the Mediterranean basin, in the WANA region Nitrogen fertilization may be a useful management tool to increase grain yield though improving water use efficiency.

References

Abeledo, L.G., Savin, R., Slafer, G.A. 2008. Wheat productivity in the Mediterranean Ebro Valley: Analyzing the gap between attainable and potential yield with a simulation model. European Journal of Agronomy. 28, 541-550.

Acevedo, E. 1987. Morphophysiological traits of adaptation of cereals to Mediterranean environments. In: Acevedo, E., Ferreres, E., Gimenez, C., Srivastava J.P. (Eds). Improvements and management of winter cereals under temperature, drought and salinity stresses. Proceedings of ICARDA-INIA Symposium. Cordoba-Spain. 485 pp.

Acreche, M.M., Slafer, G.A. 2006. Grain weight response to increases in number of grains in wheat in a Mediterranean area. Field Crops Research. 98, 52-59.

Acreche, M.M., Briceño-Félix, G., Martín Sánchez, J.A., Slafer, G.A. 2008. Physiological bases of genetic gains in Mediterranean bread wheat yield in Spain. European Journal of Agronomy. 28, 162-170.

Acreche, M., Slafer, G.A. 2009. Grain weight, radiation interception and use efficiency as affected by sink-strength in Mediterranean wheats released from 1940 to 2005. Field Crops Research. 110, 98-105.

Albrizio, R., Todorovic, M., Maticb, T., Stellacci, A.M. 2010. Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. Field Crops Research. 115, 179-190.

Anderson, W.K., Impiglia, A. 2002. Management of dryland wheat. In: Curtis, B.C., Rajaram, S., Gómez Macpherson, H. (Eds.), Wheat: Improvement and Production. Plant Production and Protection Series No. 30. FAO, Rome, p. 567

Angás, P., Lampurlanés, J., Cantero-Martínez C. 2006. Tillage and N fertilization effects on N dynamics and barley yield under semiarid Mediterranean conditions. Soil and Tillage Research. 87, 59-71.

Angus, J.F., van Herwaarden, A.F. 2001. Increasing water use and water use efficiency in dryland wheat. Agronomy Journal. 93, 290-298.

Anonymous. 1999. Agrarian Census of 1999. Official statistic website of Catalonia. http://www.idescat.cat

Araus, L., Buxo, R. 1993. Changes in Carbon Isotope Discrimination in grain cereals from the North-Western Mediterranean basin during the past seven millenia. Australian Journal of Plant Physiology. 20, 117-128.

Araus, L., Slafer, G.A., Reynolds, M.P., Royo, C., 2002. Plant breeding and drought in C3 cereals: what should we breed for? Annals of Botany. 89, 925-940.

Araus, L., Bort, J., Steduto, P. Villegas, D., Royo, C. 2003. Breeding cereals for Mediterranean conditions: ecophysiological clues for biotechnology application. Annals of Applied Biology. 142, 129-141.

Araus, J.L., Slafer, G.A., Royo, C., Dolores Serret, M. 2008. Breeding for yield potential and stress adaptation in cereals. Critical Reviews in Plant Science. 27, 377–412.

Arregui, L.M., Quemada, M. 2008. Strategies to improve nitrogen use efficiency in winter cereal crops under rainfed conditions. Agronomy Journal. 100, 277-284.

Arisnabarreta, S., Miralles, D.J. 2008. Critical period for grain number establishment of near isogenic lines of two- and six-rowed barley. Field Crops Research. 107, 196-202.

Asseng, S., Keating, B.A., Fillery, I.R.P., Gregory, P.J., Borden, J.W., Turner, N.C., Palta, J.A., Abrecht, D.G. 1998. Performance of the APSIM-wheat model in Western Australia. Field Crops Research. 57, 163-179.

Asseng, S., van Herwaarden, A.F. 2003. Analysis of the benefits to wheat yield from assimilates stored prior to grain filling in a range of environments. Plant and Soil. 256, 217-229,

Asseng, S., Turner, N.C., Keatin, B.A. 2001. Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. Plant and Soil. 233, 127-143.

Austin R.B., Cantero-Martínez C.J., Arrúe L., Playán E., Cano-Marcellán P. 1998. Yield-rainfall relationships in cereal cropping systems in the Ebro river valley of Spain. European Journal of Agronomy. 8, 239-248.

Blum, A. 2009. Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. Field Crops Research. 112, 119-123.

Calatayud, S. 2006. La transformació de l'agricultura tradicional. In: Història Agraria dels Països Catalans. 4. Segles XIX-XX. Calatayud, S., Colomé, J., Cussó, X., Alòs, L., Garrabou, R., Herrero, S., Jover, G., Moliner, R., Manera, C., Millan, J., Nicolau, R., Maresma, J., Pujol, J., Saguer, E., Tello, E., Valls, F., Viñedo, E. Publicacions i Edicions de la Universitat de Barcelona.

Calderini, D.F., Dreccer, M.F., Slafer, G.A. 1997. Consequences of breeding on biomass, radiation interception and radiation use efficiency in wheat. Field Crops Research. 52, 271-281.

Condon, A.G., Richards, R.A., Rebetzke, G.J., Farquhar, G.D. 2002. Improving intrinsic water-use efficiency and crop yield. Crop Science. 42, 122–131.

Condon, A.G., Richards, R.A., Rebetzke, G.J., Farquhar, G.D. 2004. Breeding for high water-use efficiency. Journal of Experimental Botany. 55, 2447-2460.

Cooper, P.J.M., Gregory, P.J., Keatinge, J.D.H., Brown, S.C. 1987. Effects of fertilizer, variety and location on barley production under rainfed conditions in Northern Syria 2. soil water dynamics and crop water use. Field Crops Research. 16, 67-84.

DAAR, 2005. Dossier Tecnic Nro. 5. Cereals d'hivern: Varietats, treball del sòl i control de males herbes i malalties. 36pp. Generalitat de Catalunya.

DAAR, 2006. Dossier Tecnic Nro. 15. Varietats de cereals d'hivern. 39pp. Generalitat de Catalunya.

DAAR, 2007. Dossier Tecnic Nro. 23. Avaluació varietal en cereals d'hivern. 24pp. Generalitat de Catalunya.

DAAR, 2008. Dossier Tecnic Nro. 31. Noves varietats de cereals d'hivern. 31pp. Generalitat de Catalunya.

Delogu, G., Cattivelli, L., Pecchioni, N., De Falcis, D., Maggiore, T., Stanca, A.M. 1998. Uptake and agronomic efficiency of nitrogen in winter barley andwinter wheat. European Journal of Agronomy. 9, 11-20.

Ferrante, A., Savin, R., Slafer, G.A. 2009. Floret development of wheat and barley in response to nitrogen and water availabilities. Msc. Thesis. Universitat de Lleida. 37 pp.

Fischer, R.A. 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. Journal of Agricultural Science. 105, 447-461.

Fischer, R.A. 2008. The importance of grain or kernel number in wheat: A reply to Sinclair and Jamieson. Field Crops Research. 105, 15-21.

French, R.J., Schultz, J.E. 1984a. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. Australian Journal of Agricultural Research. 35, 743-764.

French, R.J., Schultz, J.E. 1984b. Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. Australian Journal of Agricultural Research. 35, 765-775.

French R.J., Ewing M.A. 1989. Soil type influences the relative yields of different cereals and crop legumes in the Western Australian wheatbelt. Australian Journal of Experimental Agriculture. 29, 829-835.

Foulkes, M.J., Hawkesford, P.B., Barraclough, M.J., Holdsworth, S., Kerr, S., Kightley, Shewry, P.R. 2009. Identifying traits to improve the nitrogen economy of wheat: Recent advances and future prospects. Field Crops Research. 114, 329-342.

Garabet, S., Word, M., Ryan J. 1998. Nitrogen and water effects on wheat yield in a Mediterranean-type climate I. Growth, water-use and nitrogen accumulation. Field Crops Research. 57, 309-318.

Garcia del Moral, L.F., Rharrabti, Y., Villegas, D., Royo, C. 2003. Evaluation of grain yield and its components in durum wheat under Mediterranean conditions: An ontogenic approach. Agronomy Journal. 95, 266-274.

