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# Intensifying cereal management in dryland Mediterranean agriculture: Rainfed wheat and barley responses to nitrogen fertilisation

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ABSTRACT

Under dryland systems of the Mediterranean basin, water management is widely recognised critical for improving grain yield. It has been proposed that nitrogen (N) fertilisation may be a tool to increase grain yield by increasing water use efficiency. We tested in a multilocation-multiyear study in four different areas of the Mediterranean Basin if durum wheat and barley may respond positively to N fertilisation under rainfed cultivation. The study involved 16 experiments including different genotypes of durum wheat and barley sown at Morocco, Jordan, North-eastern Spain, and Southern Italy, with different nitrogen doses applied at sowing or early in crop development from 2003/04–2007/08 growing seasons. Grain yield increased 26% in average for years, locations and species compared with their respective unfertilised controls. The increased yield in response to N fertilisation was noticeable under low ($< 2$ Mg ha$^{-1}$) and under high yield potential cases ($> 5$ Mg ha$^{-1}$). There were only exceptional cases with slightly negative or no responses to N fertilisation. Grain number per unit area, and not grain weight, was the main component related to grain yield. Also, total biomass at maturity was closely related to grain yield. Barley and durum wheat responded similarly to N fertilisation.

## 1. Introduction

Dryland agriculture refers to rainfed crop growing under semiarid/arid conditions. In these systems, water provision for crop production is solely based on rainfall that, in general, is scarce and frequently erratic (rather variable among years for a location and between locations within a region). Rainfed Mediterranean agricultural systems are among of the most relevant cases of dryland agriculture, characterised also by a strong pattern of rainfall distribution concentrated in the autumn and winter and, in the case of the Mediterranean basin, with not only dry but also hot springs and summers (e.g. Acevedo et al., 1999; Loss and Siddique, 1994). Under these conditions, only autumn-sown spring crops (mainly cereals, but also some legumes and oilseed crops) can be grown, and from these wheat and barley are, by far, the two most widely cultivated (Lopez-Bellido, 1992; Ryan et al., 2008).

Water availability for crop growth is typically the main factor limiting yields in dryland cropping systems of the Mediterranean basin. Hence, water management is widely recognised as highly critical for improving crop productivity and sustainability.

Thus, opportunities for improving water availability for crop growth through water harvesting techniques (e.g. Oweis and Hachum, 2006), the use of crop residues, shifts in row spacing, use of early growing genotypes, a proper nutrition to avoid direct evaporation (Cooper et al., 1987; Siddique et al., 1990; Richards et al., 2002; Passioura and Angus, 2010), and a better control of weeds during fallow (Monzon et al., 2006) have been proposed. However, some of these alternatives are not as

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simple to implement from a farming systems approach. For instance, in much of the cereal growing regions of the Mediterranean basin, crop residues are used to fill feedstock gaps during summer, and therefore price of the straw can be quite substantial (Cossani et al., 2011; Ameur et al., 2021),and when retained only marginal positive effects on yield have been reported in other Mediterranean environments (e.g. Hunt et al., 2016). In addition, water scarcity (Fereres et al., 2003) and the current and future scenario (IPCC, 2022) reinforce the need of seeking further alternatives for increasing yields through improving either crop water capture or water use efficiency.

N fertilisation is a common practice in cereal production under rainfed systems in regions where yields are less limited by water availability than in the Mediterranean basin, as well as in the irrigated agriculture everywhere. In the southern Mediterranean basin, where agriculture is not as heavily subsidised as in the northern margin, farmers have been reluctant to fertilise rainfed cereals (as it is the case with optimising N fertilisation in other low-yielding water-stressed regions; e.g. de Oliveira Silva et al., 2020, Monjardino et al., 2015), because water is the most limiting production factor (and cereals in this region are mainly grown under dryland conditions, Loss and Siddique, 1994). Indeed, fertilising with N has been frequently considered a practice increasing the risks of farmers (van Herwanarden et al., 1998; Sadras, 2002; Lobell, 2007), particularly in this region. Even though the fertilisation with N in the WANA region started to become more common in the 1990′s, the current levels are still much lower than those used in other dryland conditions (Ryan et al., 2009). This is because, following the principles of the widely known Liebig's law of the minimum (crops would solely respond to the most limiting factor) farmers would expect no responses to fertilisation, and eventually yield penalties, and therefore are mostly reluctant to fertilise. However, evidences from other rainfed regions indicate yield gaps reductions due to this practice when matching it properly to the water conditions (Cossani and Sadras, 2018; Cossani et al., 2010; Sadras, 2004; Sadras et al., 2019), and Hochman and Horan (2018) attributed most of the Australian yield gap to N deficiency.

Although the reluctance to fertilise rainfed cereals is general, farmers and advisors in the region are even more averse to fertilise barley than wheat. This practice is based on the - assumption that barley is better adapted to marginal areas (with low soil fertility among other things), and its smaller and more erratic response in yield to fertilisation (Cossani et al., 2007 and references therein). However, this generalised assumption is based more on farmers' perception, biased comparisons and old farming management practices than on strong and consistent evidence of such different responsiveness from field trials comparing side by side modern, well adapted cultivars of both crops. In fact, the few cases in which this comparison has been made in the Mediterranean region provided evidence disputing this generalised assumption (see Cossani et al., 2009 and references therein, Savin et al., 2015).

