Universitat de Lleida

Department of Crop and Forest Sciences

Grain Yield and Resource Use Efficiency of Bread Wheat, Barley and Durum Wheat Under Mediterranean Environments

Doctoral Thesis

Submitted by

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Annex I:

Abstract

Under Mediterranean environments water and nitrogen (N) are considered the two factors most strongly limiting crop productivity. Wheat (bread and durum) and barley are the main crops grown in dryland Mediterranean environments. Within the Mediterranean basin, wheat is usually cultivated in rotations with other crops under relatively humid zones while barley is sown as a monoculture in the driest zones. Reasons behind barley monoculture are based on an hypothetical barley yield advantage over wheat under stressed environments. However, information about direct comparison between wheat (bread or durum) and barley is not abundant for the Mediterranean basin (nor for other Mediterranean regions). Neither grain yield nor biomass production, water use, nitrogen use or their use efficiency have been compared for the three species to justify the preference of one of them in monoculture in the more scarce resource availability environments.

The main objective of the present thesis was to assess the response of wheat (bread and durum) and barley in terms of productivity to different water and nitrogen availabilities within the Mediterranean conditions of dryland cereal regions of Catalonia. Within the main objective two specific objectives were formulated (i) to provide empirical support to the generalized hypothesis of a better performance of barley than wheat under stress conditions, and (ii) to analyze if N fertilization could be a management tool to increase grain yield under stressful Mediterranean conditions for small grain cereals (in cases in which soil N were low). To fulfil the objectives data taken from a literature revision, and historical and regional data were analysed combined with those from five field experiments that were carried-out using different combinations of water and N availabilities for a typical well-adapted and representative cultivar of bread wheat, durum wheat and barley during 2003/04 to 2006/07 growing seasons in a typical dryland region of Catalonia where barley represent *c.* 80 % of the total cereal acreage.

Across all the experimental conditions grain yield of the three species varied widely from c. 1 to 10 Mg ha^{-1}. Under the driest and poorest yielding conditions barley presented similar yields to wheat (bread and durum) using the experimental data, but also using the bibliographic, historical and regional data, indicating an unjustified barley monoculture in terms of productivity. Despite similar yield between durum wheat and barley a lower stability in grain weight was observed for the case of durum wheat. Neither water use or N use or their use efficiencies supported the hypothesised advantage of barley over wheat across the driest experimental conditions. Water availability and N fertilization modified grain yield, biomass and resource use efficiency. In the present thesis, it was evidenced with realistic field data for the first time that of the degree of co-limitation between factors (N and water in this case) may affect yields as well as water use efficiency of small grain cereals, which had been previously proposed but using simulation models for wheat production in Australia.

Keywords: nitrogen, water stress, nitrogen use efficiency, water use efficiency, grain number, grain weight, Hordeum vulgare, Triticum durum, Triticum aestivum

Resumen

Agua y nitrógeno (N) son considerados los principales factores que limitan fuertemente la productividad de los cultivos en ambientes mediterráneos. En ambientes mediterráneos, el trigo (harinero o duro) y la cebada son las principales especies cultivadas en condiciones de secano. En la region de la cuenca del mar Mediterráneo, el trigo generalmente es cultivado en sistemas de rotación con otros cultivos bajo condiciones relativamente húmedas, mientras que la cebada es cultivada bajo sistemas de monocultivo en las zonas mas secas. La razón sobre las que se basa el monocultivo de cebada es una hipotética ventaja en rendimiento en condiciones de estrés ambiental. Sin embargo, la información sobre comparaciones directas entre trigo (harinero o duro) y cebada no es abundante para la región de la cuenca del Mediterráneo o para otras regiones mediterráneas. Tanto el rendimiento en grano, como la producción de biomasa, uso del agua, uso del N o sus eficiencias de uso no han sido comparadas para las tres especies como para justificar la preferencia de uno de ellos en sistemas de monocultivo en condiciones de alta escasez en la disponibilidad de recursos. El objetivo principal de la presente tesis fue evaluar la respuesta del cultivo de trigo (harinero y duro) y de la cebada en términos de productividad a diferentes disponibilidades de agua y N en condiciones mediterráneas dentro de la región de agricultura de secano de Cataluña. Dentro del objetivo principal se formularon dos objetivos especificos (i) proveer soporte empírico a la hipótesis generalizada de un mejor comportamiento de la cebada frente al trigo bajo condiciones de estrés, y (ii) analizar si la fertilización nitrogenada podría constituir una herramienta de manejo para incrementar el rendimiento de los cereales de grano pequeño bajo condiciones de estrés en ambientes mediterráneos (particularmente en condiciones de baja disponibilidad de N). Para cumplimentar los objetivos, se tomaron datos a partir de una revisión bibliográfica, datos históricos y datos regionales y se analizaron conjuntamente con los datos generados en cinco experimentos de campo que fueron llevados a cabo en estaciones de crecimiento consecutivas desde 2003/04 hasta 2006/07, utilizando diferentes combinaciones de disponibilidad de agua y N en una región típica de agricultura de secano de Cataluña donde la cebada representa aproximadamente el 80% de la superficie sembrada con cereales. Para representar a cada especie se utilizó un cultivar bien adaptado y representativo de cada especie para la región. El rendimiento en grano de las tres especies presentó una amplia variabilidad que fue desde *c.*1 a 10 Mg ha^{-1}. La cebada presentó similares rendimientos al trigo bajo las peores condiciones de rendimiento, al igual que utilizando la información bibliografica, histórica o regional, indicando que la monocultura de cebada no está justificada en términos de productividad. A pesar del rendimiento similar entre la cebada y el trigo duro, se observó una menor estabilidad en el peso del grano para esta última especie. Ni el uso del agua, ni el uso del N o sus eficiencias de uso dieron soporte a la hipotética ventaja de la cebada sobre el trigo en las condiciones de mayor sequía de los experimentos. La disponibilidades de agua y N modificaron el rendimiento, la biomasa, y las eficiencias de uso del N. En la presente tesis, por primera vez, se ha puesto en evidencia utilizando datos empíricos que el grado de co-limitación entre factores (en este caso agua y N) puede afectar el rendimiento, así como también la eficiencia de uso del agua de los cereales de grano pequeño, como había sido previamente propuesto utilizando modelos de simulación para el caso de la producción de trigo en Australia.

Palabras clave: Nitrógeno, stress hidrico, eficiencia de uso del nitrógeno, eficiencia de uso del agua, Hordeum vulgare, Triticum durum, Triticum aestivum

Resum

En els ambients mediterranis l'aigua i el nitrogen (N) són considerats els dos factors que limiten mes fortament la productivitat. El blat (fariner i dur) i l'ordi són les espècies cultivades majoritàriament en els ambients mediterranis de secà. A la conca mediterrània, el blat normalment es cultiva a les zones més humides en rotació amb d'altres cultius, per contra de l'ordi que és cultiva com monocultiu en les zones més seques. Les raons que expliquen el monocultiu d'ordi es basen en un hipotètic avantatge de rendiment de l'ordi respecte del blat en els ambients estressants. Tanmateix, en la conca mediterrània o a d'altres regions mediterrànies no són molt abundants les comparacions entre blat (fariner o dur) i ordi. Tampoc s'ha comparat, per a les tres espècies, el rendiment o la producció de biomassa, l'ús d'aigua, l'ús de nitrogen o la seva eficiència com a justificació de la preferència d'una en monocultiu respecte de les altres en ambients amb pocs recursos disponibles. L'objectiu principal d'aquesta tesi va ser estudiar la resposta del blat (fariner i dur) i de l'ordi en termes de productivitat, en diferents disponibilitats d'aigua i de nitrogen dintre de les condicions mediterrànies de secà de Catalunya. Dintre de l'objectiu principal es formulen dos objectius específics (i) aportar dades empíriques a la generalitzada hipòtesi que l'ordi te millor comportament que el blat en condicions estressants, i (ii) analitzar si la fertilització nitrogenada pot ser una eina de maneig per tal d'augmentar el rendiment dels cereals de gra petit en les estressants condicions mediterrànies (particularment en casos de baix contingut de N al sòl). Per cumplir els objectius s'han analitzat dades de la literatura, regionals i històriques combinades amb les obtingudes de cinc experiments de camp realizats durant els períodes de cultiu de 2003/04 fins 2006/07 en una regió típicament de secà de Catalunya on l'ordi representa aprox. el 80% del total dels cereals sembrats. Per representar a cada espècie es va utilitzar una varietat típicament ben adaptada i representativa de blat fariner, blat dur i d'ordi. En totes les condicions experimentals el rendiment de les tres espècies va variar àmpliament, de aprox. 1 fins a 10 Mg ha^{-1}. En les condicions més seques i poc rendidores l'ordi va presentar rendiments similars als del blat (fariner i dur) utilitzant les dades experimentals, i també utilitzant les dades bibliogràfiques, històriques i regionals, fet que indica una utilització no justificada del monocultiu d'ordi en termes de productivitat. Encara que el blat dur i l'ordi van presentar rendiments semblants, el blat dur va presentar una menor estabilitat dels grans. Ni l'ús de l'aigua ni del N o les seves eficiències van explicar el hipotètic avantatge de l'ordi *vs*. el blat en les condicions més seques. La disponibilitat d'aigua i la fertilització nitrogenada van modificar el rendiment, la biomassa i l'eficiència en l'ús dels recursos. En la present tesis, s'evidencia per primera vegada amb dades reals de camp que el grau de co-limitació entre els factors (N i aigua en aquest cas) poden afectar els rendiments així com l'eficiència en l'ús de l'aigua dels cereals de gra petit, això ja havia estat prèviament postulat amb l'ús de models de simulació per la producció de blat a Austràlia.