Garcia del Moral, L.F., Rharrabti, Y., Elhani, S., Martos, V., Royo, C. 2005.Yield Formation in Mediterranean durum wheats under two contrasting water regimes based on path-coefficient analysis. Euphytica. 146, 203-212.

Garrabou, R., Pascual, P., Pujol, J., Saguer, E. 1995. Potencialidad productiva y rendimientos cerealícolas en la agricultura catalana contemporánea. Noticiario de Historia Agraria. 10, 89-130.

Josephides C.M. 1993. Analysis of adaptation of barley, triticale, durum and bread wheat under Mediterranean conditions. Euphytica. 65, 1-8.

Katerji, N., Mastrorilli, M., Nachit, M.M., van Hoorn, J.W., Hamdy, A., Oweis, T., Abdalla, O., Grando, S. 2008. Salt tolerance classification of winter cereal varieties according to grain yield performance and water use efficiency. 105-114. In: Sustainable Irrigation Management, Technologies and Policies II. Eds. Villacampa Esteve Y., Brebbia, C.A., Prats Rico, D. Witpress, Southampton, Boston, UK. 381pp.

Katerji, N., Mastrorilli, M., van Hoorn, J.W., Lahmer, F.Z., Hamdy, A., Oweis, T. 2009. Durum wheat and barley productivity in saline-drought environments. European Journal of Agronomy. 31, 1-9.

Lobell, D.B., Field, C.B. 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environmental Research Letters. 2, 1-7. 014002.

López-Castañeda, C., Richards, R.A. 1994. Variation in temperate cereals in rainfed environments I. Grain yield, biomass and agronomic characteristics. Field Crops Research. 37, 51–62.

López-Castañeda, C., Richards, R.A. 1994b. Variation in temperate cereals in rainfed environments III. Water use and water-use efficiency. Field Crops Research. 39, 85-98.

López-Castañeda, C. Richards, R.A., Farquar, G.D. 1995. Variation in early vigor between wheat and barley. Crop Science. 35, 472-479.

López-Bellido, L. 1992. Mediterranean cropping systems. In: Ecosystems of the World. Elsevier. Field

Crop Ecosystems.14. Eds C.J. Pearson. Amsterdam, the Netherlands. 311-356 pp.

López-Bellido, L., López-Bellido, R.J., Redondo, R. 2005. Nitrogen efficiency in wheat under rainfed Mediterranean conditions as affected by split nitrogen application. Field Crops Research. 94, 86-97.

Loss, S.P., Siddique, K.H.M. 1994. Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. Advances in Agronomy. 52, 229-275.

Miralles, D.J., Slafer, G.A. 1995. Individual grain weight responses to genetic reduction in culm length in wheat as affected by source-sink manipulations. Field Crops Research. 43, 55-66.

Miralles, D.J., Slafer, G.A. 1997. Radiation interception and radiation use efficiency of near-isogenic wheat lines with different height. Euphytica. 97, 201-208.

Muurinen, S., Slafer, G.A., Peltonen-Sainio, P. 2006. Breeding effects on nitrogen use efficiency of spring cereals under northern conditions. Crop Science. 46, 561-568.

Ortiz-Monasterio, J.I., Sayre, K.D., Rajaram, S. 1997. Genetic progress in wheat yield and nitrogen use efficiency under four nitrogen rates. Crop Science. 37, 898-904.

Palta J.A., Fillery, I.R.P. 1995. N application increases pre-anthesis contribution of dry matter to grain yield in wheat grown on a duplex soil. Australian Journal of Agricultural Research. 46**,** 507-518.

Palumbo, M., Boggini, G. 1994. Comparison of durum-wheat bread wheat and barley in a Mediterranean environment. Cereal Research Communications. 22, 113-120.

Prystupa, P., G.A. Slafer, and R. Savin. 2003. Leaf appearance, tillering and their coordination in response to NxP fertilization in barley. Plant and Soil. 255, 587-594.

Pujol, J. 2006. Els processos de canvi tècnic i el desenvolupament de noves activitats agroindustrials i alimentàries. In: Història Agraria dels Països Catalans. 4. Segles XIX-XX. Calatayud, S., Colomé, J., Cussó, X., Alòs, L., Garrabou, R., Herrero, S., Jover, G., Moliner, R., Manera, C., Millan, J., Nicolau, R., Maresma, J., Pujol, J., Saguer, E., Tello, E., Valls, F., Viñedo, E. Publicacions i Edicions de la Universitat de Barcelona. Spain.

Richards, R.A. 1992. The effect of dwarfing genes in spring wheat in dry environments. II. Growth, water use and water use efficiency. Australian Journal of Agricultural Research. 43, 529-539.

Richards, R.A. 2006. Physiological traits used in the breeding of new cultivars for water-scarce environments. Agricultural Water Management. 80, 197-211.

Reynolds, M.P., Pellegrineschi, A., Skovmand, B. 2005. Sink-limitation to yield and biomass: a summary of some investigations in spring wheat. Annals of Applied Biology. 146, 39-49.

Royo, C., Alvaro, F., Martos, V., Ramdani, A., Isidro, J., Villegas, D., Garcia del Moral, L.F. 2007. Genetic changes in durum wheat yield components and associated traits in Italian and Spanish varieties during the 20th century. Euphytica. 155, 259-270.

Ryan, J., Singh, M., Pala, M. 2008. Long-term cereal-based rotation trials in the mediterranean region: implications for cropping sustainability. Advances in Agronomy. 97, 273-319 Chapter Seven.

Sadras, V.O., Roget, D.K., 2004. Production and Environmental Aspects of Cropping intensification in a Semiarid Environment of Southeastern Australia. Agronomy Journal. 96, 236-246.

Sadras, V.O. 2005. A quantitative top-down view of interactions between stresses: theory and analysis of nitrogen-water co-limitation in Mediterranean agro-ecosystems. Australian Journal of Agricultural Research. 56, 1151-1157.

Sadras, V.O., Angus, J.F. 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. Australian Journal of Agricultural Research. 57, 847-856.

Savin, R., Slafer, G.A. 1991. Shading effects on the yield of an Argentinian wheat cultivar. Journal of Agricultural Science. 116, 1-7.

Savin, R., Sadras, V.O., Slafer, G.A. 2006. Do Mediterranean environments set up an upper limit in wheat nitrogen use efficiency? In: Bibliotheca fragmenta Agronomica. Vol.11. Books of proceedings, part I. European Society for Agronomy, Polish Society for Agronomy. IX ESA Congress, 4-7 September 2006. Warsaw, Poland. 439pp

Sepaskhah, A.R., Azizian, A., Tavakoli, A.R. 2006. Optimal applied water and nitrogen for winter wheat under variable seasonal rainfall and planning scenarios for consequent crops in a semi-arid region. Agricultural Water Management. 84, 113-122.

Simpson P.G., Siddique K.H.M. 1994. Soil type influences relative yield of barley and wheat in a Mediterranean-type environment. Journal of Agronomy & Crop Science. 172, 147–160.

Slafer, G.A., Araus, J.L., Royo, C., Garcia del Moral, L.F. 2005. Promising eco-physiological traits for genetic improvement of cereal yields in Mediterranean environments. Annals of Applied Biology. 146, 61–70.

Slafer, G.A. and Savin R. 2006. Physiology of yields. In: Encyclopedia of Plant and Crop Science. Editor: R. Goodman, Marcel Dekker, Taylor & Francis Group, LLC, New York, USA

Ugarte, C., Calderini, D.F., Slafer, G.A. 2007. Grain weight and grain number responsiveness to pre-anthesis temperature in wheat, barley and triticale. Field Crops Research. 100, 240-248.

van Herwaarden, A.F., Farquhar, G.D., Angus, J.F., Richards, R.A., Howe, G.N. 1998. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser I. Biomass, grain yield, and water use. Australian Journal of Agricultural Research. 49, 1067-1081.

Voltas, J., Serra, J., López, A., Capellades, G. 2009. Progrés genetic en rendiment del blat fariner (*Triticum aestivum L.*) a Catalunya. In: Dossier Tecnic. Nro. 37. "Noves varietats de cereals d'hivern. Resultats 2008-2009 i recomanacions 2009-2010" DAR.

Wahbi A., Sinclair T.R. 2005. Simulation analysis of relative yield advantage of barley and wheat in an eastern Mediterranean climate. Field Crops Research. 91, 287-296.