Passioura (2002) elegantly showed that Australian wheat yields steadily rose since farmers started to fertilise with N more heavily and consistently at the end of the 20th Century (after they were able to grow healthier crops due to rotations with breaking crops reducing the root-based diseases). And this trend continued until nowadays (Hunt et al., 2021). Thus, even in Australian farming conditions, lower N rates than those which would be optimum are being applied, considering the expected variability in response over years (Asseng et al., 2001; Sadras and Roget, 2004; Sadras et al., 2012, Hochman, 2020); a situation that has been also found in other dryland conditions (Lollato et al., 2019). Indeed, Monjardino et al. (2013) found that even in highly variable dryland regions, the economic risks of wheat production would decrease if farmers increased the rates of N fertilisation, as lack of sufficient N may limit yields of cereals even in regions with droughts (Savin et al., 2019). All this evidence from Australia seems quite relevant in the context of the rainfed cereal production in the Mediterranean basin, as Australian wheat is almost completely grown under rainfed systems characterised by regularly exhibiting low yields. Thus, it seemed that in the case of Australia the Liebig's law does not apply well indicating that even in regions where water is one of the most limiting factors (Sadras and Dreccer, 2015), N fertilisation would have favoured either crop transpiration or water use efficiency (Angus and van Herwaarden, 2001; Sadras and Rodriguez, 2010). As there are several differences between the Australian and the Mediterranean basin agronomic conditions and responsiveness to N –particularly so under harsh dryland conditions-could be strongly affected by the genotypic differences of cultivars adapted to particular regions and other environmental conditions (soil water holding capacity, temperature patterns, diseases), direct extrapolation of the results are not possible without a proper local experimentation.

To the best of our knowledge there is only a scarce and fragmentary body of evidences from experiments done in the Mediterranean region (e.g., Karam et al., 2009; Albrizio et al., 2010; Cossani et al., 2009, 2011) comparing both species locally side by side and using wide ranges of N availability. Simulation exercises suggest that it is likely that the more consistent use of N-fertilisation in dryland Mediterranean conditions may result in an increase in crop productivity and would then be a tool to improve sustainability of these systems (Pala et al., 1996; Abeledo et al., 2008). In addition, Sadras (2004) and more recently Meier et al. (2021) using simulation models for the case of dryland Malle region of Australia, highlighted the importance of matching the levels of N in soil according to the water availability to balance the stress exposure of the crops for minimise yield gaps between attainable and actual yield under a certain level of stress. Cossani et al. (2010) provided empirical evidence, from a Mediterranean growing area, that yield gaps (potential minus actual yields) can be reduced if N and water stresses for wheat and barley would tend to be similar.

However, it is unclear whether the interpretation of causes of productivity trends (Passioura, 2002), responsiveness in simulations (e.g., Abeledo et al., 2008) or in particular experiments (e.g., Cossani et al., 2009) would actually represent what can be expected in a wide range of Mediterranean field conditions for both wheat and barley. As the eventual extrapolation would conflict the concept behind the widely accepted Liebig's law, a very wide empiric testing would be appropriate.

In this case, we used a set of multilocation-multiyear study to test whether it may be feasible use N-fertilisation as a tool to raise durum wheat and barley yields in the rainfed systems of the Mediterranean basin. If the implicit assumption in the reluctant attitude to regularly fertilise cereals is unsupported by evidence of barley and/or durum wheat yield responsiveness to N fertilisation, it may be possible to obtain gains from intensifying agriculture even in dryland, low-yielding conditions. The experiments were carried out in four different areas of the Mediterranean Basin: Morocco, Jordan, Italy, and Spain.

## 2. Materials and methods

In the context of the EU INCO project WatNitMED, field experiments were conducted in which wheat and barley were grown under rainfed conditions either unfertilised or N-fertilised to test to what degree improved N availability may help to mitigate the yield penalties imposed by water-limitations in dryland agricultural systems of the Mediterranean basin (i.e. to close the gap between water-limited achievable yield and what farmers most frequently harvest). In all cases, the cultivars used were well adapted to the particular conditions and a common preferred choice between farmers of each region. Thus, some cultivars may have been very successful releases of a long time ago but still being a preferred option for farmers and well performers in yield comparative trials of the specific countries at the time of the initiation of the study.