Claus: nitrogen, estrès d'aigua, eficiència en l'ús del nitrogen, eficiència en l'ús d'aigua, numero de grans, pes del gra, Hordeum vulgare, Triticum durum, Triticum aestivum

Chapter I

General introduction

1.0 General introduction

1.1 Wheat and barley importance

Wheat and barley are the two most important temperate cereals cultivated around the world, both in terms of production and cultivated area (Slafer et al., 1994). Wheat is used mainly to satisfy food demands, while barley (based on the volume of production) is mainly used for animal feed and secondly for malting (Savin and Molina-Cano, 2002). Both cereals are so widely grown in the world thanks to their wide ecological adaptation. Within the wheat crops, it can be defined the more important modern wheat species: the hexaploid bread wheat and the tetraploid durum wheat. They differ in grain composition and, therefore, in food end-use quality attributes (Peña et al. 2002), but once the difference in grain quality is taken into account, they are physiologically similar.

Cereal crops in the European continent cover an area of approximately 127 million hectares (FAOSTAT, 2009). Wheat and barley are the main cereals in the Mediterranean basin representing *c.* 55 and 27 %, respectively, of the cultivated area of cereals for the last 40 years (FAOSTAT, 2009). Within the European and African continents, the Mediterranean Basin's countries (Albania, Algeria, Croatia, Cyprus, Egypt, France, Greece, Israel, Italy, Jordan, Lebanon, Libya, Morocco, Spain, Syria, Tunisia, and, Turkey) constitute a substantial area in which wheat and barley are grown under Mediterranean environments: 26 Mha of wheat and 13 Mha of barley (FAOSTAT, 2009).

In the Mediterranean basin, as well as in the other Mediterranean environments, wheat and barley are mainly cultivated under rainfed conditions reserving much of the cultivated area under irrigation to crops with a higher productivity like corn, sorghum, lucerne or fruit production. The geographical distribution of wheat and barley crops within the Mediterranean region of Southern Europe is defined according to water availability within the region, targeting the lands of most humid weather (rainfall > 400 mm per year) for growing wheat and the drier areas (raining less than 400 mm per year) for the cultivation of barley (López-Bellido, 1992). Anderson and Impiglia (2002) as well as Ryan et al. (2008) reported a similar situation for wheat and barley distribution within the rainfed agricultural surface of the whole Mediterranean basin although with a few different water availabilities limits and with a difference in geographical distribution for the two main different species of wheat, indicating that most of the durum wheat is destined to the intermediate humid regions (250 to 450 mm) while bread wheat is limited to the wetter areas (more than 450 mm). In this case, barley is reported to be mainly grown in rainfed zones with average annual rainfall below 250 mm. The preference of farmers to choose barley in the driest areas is based on the general belief/understanding of its better adaptation to stress condition than bread or durum wheat. This belief not only is restricted to the Ebro Valley, but is extrapolated to other rainfed systems around the Mediterranean basin.

1.2 Regional characterization

The Mediterranean environments are found between 30º and 45º latitude to the west of the continents. The Mediterranean regions around the world represent an important percentage of the cultivated land with these cereals (approximately 10% of the wheat growing area is within Mediterranean 'mega-environments'). These regions are mainly characterized by a long hot and dry summer alternated with a cold wet and relatively short winters (Loss and Siddique, 1994). The dry seasons can be extended from 1 to 8 months during the summer, and the rainfall period generally occurs in winter, with values around 500 mm year^{-1} but frequently less (Acevedo et al., 1999). Rainfall frequency, as well as the quantity, is erratic but it is normally (almost by definition) scarce and badly distributed.

The period of scarce rainfall in the Mediterranean basin, as well as in other Mediterranean regions like Western Australia, coincides with the increasing temperatures (Fig. 1). As a consequence of the weather conditions of the Mediterranean regions, wheat and barley productivity are frequently exposed to several stress conditions such as water or high-temperature stress which is most frequently increasing its intensity towards the grain filling part of the growing season. The fact that water and temperature stress occur frequently during the grain filling period in Mediterranean environments expose the crops to frequent variability in grain weight. Hypothesized barley higher stability in grain weight and grain filling parameters than wheat could be one of the reasons supporting the actual preference of barley against wheat under stressed Mediterranean environments. However, data regarding differences in grain stability between wheat and barley under Mediterranean environments is not available in the literature.

In the Mediterranean region of Southern Europe, in Catalonia more specifically, rainfall is sporadic and often has a large inter-annual variability and with a distribution variability within a season (Lana et al., 2001). López-Bellido (1992) described the ecosystems of the southern regions of Europe making a distinction between rainfed crop areas with shallow soils, and rainfed crop areas with wetter deep soils as mentioned in the previous section.

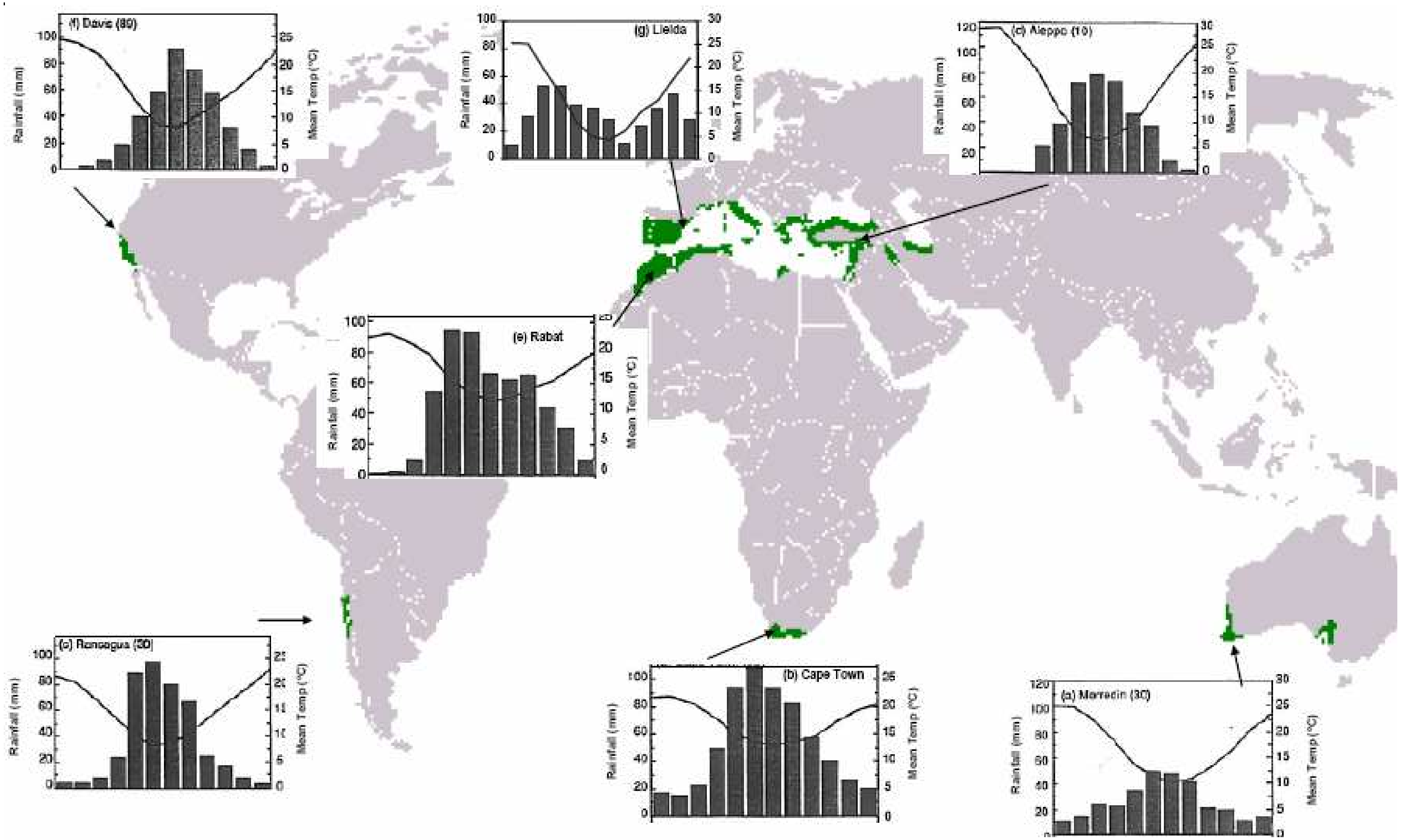

Figure 1. Accumulated rainfall and mean temperature for monthly periods at different locations with Mediterranean environments; (a) Merredin, Australia (31º 20’S 118º 17’E; (b) Cape Town, South Africa (33º 56’S 19º 29’E); (c) Rancagua, Chile (34º 10’S 70º 45’W); (d) Aleppo, Syria (36º 11’N 37º 13’ E); (e) Rabat, Morocco (34º 00’N 6º50’ E); (f) Davis, California (38º 32’N 121º 45’W); and Agramunt-Lleida, Spain (41º 47´N 1º 5´E), the focal experimental location where the studies of this thesis were conducted. Figures shows bars ordered from January to December for sites in the Southern Hemisphere and from July to June for those in the Northern Hemisphere. Adapted from Loss and Siddque (1994).

1.3 Nutrients and crop performance

Water and nitrogen (N) are the key edaphic factors limiting the primary production in arid and semiarid ecosystems (Alon and Steinberger, 1999; Mazzarino et al., 1998).

Stored water in the soil from untimely rainfall events supports the development and growth of the crops. At the farming level of organization, a large proportion of the water entering the soil system as precipitation is lost by direct soil evaporation (Sadras, 2003). However, crop yields can be increased and maintained their productivity to acceptable levels when using appropriate measures that permit management to enhance the efficiency of water use, reducing water losses by evaporation of soil water, or decreasing weed evapotranspiration (Bouaziz and Chekli, 2000), or simply by increasing transpiration water use efficiency (French and Schultz, 1984b).

As mentioned above, N is one of the major nutrients required for barley and wheat yields, and the production of these cereals is affected by the form and amount that this nutrient is in soil (Baldridge et al., 1985; Borghi, 1999). Nitrogen is absorbed by crops mainly in the anionic form of nitrate (NO^{-3}) which is present in the soil solution (Marschner, 1995). The available N, its rate of absorption and its partitioning are determined by supply and demand during different stages of the crops (Delogu et al., 1998).