Witcombe, J.R., Hollington, P.A., Howarth, C.J., Reader, S., Steele, K.A. 2008. Breeding for abiotic stresses for sustainable agriculture. Philosophical Transactions of the Royal Society B. 363, 703-716.

Annex I

Improving wheat yields through N fertilization in Mediterranean Tunisia

Submitted to Experimental Agriculture

Improving wheat yields through N fertilization in Mediterranean Tunisia

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Abstract

Rainfed wheat under Mediterranean conditions is frequently exposed to periods of water stress that generate low and variable grain yields. In this context, field experiments indicated that N fertilization may be a tool to increase productivity; these experiments included those carried out in the context of a European research project of International Cooperation (WatNitMED) with studies in Tunisia and Morocco, which constitute a major Mediterranean cereal production region of the world. However, most farmers in Northern Africa do not fertilize their rainfed cereals. In the present study, we aimed to analyze whether the generally accepted positive response of grain yield to N fertilization in rainfed Mediterranean conditions observed in experimental conditions correspond to actual advantages achieved in realistic farmer fields, attempting a further up-scaling the knowledge from field experiments to real fields, by conducting a farm pilot experience in two distinct regions (a low-yielding and a relatively high-yielding) of cereal production in Tunisia (a typical rainfed Mediterranean wheat production system in North Africa). For this purpose, yield response to N fertilization was firstly analyzed against un-fertilized conditions (a common situation for many of the farmers in North Africa), and secondly we aimed to compare what the farmers would suggest as an optimal N fertilization practice in their fields with the recommendation based on a N-fertilization scheme derived from WatNitMED specific field experiments. Both comparisons were carried out together in a number of farmer fields within two contrasting Tunisian growing regions. WatNitMED fertilization scheme generally suggested higher rates of fertilization than those that would be considered optimal by [illegible] Unfertilized grain yields across both locations ranged, within what are usual rainfed yields in the region, from [illegible] 3.5 Mg ha^{-1}, and fertilizing increased these yields in most situations. Within the two alternative fertilizations schemes, WatNitMED fertilization tended to produce higher yields than those obtained with the fertilization rate considered optimal by farmers. This was observed in low-yielding as well as in the high-yielding region. These responses evidenced that fertilization in realistic field conditions may actually be a trustworthy tool to improve dryland wheat grain and straw yields, and also that rates of fertilization regarded as optimal by real farmers were below the optimum. This is critical in the region, as grain and straw are both part of the harvestable and marketable yield in the WANA region.

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1. Introduction

In the Mediterranean basin, most wheat (and barley) is cultivated under rainfed conditions. Due to rainfall variability Mediterranean wheat is exposed to water stress of different severity. For farmers in the region this is a scenario where yields are uncertain, but frequently rather low (Yankovitch 1956; Kopp 1981; Loss and Siddique 1994; Acevedo et al. 1999; Sadras 2002). Sadras et al. (2003) analyzed the performance of Australian dryland wheat to contrasting cropping strategies (conservative vs. risky) for various locations across years differing in rainfall. The conservative strategy seemed more profitable in years with low water availability, but it was less profitable in wet seasons. Rainfed productivity in the Southern Mediterranean basin is intrinsically risky due to water stresses (López-Bellido 1992). As water is intrinsically limited in Mediterranean systems, nitrogen (N) fertilization might be a tool to increase either water capture or its use efficiency in rainfed conditions. Nitrogen fertilization has become in the last 20 years the most useful management practice to increase grain yield of cereal crops in other regions with Mediterranean weather (Angus 2001; Passioura 2002). French and Shultz (1984a and 1984b) had reported increments in wheat yield for the Mediterranean region of Australia when crops were fertilized by allowing the use of the available water with a higher efficiency. This may has been due to the fact that N fertilization would allow to reduce water losses by direct evaporation (decreasing the evaporation-to-transpiration ratio) or to increase the capture of soil water from deeper layers due to a larger root system..On the other hand, N fertilization might produce an adverse effect on grain yield of rainfed wheat, known as "haying-off" (van Herwaarden et al. 1998), although we are not aware of this sort of yield penalties reported for agricultural conditions beyond those of Eastern Australia. The occurrence of "haying-off" does not seem to be common even in Western Australia (Palta and Fillery 1995, Asseng et al. 1998; Asseng and van Herwaarden 2003), one of the most important Mediterranean wheat production regions of the globe.

Rates of N fertilization in the Mediterranean basin vary widely. This range has been broadly described from zero under low rainfall areas of Morocco to 120 kg N ha^{-1} in Spain on durum wheat crops in high rainfall areas (López-Bellido 1992). These widely variable rates reflect a different risk propensity of farmers in the European and in the North African areas of the Mediterranean basin. The more-conservative strategy followed in most of the wheat rainfed regions of North Africa is translated into relatively low levels of producti[illegible] cereals would be grown year after year under N deficiency in the WANA (Wes[illegible] region in general (*e.g.* Mossedaq and Smith 1994; Oweis et al. 1998; Ryan 2000; Ryan 2008), and in Tunisia in particular (Latiri et al. 2005). The experience cannot be extrapolated for European farmers due to differences in subsidies to crop production, and the European frequent integration of intensive animal production with cropping systems regularly using animal wastes as organic fertilization. However, the experience of non-subsidiased Australian farmers (Passioura 2002) suggests that mineral N-fertilization might overcome part of the yield penalties imposed by the Mediterranean weather in North African rainfed cereal production. Similarly, although with much less experiences than those available for Australian Mediterranean regions, N fertilization has also been reported (from either results of experiments or from outputs of simulation models) to be a valuable tool to increase grain yield in the WANA region (Pala et al. 1996; Garabet et al. 1998; Pilbeam et al. 1998; Kabengi et al. 2003; Ryan 2008). Most of the new information regarding WANA region was generated since the establishment of the International Center for Agricultural Research in the Dry Areas (ICARDA) in Syria in1977 and its research in collaboration with other national research institutes in order to address problems of dryland agriculture within the region. However, the attitude of farmers in Mediterranean Australian regions (of increasingly use fertilization as a tool to systematically rise yields in the severely water stressed conditions of their crops) differs with that of farmers from North Africa, mostly reluctant to use such a tool. It may reflect simply different attitudes of farmers (likely due to different socio-economic conditions in which they operate), or to the different degree of confidence in the extrapolation of results from field experiments and simulation exercises to realistic farm conditions.

A limited confidence in extrapolating results from field experiments to farm practice in North Africa may be expected as the research done within the region (either field experiments and simulation exercises) compared to that done in Australia is far less in number and comprehensiveness. The farmers may mistrust on the results extrapolation. The farms are far more complex than what most field experiments can take into account, particularly so when they are conducted in research stations, frequently under lower and with lower variability stress than in real farms nearby. This is why, the inclusion of farmers in the experimentation, allows for a better targeting of technology, and more realistic technology evaluation (Ashby and Sperling 1995). This may be why, while it is apparently known that management practices offer options to reach a more efficient nutrient use in the WANA region, they are [illegible]

In order to study likely improvements in Water Use E[illegible] wheat grown in Southern Mediterranean countries an European research project of cooperation with Mediterranean partner countries (WatNitMED) was aimed to analyze to what degree deficiencies in N-nutrition, rather than solely water stress, may be behind low wheat productivity in the region. Based on experimental results from several locations and years, a fertilization scheme was initially proposed. In this paper we reported the results of an experience conducted in real farms to analyze the generally accepted positive response of grain yield to N fertilization observed in field experiments, up-scaling the knowledge by conducting a farm pilot experience.

To carry out the objective, the yield response to N fertilization was analyzed using two different comparisons: (i) the effect of N fertilization on wheat yield compared to the un-fertilized conditions and (ii) the response to N fertilization doses considered optimal by farmers *vs* those derived from a fertilization scheme derived from the European research project (WatNitMED).