Most experiments were far more complex of what is herein reported and further more detailed information about them can be found in Cossani et al. (2009) and Albrizio et al. (2010). All experiments had in common that under rainfed conditions there were a control unfertilised treatment and at least one, though frequently more than one, N-fertilised treatment for each particular cultivar of each of the two species. In the cases in which there were several timings of N-fertilisation treatments, we used for this study the treatments applying N up to the onset of stem elongation (31; Zadoks et al., 1974). When more than a single fertilisation rate was compared in a particular experiment, for analysing results we used yield of the fertilised treatment both as that averaged across the different doses used (the average response to N-fertilisation), or as that of the most responsive treatment (the optimised response to N-fertilisation). For interpretation of results, the first approach would give indications of the expected outcome when the requirements of N to be added as fertiliser were not accurately predicted. The second approach would apply for cases in which the determination of crop N requirements were more accurate and farmers would usually apply the doses maximising responsiveness.

Experiments were carried out in four regions across the Mediterranean basin, in Morocco, Jordan, North-eastern Spain, and Southern Italy. A total of 16 field trials were carried out under rainfed conditions from 2003/04–2007/08 growing seasons. Details of the experimental sites (including soil types and rainfall throughout the growing season) and genotypes grown are shown in Table 1.

At all experimental sites, the crops were sown within the optimal sowing dates corresponding to each location, as well as with the sowing density commonly used in each region (Table 1). Treatments consisted of a range of N rates and timings of application (see details in Table 1). The treatments were arranged in completely randomized block design in Morocco and Italy or in a split plot experimental design where genotypes and nitrogen comprised the main and sub-plots, respectively in Spain and Jordan, with 3 or 4 replications. Control of weeds and pests were done following the common practices recommended to farmers by manufacturers of each region in all the experiments to avoid presence of weeds, diseases and pests.

At maturity, aboveground biomass and grain yield and its main components (grain number per $m^2$ and average grain weight) were determined by harvesting a sample area, depending on the experiment, from 0.25 to 9.0 $m^2$ at the centre of each plot. Samples were then processed as standard in agronomic experiments. Harvest index (HI) was determined as the ratio of grain yield by aboveground biomass at maturity.

Regression analyses were used to analyse the relationships of different traits between the species, locations and N fertilisation.

## 3. Results

Grain yield varied from 0.3 to 8.7 Mg $ha^{-1}$ (Fig. 1a) throughout 289 values from 16 experiments in four Mediterranean regions (Fig. 1a). Yields (considering the fertilised treatments) were in average higher in Northern Spain and Southern Italy (c. 4.5 Mg $ha^{-1}$) compared to Jordan (3.0 Mg $ha^{-1}$) and Morocco (1.9 Mg $ha^{-1}$). Barley did not yield better than wheat in the lowest-yielding conditions neither did wheat yield more than barley in the highest-yielding conditions (Fig. 1a). The range of yields for the fertilised rainfed crops was much larger, but not only because of responsiveness at high yielding conditions (Fig. 1b). The increased yield in response to fertilisation was noticeable for each the four quartiles of yields. The median yield increased was from 1.96 to 2.97 Mg $ha^{-1}$ (Fig. 1b). As, in each country, cultivars were selected to represent well adapted germplasm, the differences in year of release was irrelevant to explain differences in yield ($R^2 = 0.001$ when considering unfertilised controls and $R^2 = 0.004$ when considering the fertilisation treatment maximising yield of each cultivar).

Yield from the fertilised crops was almost always significantly higher than their respective controls (Fig. 2a, b). Considering the average of all fertilisation treatments, there were only exceptional cases with slightly negative or no responses to nitrogen fertilisation (Fig. 2a). These cases were naturally less, and less noticeable, when the relationship was based on the treatments maximising responsiveness to fertilisation (Fig. 2b). In these particular exceptional cases, soil N availability was presumably enough to meet the demands of the crop, whose growth was severely penalised by other factors. But these were truly exceptions: in the majority of cases in which growth was severely penalised by other factors (i.e. yield of the fertilised crop was still rather low) there was a yield response to fertilisation (i.e. soil N availability was still poor respect to the demands of the crop). There was a general trend to increase the responsiveness of yield to fertilisation (both considering the average of all fertilising treatments or that maximising responsiveness) with the yield of the unfertilised controls, as shown by the slopes of the relationships being higher than 1 (Fig. 2a, b). There was no cross-over of the regression line with the 1:1 line, as the intercept was very close to zero, only negligibly negative (Fig. 2a) or positive (Fig. 2b). In other words, even at very low yielding conditions (say less than 1 Mg $ha^{-1}$) there was a general positive response to N fertilisation by both cereals, and particularly so when the fertilisation rate optimising responsiveness rather than the average of any fertilisation treatment was considered (Fig. 2b).

Although the linear regression was appropriately fitted and highly significant, the averaged residuals (for intervals of 1 Mg $ha^{-1}$) from the 1:1 line indicated that the trend to increase responsiveness with the yielding condition of each experiment (revealed by the yield of unfertilised control) was not linear (Fig. 2, insets). The averaged response to N fertilisation was noticeable throughout all the explored environmental ranges, but remained relatively small for environments with unfertilised yields being lower than 2.5 Mg $ha^{-1}$ and increased substantially with higher yielding environments (Fig. 2, insets).