The availability of N determines, largely linearly, the productivity of cereal crops. Further increasing availability of the nutrient makes the crop productivity reaching a plateau as it becomes firstly a less- and then a no-limiting growth. Increases in biomass as a result of increased N availability are the result of an increase in leaf area and therefore in the accumulated radiation intercepted by the crop. This biomass of wheat and barley crops is generated by a larger number of tillers, providing a greater number of leaves and increased leaf area (Fischer, 1993; Garcia del Moral et al., 1984; Baethgen et al., 1995).

Morphological, physiological and metabolic attributes of cereal crops are modified under water and nutrients stress conditions modifying the final productivity of the agricultural system (Munns et al., 2000; Passioura, 2002; Slafer et al., 2005). Productivity of the cereal crops could be expressed as grain yield (for the grain market) or in terms of biomass (if it is analysed in terms of primary productivity).

1.4 Grain yield determination

Grain yield of wheat and barley is the consequence of the interaction between crop growth and developmental processes across the whole growing season. However, it can be defined the most critical stages for grain yield determination, as the period around flowering (Fischer, 1985; Savin and Slafer, 1991; Calderini et al., 2001).

Grain number per unit land area (Slafer et al., 1996) and mean grain weight (Calderini et al., 2001; Ugarte et al. 2007) are the two main determinants for grain yield determination for wheat and barley. While mean grain weight is determined from a few days before anthesis to maturity (Calderini et al., 2001), grain number per m^2 is actually generated from sowing to immediately after anthesis, but is ultimately defined in a much shorter window of time: from 20 days before and 10 days after anthesis approximately (Fischer, 1985; Savin and Slafer, 1991).

Potential grain number per unit land area is the consequence of the development of its component structures (yield components) as spike number per unit land area and spikelets per spike which occur from the tillering period and from the early developmental stages of the reproductive phase and to the terminal spike stage. Differences in the crop's intrinsic duration of development phases may expose these to different situations of resource availability even though they are grown in the same season as it occurs for bread wheat, durum wheat and barley (as barley tends to be constitutively earlier than wheat specially during vegetative development; López-Castañeda et al. 1995).

The early flowering time and shorter cycle of barley could be interpreted as an advantage under stress environments over wheat, as lower temperatures may be explored by barley crops during both the critical period for grain yield definition and grain filling period than for wheat. On the other hand, under non-stressfull years the earlier flowering and shorter cycle of barley can be interpreted as a disadvantage due to low amount of radiation intercepted (and in consequence less biomass production) by the crops.

The different structures defining final grain number are influenced by the canopy structure and environmental conditions (Satorre, 1999). In consequence, depending on the timing of stress, final grain number per unit area of bread wheat, durum wheat and barley can be differently modified affecting different structures of yield components. Although they are generally similar, bread wheat, durum wheat and barley present some specific differences in yield physiology that makes it difficult a simple extrapolation from one crop to another, as it is usually done in the literature. Although it is known that their response to photoperiod is similar reducing the duration of the phase from sowing to the beginning of the reproductive stage (double ridge) under constant longer photoperiod (Miralles and Richards, 2000), there are some differences regarding some aspects of the development. As an example, rates of development (for the primordia of leaves and spikelets) are normally higher in barley than in bread wheat (Miralles and Richards, 2000). The rate of appearance of tillers and leaves is frequently higher in barley than in bread wheat (Lopez-Castaneda et al., 1995; Miralles and

Richards, 2000). Also, it was observed a tendency to have less N loss (higher absorption efficiency) when the timing of fertilization was delayed to stem elongation. Nevertheless, there are not enough evidences of comparisons between wheat and barley under Mediterranean environments on their responsiveness to N fertilization.

Current research, on nutrient availability and crop production has shown a simultaneous process of growing concern about the productivity and sustainability in most agricultural regions worldwide. Understanding the physiological differences in the use efficiency of nutrients between crops is important, especially in environments with scarce availability of other resources such as water in the Mediterranean region (Araus, 2004).

1.5 Resource use and resource use efficiency

In agronomic terms and for the purposes of optimizing the use of resources through management practices, those efficiencies involving the main resources for the growth of crops such as water and N are critical. Increasing water and N use efficiencies are necessary to improve yields and productivity in dryland growing areas, as it occurs in much of the Mediterranean regions (Araus, 2004). Raun and Johnson (1999) based on the use of fertilizers estimated that increasing 1% in N use efficiency for world cereal production, would save c. U$S 234,658,462 in N fertilizer costs, while a 20% increase could result in savings of U$S 4.7 billion per year.

Water use efficiency (WUE) can be defined as the biomass produced per unit of water used to generating this biomass. This definition may be referring to different processes depending on the level of complexity at which accumulation of biomass and water consumption is considered. Biomass can be expressed in terms of carbon assimilation in the photosynthetic process, to total crop biomass, and grain yield. Regarding the source, water consumed can be expressed from leaf transpiration through crop evapo-transpiration, to water availability or even water entering the system.

Different processes of crops and scales of study reporting requirements for bread wheat, durum wheat and barley can be analysed depending on how both factors (biomass and water) are considered. Also these differences in the scales should be taken into account when comparing values of efficiencies because they can cause interpretation errors due to different processes involved.

Regarding N use efficiency (NUE), results may differ depending on the source evaluated (soil, soil + fertilizer, fertilizer) and naturally depending on the approach different conclusions could be achieved. As defined by Moll et al. (1982), NUE is the grain production per available unit of N in soil. It suggests that it may also be partitioned into *uptake efficiency* of this nutrient (N content in the crop per unit of either soil N availability or N fertilizer applied, the latter frequently termed apparent recovery) and *N utilization efficiency* (N in grain per unit of N absorbed by the crop).

Ortiz-Monasterio et al. (1997) have shown for bread wheat genotypic variations in the relative importance of N uptake and utilization efficiencies in contributing to the genotypic variations in NUE, largely depending on the levels of soil N availability: at low availabilities, the uptake efficiency is the dominant component of the NUE while at increasing the availability of N it becomes higher the relative importance of the utilization efficiency. Furthermore, overall NUE decreases with increasing N availability (Fischer et al., 1993, Ortiz-Monasterio et al., 1997).

When the work of the present Thesis begun, there was some evidences regarding differences in bread wheat's NUE under Mediterranean conditions depending on the availability of N across the growing period. NUE was greatest when applying the fertilizer at the stage of beginning of stem elongation (López-Bellido et al., 2005). However, it was difficult to find papers that have simultaneously analyzed the effect of N and water stress (and their possible combinations) in the NUE and WUE for wheat and barley.

It is generally assumed that barley use soil resources better than wheat under drought conditions (see above). However, there are not many direct comparisons in the literature that tested this assumption. Delogu et al. (1998) found differences in N utilization efficiency between wheat and barley. In this case, barley used N more efficiently than wheat. However, the example may not be quite valid for low-N conditions as soil N initial conditions must have been very high, due to grain yields obtained in unfertilized controls were between 6 and 7 t ha^{-1} for wheat and barley respectively (Delogu et al., 1998).

Although N fertilization was reported to be a useful tool to increase grain yield and WUE of bread wheat in stressful Mediterranean conditions (French and Shultz, 1984a and 1984b; Sadras, 2002), it is known that the response interacts with soil N availability (Fischer et al., 1993, Ortiz-Monasterio et al., 1997), that is why N fertilization should be formulated accounting N availability, so that the expected reduction in NUE can be balanced with a relatively higher increase in WUE (Aggarwal and Kalra; 1994; Sadras and Roget; 2004; Sadras, 2004; Sadras 2005).

The degree of stress and degree of nutrient co-limitation given a level of stress seem related to the yields of wheat. Sadras (2004), using simulation models, indicated that yield gap between actual and potential yield is reduced when the degree of water and N co-limitation increases. While this theory seems well supported from outputs of simulation exercises, the evidences from empirical data are lacking. Empirical evidences supporting the information generated from simulation models allow extrapolating results without the supposed restrictions behind the simulation models parameters. In addition, the simulations support to the positive relationship between yield gap closure and degree of co-limitation has been provided for wheat, while there were no attempts to extrapolate from it to other cereals such as durum wheat and barley. Also, all the cases reported for the relationship between grain yield, WUE and NUE are based on Australian conditions without other information for different Mediterranean sites.

1.6 Evidences for comparative performance of wheat and barley at the start point of the present thesis

While there were many scientific papers that explored the responses on grain yield and quality in wheat or barley crops to different environments and management conditions, there are only a few papers that compared the two species in the same experimental design. In particular, for the Mediterranean region of Catalonia, as far as I am aware no scientific papers were published comparing both species which would have required to demonstrating the existence of the assumed superiority of barley over wheat under stress conditions. This sort of direct comparison were needed, as the tendency to barley monoculture commonly found in dryland cereal production of the country is based on the assumed advantages of barley over wheat that most farmers of the region seem to accept, likely based in 'popular knowledge' rather than in empirical evidences..

Table 1: Results found using the ISI Web of Knowledge^{SM} server during the bibliographic search carried out during July, 2005.

Topic field ***(word should be in the publication title, abstract or keywords)***	***Results*** ***(articles number)***
("barley")	35263
("wheat")	83184
("nitrogen")	>100000
("water")	>100000
("wheat AND barley")	1427
(barley AND wheat)	9364
(nitrogen AND water)	33277
("nitrogen AND water")	760
("wheat AND barley" AND (nitrogen use efficiency AND water use efficiency))	0
("wheat AND barley" AND nitrogen use efficiency AND water use efficiency)	0
("barley" AND nitrogen use efficiency AND water use efficiency)	2
("wheat" AND nitrogen use efficiency AND water use efficiency)	22
("barley" AND nitrogen AND water)	570
("wheat" AND nitrogen AND water)	1696
(barley AND nitrogen use efficiency)	26
(wheat AND nitrogen use efficiency)	136
(barley AND water use efficiency)	192
(wheat AND water use efficiency)	757
(wheat AND barley AND water use efficiency)	143
(wheat AND barley AND nitrogen use efficiency)	18
(wheat AND barley AND Mediterranean)	195
("wheat AND barley AND Mediterranean")	1
("nitrogen use efficiency AND water use efficiency")	1
(nitrogen use efficiency AND water use efficiency)	111

Note: The search was carried out on the website server of the Web of Science section, using the methodology of "General Search", Topic Field. The search resulted in all those publications cited that include in their abstract, title, or keywords the words chosen. It should be taken into account that sometimes the words searched appeared in a publication as a 'keyword plus', and the publication could not be referred exactly to the searched word overestimating the amount of publications referring to publications linked to the word.