2. Materials and Methods

The experience was carried out in two locations with different weather conditions of Tunisia: Béja (sub-humid) and Siliana (semi-arid). In each case we compared the response of three different N fertilization

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strategies for durum wheat in farmer fields (9 fields in

condition of the crop (Fig. 1a). With all the mentioned

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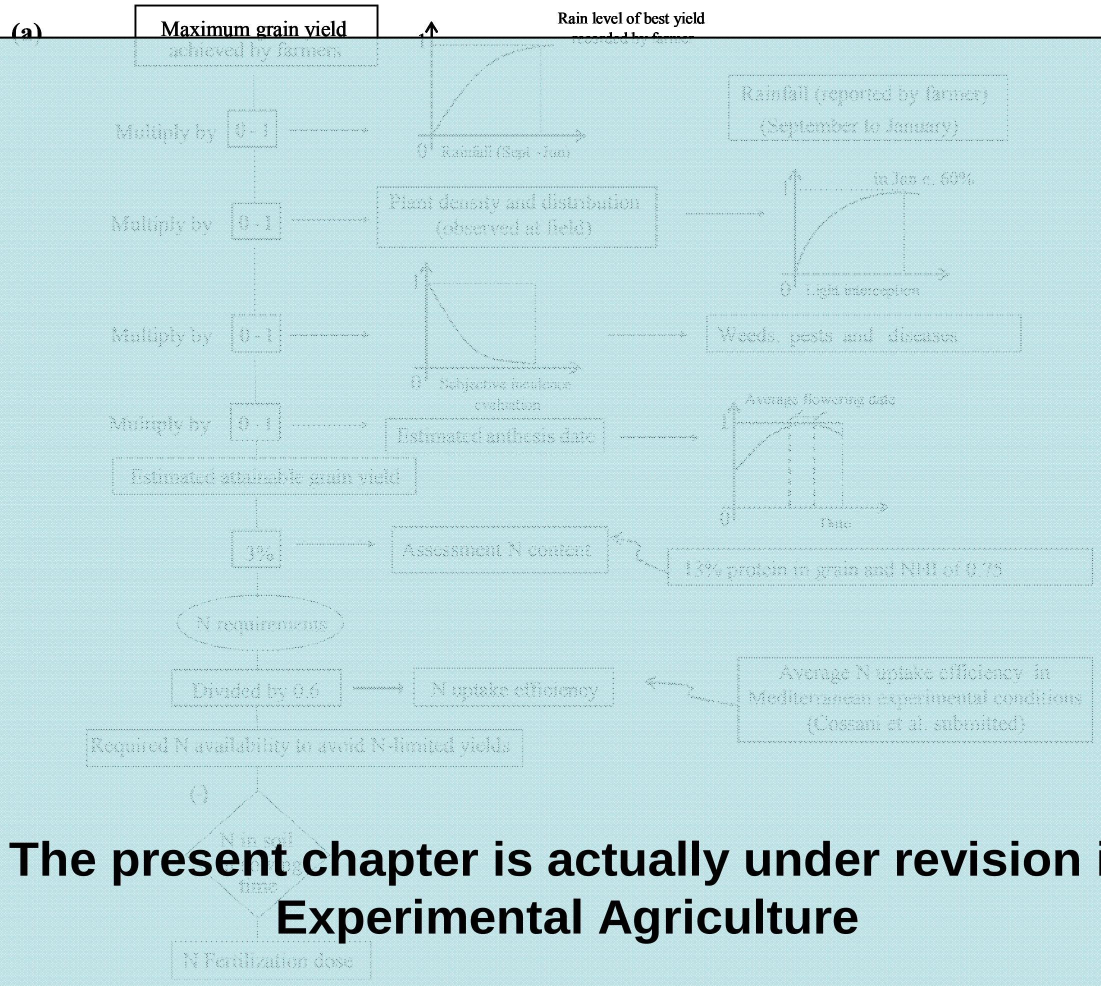

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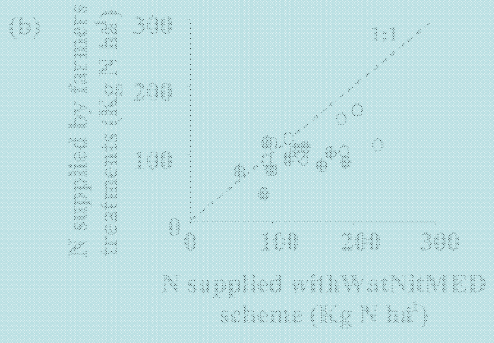

Figure 1. a) Scheme of the procedure used for N recommendation in each of the twenty fields in which the experience was carried out (for details see text). b) Comparison of N-fertilization rates applied by farmers and those derived from WatNitMED. Open and closed symbols represent Béja (relatively high-yielding region) and Siliana (relatively low-yielding region)

Experimental units consisted of a subdivision of farmer fields into large plots of 0.5 ha for each of the treatment assigned randomly. Although instructions were explicit and equal to all farmers, unfortunately some of them did not follow the scheme and did not leave the half-hectarea unfertilized. All in all, there were 11 fields with all the three treatments while the other 9 fields only had the farmer's treatments and WatNitMED's fertilization schemes. Before sowing, soil samples were taken to determine N soil content of each field (Table 1).

Due to the limitations in structure to take, transport and process the field samples, only two samples of 1 m^2 of aboveground biomass were taken at maturity per experimental unit, and grain yield, yield components and total biomass were determined. Additionally, to perform a joint analysis for grain yield and straw yield a total yield was calculated using the relationship between the price of straw and grain to transform the straw yield as it is reported in Equation 1.

Then grains and shoots were milled and N content was measured with Micro-Kjeldahl methodology.

$$[\text{Eq. 1}]\quad \text{Yield}_{\text{Total}} = \text{Yield}_{\text{Grain}} + (\text{Yield}_{\text{Straw}}\,[\text{Price}_{\text{Straw}}\,\text{Price}_{\text{Grain}}]^{-1})$$

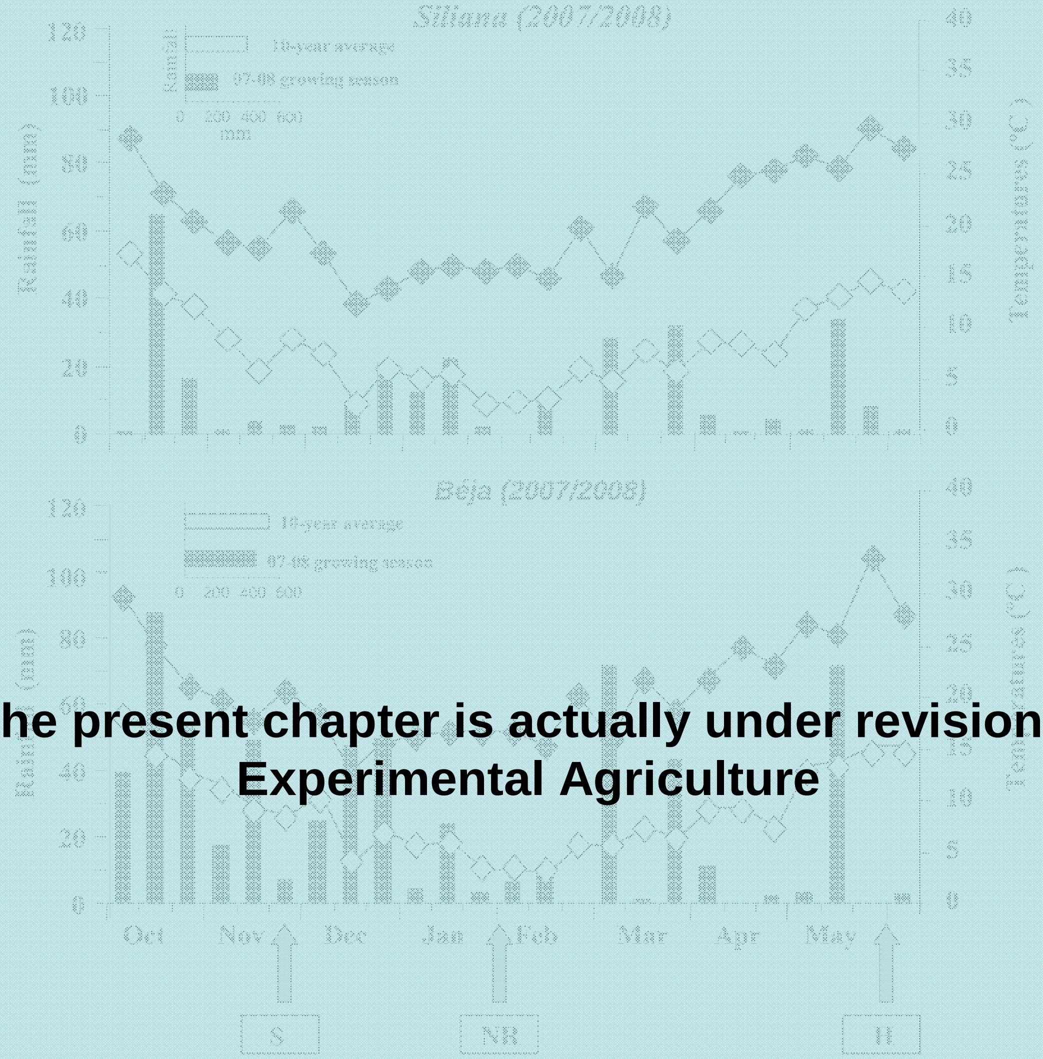

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Figure 2. Accumulated precipitation (bars), average maximum (closed rhombs) and minimum (open rhombs) temperatures for periods of 10 days during the growing season. Timing of sowing (S), N-fertilization recommendation (NR) and harvest (H) (they were similar for both locations) are indicated. Inset is the comparison of the accumulated precipitation for the whole growing season (November-June) both on average of the last 10 years (open bars) and that for this the experimental growing season (closed bars