There were no differences in responsiveness to N fertilisation between barley and wheat (Fig. 2a, b). Considering the average response to all fertilisation treatments in each experimental condition (Fig. 2a), the slope of the relationship between fertilised and unfertilised crops for barley and wheat were virtually identical (1.31 $\pm$ 0.10 and 1.28 $\pm$ 0.07 for barley and wheat, respectively). Similarly, considering the most responsive treatment (Fig. 2b) barley and wheat exhibited again very similar slopes (1.35 $\pm$ 0.12 and 1.33 $\pm$ 0.09, respectively).

Even though the experiments were carried out at four Mediterranean locations characterised by terminal stresses during grain filling (whose intensity varied among locations and between years within locations), yield was closely related to the number of grains per unit land area (Fig. 3). There was not noticeable difference in the parameters of the relationship whether the values of the fertilised treatments considered for each experiment were the averages of all fertilisations (Fig. 3a) or those of the fertilisation rate maximising yield responsiveness (Fig. 3b). In particular, for N fertilisation responses (values of the fertilised treatment minus those of the unfertilised control) within each particular experiment, it was also clear that yield response was associated with that of grain number (Fig. 3, insets). Once again there was no difference on whether the fertilisation used in the analysis was the average of all fertilisations (Fig. 3a, inset) or the fertilisation regime maximising yield responsiveness (Fig. 3b, inset). The slopes of the insets of Fig. 3 were lower than those of the corresponding main panels, suggesting that although fertilisation did consistently increase grain number, it did also bring about a slight reduction in average grain weight.

Opposite to what was shown for the number of grains, yield was unrelated to individual grain weight, disregarding whether we considered the average of the fertilisation treatments (Fig. 4a) or those in which yield responsiveness was maximised (Fig. 4b). Although the data-points of fertilised and unfertilised crops are mostly overlapping, the former appear to be slightly skewed to the left of each panel (Fig. 4a, b), resulting in a slighter lower average grain weight, mainly in the conditions in which average grain weight was lowest (the difference becomes clear for the bottom quartile in which the average weight of the grains was almost 20% lower in fertilised than in unfertilised crops; see boxplots at the bottom of Fig. 4b). Therefore, as fertilisation consistently increased grain number while tended to slightly reduce the average weight of the grains, there was a negative trend between these yield components (Fig. 4c, d). Much of the scattering of the data-points is due

**Table 1**
Details of all field experiments carried out from 2003 to 2008, including total rainfall during the corresponding growing cycle season (from sowing to maturity).

| Country | Location | Exp. number | Year | Soil type (USDA, 2006) | Rainfall (mm) | Species | Cultivar (year of release)[1] | Sowing date | Sowing rate (plants per $m^2$) | Nitrogen fertilisation | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Rate (Kg N $ha^{-1}$) | Stage when applied[2] Fertiliser used |
| Spain | Agramunt (Lat. 41° 47′ N, long. 01° 6′ E, alt. 337 m) | Exp 1 | 2003–2004 | Xerofluvent typic | 294 | Barley (2-row) Durum wheat Bread wheat | Sunrise (1993) Claudio (2015) Soissons (1990) | November 21, 2003 | 300 | 0, 40, 80, 120, 160,200 | DC 12, 31 Ammonium nitrate |
| | | Exp 2 | 2004–2005 | | 163 | | | November 16, 2004 | 300 | 0, 200 | DC 12, 31 Ammonium nitrate |
| | | Exp 3 | 2005–2006 | | 94 | | | November 28, 2005 | 300 | 0, 50, 100, 150 | DC 12, 31 Urea |
| | | Exp 4 | 2006–2007 | | 331 | | | November 6, 2006 | 300 | 0, 40, 80, 120, 160 | DC 12, 31 Urea |
| Morocco | Sidi El Aydi (Lat 0.33° 07′ N, long. 07° 38′ W, alt. 240 m) | Exp 5 | 2004–2005 | Vertic calcixeroll | 190 | Durum wheat | Karim (1985) Irden (2003) Nassira (2003) Chaoui (2003) Merouane (2003) | December 10, 2004 | 300 | 0, 120 | DC 0, 31, 37, 60 Ammonium nitrate |
| | | Exp 6 | 2005–2006 | | 332 | Barley (6-row) Barley (2-row) Durum wheat | Massine (1994) Amira (1996) Tissa (1984) Karim Ourgh (1995) Nassira | November 20, 2005 | 300 | 0, 40, 80, 120, 160 | DC 0, 22, 31 Ammonium nitrate |
| | | Exp 7 | 2006–2007 | | 153 | Barley Durum wheat | Massine, Tissa Amira Karim, Ourgh Nassira | November 19, 2006 | 300 | 0, 40, 80, 120, 160 | DC 0, 22, 31 Ammonium nitrate |
| | Merchouch (Lat. 33° 36′ N, long. 06° 43′ W, alt. 430 m) | Exp 8 | 2007–2008 | Vertisoil | 300 | Barley Durum wheat | Massine Tissa Amira Karim Ourgh Nassira | November 19, 2007 | 300 | 0, 40, 80, 120, 160 | DC 0, 22, 31 Ammonium nitrate |
| Italy | Valenzano, Bari (Lat. 41° 03′ N, long. 16° 52′ E, alt. 72 m) | Exp 9 | 2005–2006 | Lithic-Ruptic-Inceptic-Haploxeralfs | 480 | Barley (6-row) Durum wheat | Ponente (2000) Quadrato (1999) | December7 and 8, 2005 | 250 | 0, 60, 120 | DC 12, 31 Ammonium sulphate; ammonium nitrate |
| | | Exp 10 | 2006–2007 | | 347 | | | November 27 and 28, 2006 | 250 | 0, 120 | DC 12, 31 Ammonium sulphate; ammonium nitrate |
| | | Exp 11 | 2007–2008 | | 395 | | | November 23 and 24, 2007 | 250 | 0, 120 | DC 12, 31 Ammonium sulphate; ammonium nitrate |
| Jordan | Maru (Lat. 31° 51′ N, long. 32° 33′ E, alt. 620 m) | Exp 12 | 2004–2005 | Entic Chromoxererts | 414 | Durum wheat | Hourani (1976) | November 15, 2004 | 250 | 0, 50 | DC 40 Urea |
| | Jubeiha (Lat. 32° 01′ N, log. 35° 52′° E, alt. 980 m) | Exp 13 | 2005–2006 | Entic Chromoxererts | 433 | Barley (6-row) Durum wheat | Rum (1986) Hourani | December 12, 2005 | 250 | 0, 50, 100 | DC 0, 31 Urea |
| | | Ep 14 | 2006–2007 | | 512 | Barley (6-row) Durum wheat | Rum Acsad (1987) Hourani Om Qais (2004) | December 15, 2006 | 250 | 0, 50, 100 | DC 0, 31 Urea |
| | Mushaqqar (Lat. 31° 05′ N, long. 35° 47′ E, alt. 790 m) | Exp 15 | 2005–2006 | Entic Chromoxererts | 312 | Durum wheat | Hourani Dair Alla 6 (1974) | December 18, 2005 | 250 | 0,50, 100 | DC 0, 31 Urea |
| | | Exp 16 | 2007–2008 | | 173 | | Hourani Om Qais | December 15, 2007 | 250 | 0,50, 100 | DC 0, 31 Urea |

