Multiple resources limitation and its impact on resource use efficiency and yield gaps of cereal crops under Mediterranean conditions

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Abstract

Resource limitation, chiefly water and nitrogen, is common for farming systems in Mediterranean environments. Co-limitation of resources was proved in cereal and oilseed crops as well as in many other ecosystems. However, co-limitation involving more than two resources is not frequently explored. In this study, the objective was to develop and test a new method for estimating co-limitation of multiple resources in a case study with wheat and barley crops in Mediterranean environments. The three-way co-limitation between water, nitrogen and radiation explained the yield gaps and water use efficiency of the crops.

Keywords

Wheat, barley, nitrogen, radiation, water, co-limitation.

Introduction

The cultivation of wheat and barley in Mediterranean environments is usually limited by water and nitrogen, as related to soil properties, rainfall amount and its distribution, radiation, and temperature. Agricultural research has proved that water and nitrogen are the major limiting resources in Mediterranean environments. Solar radiation constitutes a third limiting resource to crop productivity through its main role in photosynthesis and in defining the temperatures ranges. Previous studies in Mediterranean environments indicate the influence of resource availability on photothermal conditions explored by the crop during the critical period and yield of wheat and barley. Moreover, intercepted radiation plays a key role in determining the different ability of cereals to accumulate biomass and nitrogen. Despite the already known independent importance of water, nitrogen, and radiation as main limiting resources, the analysis of how all of them interact is still a challenge. Based on the knowledge that response to one resource will depend on the changes in other resources, the problem of how to assess co-limitation by more than two resources appears on the horizon of resource capture research. In this study, the objective was to analyse the collective impact of water, nitrogen and radiation on wheat and barley yield in a co-limitation framework.

Methods

Source of field data

Three field experiments were carried out in Agramunt, Catalonia, north-eastern Spain, a typical rainfed Mediterranean growing region during three growing seasons (2004-05, 2005-06 and 2006-07). Treatments consisted of factorial combinations of a single cultivar of the three species (bread wheat, barley and durum wheat), different nitrogen (N) availability (fertilised and unfertilised) and different water availability (rain-fed and irrigated). The treatments generated a wide range of variability in yield and resources use efficiency appropriate for the analysis in this paper. Further details are in Cossani et al. (2009).

Resource capture and co-limitation analysis

Data to calculate nitrogen and water use efficiency for bread wheat, barley and durum wheat were obtained from previously published articles (Cossani et al. 2009; 2010; 2012). Intercepted radiation was measured at 1 – 2 week intervals, depending on cloudiness, from mid-tillering to advanced grain filling. Intercepted radiation between dates of measurement was calculated by linear interpolation. The total amount of intercepted photosynthetic active radiation (IPAR) was calculated by multiplying the percentage of PAR intercepted by daily global incident radiation and assuming a PAR to be 50% of the global radiation. Radiation use efficiency (RUE) was calculated as the ratio between biomass or grain yield and IPAR.
For all cases, grain yield, water use, N uptake, and N availability were measured, and water use efficiency (WUE), nitrogen use efficiency (NUE) and yield gap were calculated. WUE and NUE were calculated as the ratios of yield to water use and N availability, respectively. Yield gap was calculated as the difference

between actual yield in each treatment and maximum attainable grain yield (Cossani et al. 2010).

Water Stress Index (WSI) and Nitrogen Stress Index (NSI) were estimated as the ratio between actual use of resources and the requirements for maximum attainable yield as reported in Cossani et al. (2010) and are expressed in equations 1 and 2.

$$\mathrm{WSI} = 1 - \frac{\text{Actual evapotranspiration (from sowing to maturity)}}{\text{(Max grain yield/upper limit for water use efficiency) + Soil evaporation}} \quad \text{[Eq. 1]}$$

$$\mathrm{NSI} = 1 - \frac{\text{Actual N uptake (from sowing to maturity)}}{\text{(Max grain yield/upper limit for N utilisation efficiency)}} \quad \text{[Eq. 2]}$$

A Radiation Limitation Index (RLI) was estimated by using the intercepted radiation by the crops during the critical period for yield determination following equation 3.

$$\mathrm{RLI}=1 - \text{(\% of intercepted radiation)} / 100 \quad \text{[Eq. 3]}$$