To quantitatively explore to what degree the abovementioned lack of abundant comparisons of these crops, on which the supposed consistent superiority should be based on, a bibliographic search was carried out at the beginning of the present thesis (July, 2005) using the ISI Web of Knowledge^{SM} database with different words and cross-words as entries in "Topic" Field of the server (see Table 1 for the words used in the search). Only 8% of the publications of wheat and barley were conducted comparing both species. The result is even lower when comparisons included both species and the N or water use efficiency representing around a 0.015% and 0.12%, respectively (Table 1). No papers were found including the four cases (wheat, barley, N use efficiency and water use efficiency) or including wheat, barley and Mediterranean (Table 1). However, the numbers of papers reported by the database sometimes could differ with the reality due to some papers that are reported as only "barley" or "wheat" research papers have included in the experiments cultivars of the other species and comparisons can be done.

1.7 Objectives

The general objective of the present thesis was to assess the response of wheat (bread and durum) and barley in terms of productivity to different water and N availabilities within the Mediterranean conditions of dryland cereal regions of Catalonia. Within this general objective it was tested whether (i) a direct comparison would provide empirical support to the generalized hypothesis of a better performance of barley than wheat under stress conditions for the Mediterranean region, and (ii) N fertilization can be a management tool to increase grain yield under stressful Mediterranean conditions for small grain cereals (in cases in which soil N were low).

To contrast the hypothesis different specific objectives were outlined:

I. To analyze (i) databases of wheat and barley yield for comparative experiments carried out under Mediterranean regions, as well as (ii) regional yield data corresponding to different counties of Catalonia (Chapter II).

II. To compare grain yield and its components of bread wheat, barley and durum wheat in common experiments under different water and N managements through a number of background environmental conditions, in which these managements were tested, under Mediterranean experimental conditions (Chapters II and III).

III. To study WUE and NUE of barley, bread and durum wheat crops grown under a wide range of water and N levels under Mediterranean conditions, including the relationships between crop yield and N and water availability (Chapter IV).

IV. To determine grain weight stability of bread wheat, barley and durum wheat under a wide range of Mediterranean conditions (Chapter V).

V. To provide empirical evidences for the relationship between yield gap (the difference between potential and actual yields) of wheat and barley and the degree of N and water co-limitation (Chapter VI).

In addition, an Annex is included in the present thesis, in which it is presented a case study regarding the possibility of actually increasing durum wheat yields with a more appropriate N management scheme in Tunisia (a typical cereal growing region of dryland Mediterranean environments).

1.8 Outline of the present thesis

The present thesis is divided into eight chapters. These chapters include the general introduction (Chapter I), six experimental research articles (Chapters II, III, IV, V, VI, and Annex I) and a global discussion and conclusion of the entire thesis (Chapter VII). Each chapter (excepting I and VII) is based on published (2) and submitted (4) papers to SCI journals. As the papers themselves are the chapters and papers are independent units of information, when gathered together in the thesis, there is some repetition, always associated with the general focus of the thesis.

Chapter II is a descriptive research article presenting the main hypothesis and the information available in the literature together with a regional analysis of the issue. Chapters III, IV, V, VI and provide experimental evidences to contrast the hypothesis, and the physiological causes of the relative performance of the different cereals. Finally, Chapter VII contains a general discussion ending in a conclusion of the thesis. This last chapter highlights key results and conclusions of each chapter whilst exhibits the consistencies and inconsistencies across the different studies reported throughout the thesis.

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Chapter II

Contrasting performance of barley and wheat in a wide range of conditions in Mediterranean Catalonia (Spain)

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rise) were sown with a factorial combination of six levels

of rainfall during the growing season (with 90% of the total rain occurred during preflowering in both species, which is critical for yield determination; Slafer, 2003), while 2004–05 was far drier with only 163 mm of rainfall during the growing season, and with the highest precipitation event occurring in late flowering (a rather late opportunity to have reasonable yield responsiveness). As a consequence, we have two dramatically different growing seasons (with yields in the unfertilised and rainfed treatment differing noticeably: more than 4 Mg $ha^{-1}{}_{(2003-04)}$ and less than 1.5 Mg $ha^{-1}{}_{(2004-05)}$, averaged across species) in which comparisons were carried out.

Results

Yield performance at county level

County yields during the analysed period showed a great range of productivity levels from 0.8 to 6 Mg ha^{-1} (Fig. 2). Across the whole range, no significant differences between barley and wheat yields were found, although there seemed to be a bilinear trend because of a consistent tendency of wheat to outyield barley under relatively high yielding conditions (Fig. 2). In the lower yield range, that is, yields below the breakpoint of the bilinear [illegible] ha^{-1}), wheat and barley tend to yield remarkably similarly (slope = 1), but for higher yields, wheat tended to have a better performance (slope = 0.37).

When focusing on the three lowest yielding years for each county, again barley and wheat yields were, on average, remarkably similar (residuals respect the line with the slope 1 and intercept 0 were close to zero, −0.01 ± 0.34 Mg ha^{-1}). Under the three highest yielding seasons of each county, wheat tended more consistently to outperform barley (residuals to the 1:1 line were negative −0.18 ± 0.55 Mg ha^{-1}, i.e. on average wheat yielded approximately 200 kg ha^{-1} more than barley, but with large variability between counties × years).

In no cases, a clear and consistent advantage of barley over wheat was found, even if restricting the analysis to the poorest yielding conditions of the analysis (i.e. for any county × year condition in which yields has been <2 Mg ha^{-1}; Fig. 2 inset).

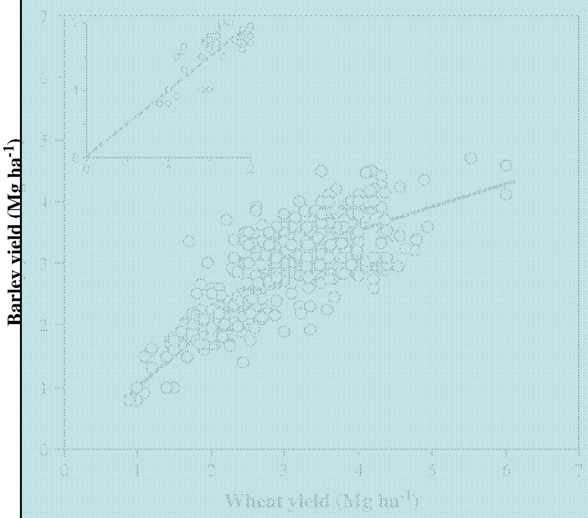

Figure 2 Relationship between barley and wheat yields for the 41 counties from Catalonia during the 13-year period 1992–2004. The bilinear model shown was fitted by an optimisation model as follows: BY = WY (for WY ≤ 3.27 Mg ha^{-1}) + BY = 3.27 + 0.37 [WY − 3.27] (for WY > 3.27 Mg ha^{-1}), r^2 = 0.64 ($P < 0.001$), where BY and WY represent barley and wheat yield, respectively. Inset is a detail of this relationship restricted to the poorest yielding conditions (for all the cases in which yields were lower than 2 Mg ha^{-1} and the dotted line represents the 1:1 ratio).

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Performance in experimental conditions

Wheat had a higher yield than barley in the unfertilised treatments in experiment I (4.58 and 3.60 Mg ha^{-1}, [illegible] also responded to N fertilisation in these conditions than barley, [illegible] rate than barley (120 and 200 kg_N ha^{-1}, respectively). As barley in this experiment did respond to nitrogen until 200 kg_N ha^{-1} (disregarding its inexplicable low yield in plots fertilised with 120 kg_N ha^{-1}), maximum yields of both cereals were not significantly different (just above 7 Mg ha^{-1} with 120 kg_N ha^{-1} in wheat and slightly below 7 Mg ha^{-1} with 200 kg_N ha^{-1} in barley; Fig. 3a).

Differences were even less noticeable in the drier growing season. Wheat and barley yields were similar in all treatments in experiment II (Fig. 3b), and responded in a similar way to nitrogen supply in experiment II (Fig. 3b). In this experiment, nitrogen supply resulted in an increase of grain yield of approximately 24%. Comparing the nitrogen response between the two experimental years and the two crops, both species responded markedly higher in experiment I than in experiment II (Fig. 3a and Fig. 3b), but it is important to note that there were large differences in water availability between the two experimental years, mainly in rainfed conditions.

There was a close relationship between grain yield and grain number per m^2 for the two experimental years (Fig. 4). Nitrogen supply increased grain number per m^2 in both experiments. Non-fertilised treatments had 37% and 35% less grains per m^2 than fertilised treatments for wheat and barley, respectively, in experiment I, and 21% and 19% less in experiment II (Fig. 4). Grain weight explained a little proportion of grain yield, but

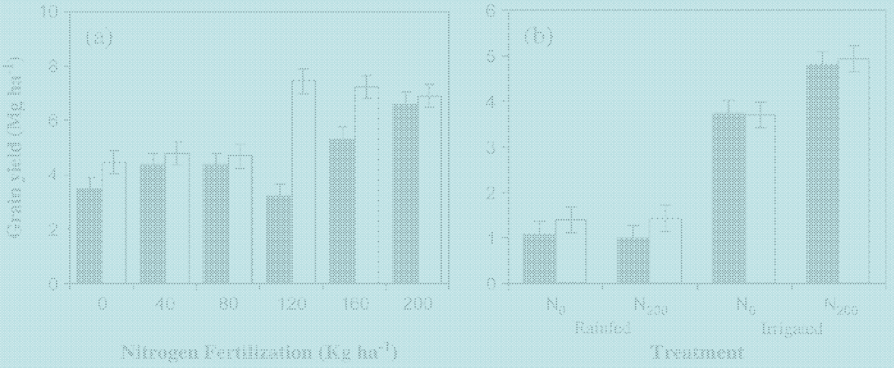

Figure 3 Grain yield for wheat (□) and barley (▩) from experiments I (a) and II (b). Segments on top of bars stand for the standard error of the means.

barley crops presented 16% ($P < 0.05$) higher grain weight values than wheat in experiment II, while the difference was only 6% in experiment I.