3. Results

3.1 *Weather conditions*

As expected, the two regions differed significantly in their environmental conditions during the growing season, particularly in total rainfall. While in Siliana rainfall from November 2007 to June 2008 was only 198 mm, in Béja it was 448 mm. In both locations rainfall distribution was typically Mediterranean with c. 70% of the rainfall ocurring before 1 April. Total rainfall from November to June was below the average of the last ten years in both locations, although the difference was greater in Siliana than in Béja (Fig. 2 insets). In both sites average minimum temperatures were higher than 0 °C during the whole growing season, while average maximum temperatures reached more than 30°C at the end of May.

3.2 *Yield and components*

Unfertilized grain yield across both locations ranged from c. 1 to c. 3.5 Mg ha^{-1}, whilst the range widened when fertilized to more than 7 Mg ha^{-1}. Average yield in Siliana was 1.6 Mg ha^{-1} lower than that in Béja.

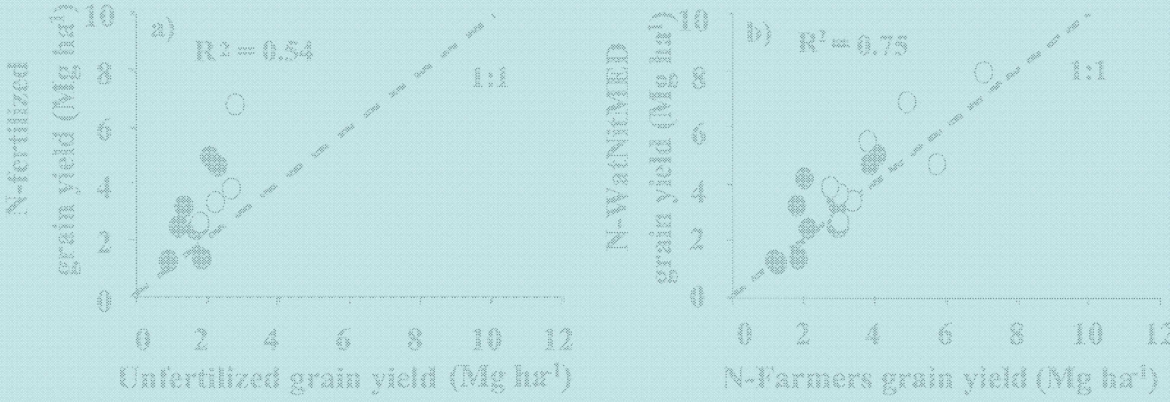

Figure 3. Relationships between grain yield of (a) fertilized (average of the two fertilization treatments, farmers and WatNitMED) and unfertilized fields and (b) fields receiving fertilization rates derived from the WatNitMED scheme and farmer fertilization. Open and closed symbols represent Béja and Siliana fields, respectively.

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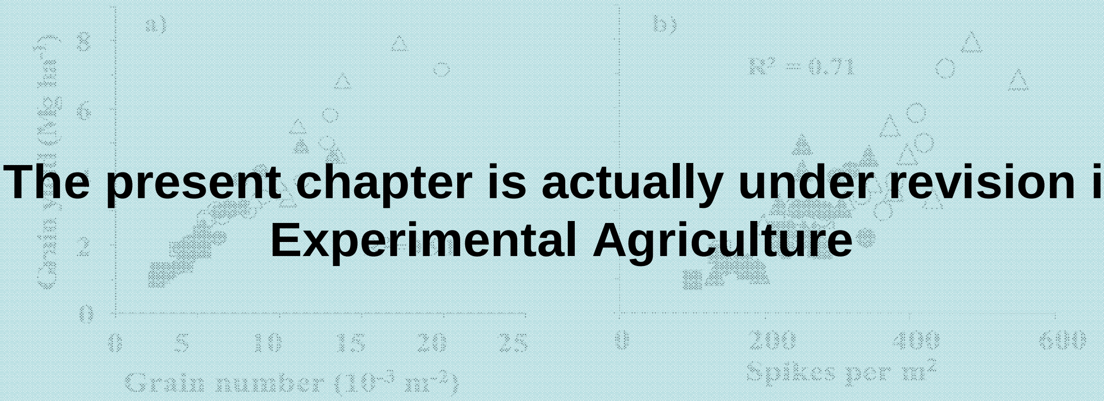

Figure 4. Relationship between grain yield and either (a) grain number or (b) spikes number per unit land area for (□) un-fertilized, (○) farmer fertilizations or (△) WatNitMED fertilizations. Open and closed symbols represent Béja and Siliana fields, respectively.

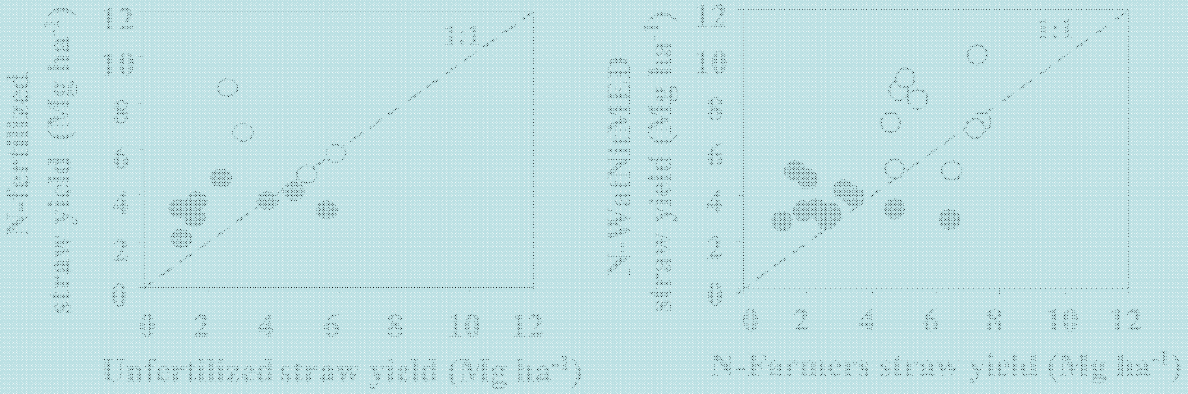

Figure 5. Relationships between straw yield of (a) fertilized (average of the two fertilization treatments, farmers and WatNitMED) and un-fertilized fields and (b) fields receiving fertilization rates derived from the WatNitMED scheme and farmer fertilization. Open and closed symbols represent Béja and Siliana fields, respectively.