[1] when the cultivar was sown in more than one experiment, the year of release was indicated only the first time it was mentioned.
[2] stage of development following Zadoks et al. (1974) decimal code (DC).

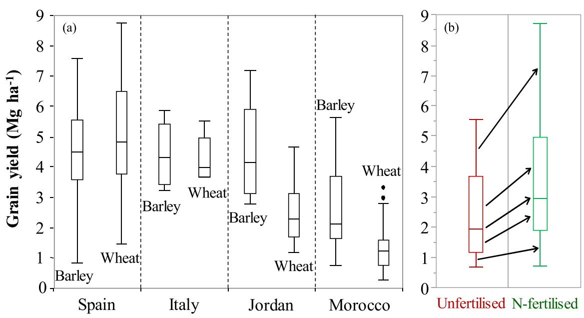


**Fig. 1.** Boxplots of yields (i) of barley and wheat in each of the four locations across all experiments carried out, and treatments imposed, in those locations (a), and for the unfertilised and fertilised crops across all experiments (b). The straight arrows indicate the increased yield in response to fertilisation for the different quartiles and the median of the yield distribution.

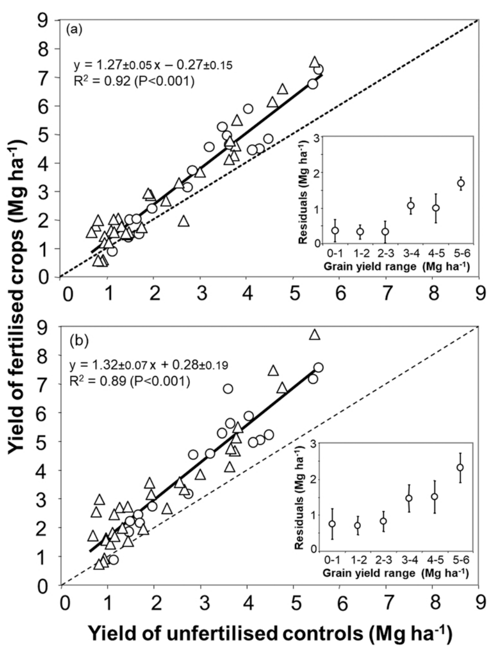


**Fig. 2.** Relationship between yields of the fertilised and the unfertilised controls for barley (circles) and wheat (triangles) from the 16 experiments mentioned in Table 1. Yield of fertilised crops are either the average of all fertilisation treatments in each individual experiment (a) or the average of the fertilisation treatment maximising responsiveness of the crop in each particular experiment (b). In both panels the dotted lines indicate the 1:1 ratio. Inset in each panel are the averaged residuals (and its standard deviation) to the 1:1 line for each interval of 1 Mg ha$^{-1}$ in the unfertilised controls.

to inherent differences in average grain weight among experiments (locations x years). The overall trend, disregarding whether we used the average of the fertilisations of each experiment or the fertilisation regime optimising yield responsiveness, was to reduce average grain weight by 0.6 mg grain$^{-1}$ per each thousand grains increased (Fig. 4c, d).

