Selection for yield increased nitrogen-water co-limitation, NUE and WUE in Australian wheat

C. Mariano Cossani[1, 2], Andrew Ware[2] and Victor O. Sadras[1]

[1] SARDI, Waite Building 11a Hartley Grove, Adelaide, SA 5001, http://pir.sa.gov.au/research, mariano.cossani@sa.gov.au
[2] SARDI, 1 Hinmarsh St., Port Lincoln, SA 5606

Abstract
The co-limitation approach has mainly been used in ecological studies. Fewer studies tested co-limitation in crops, providing insights into the link between water and N co-limitation and yield gaps in rainfed wheat. The current work analysed a set of modern and old wheat cultivars in terms of water and N co-limitation in a low rainfall location of Eyre Peninsula. The objective was to improve the understanding in water and N economy of wheat crops, and to test the co-limitation theory using an empirical approach under experimental field conditions. Results indicated genetic gains in wheat yields are associated with better resource use efficiency mostly driven by a higher capacity of N uptake per each mm of water used and improved root systems.

Keywords
Nitrogen, water, genetic gains.

Introduction
Availability of both N and water constrain crop production in low rainfall environments of Eyre Peninsula, South Australia, where infertile soils are common. Fertiliser is a costly input, and risk management may often lead to under-fertilisation. Low nutrient availability reduces potential yield and potential water use efficiency which is currently about 24 kg/ha/mm (Sadras and Lawson 2013). Therefore, higher resource use efficiency is imperative to reduce the gap between maximum attainable and actual yields under farming systems of Eyre Peninsula. The focus on resource co-limitation has increased in the last decade in an effort to improve the understanding of the primary productivity constraints (Sperfeld et al. 2016). In the broadest sense, co-limitation can be understood as the simultaneous limitation of yield, or growth by two or more resources (Bloom et al. 1985). The co-limitation theory was tested in rainfed crops by using simulation models and empirical approaches. These studies showed that high water and N co-limitation in cereals were associated with increased water use efficiency and reduced yield gaps in Australia and Spain (Sadras 2004; Cossani et al. 2010). In this paper, the objective was to improve the understanding in water and N economy of wheat crops, and to test the co-limitation theory using an empirical approach and local parameters under field experimental conditions.

Methods
A field experiment combining four wheat genotypes released in different decades, two N rates, and two water availabilities was sown on 13 May 2016 at Minnipa Agricultural Centre, Eyre Peninsula, South Australia. The genotypes span the last 50 years: Halberd (1969), Spear (1984), Mace (2007), and Scepter (2015). N conditions consisted of a control plot with only 12 kg of N/ha applied at sowing and, a second N fertilised treatment with 120 kg/ha of N applied in two different times before Zadocks 3.1. The two water treatments were 1) rainfed and 2) a crop with an additional 25 mm at beginning of stem elongation applied using a drip irrigation system. The sowing density was targeted at 180 plants per square meter, and rows spaced approximately at 27 cm. Prior to sowing, P was applied as MAP at a rate of 120 kg/ha. Weeds, pests, and diseases were controlled following the practices used for NVT trials.

We measured yield, nitrogen uptake at maturity, and gravimetric soil water content at sowing and maturity to 1m depth. Water use was calculated as the change in soil water between sowing and maturity plus in-season rainfall. Water use efficiency (WUE yield or biomass) was calculated as the ratio between grain yield and biomass (kg/ha) and water use (mm). Nitrogen use efficiency (NUE) and nitrogen utilisation efficiency (UTE). The levels of water stress (WSI) and N stress (NSI) were calculated using the method developed by Cossani et al. (2010) in another Mediterranean environment but using local parameters for WUE (24 kg/ha/mm), and yield potential (6.35 t/ha) and expressed in Equation 1 and 2.