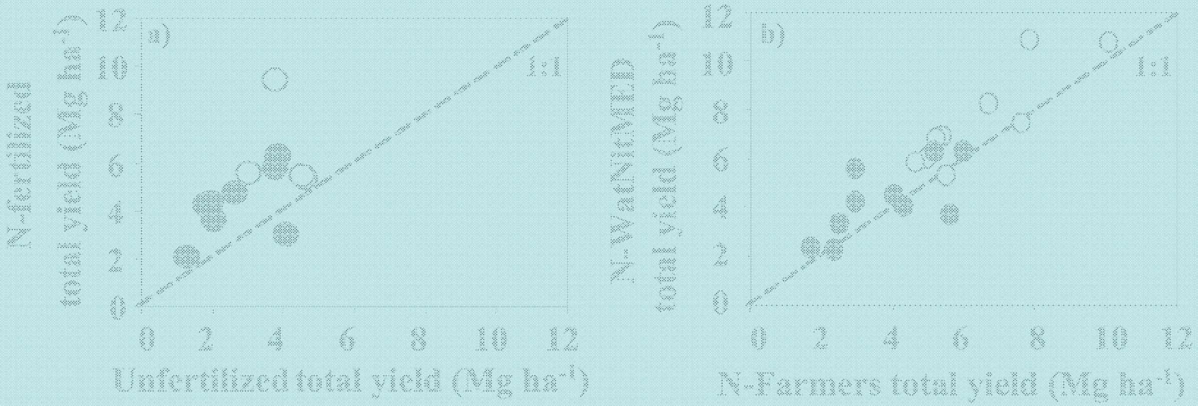

Figure 6. Relationships between total yield (grain yield + straw yield*0.4) of (a) fertilized (average of the two fertilization treatments, farmers and WatNitMED) and unfertilized fields and (b) fields receiving fertilization rates derived from the WatNitMED scheme and farmer fertilization. Open and closed symbols represent Béja and Siliana fields, respectively.

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Fertilizing has consistently increased yields, being crop responsiveness in general larger when attainable yields increased than at low yields (Fig. 3a). The fertilization recommendation produced by the project also showed a trend to improve yields compared to the farmer's scheme (Fig. 3b). The slight advantage of fertilizing more t[illegible]d to Béja, the relatively high-yielding region, but also evident in Siliana (Fig. 3b).

Even though the weather was typically Mediterranean, with low rainfall after antesis, grain yield was positively and directly related to in all the treatments of both locations (Fig. 4a). The average grain weight did not show a clear relationship with grain yield. Spikes' number per unit land area was the main sub-component explaining N effects and location differences in number of grains per square meter. Also spikes' number per unit land area showed a good relationship with grain yield (Fig. 4b).

Fertilized plots had 1.5 Mg_{straw} ha^{-1} higher straw yield than unfertilized ones (Fig. 5a). Differences between fertilized and unfertilized plots were higher in Béja than in Siliana. Comparing between the two fertilized options [illegible]ined after the N-WatNitMED recommendation was 1.02 M[illegible]hat obtained in farmers' plots (Fig. 5b).

If the analysis of yield is performed including the yields of grain and straw, it can be observed that total yield of the unfertilized fields was clearly lower than the fertilized plots (Fig. 6a). Total yield of N-WatNitMED recommendation was in most of cases above the 1:1 line when comparing with the farmer fertilizations option (Fig. 6b).

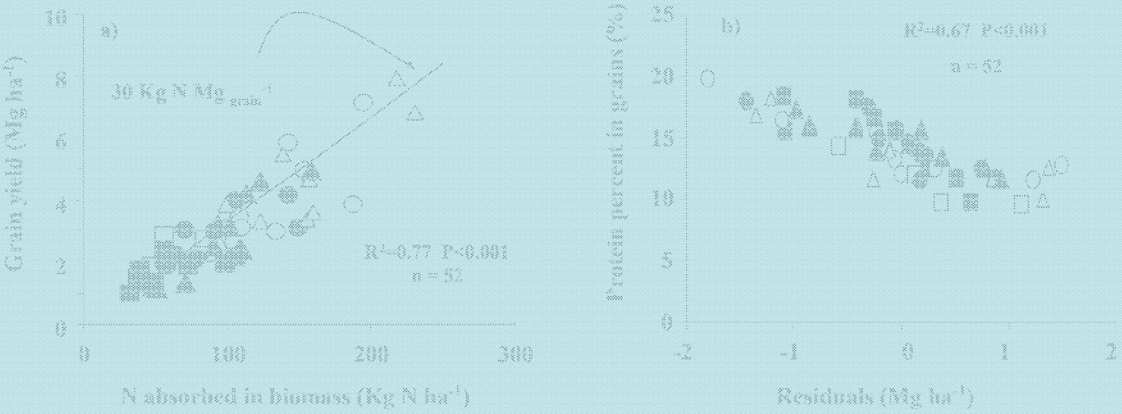

Figure 7. Relationship between (a) grain yield and N absorbed at maturity and (b) grain protein concentration and the residuals of the relationship between actual grain yield and grain yield expected with a certain amount of N

absorbed with a conversion efficiency of 30 Kg N per Mg grain^{-1} for (□) un-fertilized, (○) farmer fertilization or (△) WatNitMED fertilization. Open and closed symbols represent Béja and Siliana fields, respectively.

3.3 Nitrogen uptake and N utilization efficiency

Nitrogen uptake was significantly (R^2 =0.77; P<0.001) and positively related to grain yield (and biomass at maturity) across all treatments and locations. As it was expected, N uptake increased with the amount of N supplied. In general, crops receiving WatNitMED fertilizations had higher amounts of absorbed N (averaging across conditions 122 kg N ha^{-1}) than treatments representing the farmers fertilization dose (106 kg N ha^{-1}), and the difference became larger when compared with unfertilized crops (65 kg N ha^{-1}). Differences in N absorption were behind responsiveness to fertilization (Fig. 7a). There were not clear differences in N utilization efficiency (UtE) between plots fertilized by the farmers or following the scheme proposed by the project (Fig. 8).

Protein percent in grains was higher in Siliana (14.7% of protein) than in Béja (13.9% of protein). There were differences in protein percent between un-fertilized (11.4%) and fertilized crops (c.13.5%) in Béja while differences between treatments were less noticeable (whole range was 14.2% to 15.2 %) in Siliana. Protein percent was explained by the residuals in grain yield of the relationship between the actual grain yield and the grain yield expected with the same N uptake and a N conve[illegible]

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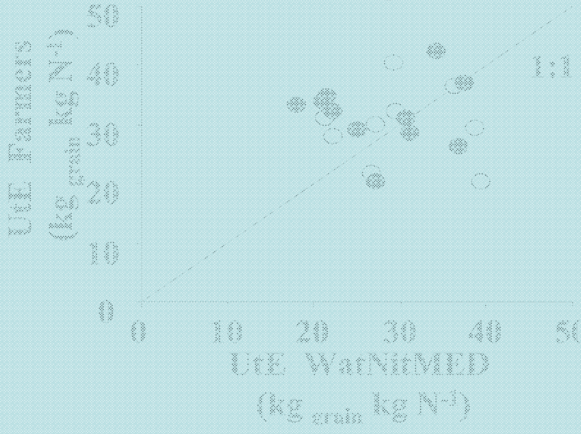

Figure 8. Relationship between N utilization efficiency of farmer fertilizations and N utilization efficiency of WatNitMED fertilizations. Open and closed symbols represent Béja and Siliana fields respectively.

4. Discussion

Despite of the difficulties in carry out the experience (i.e to convince farmers of apply the recommended N rate in WatNitMED fields; the withdrawal by some farmers of some of the treatments; the relatively small sampling), the reported pilot experience produced results with similar trends to those observed for experimental or simulated conditions across the WANA (Pala et al. 1996; Garabet et al. 1998; Oweis et al. 1999) or other Mediterranean regions involved in the design of the fertilization scheme reinforcing the knowledge generated at different scales (Cabrera-Bosquet et al. 2009; Cossani et al. 2009; Albrizio et al. 2010) about N fertilization.

In spite of the undisputed fact that water availability affects yield and yield responsiveness to N-fertilization in Mediterranean conditions, we hypothesized that, as it was the case in Australia (Passioura 2002), the low-yields normally achieved in the rainfed North African wheat production systems would be associated, at least partially, to N limitations if cereals are not fertilized (which is commonly the case in the WANA region and North Africa; Mossedaq and Smith 1994; Oweis et al. 1998; Heng et al. 2007). Differences in rainfall during the growing season could be responsible for the differences in average yield response to N between the two experimental regions, as previously reported for other Mediterranean regions (Kopp 1981; Anderson 1985; Austin et al. 1998a; 1998b). The poor relationship between unfertilized and fertilized yields with clear advantages for most of the fertilized plots supports the [illegible] cases farmers not fertilizing their wheats in Tunisia would be [illegible] to improve their productivity, even in Siliana, a relatively low-yielding region for rainfed wheat.