There was a close relationship between yield and total biomass considering simultaneously the unfertilised and fertilised treatments, either as average response or as the greatest response (Fig. 5a, b). This overall relationship was driven by all sources of variation (experiments, cultivars and N availability), but focusing exclusively on the N

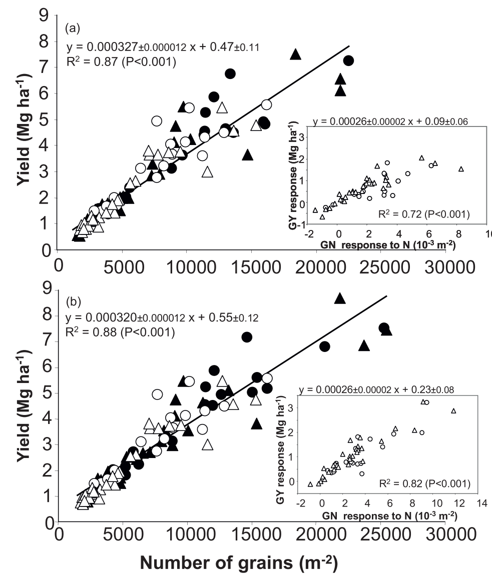


**Fig. 3.** Relationship between yield and number of grains per m$^2$ considering (a) the average response to all fertilisation treatments in each individual experiment, or (b) the fertilisation treatment maximising responsiveness of the crop in each particular experiment. Open and closed symbols represent the unfertilised controls and fertilised crops of both barley (circles) and wheat (triangles). Insets are the yield and grain number responses to N fertilisation for barley and wheat in each experiment.

fertilisation effects it was also noticeable that yield responses were due to responses of biomass ($R^2$ =0.85, $P < 0.001$ when considering the average response to N and $R^2$ =0.80, $P < 0.001$ when considering the treatment maximising response). The relationship between yield and harvest index (Fig. 5c, d) was still statistically significant though much weaker than that with biomass and more importantly the weak relationship was driven by the experiments x cultivars but not by N fertilisation: the relationship between the responses of yield and HI to N fertilisation were negligible $R^2 = 0.04$ and 0.18 when considering the average of all N treatments and the N fertilisation maximising the response in each experiment.

## 4. Discussion

In a wide range of environmental conditions within Mediterranean Basin we confirmed that even in stress-prone regions characterised by relative low yields, further intensifying wheat and barley management through more universal use of N fertilisation seems a valid alternative to increase yield. Disregarding the fact that, as recognised since long time ago, water availability is indisputably the most severe stress reducing yields in the region (Cooper et al., 1987; Acevedo et al., 1999), N-stress in non-fertilised fields does also impose additional yield penalties. In the present study, overall the yielding ranges analysed, there was a consistent positive response of yield to N fertilisation, and naturally the magnitude of response increased if the rate/timing were those optimising yield responsiveness. Thus, similarly to what was concluded for dryland wheat in Australia (Monjardino et al., 2013, 2015; Hochman and Waldner, 2020; Meier et al., 2021) and in the US (de Oliveira Silva et al., 2020), it seems that farmers in the Mediterranean Basin would likely benefit of intensifying their water-limited cereal cropping systems through applying higher levels of N fertilisation. Thus, it is relevant that continuously updated tools be made available to farmers and farmer advisors of the region in order to benefit from fertilisation decisions