Discussion

Against the strong belief behind the patterns of land use in Catalonia [illegible] areas), no consistent differences were found between wheat and barley yields under a wide range of yields during the period 1992–2004. The slope of the relationship between wheat and barley regional yields indicated a rather similar performance in the poorest yielding conditions and a trend for a slightly superior performance of wheat at higher yields. This similar performance of both cereals was evident not only for the whole set of data collected but also within each individual year of the period analysed. Therefore, at least for the 1992–2004 period, there was no relationship between the ratio of wheat-to-barley yields and year.

Although barley grains may be preferred by farmers for stockfeed, farmers in the region only reserve approximately [illegible] eed and sell the rest in the market (Anon., 1992–2004), where the price [illegible] eat across the analysed period. Despite this, the proportion of total cereal area sown with barley at county level was approximately 65%, with the per cent of wheat only approximately 15% during the period 1992–2004. Therefore, the pattern of land use is largely the consequence of the strong belief of farmers on the better performance of barley rather than animal health or profit reasons.

Conclusions from these regional data should be taken with some caution as wheat might have been often grown in better soils than barley (Lopez-Bellido, 1992); although within the large database used (533 comparisons) surely this has not been universally true.

Results obtained in actual field experiments, across two contrasting growing seasons support the conclusion that it may not be universally true that under harsh Mediterranean conditions, barley would unequivocally behave better than wheat. Fig. 5 summarises findings by combining results from the literature, experiments in two contrasting years and under contrasting treatments with those from comparisons of 13 years of wheat and barley yields in 41 counties of Catalonia. Tendencies observed in Fig. 5 agree noticeably in that no clear advantages of barley can be universally expected under low-yielding conditions (while it seemed that wheat tended to over-yield barley under higher yielding conditions; Fig. 5).

The similar yields of both cereals under low-yielding conditions could reflect their similar capacity to use nitrogen and water, the two most limiting resources in

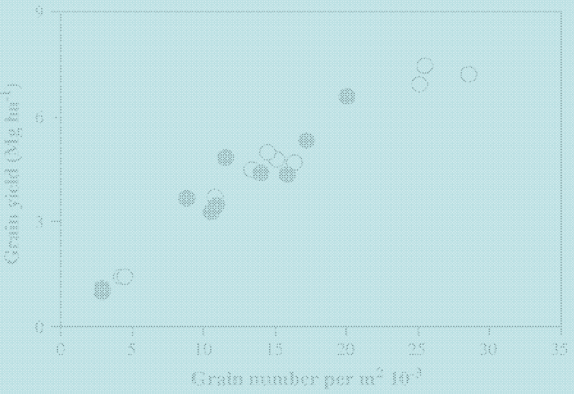

Figure 4 Relationship between grain yield and number of grains per m² for wheat (○) and barley (●) across the two experimental years (r^2 = 0.94; P < 0.001).

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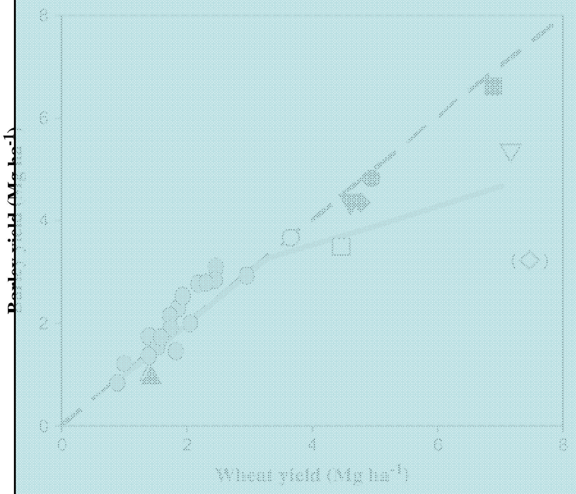

Figure 5 Relationship between barley and wheat yields for the two experimental years 2003–04 and 2004–05. Experiment I: □ N_0; ◆ N_{40}; ▼ N_{80}; ◇ N_{120}; ▽ N_{160}; ▩ N_{200} and experiment II: △ rainfed N_0, ▲ rainfed N_{200}; ○ irrigated N_0; ● irrigated N_{200}. The dashed straight line represents the 1:1 ratio, while the solid grey line represents the bilinear fit of county yields ([illegible]) from Fig. 1. The data point for barley fertilised with 120 kg [illegible] able indication of far better performance of wheat in this treatment. Grey circles [illegible] ranean conditions of Western Australia (see Fig. 1).

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Mediterranean conditions. This similarity contrasts with results showing a higher nitrogen use efficiency in barley than in wheat (Delogu *et al.*,1998), although this study was carried out under pretty high-yielding conditions (>6 Mg ha^{-1} for unfertilised plots). In agreement with Passioura (2002), the level of nitrogen availability affected water use and its efficiency, and fertilisation may be a tool to increase water use efficiency (see also Latiri-Souki *et al.*, 1998).

Austin *et al.* (1998) suggested that barley responds better to precipitations than wheat in a region near to (although normally even drier than) where our experiments were performed. However, their study did not include direct experiments in which both cereals were grown side-by-side, but farm yields from different paddocks, and their conclusions seemed slightly biased by a couple of extraordinary yields of barley (outliers well away from the general cloud of yield data). In fact, the estimated minimum rainfall needed to obtain any yield was slightly lower for wheat than for barley, supporting the fact that in the range of low-yielding conditions, barley did not actually perform better than wheat (Austin *et al.*, 1998).

When data from experiments where both species were compared in low-yield conditions, which is the most frequent situation in Mediterranean environments, there was no clear evidence supporting the belief of a consistent advantage of barley over wheat (Simpson & Siddique, 1994), although in some studies this seemed to have been the case (Josephides, 1993). Although in our experiments we only analysed differences between one cultivar for each species, these cultivars were chosen to be representative of modern wheats and barleys actually grown by Catalonian farmers. Also, comparisons of other cultivars in other Mediterranean regions support our experimental results (Fig. 1) and it is important to note that in the regional analysis approach, the comparisons include 13 years and 41 different counties of Catalonia, in which cultivars varied widely (Anon., 1999–2004). Combining the bibliographic data (Josephides, 1993; Palumbo & Boggini, 1994; Simpson & Siddique, 1994) with our results indicates that at least since early 1990s wheat seemed to perform similarly to barley in Mediterranean Catalonia in agreement with evidences from other Mediterranean regions. Furthermore, evidences of [illegible] barley in other regions under unfavourable conditions (Warren, 1971) [illegible] advances for barley in Mediterranean unfavourable conditions (Muñoz *et al.*, 1998) would allow speculating that the similarity of performance is older than what we could explore with available data.

Although in Mediterranean rainfed conditions, particularly when yields tend to be lower than 3 Mg ha^{-1}, barley is the crop normally preferred by farmers, wheat seemed to have an equal, if not better, performance than barley in the present study. If this can be confirmed in further studies, wheat may become an important realistic alternative to barley monoculture in the driest agricultural areas of Catalonia and other sites within the Mediterranean region.

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Chapter III

Yield and biomass in wheat and barley under a range of conditions in a Mediterranean site

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Table 1
Experimental details including dates of key developmental stages of the three species and the initial water and nitrogen contents in the soil at 1 m depth at Agramunt (NE Spain)

Experiment	Species	Sowing date	First node detectable (DC 3.1)	Flowering date (DC 6.5)	Harvest date (DC 9.0)	Fertilizer treatments (kg N ha⁻¹)	Water regime treatments	Initial water content (mm)	Initial N-NO$_3^-$ content (kg N ha^{-1})	Irrigation amount (mm)	Rainfall (sowing–harvest) (mm)
I	Barley Bread wheat	21-Nov-03	13 Apr 04	11 May 04 31 May 04	21 June 04 12 July 04	0-40-80-120-160 and 200	Rainfed	288	94	0	284 304
II	Barley Bread wheat	16-Nov-04	12 Apr 05	03 May 05 10 May 05	20 June 05 20r*; 28i June 05	0 and 200	Rainfed and irrigated	83	34	222 222	159 160r; 168i
III	Barley Durum wheat Bread wheat	28-Nov-05	11 Apr 06 17 Apr 06 17 Apr 06	03 May 06 09 May 06 16 May 06	06 June 06 13r-20i June 06 13r-20i June 06	0-50-100 and 150	Rainfed and irrigated	240	115	76 95 95	92 92r; 95i 92r; 95i
IV	Barley Durum wheat Bread wheat	06-Nov-06	26 Mar 07	30 Apr 07 07 May 07 15 May 07	18 June 07 25 June 07 25 June 07	0-75 and 150	Rainfed and irrigated	201	150	318 336 336	331 332 332
V	Barley Durum wheat	22-Feb-07	01 May 07 07 May 07	21 May 07 27 May 07	28 June 07 28 June 07	0 and 150	Rainfed	153	143	0	281 281

* When harvest dates or associated with this, total rainfall differed between water regimes the values for irrigated [illegible] rainfed (r) treatments were labelled.

filling occurs during the remaining post-anthesis period (Ugarte et al., 2007).

Grain yield is usually strongly associated with the number of grains per unit area (Fischer, 1985; Savin and Slafer, 1991). While this association has been extensively reported for a relatively wide range of environments, it has not often been reported under Mediterranean conditions. This is particularly important as drought and high temperatures during grain filling which are typical under Mediterranean environments are known to reduce grain weight (Sofield et al., 1977; Wardlaw et al., 1980). Thus, unlike in most other regions, it is possible that grain weight may become more important than grain number per unit area in determining cereal grain yield in Mediterranean conditions.