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

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

A co-limitation index (C_{WN}) was calculated following the method of Cossani et al. (2010) as expressed in equation 3, where Cwn tended to 1 when the magnitude of the limitation due to water stress was similar to that attributable to N stress.

$$C_{WN} = 1 - |WSI - NSI| \quad \text{(Equation 3)}$$

Results

General results

In 2016, April to October rainfall was 27% greater than the long-term average for the experimental site. Critical period and grain filling (August to November) were cooler than the long-term average with a 1.6˚C lower minimum temperature and a 1.1˚C lower maximum. Grain yield of wheat increased with the year of release of the cultivar at a rate of approximately 24 kg/ha/year. There was a genotype x water availability interaction showing a higher response to extra water supply for the modern cultivars in comparison with the older lines. Yield ranged from 4.8 t/ha for Scepter with the extra-supply of water, to 3.5 t/ha for Halberd (with no irrigation). High seasonal rainfall combined with previous crop (legume pasture) limited the range of stresses, from 0.06 to 0.25 for WSI and 0.16 to 0.33 for NSI, and also reduced the yield range in response to treatments.

Nitrogen and water economy

Water use from sowing to maturity ranged between 249 mm and 312 mm among all treatments. The oldest cultivars used more water (P<0.001) than the new cultivars (269 mm, 270 mm, 289 mm and 291 mm for Mace, Scepter, Halberd and Spear, respectively). Water use efficiency (kg $_{grain}$/ha/mm) was significantly affected by water availability x cultivar interaction and ranged between 10.8 and 17.5 kg $_{grain}$/ha/mm for all cultivars and conditions. The highest water use efficiency was observed for Scepter with extra water supply (17.2 kg $_{grain}$/ha/mm) which was approximately 50% more efficient in using water than Halberd. Intermediate water use efficiency was found for Spear (13.2 kg $_{grain}$ /ha/mm) and Mace (15.4 kg $_{grain}$/ha/mm). The observed rate of genetic improvement in WUE was 0.11 kg $_{grain}$/ha/mm/year (Figure 1).

Nitrogen uptake ranged from 126 kg $_{N}$/ha to 155 kg $_{N}$/ha among all treatments, depending on cultivar*N*water interaction, although there was no trend related to the year of release. Scepter was the most responsive cultivar to nitrogen supply. Nitrogen use efficiency (NUE) ranged from 12.5 to 21.4 kg $_{grain}$ /kg $_{N}$ available and decreased with the higher soil N supply / availability as expected (14.2 kg $_{grain}$ /kg $_{N}$ available *vs*. 17.6 kg $_{grain}$ /kg $_{N}$ available for fertilised and unfertilised treatments, respectively). Similarly to grain yield and to WUE, NUE increased with the year of release at a rate of 0.087 kg $_{grain}$/kg $_{N}$ available/year. There was a general increase in NUE as a consequence of higher water availability (16.7 kg $_{grain}$ /kg $_{N}$ available *vs.* 15.0 kg $_{grain}$ /kg $_{N}$ available for extra water and rainfed treatments, respectively). Furthermore, there was an increase (r^2= 0.88***) in N utilisation efficiency (UTE) (kg $_{grain}$ /kg $_{N}$ uptake) with the year of release at a rate of approximately 0.13 kg $_{grain}$ /kg $_{N}$ uptake/year (Figure 1).

Given the high N in soil and high rainfall during the growing season, co-limitation range was narrow, between 0.79 and 0.96, indicating balanced stress of water and N. Following the same pattern observed for grain yield, the higher co-limitation between N and water stress was obtained by Scepter (0.95) while the poorest balance was observed for Halberd (0.86). Interestingly, and in line with the resource use efficiency, the balance between water and N limitations, expressed as co-limitation, was higher in the modern than in the old cultivars (Figure 2). There was a positive correlation between grain yield and water and N co-limitation (r=0.95***). N and water co-limitation was also positive related to WUE, NUE, and UTE (Figure 3).