The stress index for each resource ranged from 0 (no stress) to 1 (maximum stress). The stress of the three resources combined was calculated in two different ways: Total Stress Index (T_{WNR}) (Equation 4) and Maximum Stress Index (M_{WNR}) (Equation 5). T_{WNR} ranged from 0 (minimum stress) to 3 (maximum stress) while M_{WNR} ranged from 0 (minimum stress) to 1 (maximum stress).

$$T_{WNR} = \mathrm{WSI} + \mathrm{NSI} + \mathrm{RLI} \quad \text{[Eq. 4]}$$
$$M_{WNR} = \mathrm{Max}\,(\mathrm{WSI}, \mathrm{NSI}, \mathrm{RLI}) \quad \text{[Eq. 5]}$$

The co-limitation index (C_{WNR}) was calculated as:

$$C_{WNR} = 1- \left| \text{(Standard deviation (WSI, NSI, RLI)) / (Average (WSI, NSI, RLI))} \right| \quad \text{[Eq. 6]}$$

C_{WNR} tended to 1 when the magnitude of the limitation resources was similar. As per Cossani et al. (2010) and Sadras (2004), two additional indices were calculated to account for the intensity of the stress with the degree of co-limitation. The additional indices were co-limitation accounting for the total stress (CT_{WNR}) and co-limitation accounting for the maximum stress (CM_{WNR}), which were calculated as expressed in Equations 7 and 8, respectively.

$$CT_{WNR} = C_{WNR} / T_{WNR} \quad \text{[Eq. 7]}$$
$$CM_{WNR} = C_{WNR} / M_{WNR} \quad \text{[Eq. 8]}$$

Finally, regression analysis was used to explore the interactions between resource use and their efficiency, yield and yield components, and limitation and co-limitation indices.

Results

Grain yield, capture, and efficiency in the use of resources and the levels of stress were highly modified by the environmental conditions (Table 1).

Table 1. Percentile range (P) and mean (M) for yield gap (YG), total dry matter (TDM), water use (WU), intercepted photosynthetic active radiation accumulated (IPAR), N uptake (N up as kg N/ha), water use efficiency (WUE_g for grain), nitrogen use efficiency (NUE_g for grain per available N), radiation use efficiency (RUE_g for grain and RUE_b for biomass), co-limitation of multiple resources (C_{WNR}), radiation limitation index (RLI), water stress index (WSI) and nitrogen stress index (NSI) of wheat and barley across the three experimental years and treatments.

P %	YG t/ha	TDM t/ha	WU mm	IPAR MJ/m^2	N up kg/ha	WUE_g kg/ha/mm	NUE_g kg/kg	RUE_g g/MJ	RUE_b g/MJ	C_{WNR}	RLI	WSI	NSI
10	-5.9	7.1	222	326	89	9.5	12	0.9	2.0	0.1	0.1	0.0	0.1
90	-1.5	18.0	650	682	239	21.0	30	1.3	2.9	1.1	0.6	0.5	0.7
M	-3.8	12.0	345	475	154	16.0	23	1.1	2.5	0.5	0.3	0.3	0.4

Yield gap of grain cereals was significantly related to the degree of water-nitrogen-radiation co-limitation (Figure 1). A higher percentage of the variation in yield gap was explained when the co-limitation index accounted for the level of total stress (CT_{WN}) or by maximum stress (CM_{WNR}).