The main objective of the present work was to compare the performance (yield and its components) of bread wheat, durum wheat and barley under different combinations of water and nitrogen (N) availabilities in a typical Mediterranean area of the Ebro valley (NE Spain; SW of the Mediterranean basin).

2. Materials and methods

2.1. Trial sites

Five experiments were conducted in farmer fields at Agramunt (lat. 41° 47′17″ N, long. 1° 5′59″ E, altitude 337 m), province of Lleida (Catalonia, north-eastern Spain) during 2003–2004 (experiment I), 2004–2005 (experiment II), 2005–2006 (experiment III), and 2006–2007 (experiments IV and V) growing seasons. [illegible] of Catalonia, with an average annual rainfall of 400 mm, from which approxi-[illegible] growing season. Soil types were [illegible] (experiment I), and Fluvisol calcari (experiments II, III, IV and V) following the soil classification of FAO (1990).

2.2. Treatments

Treatments consisted of different factorial combinations of: species (barley, bread wheat and durum wheat), water regime (rainfed, irrigated) and N fertilization within each experiment. Experimental details for each growing season and treatments combinations were summarized in Table 1.

Due to limitations with the high intensity of sampling, only one cultivar of each species was used. The cultivar chosen was one of the most widely grown and, highly adapted for barley and bread wheat in the region. Since durum wheat is not widely grown in Catalonia we chose a cultivar having outstanding performance in comparative trials conducted across the region by IRTA (Institut d' Recerca i Tecnologia Agroalimentaries). These cultivars are not only well adapted, representatives of these species in Catalonia, but also possess the common characteristics of these three species in the Mediterranean, i.e., when sown simultaneously barley flowers first, bread wheat last and durum wheat between them. The barley was a two-rowed cultivar (cv. *Sunrise*) registered in 1993 in the UK, bread wheat (cv. *Soisson*), is a long cycle cultivar registered in 1988 in France, and finally durum wheat (cv. *Claudio*), is a mean winter cycle cultivar registered in 1998 in Italy. In addition to their popularity with farmers, these cultivars have been used as standard controls in previous years by the CENVCE (Group for the Evaluation of the New Cereals Varieties in Spain; Anonymous, 1999-2004a,b).

In experiment I, bread wheat and barley were sown in a factorial combination of six levels of N fertilization (Table 1) under rainfed conditions. N was applied 30 days after sowing as ammonium nitrate (34.4-0-0). The experiment was arranged in

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a split-plot design with three replicates. Main plots consisted of the combination of the two species and sub-plots consisted of the six nitrogen levels.

In experiment II, the same species were sown combined with two levels of N fertilization and two water regimes (Table 1). In this experiment, due to lack of facilities (the field was in the middle of a rainfed area without water facilities), drip irrigation was used. Drip lines were separated at 25 cm, at a right angle to the crops rows. The frequency of irrigation was weekly (twice weekly on a few occasions) each time applying c. 17 mm, starting at the beginning of stem elongation (DC 3.1, Zadoks et al., 1974). The total amount of water applied was 222 mm. N as ammonium nitrate (34.4-0-0) was applied as a split dose, at DC 1.2 and DC 3.1. Treatments were arranged in a split-block split-plot design with three replicates. Main plots consisted of the two species sown in strips, randomized within blocks, with two water regimes paired across the strips (also randomized within blocks) in the entire replication. Sub-plots consisted of the two N levels.

Experiment III consisted of a factorial combination of durum wheat, bread wheat and barley sown with two water regimes and four levels of N fertilization. N was applied in a split dose as in experiment II. Drip irrigation was used with the drip lines between all crop rows. The frequency of irrigation was weekly (twice weekly on few occasions) with c. 7 mm, starting at one week before of the beginning of stem elongation (DC 3.1) resulting in a total application of 75 mm for barley and 95 mm for both wheat (only due to their differences in cycle). Main plots consisted of the three species sown in strips, randomized within blocks, with the two water regimes applied in each strip (also randomized within blocks) in the entire replication; the sub-plots consisted of the four N levels.

Experiments IV and V were both carried out during the 2006/07 growing season. [illegible] tion of durum wheat, [illegible] regimes, and four levels of N fertilization (Table 1). Experiment V was set to expose the crops to a stronger stress by sowing later (three months later than usual practice). Only the performance under the two contrasting N levels was tested in rainfed conditions (Table 1) for the three species. Bread wheat (cv. Soissons) did not reach anthesis in experiment V (probably because of its vernalisation requirements), and therefore there is no data available for this particular experiment.

Each experimental unit was 3 m wide and 5 m long in experiments I, II, III, and IV and 1.4 m wide and 3 m long in experiment V, with rows sown 17 cm apart in all the experiments. Prior to sowing, P and K were applied at a rate of c. 60 kg P ha^{-1} and 120 kg K ha^{-1} in all experiments. Weeds and pest were controlled during all growing seasons following the typical farmer's practices in the region.

2.3. Sampling and data analysis

Samples of aboveground biomass were taken at maturity and separated into culms and leaves, spikes and grains. The biomass was oven dried at 65 °C for 48 h before weighing. Grain yield and its main components (grain number per m^2 and mean grain weight) were also determined.

Prior to sowing, soil samples were taken at four different depths (0–25; 25–50; 50–75 and 75–100 cm). NO_3 content was determined with Nitracheck reflectometer methodology (Merckoquant Nitrate strips) and water content was estimated gravimetrically after drying samples at 105 °C for 48 h.

Global radiation (MJ m^{-2}), minimum and maximum temperatures (°C), and precipitation (mm) distribution were recorded during the four growing seasons. Photothermal quotient (PTQ) was calculated as $PTQ=\sum(\text{Global radiation}*0.5*\text{PAR intercepted}/\sum(T_{mean}-T_{base}))$ where global radiation was the incident global radiation (MJ m^{-2}) measured at hourly intervals with a standard meteorological station belonging to the Catalonian Agrometeorological station network located close to the experimental location. Photosynthetic active radiation (PAR) intercepted by the canopy measured with a Linear PAR Ceptometer (AccuPAR, Decagon, Washington, USA) on cloudless days. T_{mean} is the air mean temperature and T_{base} is the base temperature estimated in 4.5 °C (Fischer, 1985). PAR was assumed to be 50% of the global radiation. PTQ was calculated for experiments II, III and IV for 20 days pre- and 10 post-flowering, following Savin and Slafer (1991) and (Ortiz-Monasterio et al., 1994), who adopted the original period to estimate PTQ of 30 days before flowering (Fischer, 1985).

Data were analyzed by an ANOVA to evaluate the main effect of species, nitrogen, and water and their interactions using GenStat® 11th edition software (Payne et al., 2008).

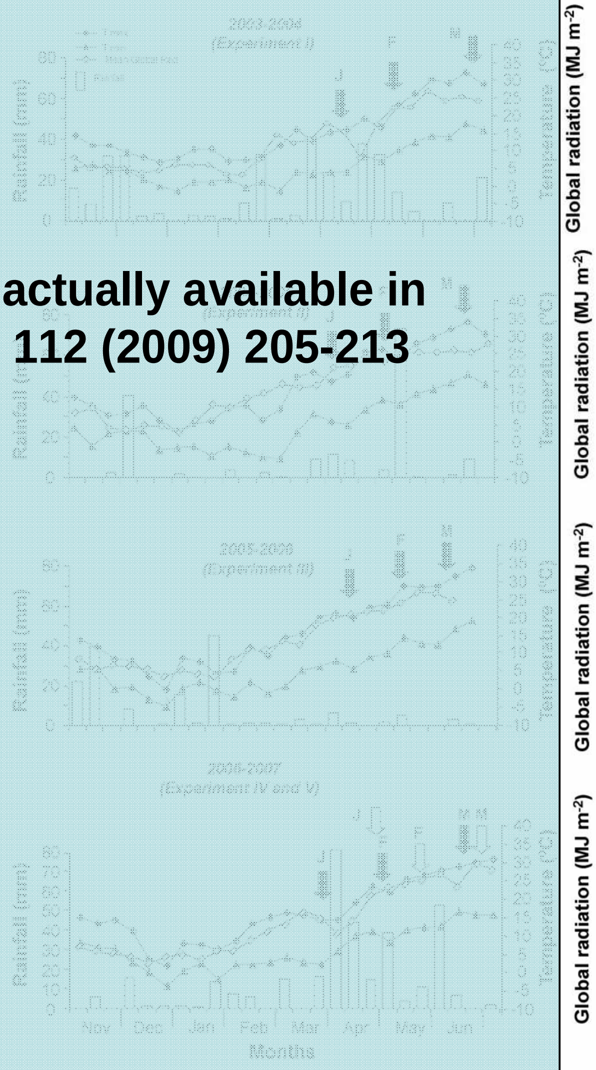

Fig. 1. Rainfall, temperatures and mean global radiation distribution for each growing season of the five experiments at Agramunt (NE Spain). Arrows indicate the average date of jointing (J), flowering (F) and maturity (M) in each experiment. Black arrows stand for optimal sowing dates; (white arrows stand for a very late sowing date only used in 2006-2007, experiment V).