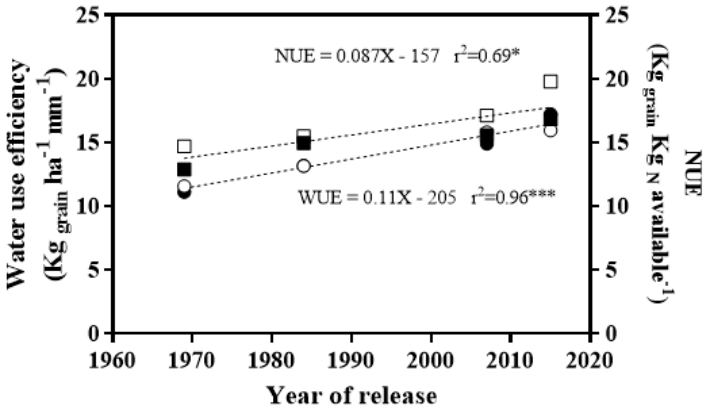

Figure 1. Water use efficiency (left Y axis and circle symbols) and nitrogen use efficiency (right Y axis and square symbols) as a function of the year of release for all 4 cultivars evaluated. Closed symbols represent treatment with 25mm of extra water, while open symbols represent rainfed conditions.

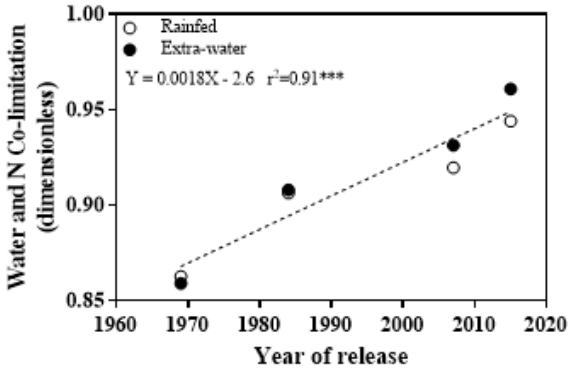

Figure 2. Water and N co-limitation as a function of the year of release for all 4 cultivars. Closed circles represent treatment with 25mm of extra water, while open circles represent rainfed conditions.

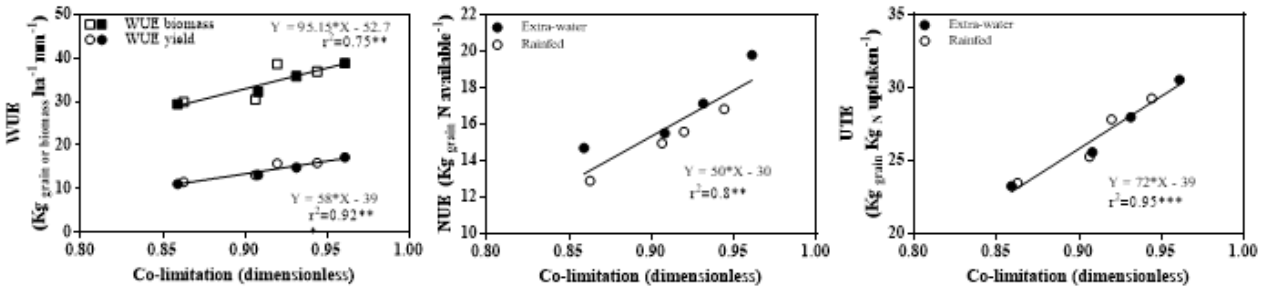

Figure 3. Water use efficiency (WUE), nitrogen use efficiency (NUE), and nitrogen utilisation efficiency (UTE) as a function of water and N co-limitation for all 4 cultivars. Closed symbols represent treatment with 25mm of extra water, while clear symbols represent rainfed conditions.