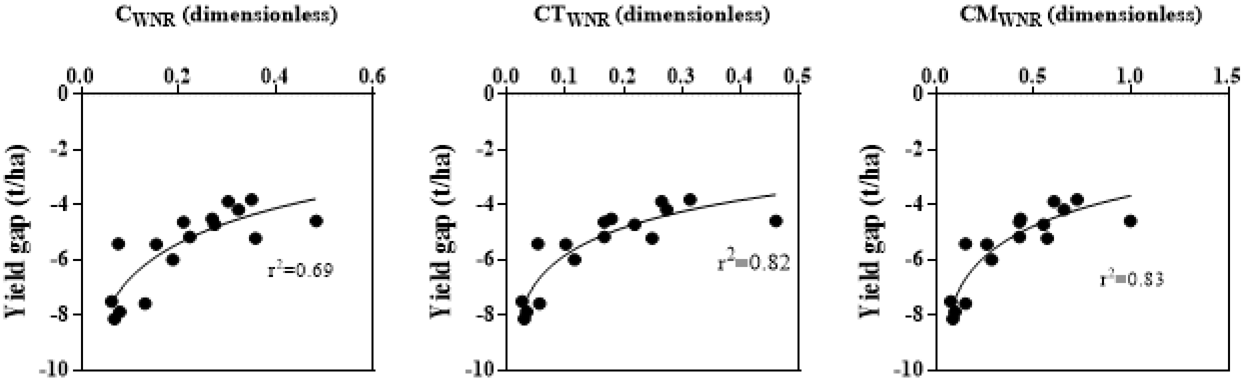

Figure 1. Yield gap as a function of C_{WNR} (left panel), CT_{WNR} (center panel) and CM_{WNR} (right panel) using the subset of data published in Cossani et al. (2010).

Similarly, a close and curvilinear relationship was found between water use efficiency and the co-limitation index (Figure 2), with a higher proportion of the variation in water use efficiency explained by CT_{WNR} and CM_{WNR}. The curvilinear relationship observed in figure 1 and 2 seems to have different reasons. In the first case, the low range of variability in co-limitation seems to be behind the curvilinear response of yield gap. However, in the second case, reaching maximum attainable levels of water use efficiency (24 kg grain/ha/mm) is the main reason for the curvilinear response.

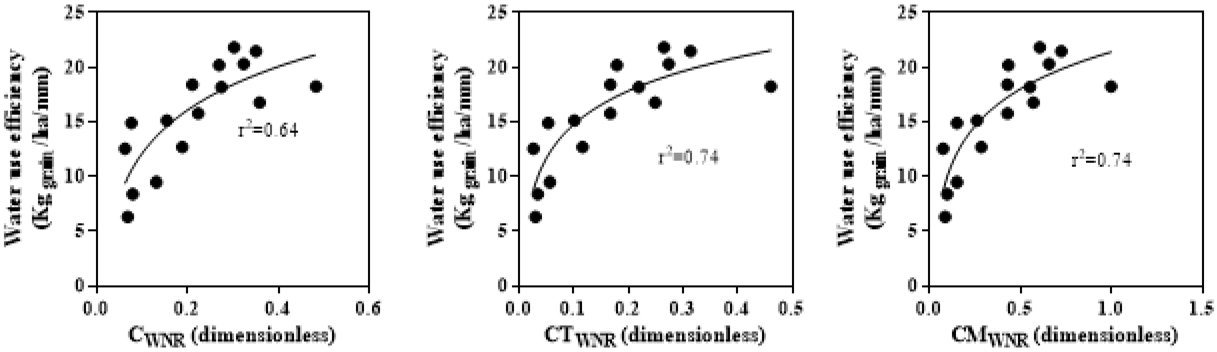

Figure 2. Water use efficiency as a function of C_{WNR} (left panel), CT_{WNR} (center panel) and CM_{WNR} (right panel) using the subset of data published in Cossani et al. (2010).

NUE correlated positively with C_{WNR} and was unrelated to CT_{WNR} and CM_{WNR} (data not shown). RUE was unrelated with the co-limitation index for the subset of data. However, when using all data from experiments, the RUE was positively correlated ($P < 0.01$) to CT_{WNR} and CM_{WNR} (data not shown).
IPAR declined with increasing intensity of stress for all three resources (Figure 3, left panel), and declined with increasing T_{WNR} or M_{WNR} (Figure 3, right panel). However, the combination of all resources explained a higher proportion of IPAR than each limitation independently.

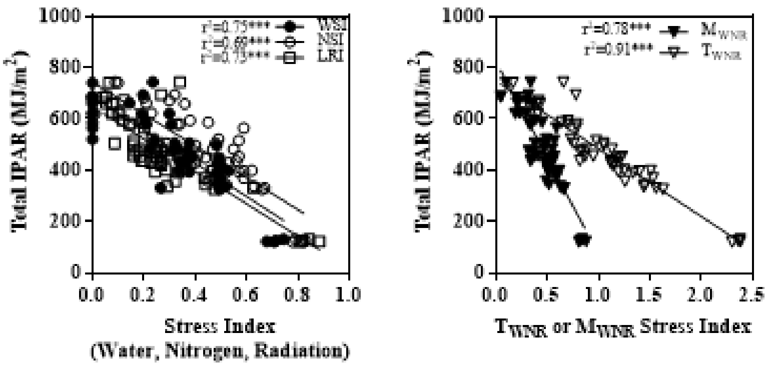

Figure 3. IPAR as a function of independent resource limitation or stress (left panel) and as a function of the combination of the all three resources limitation (right panel).