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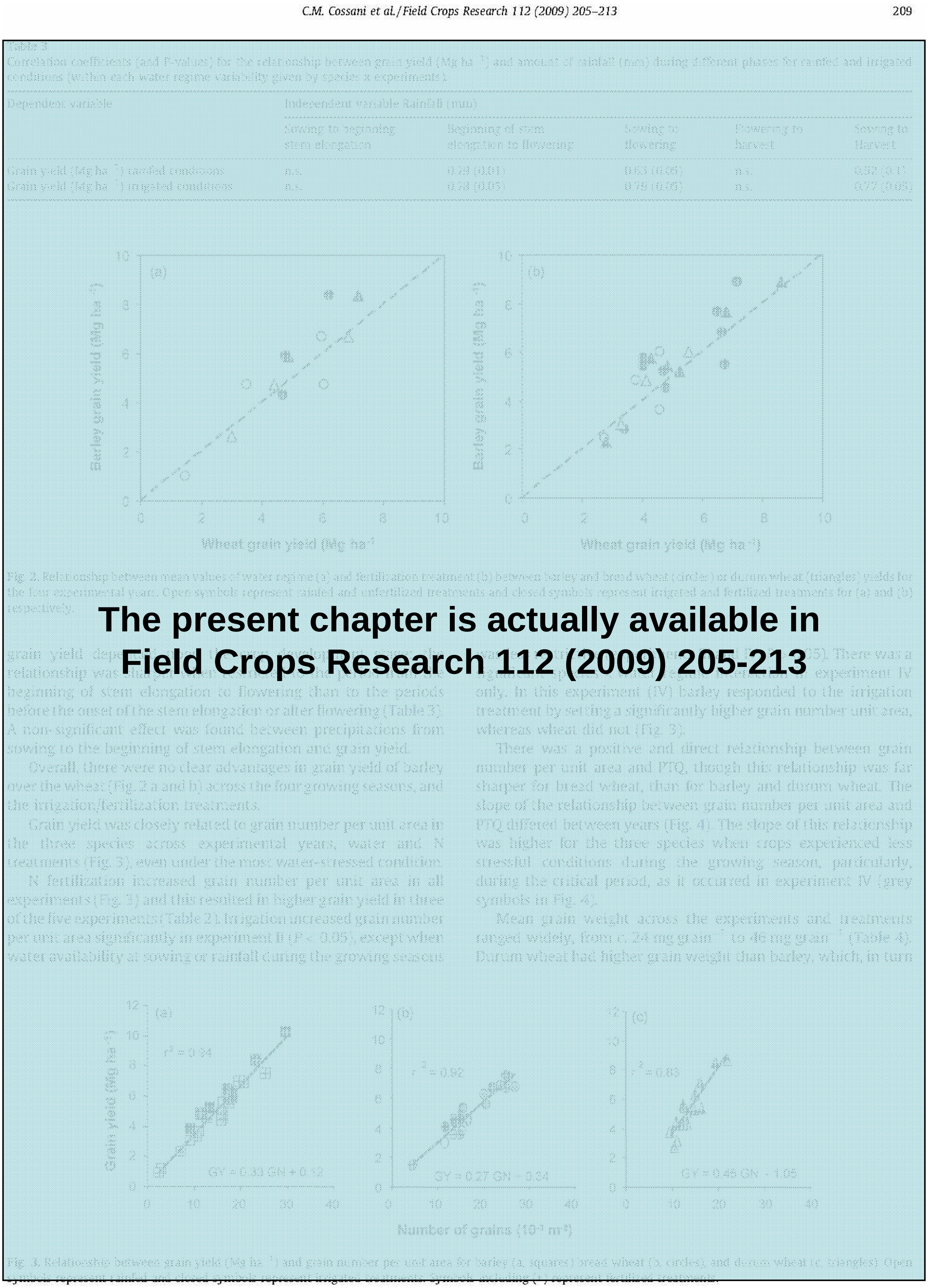

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Table 3
Correlation coefficients (and P-values) for the relationship between grain yield (Mg ha^{-1}) and amount of rainfall (mm) during different phases for rainfed and irrigated conditions (within each water regime variability given by species x experiments).

Dependent variable	Independent variable Rainfall (mm)				
	Sowing to beginning stem elongation	Beginning of stem elongation to flowering	Sowing to flowering	Flowering to harvest	Sowing to Harvest
Grain yield (Mg ha^{-1}) rainfed conditions	n.s.	0.79 (0.01)	0.63 (0.05)	n.s.	0.52 (0.1)
Grain yield (Mg ha^{-1}) irrigated conditions	n.s.	0.78 (0.05)	0.79 (0.05)	n.s.	0.77 (0.05)

Fig. 2. Relationship between mean values of water regime (a) and fertilization treatment (b) between barley and bread wheat (circles) or durum wheat (triangles) yields for the four experimental years. Open symbols represent rainfed and unfertilized treatments and closed symbols represent irrigated and fertilized treatments for (a) and (b) respectively.

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grain yield dep[illegible] relationship was [illegible] beginning of stem elongation to flowering than to the periods before the onset of the stem elongation or after flowering (Table 3). A non-significant effect was found between precipitations from sowing to the beginning of stem elongation and grain yield.

Overall, there were no clear advantages in grain yield of barley over the wheat (Fig. 2 a and b) across the four growing seasons, and the irrigation/fertilization treatments.

Grain yield was closely related to grain number per unit area in the three species across experimental years, water and N treatments (Fig. 3), even under the most water-stressed condition.

N fertilization increased grain number per unit area in all experiments (Fig. 3) and this resulted in higher grain yield in three of the five experiments (Table 2). Irrigation increased grain number per unit area significantly in experiment II ($P < 0.05$), except when water availability at sowing or rainfall during the growing seasons [illegible]05). There was a [illegible] experiment IV only. In this experiment (IV) barley responded to the irrigation treatment by setting a significantly higher grain number unit area, whereas wheat did not (Fig. 3).

There was a positive and direct relationship between grain number per unit area and PTQ, though this relationship was far sharper for bread wheat, than for barley and durum wheat. The slope of the relationship between grain number per unit area and PTQ differed between years (Fig. 4). The slope of this relationship was higher for the three species when crops experienced less stressful conditions during the growing season, particularly, during the critical period, as it occurred in experiment IV (grey symbols in Fig. 4).

Mean grain weight across the experiments and treatments ranged widely, from c. 24 mg grain^{-1} to 46 mg grain^{-1} (Table 4). Durum wheat had higher grain weight than barley, which, in turn

Fig. 3. Relationship between grain yield (Mg ha^{-1}) and grain number per unit area for barley (a, squares) bread wheat (b, circles), and durum wheat (c, triangles). Open symbols represent rainfed and closed symbols represent irrigated treatments. Symbols including (+) represent fertilized treatments.

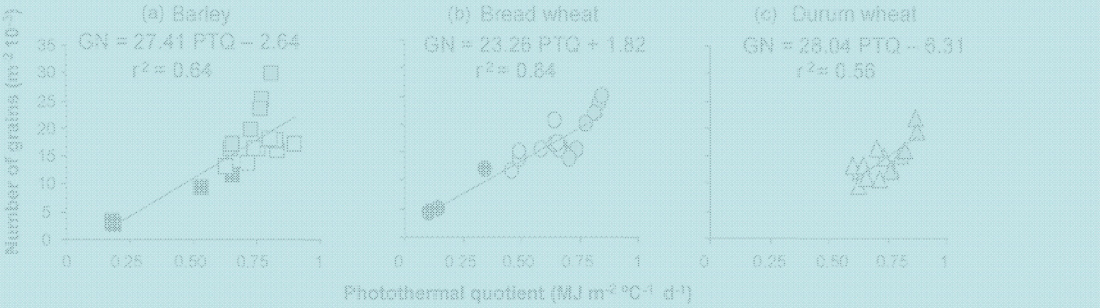

Fig. 4. Grain number per unit area as a function of photothermal quotient explored during 20 days before and 10 days after flowering for barley (a, squares), bread wheat (b, circles), and durum wheat (c, triangles). In each panel black, open and grey symbols represent experiments II, III and IV respectively.

tended to have heavier grains than bread wheat ($P < 0.05$). Overall mean grain weight (across years, water regimes, and N levels) was 38.3 mg grain^{-1}, 33.7 mg grain^{-1} and 29.3 mg grain^{-1} in durum wheat, barley and bread wheat respectively (Table 4). There was no relationship between mean grain weight and grain yield in bread wheat and barley. However, there was a marginal relationship between mean grain weight and grain yield for durum wheat ($r^2 = 0.43$, $P < 0.01$).

There was a negative response of grain weight to N fertilization for all the three species, although the magnitude of the effect differed with the environmental conditions of each year (Table 4; Fig. 1). However, increasing water availability with irrigation generally resulted in heavier grains than under rainfed conditions (see closed [illegible] in Fig. 3), although the effect was only significant in [illegible]

3.3. *Biomass at maturity and post-flowering growth*

Total biomass at maturity ranged between 2.5 Mg ha^{-1} and 23.6 Mg ha^{-1}, 3.0 Mg ha^{-1} and 17.5 Mg ha^{-1}, and 8.5 Mg ha^{-1} and 19.9 Mg ha^{-1} for barley, bread wheat and durum wheat, respectively. Differences in total biomass (Fig. 5) between species were even less noticeable than those in grain yield (Table 2). In fact, in experiment IV where barley grain yield was higher than that of bread wheat (Table 2), the difference in total biomass was negligible (Fig. 5a). Nevertheless, total biomass at maturity followed the patterns observed for grain yield ($P < 0.05$) in experiments I, II, and III. N fertilization increased biomass at maturity in all the experiments and species except in the late sown (experiment V) [illegible] increased total [illegible] there was a

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Table 4
Averaged individual grain weight of barley, bread wheat and durum wheat in each of the five experiments at Agramunt (NE Spain).