WatNitMED recommendation produced in many cases yield advantages over what it would be the optimal dose by farmers for their fields. The advantage was small, but it might be higher if the farmers would have fertilized their fields with the rates they usually do, rather than with what they regarded as optimal. There are several reasons for speculating that the actual rates these farmers would have used are lower than what they selected as optimal, the main one being the farmers were questioned, before entering into the experience, on which was their fertilization schemes and most of them replied that they would apply at least 20 Kg N ha^{-1} less than what they finally applied in the study afterwards (Thabet et al. 2006). Due to the fact that the farmers themselves applied the doses suggested from our project, they learnt that information before applying their dose, and probably felt influenced and raised their doses to get closer to that “recommended” from the model. Thus, the general view of the relative advantage of the recommendation process used compared to that used by the farmers was minimised, and for much of the farmers in the region (particularly in Siliana) the comparison that more truly reflects the reality is that against unfertilized crops.

Differences in yield were based mainly in responsiveness of the number of grains per square meter, consequence in turn of the improved number of spikes per unit land area in response to the treatments. As crops were fertilized at the end of tillering, is seemed clear than the main attribute by which yield responded to N availability was the reduction in tiller mortality determining more spike-bearing tillers per square meter. Similar results were found for Morocco, fertilizing with N just prior to the growth's stage when N demand by the crop is greatest (beginning of stem elongation). The increased grain number per square meter accounted by increased numbers of spikes per unit area, increased kernel numbers per spike, or both components (Mossedaq and Smith 1994). The fact that even under Mediterranean conditions yield differences are tightly linked to the number of grains per square meter is in line with evidences reported in experimental conditions of the WatNitMED project (e.g. Cossani et al. 2007 and 2009; Albrizio et al. 2010) This agrees with the view that grain growth, after the number of grains has been set in wheat, proceeds under low or no competition for carbohydrates (e.g. Cartelle et al. 2006; Acreche and Slafer 2009) alike in non-Mediterranean conditions (Slafer and Savin 1994; Borrás et al. 2004 an several references quoted there in).

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As straw [illegible] countries of the Mediterranean region) the profitability of a system must take crop resi[illegible] Despite of differences observed in grain yield between fertilized and unfertilized plots was clear, the advantage obtained in straw yield for the fertilized plots (1.58 Mg_{straw} ha^{-1} equivalent to c. 130 € ha^{-1} using the straw average price for the last five years in Tunisia) showed an additional-advantage. In addition, WatNitMED recommendation produced an advantage of straw yield over the farmers strategies that represented an extra income of c. 85 € ha^{-1} for the farmers. These differences are evidenced in the superiority in terms of total yield of the fertilized and WatNitMED recommendation over the unfertilized and farmers' fertilization options, respectively.

In the present pilot experience we focused in up-scaling to realistic farmers conditions the quantification of the opportunity to increase grain yields in rainfed wheats in Tunisia without focusing on grain quality. Focusing on grain protein concentration, it could be stated that even in the cases in which yield did not respond to fertilization strongly there was an increase in grain quality. This increase was the result of a compensation reinforcing even more the recommendation that farmers should avoid growing wheat continuously without fertilizing in the region, even if it is under conditions in which water availability limits yields strongly.

Beyond accepting the implicit hypothesis that wheat yield is N-limited if fields are not fertilized even in a Mediterranean rainfed system, the project delivered a tool that proved useful in two contrasting regions of Tunisia. The use of crop management guides such as decision schemes, like that used in the present study, or simulation models (Abeledo et al. 2008; Asseng et al. 2008), seems critical for optimising wheat yield under dryland Mediterranean conditions of North Africa. Despite of the higher yield achieved following the recommendation based on WatNitMed decision scheme, it should be noted with caution that the present paper attempts only to report a single pilot experience (the only kind of experience we could conduct within the funding scheme available). The main limitations are based on that it only has one growing season (although unfertilized yields resembled closely "normal" yields in the region). Thus, it is not intended to provide quantitative tools in terms of recommended doses, but to simply illustrate that the up-scaling from field experiments to realistic farms managed by their farmers suggest similar results to the observed in experimental conditions. In these regions not only fertilization should be used to improve productivity far more widely than it is used so far, but also that even what farmers regard as optimal doses would likely underestimate achievable yields. If further tested nationally, or in other WANA regions, the scheme used in this pilot experience [illegible] to determine fertilization doses.

N [illegible] improving grain yield through improving the use of limited resources by the crops. N fertilization increased water use efficiency (WUE) at least in terms of rainfall use (Fig. 9).

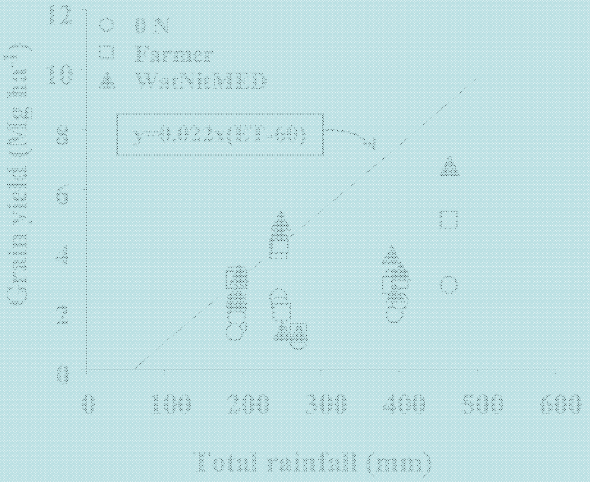

Figure 9. Grain yield as a function of total rainfall during the growing season for (□) un-fertilized, (○) farmer fertilizations and (▲) WatNitMED fertilizations.

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Solid line represents the upper WUE threshold as defined by Sadras and Angus (2006).

The response of WUE to the N fertilization coincides with that indicated in the classic papers by French and Shultz (1998a; 1998b). The improved WUE could be mediated by an earlier soil cover reducing direct evaporation (Passioura 2006), or by allowing the capture of more water from deeper soil layers (Angus and van Herwaarden 2001; Kirkegaard et al. 2007) due to a greater root system (Brown et al. 1987).

In conclusion, N fertilization analysed at realistic conditions actually faced by farmers, proved to be a useful strategic farm management tool to increase wheat yield and productivity in rainfed Mediterranean Tunisia. The use of a scheme accounting for the crop status, environmental and management conditions resulted in an additional yield and biomass productivity advantage over the N management most frequently adopted by farmers.

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References

Abeledo, L.G., R. Savin, R., G.A. Slafer. 2008. Wheat productivity in the Mediterranean Ebro Valley: Analyzing the gap between attainable and potential yield with a simulation model. European Journal of Agronomy. 28, 541-550.

Acevedo, E.H., P.C. Silva, H.R. Silva, B.R. Solar, 1999. Wheat production in Mediterranean environments. Chapter 14. In:Wheat. Ecology and physiology of yield determination. Eds. Satorre, E.H., Slafer, G.A. Food Products Press. NY.

Acreche, M.M., G.A. Slafer, 2009. Grain weight, radiation interception and use efficiency as affected by sink-strength in Mediterranean wheats released from 1940 to 2005. Field Crops Research. 110, 98-105.

Albrizio, R., M. Todorovic, T. Matic, A.M. Stellacci, 2010. Comparing the interactive effects of water and nitrogen on durum wheat and barley grown in a Mediterranean environment. Field Crops Research. 115, 179-190.

Anderson, W.K., 1985. Differences in response of winter cereal varieties to applied nitrogen in the field. I. Some factors affecting the variability of responses between sites and seasons. Field Crops Research. 11, 353-367.

Angus, J.F., 2001. Nitrogen supply and demand in Australian agricultrure. Australian Journal of Experimental Agriculture. 41, 277-288.

Angus, J.F., A.F. van Herwaarden, 2001. Increasing water use and water use efficiency in dryland wheat. Agrononmy Journal. 93, 290–298.

Austin, R.B., C.J. Cantero-Martínez, L. Arrúe, E. Playán, P. Cano-Marcellán, 1998a. Yield-rainfall relationships in cereal cropping systems in the Ebro river valley of Spain. European Journal of Agronomy. 8, 239–248.