Radiation use efficiency was positively correlated to the N uptake/water use ratio (Figure 4) with a stronger correlation for biomass than for grain. Although in both cases the relationship between N uptake/water use ratio and radiation use efficiency were significant, it is important to note that in the best case the N uptake/water use ratio only explains 16% of the variability in radiation use efficiency.

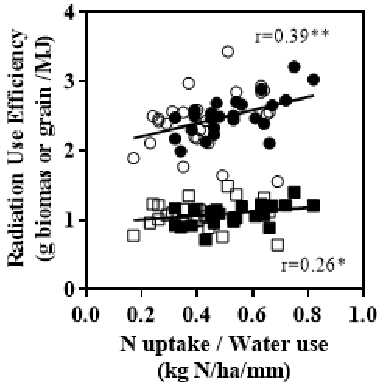

Figure 4. Radiation use efficiency as a function of the N uptake/water use ratio. Square symbols represent RUE $_{grain}$ while circles represent RUE $_{biomass}$. Closed symbols indicate rainfed conditions while open symbols indicate irrigated conditions.

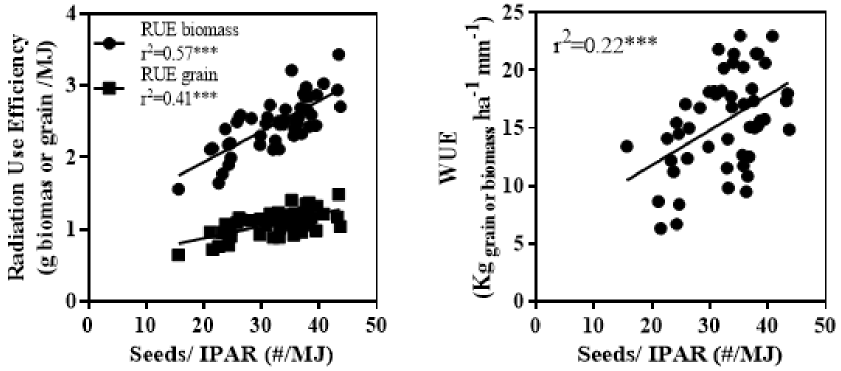

Figure 5. Radiation use efficiency (left panel) and water use efficiency (right panel) as a function of seed set per total intercepted photosynthetic active radiation. Squares represent RUE$_{grain}$ while circles represent RUE $_{biomass}$.

Furthermore, radiation use efficiency and water use efficiency were significantly ($P < 0.001$) related to the number of seeds per MJ of radiation intercepted (Figure 5).

Conclusion

A new method for estimating multiple co-limitation of resources was developed and evaluated for assessing wheat and barley productivity and resources use efficiency in Mediterranean environments. Multiple resources co-limitation explained the yield gaps and water use efficiency of the crops. IPAR was negatively related to all resources limitation and was better explained by the combination of all of them. While the N uptake/water use ratio explained 16% of the variability in radiation use efficiency, the competition for resources explained approximately 57% of the variability in radiation use efficiency. The higher competition for resources (measured by sink strength) increased the efficiency of using other resources such as water in a lower proportion (22%). These findings support the importance of considering multiple resources limitations for reducing yield gaps under Mediterranean conditions, as well as the importance of increasing the grain number for increasing resource use efficiency.

References

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

Cossani CM, Slafer GA and Savin R (2010). Co-limitation of nitrogen and water, and yield and resource-use efficiencies of wheat and barley. Crop and Pasture Science 61, 844-851.

Cossani CM, Slafer GA and Savin R (2012). Nitrogen and water use efficiencies of wheat and barley under a Mediterranean environment in Catalonia. Field Crops Research 128, 109-118.

Sadras VO (2004). Yield and water-use efficiency of water- and nitrogen-stressed wheat crops increase with degree of co-limitation. European Journal of Agronomy 21, 455-464.