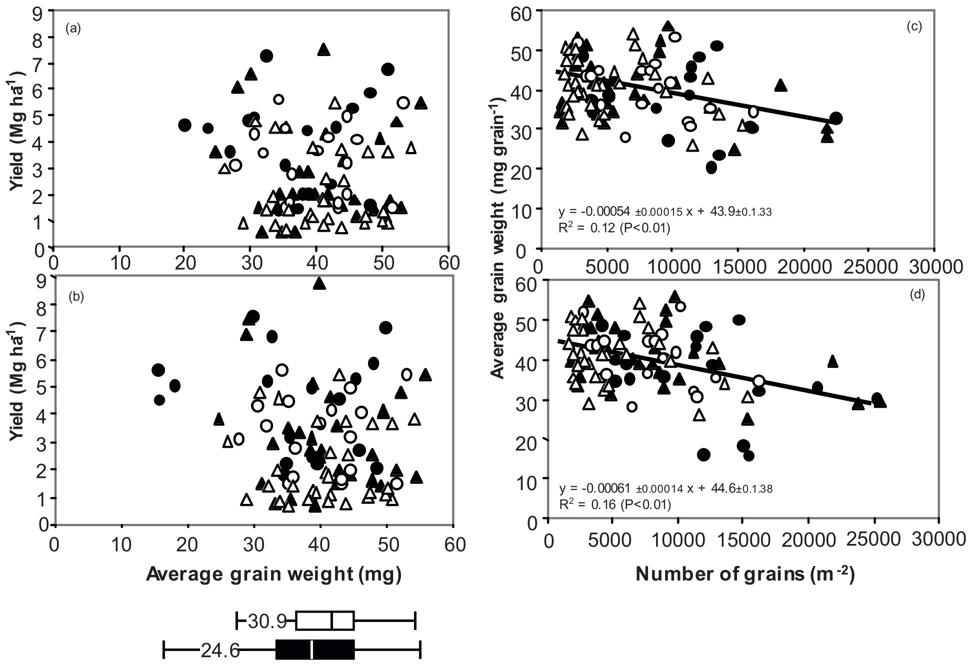


**Fig. 4.** Relationships between (i) yield and average grain weight (a, b) and (ii) the latter and the number of grains per unit land area (c, d); in both cases considering the average response to all fertilisation treatments in each individual experiment (a, c), or the fertilisation treatment maximising responsiveness of the crop in each particular experiment (b, d). Open and closed symbols represent the unfertilised controls and fertilised crops of both barley (circles) and wheat (triangles). The box-plots underneath (b) stand for the distribution of average grain weight in the unfertilised controls (open box) and fertilised maximising responsiveness crops (closed box) and figures inside the bottom whisker.

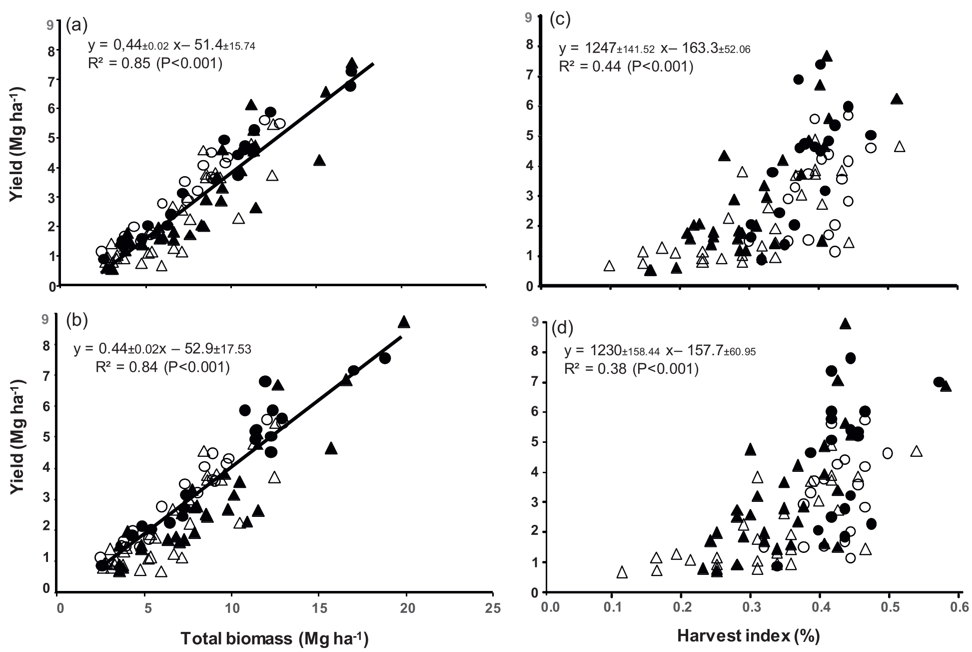


**Fig. 5.** Relationships between (i) yield and total biomass (a, b) and (ii) yield and harvest index (c, d); in both cases considering the average response to all fertilisation treatments in each individual experiment (a, c), or the fertilisation treatment maximising responsiveness of the crop in each particular experiment (b, d). Open and closed symbols represent the unfertilised controls and fertilised crops of both barley (circles) and wheat (triangles).

based on an estimate of crop responsiveness as accurate as possible (e.g., see model proposed, and tested in two contrasting regions of Tunisia, by Cossani et al., 2011). Recently, Villalobos et al. (2020) developed a decision support system for fertilizer management "Ferticalc" to calculate the required seasonal N, P and K rates, and the most cost-effective combination of commercial fertilizer that proved to be useful in Mediterranean conditions. Their system estimates N requirements and N losses, being useful also for teaching farmers as it helps understanding the rationale behind estimations. Naturally it is relevant to have these updated tools to avoid overfertilisation as well. Although N losses in semi-arid Mediterranean conditions are low and in the event of an eventual slight overfertilisation there would be N stored in the soil (e.g. Smith et al., 2019 and Meier et al., 2021). Indeed, intensifying wheat management, including N fertilising wheat in semi-arid conditions, would reduce the carbon footprint per unit of grain produced (Simmons et al., 2020). On the other hand, chronic underfertilisation may be environmentally damaging as it would decline soil organic N and associated soil organic C (Alvarez, 2005; Ladha et al., 2011).