Austin R.B., E. Playán, J. Gimeno, 1998b. Water storage in soils during the fallow: prediction of the effects of rainfall pattern and soil conditions in the Ebro valley of Spain. Agricultural Water Management. 36, 213–231.

Ashby, J.A., L. Sperling, 1995. Institutionalizing participatory, client-driven research and technology development in agriculture. Development and Change. 26, 753-770.

Asseng, S., B.A., Keating, I.R.P. Fillery, P.J. Gregory, J.W. Borden, N.C. Turner, J.A. Palta, D.G. Abrecht, 1998. Performance of the APSIM-wheat model in Western Australia. Field Crops Research. 57, 163-179.

Asseng, S., A.F. van Herwaarden, 2003. Analysis of the [illegible] prior to grain filling in a range of environments. Plant and [illegible]

Asseng, S., S.P. Milroy, M.L. Poole, 2008. Systems analysis of wheat production on low water-holding soils in a Mediterranean-type environment I. Yield potential and quality. Field Crops Research. 105, 97-106.

Borrás, L., G.A. Slafer, M.E. Otegui, 2004. Seed dry weight response to source–sink manipulations in wheat, maize and soybean: a quantitative reappraisal. Field Crops Research. 86, 131-146.

Brown, S.C., J.D.H. Keatinge, P.J. Gregory, P.J.M. Cooper, 1987. Effects of fertilizer, variety and location on barley production under rainfed conditions in Northern Syria 1. Root and shoot growth. Field Crops Research. 16, 53-66.

Cabrera-Bosquet, L., R. Albrizio, J.L. Araus, S. Nogués, 2009. A Photosynthetic capacity of field-grown durum wheat under different N availabilities: A comparative study from leaf to canopy. Environmental and Experimental Botany. 67, 145-152.

Cartelle, J., A. Pedró, R. Savin, G.A. Slafer, 2006. Grain weight responses to post-anthesis spikelet-trimming in an old and a modern wheat under Mediterranean conditions. European Journal of Agronomy. 25, 365-371.

Cossani, C.M., R. Savin, G.A. Slafer, 2007. Contrasting performance of barley and wheat in a wide range of

The present chapter is actually under revision in Experimental Agriculture

conditions in Mediterranean Catalonia (Spain). Annals of Applied Biology. 151, 167-173.

Cossani, C.M., G.A. Slafer, R. Savin, 2009. Yield and biomass in wheat and barley under a range of conditions in a Mediterranean site. Field Crops Research. 112, 204-213.

Latiri, K., 2005. Les céréales en Tunisie. In: Les defies de la Terre..L'agriculture en Espagne et en Tunisie face aux défis de la libéralisation. Analyse comparée. Eds. Ceña, F., Gallardo, R., Elloumi, M., Sai, M.E. IRESA, Cérès Editions. Tunis. 259-279.

López-Bellido, L., 1992. Mediterranean cropping systems. In Ecosystems of the World. Field Crop Ecosystems, 14, pp. 311-356. Ed C.J. Pearson. Netherlands: Elsevier.

Fischer, R.A., 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. Journal of Agricultural Science. 105, 447-461.

French R.J., J.E. Schultz, 1984a. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and Climate. Australian Journal of Agricultural Research. 35, 743-764.

French R.J., J.E. Schultz, 1984b. Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. Australian Journal of Agric[illegible] Research. 35, 764-77[illegible].

Garabet, S., M. Wood, J. Ryan, 1998. Nitrogen and water effects on wheat yield i[illegible] climate: I. Growth, water-use and nitrogen accumulation. Field Crops Research. 57, 309-318.

Heng, L.K., S. Asseng, K. Mejahed, M. Rusan, 2007. Optimizing wheat productivity in two rain-fed environments of the West Asia–North Africa region using a simulation model. European Journal of Agronomy. 26, 121-129.

Kabengi, N.J., R.A. Zurayk, R.Z. Baalbaki, J. Ryan, 2003. Phosphorus dynamics and characterization under long-term rotation trial. Communications in soil science and plant analysis. 34, 375-392.

Kirkegaard, J.A., J.M. Lilley, G.N. Howe, J.M. Graham, 2007. Impact of subsoil water use on wheat yield. Australian Journal of Agricultural Research. 58, 303-315.

Kopp, E., 1981. Efficacité de la fumure azotée : Régime de l'azote et fertilité latente des sols conduits en sec ou à l'aspersion dans la Haute vallée semi-aride e la Medjerda en Tunisie. Annales de l'Institut National de la Recherche Agronomique de Tunisie, 252 pp.

López-Bellido, L., 1992. Mediterranean cropping systems. In Ecosystems of the World. Field Crop Ecosystems, 14, pp. 311-356. Ed C.J. Pearson. Netherlands: Elsevier.

Loss, S.P., K.H.M. Siddique, 1994. Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. Advances in Agronomy. 52, 229-276.

Mossedaq, F., D.H. Smith, 1994. Timing nitrogen application to enhance spring wheat yields in a Mediterranean climate. Agronomy Journal. 86, 221-226.

Oweis, T., M. Pala, J. Ryan, 1998. Stabilizing rainfed wheat yields with supplemental irrigation and nitrogen in a Mediterranean climate. Agronomy Journal. 90, 672-681.

Oweis, T., M. Pala, J. Ryan, 1999. Management alternatives for improved durum wheat production under supplemental irrigation in Syria. European Journal of Agronomy. 11, 255-266.

Pala, M., C.O. Stockle, H.C. Harris, 1996. Simulation of durum wheat (Triticum turgirium ssp. durum) growth under different water and nitrogen regimes in a Mediterranean environment using CropSyst. Agricultural Systems. 51, 147-163.

Palta J.A., I.R.P. Fillery, 1995. N application increases pre-anthesis contribution of dry matter to grain yield in wheat grown on a duplex soil. Australian Journal of Agricultural Research. 46, 507-518.

Passioura, J.B., 2002. Environmental biology and crop improvement. Functional Plant Biology. 29, 537-546.

Passioura, J.B., 2006. Increasing crop productivity when [illegible] Agricultural Water Management. 80, 176-196.

[illegible] H.C. Harris, J. Tuladhar, 1998. Productivity and nitrogen use of three different wheat-based rotations in North West Syria. Australian Journal of Agricultural Research. 49, 451-458.

Ryan, J., 2000. Soil and plant analysis in the Mediterranean region: limitations and potential. Communications in Soil Science and Plant Analysis, 31, 2147-2154.

Ryan, J., 2008. A perspective on balanced fertilization in the Mediterranean region. Turkish Journal of Agriculture and Forestry. 32, 79-89.

Ryan, J., H. Ibrikci, A. Rashid, S. Masri, M. Pala, A. Matar, M. Singh, 2008. Residual and currently applied phosphorus in dryland cereal/legume rotations across a rainfal gradient in a Mediterranean ecosystem. European Journal of Agronomy. 28, 126-137.

Sadras, V.O., 2002. Interaction between rainfall and nitrogen fertilisation of wheat in environments prone to terminal drought: economic and environmental risk analysis. Field Crops Research. 77, 201-215.

Sadras, V.O., D. Roget, M. Krause, 2003. Dynamic cropping strategies for risk management in dry-land farming systems. Agricultural Systems. 76, 929-948.

Sadras, V.O., J.F. Angus, 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments.

Australian Journal of Agricultural Research. 57, 847-856.

Savin, R., G.A. Slafer, 1991. Shading effects on the yield of an Argentinian wheat cultivar. Journal of Agricultural Science. 116, 1-7.

Thabet C., A. Chebil, H. Elouaer., 2006. Valuing Water and Nitrogen: Case of Tunisian cereals. Abstracts. Séminaire Méditerranéen sur les Céréales Irriguées (SMCI), le Kef 23-26 May 2006, Tunisia.

van Herwaarden, A.F., G.D. Farquhar, J.F. Angus, R.A. Richards, G.N. Howe, 1998. 'Haying-off', the negative grain yield response of dryland wheat to nitrogen fertiliser I. Biomass, grain yield, and water use. Australian Journal of Agricultural Research. 49, 1067-1081.

Yankovitch, L., 1956. Resultats de 22 années d'expériences dans les case lysimétriques et cases de végétation du service botanique et agronomique de Tunisie. Annales du Service Botanique et Agronomique de Tunisie. 29, 1-223.

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