Experiment	Water regime treatment (W)	Fertilized treatment (F) (kg N ha^{-1})	Species treatment (S) Grain weight (mg)			LSD ($P = 0.05$)						
			Barley	Bread wheat	Durum wheat	(S)	(W)	(F)	(S × W)	(S × F)	(W × F)	(S × W × F)
I	Rainfed	0	32.0	33.8	–	5.0 ns	–	1.8	–	3.8 (1) 2.6	–	–
		40	27.6	31.3	–							
		80	31.3	28.6	–							
		120	30.5	29.3	–							
		160	31.1	25.1	–							
		200	32.9	27.0	–							
II	Rainfed	0	35.8	32.4	–	2.4	4.2 ns	2.2 ns	3.5 ns (1) 3.6	3.4 ns (1) 3.1	3.3 ns	3.9 ns (1) 4.1 (2) 3.6 (3) 4.3 (4) 4.1 (5) 3.6
		200	33.6	31.1	–							
	Irrigated	0	41.2	34.0	–							
		200	41.2	33.8	–							
III	Rainfed	0	35.3	26.1	39.6	2.4	3.1 ns	1.9	2.8 ns (1) 2.5 (2) 2.4	3.4 ns (1) 3.3	2.9 ns (2) 2.7	4.6 (1) 4.4 (2) 4.5 (3) 4.7 (4) 4.4 (5) 4.5
		50	32.1	25.7	34.6							
		100	30.3	23.8	32.8							
		150	27.5	24.8	30.1							
	Irrigated	0	38.3	29.9	41.2							
		50	35.5	27.6	40.5							
		100	33.3	26.9	36.0							
		150	33.2	26.7	32.9							
IV	Rainfed	0	34.3	30.9	42.9	3.1	4.3 ns	1.4	3.7 ns (1) 3.5 (2) 3.1	3.3 ns (1) 2.4	3.2 ns (2) 2.0	4.3 ns (1) 3.7 (2) 3.8 (3) 3.4 (4) 3.7 (5) 3.8
		75	35.1	31.4	42.5							
		150	30.0	28.9	39.8							
	Irrigated	0	37.5	32.5	45.5							
		75	36.4	30.7	45.4							
		150	34.3	30.1	44.4							
V	Rainfed	0	32.1	–	28.9	3.6	–	3.6 ns	–	5.1 ns	–	–
		150	31.1	–	26.2							

LSD ($P < 0.05$) values for mean treatments 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.

Fig. 5. Relationship between biomass at maturity of barley and (a) bread wheat or (b) durum wheat in each experiment. Experiments are represented by different symbols: a ○ experiment I ◇, experiment II, □ experiment III, △ experiment IV ▽ and experiment V. Closed and open symbols represent irrigated and rainfed conditions respectively.

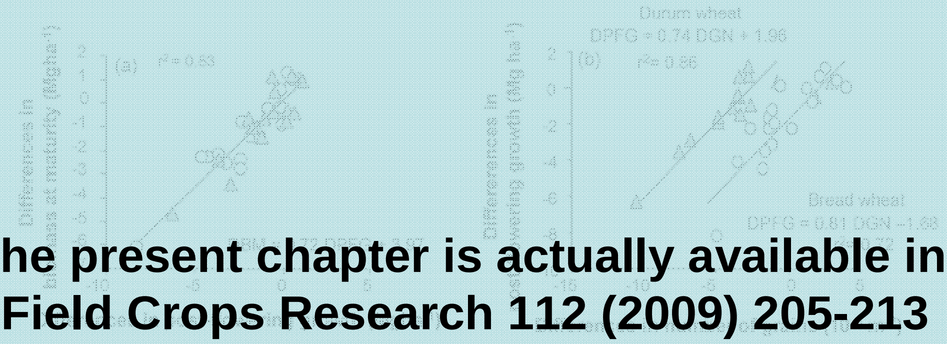

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Fig. 6. (a) Differences between wheat (bread or durum) and barley in biomass at maturity (DBM) as a function of the differences in post-flowering growth (DPFG) between them for all experiments, except for experiment I. (b) Differences between wheat (bread or durum) and barley in post-flowering growth as a function of the differences in grain number unit area (DGN) between them except for experiment I. Open and circle symbols represent differences of bread wheat vs. barley and grey triangles represent durum wheat vs. barley. Note that the two points (triangles) corresponding to the late sowing of experiment (V) were not included in the (b) regression analysis.

tendency to produce higher biomass in irrigated treatments for experiments III and IV (Fig. 5).

For all three species, total biomass at maturity was related to post-flowering growth ($r^2 = 0.70$). Bread wheat presented a relatively higher variability ($r^2 = 0.56$) in post-flowering growth response than barley and durum wheat $r^2 = 0.79$ and 0.77, respectively).

Differences in biomass at maturity between wheat (bread or durum) and barley were closely and positively related ($r^2 = 0.86$ and slope = 0.72 Mg$_{\text{biomass at maturity}}$ Mg $_{\text{biomass during post-flowering growth}}^{-1}$) to their differences in post-flowering growth (Fig. 6a). Differences in post-flowering growth between wheat (bread or durum) and barley were directly related to the differences in grain number per unit area set soon after flowering (Fig. 6b).

4. Discussion

Inter-annual grain yield variability was the result of the potential growing conditions in each year generated by differences in total rainfall and its distribution during the vegetative and reproductive stages (Table 3). This was also reported in other studies under Mediterranean environments (Austin et al., 1998a,b), where grain yield was positively related to rainfall during stem elongation, coinciding with the most active growing period of the crops (Seif and Pederson, 1978).

Although, there was great inter-annual yield variability due to environmental conditions (years × treatments) that produced a wide range in grain yield of the three species (Table 2), we did not identify any consistent yield advantage of barley over wheat under the lowest-yielding conditions. Therefore, the data of this study do not confirm the hypothetically better performance of barley over wheat under Mediterranean environments that justify the patterns of land use with barley monoculture in rainfed conditions in Catalonia (Cossani et al., 2007) as well as in the rest of the region (Anderson and Impiglia, 2002; Ryan et al., 2008). Farmers have to use other criteria in deciding the pattern of land use (gross margin if the grain is sold; feed quality if consumed in farms; control of weed/diseases), but not on the presumption that barley would perform better than wheat particularly in poorer conditions.

The fact that we only used a single cultivar for each species would restrict, in the strictest sense, the conclusions of our study to the cultivars selected in this case. However, as mentioned in the materials and methods section, these cultivars were carefully chosen to represent the current preferences of farmers in the region, and therefore this study can be interpreted to reflect the general performance tendencies of the three species. As the cultivars tested in our study were released in the late '80 s and early '90 s, it could be thought that the pattern of land use reflects an older reality of farmers that still remains in their beliefs, despite the release of newer cultivars of wheat and barley.

Furthermore, in the few studies published where barley and wheat performances were compared directly under Mediterranean conditions, there were no uniform conclusions: sometimes results have supported the hypothesized advantage of barley over wheat

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(e.g. Josephides, 1993 in Cyprus; López-Castañeda and Richards, 1994 in New South Wales-Australia), while in other cases it has been evident that barley did not perform better than wheat, agreeing with results observed in the present study (e.g. Simpson and Siddique, 1994 in Western Australia; Palumbo and Boggini, 1994 in Italy). To the best of our knowledge there has only been one case (Austin et al., 1998a) reported in the literature (excepting the recent publication of Cossani et al., 2007) where wheat was compared to barley (although not in the same experiment) within the region where we have done this study (the Ebro valley). The data from the study by Austin et al. (1998a), using other cultivars clearly showed barley did not perform better than wheat, particularly in the lowest-yielding conditions, a finding that coincided with our results. This could be due to the lack of new higher yielding barley cultivars for "unfavorable conditions" in the region as reported by Muñoz et al. (1998).

Grain yield for all treatments and species was mainly determined by grain number per unit area. In turn, grain number per unit area was determined by the combined effect of intercepted radiation and temperature (evaluated as PTQ) explored during the period from 20 days before to 10 days after flowering. This relationship was also reported by others authors for wheat (Fischer, 1985; Savin and Slafer, 1991) and barley (Arisnabarreta and Miralles, 2008). The relationship observed in this study showed a higher variability but the same tendency in the case of durum wheat and barley. The slope of the relationship between PTQ and grain number per unit area was higher in barley than in bread and durum wheat in experiment IV, which was likely due to a higher fruiting efficiency in years with non-stressful conditions during the critical period (Savin and Slafer, 1991; Arisnabarreta [illegible] may be the cause of a lower r^2 of the relationship between PTQ and grain number pe[illegible]

Among the rang[illegible] it was observed that differences generated between the species in terms of grain number per unit area seemed to have been determinant to the differences in post-flowering growth. The sink strength (largely the number of grains per unit area set soon after anthesis) might have been a major factor affecting post-anthesis growth, as previously reported by other authors (Calderini et al., 1997; Reynolds et al., 2005) even under Mediterranean conditions (Acreche and Slafer, 2009).

N fertilization increased grain yield (Table 2) through a positive effect on grain number per unit area in the three species. However this positive effect of N fertilization was only significant in the experiments with higher water availability (experiments I, III, and IV). The negative response to N fertilization observed as a decrease in mean grain weight seems to be a result of the increased grain number per unit area. By improving the grain number per unit area, N fertilization has concomitantly increased the number of grains in the distal positions of the spike or in secondary tillers spikes. As reported previously (Miralles and Slafer, 1995; Acreche and Slafer, 2006) these additional grains have lower potential weight than proximal grains in the main shoot spikes. Thus increasing grain number per unit area may reduce mean grain weight.

Under some rainfed Mediterranean environments, higher N availability might produce "haying off" as reported by van Herwaarden et al. (1998). However, in this study, N fertilization seemed a good management practice to partially overcome water limitations in Mediterranean rainfed systems, as also reported for Australia by Passioura (2002) and predicted for Catalonia with simulation approaches by Abeledo et al. (2008). Thus, it seems that N may have increased the ability of the crop to capture more water (likely through an increase in root size) and thus the improved uptake of water could have sustained a higher water consuming biomass. Unpublished data from a project conducting fertilization experiments in different rainfed Mediterranean wheat/barley crops (in Southern Italy, Jordan, Morocco and Spain) support this hypothesis.

A clear yield advantage of barley over wheat under the Mediterranean environments explored here was not confirmed, and therefore did not justify the actual patterns of land use in Catalonia. This conclusion is not only based on the results of the present study but also on those of the other few direct comparisons of wheat and barley performance in Mediterranean conditions (since the early work of Warren, 1971), thus preventing acceptance of the assumption that barley possesses a universal advantage over wheat when grown in stressful Mediterranean conditions. Different water and N availabilities resulted in a similar response of the three species. Water and N availabilities affected yield in the three species mainly through differences in grain number per unit area and thus grain yield.

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