Our results conflict with the widely recognised law of the minimum. That was expected as its inadequacy was demonstrated long time ago (de Wit, 1992; Sinclair and Park, 1993). Crops do actually respond to the interaction between co-limiting factors rather to a single limiting one

(Sadras, 2004; Cossani et al., 2010; Cossani and Sadras, 2018). Therefore, the use efficiency of the most limiting factor (e.g., water) is increased when other co-limiting factors (e.g., N) are more available (Sadras, 2005), justifying the need of intensifying management even under low-yielding conditions. This is likely explained because fertilised crops would be able to extract more water and using the water extracted more efficiently (as shown for Australia by Norton and Wachsmann, 2006).

Even though it is commonly conjectured that (i) barley performs better than wheat in dryland low-yielding conditions and vice-versa, and (ii) when there is response to N fertilisation, barley would respond much less markedly than wheat, the results of the present study conflict strongly with both assumptions. The former is the basis for the most common land distribution throughout the Mediterranean Basin: barley is virtually a monoculture in the more stressful areas while wheat dominates the acreage where the stress is most frequently milder (Ryan et al., 2008). In previous studies, it had been argued that this belief was not universally supported from experimental evidences (Cossani et al., 2007). In the present study, the database provided is far stronger in that it included a very wide range of low-yielding conditions in which we again found that there was not support to the assumption that under low-yielding conditions barley performs consistently better than wheat, and also found that barley does respond to N fertilisation similarly to wheat. However, it might be possible that in high-yielding environments N fertilisation may induce lodging more severely in barley than in wheat and therefore the assumption of a low responsiveness may be supported in those conditions. But under dryland Mediterranean conditions, in which crop growth and yield is limited by water, lodging is an extremely unusual adversity given the reductions observed in plant height as consequence of limited growth.

It has been reported, from studies in Eastern Australia, that N fertilisation under severe drought conditions may impose a yield penalty, termed "haying-off" (van Herwanarden et al., 1998). Even though the present study included a number of experiments under very stressful conditions, no consistent evidences of haying off were found. Even in the range of yields lower than 1–2 Mg $ha^{-1}$ the overall response to N fertilisation was positive and the magnitude of the response was not negligible, particularly so if the rates applied were those maximising responsiveness. This is not truly surprising as evidences of haying off are not often reported in other Mediterranean conditions, not even in Western Australia (Palta and Fillery, 1995; Asseng et al., 1998; Asseng and van Herwaarden, 2003; Cossani et al., 2011; de Oliveira Silva et al., 2020) or only occurs at extremely high N conditions (Sadras et al., 2019).

Grain yield was mainly determined by the number of grains per unit land area. This is obviously expected in most growing conditions of the world (Slafer et al., 2006; Peltonen-Sainio et al., 2007; Reynolds et al., 2009). However, as Mediterranean conditions of rainfed cereals are characterised by terminal stress occurring preferably during grain filling, it might be expected that the average weight of the grains be the main yield component determining yield differences. Results from this study (as well as from other sources; Acreche et al., 2008; Cossani et al., 2009, Albrizio et al., 2010) showed that even in Mediterranean conditions grain number dominates grain weight in the determination of yield. In other words, even in Mediterranean conditions the capacity of the canopy to provide the carbohydrates to the growing grains during post-anthesis would be enough, if not in excess, to satisfy the demand (Cartelle et al., 2006; Acreche and Slafer, 2009; Pedro et al., 2011; Serrago et al., 2013), alike the situation of grain filling in most regions worldwide (Borrás et al., 2004 and references quoted therein). The negative relationship found between average grain weight and grain number would not represent competition among grains for limited resources during grain filling, but simply the fact that whenever grain number is increased there is an increase in the proportion of grains that are constitutively smaller (Miralles and Slafer, 1995; Acreche and Slafer, 2006).

We concluded that even in dryland conditions it is likely to expect a positive response to N fertilisation in systems characterised by farmers being averse to fertilise due to the predominantly water stress in which rainfed cereals must grow. This response would probably be due to fertilised crops are able to explore more the soil and then extract more water or are able to use the transpired water more efficiently, though we did not analyse the causes in the present study. Disregarding the nature of the response, the final result is that fertilised wheat and barley produced consistently more grains even in very low yielding conditions, and these additional grains are normally filled as the increased grain number would not represent a stronger competition than in the unfertilised treatments.

## CRediT authorship contribution statement

**R. Savin:** Conceptualization, Supervision, Methodology, Visualization, Data curation, Writing – original draft, Writing – review & editing. **C.M. Cossani:** Investigation, Formal analysis, Writing – review & editing. **R. Dahan:** Investigation, Formal analysis, Writing – review & editing. **J.Y. Ayad:** Investigation, Formal analysis, Writing – review & editing. **R. Albrizio:** Investigation, Formal analysis, Writing – review & editing. **M. Todorovic:** Investigation, Formal analysis, Writing – review & editing. **M. Karrou:** Investigation, Formal analysis, Writing – review & editing. **G.A. Slafer:** Conceptualization, Supervision, Methodology, Visualization, Data curation, Funding acquisition, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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