In general, modern cultivars tended to take up more N per each mm of water used (Figure 4). There were no significant differences between both modern cultivars (Mace, Scepter), while differences between old cultivars indicated a higher capacity to take up N per each mm of water used for Spear than for Halberd. The higher capacity to take up N per each mm of water used was also positive related to the grain yield (r =0.82**), WUE (r =0.95***), NUE (r=0.70*), UTE (r = 0.90**) and co-limitation (r =0.87**). Moreover, the results are in line with recently published research for Australia which demonstrates that modern cultivars have higher N uptake per unit root biomass in comparison with old cultivars (Aziz et al. 2016).

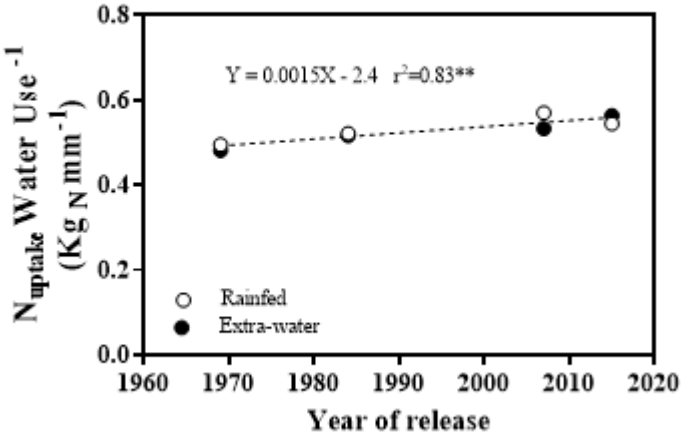

Figure 4. N uptake per mm of water used as a function of the year of release for all 4 cultivars. Closed dots represent treatment with 25mm of extra water, while clear dots represent rainfed conditions.

Conclusions

Our study supports previous evidence about the association between yield and resource use efficiency with water and N co-limitation in wheat (Cossani et al. 2010; Sadras 2004), and has implications for both wheat breeding and agronomy in Australia. Similar to previous reports, we found no trends for water use among the different periods of breeding; resources use efficiency was the main driver of yield improvement as previously reported (Sadras and Lawson 2013; Siddique et al. 1990). Our results coincided with previous prospective studies of Australian wheat indicating a shift in the resources economy (UTE) of the crop (Sadras and Lawson 2013). The genetic gains in WUE fits with the previously reported rate for Australian wheat between 1900s and 2007 (Sadras and Richards 2014). An improved capacity for uptake of nitrogen by each mm of water used was observed in the modern wheat cultivars. These improvements were associated with a better resource use efficiency (water and N) and with higher degree of co-limitation.

Acknowledgments

Authors thank the support of Grains Research and Development Corporation for co-funding the research project activities and to Leigh Davies, Brenton Spriggs and Sue Budarick for their collaboration with field and lab activities.

References

Aziz MM, Palta JA, Siddique KHM and Sadras VO (2016). Five decades of selection for yield reduced root length density and increased nitrogen uptake per unit root length in Australian wheat varieties. Plant and Soil, 1-12.

Bloom AJ, Chapin Iii FS and Mooney HA (1985). Resource limitation in plants - an economic analogy. Annual Review of Ecology and Systematics 16, 363-392.

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

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.

Sadras VO and Lawson C (2013). Nitrogen and water-use efficiency of Australian wheat varieties released between 1958 and 2007. European Journal of Agronomy 46, 34-41.

Sadras VO and Richards RA (2014). Improvement of crop yield in dry environments: Benchmarks, levels of organisation and the role of nitrogen. Journal of Experimental Botany 65, 1981-1995.

Siddique KHM, Tennant D, Perry MW and Belford RK (1990). Water use and water use efficiency of old and modern wheat cultivars in a Mediterranean-type environment. Australian Journal of Agricultural Research 41, 431-447.

Sperfeld E, Raubenheimer D and Wacker A (2016). Bridging factorial and gradient concepts of resource co-limitation: Towards a general framework applied to consumers. Ecology Letters 19, 201-215.