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Benchmarking wheat yield against crop nitrogen status

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ABSTRACT

Availability of nitrogen and water are major constraints for crop yield, and their interactions are manyfold. Yield gap analysis in rainfed systems commonly uses water-limited yield potential (Y_w) as a benchmark; benchmarking against nitrogen-limited yield potential (Y_N) is less common. The aim of this study was to benchmark wheat yield against Y_N in winter-rainfall regions of Australia. We established experiments, and sampled both farmers' fields and National Variety Trials spanning wide ranges of soils, management practices, and water supply (seasonal rainfall + irrigation) from 153 to 759 mm in South Australia, and from 178 to 428 mm in Western Australia. We measured yield, quantified crop nitrogen nutrition index (NNI) at stem elongation, anthesis or both, derived boundary functions relating Y_N and NNI, calculated yield gaps as the difference between Y_N and actual yield, and explored the associations between yield gaps and environmental, crop and agronomic factors.

In South Australia, NNI at anthesis ranged from 0.45 to 1.45 and yield from 0.9 to 8.9 t ha^{-1}; in Western Australia NNI at stem elongation ranged from 0.27 to 1.16 and yield from 1.0 to 7.1 t ha^{-1}. Bi-linear boundary functions were fitted with a linear Y_N – NNI phase up to a NNIx threshold (0.95 ± 0.134 in South Australia, 0.87 ± 0.145 in Western Australia), and a plateau reflecting yield potential (7.8 ± 0.38 t ha^{-1} in South Australia, 6.5 ± 0.52 t ha^{-1} in Western Australia). Similar bi-linear boundaries, with congruent NNIx (≈0.9), were found for grain number and shoot biomass at maturity. In South Australia, water supply explained 54% of the yield gap, which declined linearly from about 6 t ha^{-1} to zero with increasing water availability. Further, the yield gap correlated negatively with carbon isotope discrimination at anthesis, a direct measure of crop water status. In Western Australia, the direct association between yield gap and rainfall was weak, but there was an indirect agronomic link, where low seeding rate in low rainfall environments contributed to low biomass at stem elongation, which in turn explained a large part of the yield gap.

In two out of five National Variety Trials, where the aim is comparing the yield of current and emerging varieties, crops were nitrogen deficient. This is a potential source of bias as some varieties were above and others below the NNIx threshold of nitrogen sufficiency. Supply of nitrogen in varietal comparisons needs attention.

The approach advanced in this paper can be applied to benchmark yield against crop nitrogen status and identify causes of yield gaps, and for in-season quantification of crop nitrogen status to assist fertiliser decisions directly, or indirectly as a reference for spectral indices.

1. Introduction

The interactions between nitrogen and water are manyfold, and have recently been reviewed from the perspective of co-limitation (Cossani and Sadras, 2018) and with a narrower focus on wheat-based systems of Australia (Sadras et al., 2016), the subject of this paper. In the winter-rainfall regions of south-eastern and western Australia, uncertain and often low rainfall has a two-fold effect: direct on crop growth and yield, and indirect influencing farmer's attitude to risk and input level. Combined with low soil fertility, low nitrogen rates as a risk management strategy might contribute to nitrogen deficiency (Monjardino et al., 2013; Monjardino et al., 2015).

French and Schultz (1984b,a) developed a widely used benchmark for wheat yield against evapotranspiration, which has been updated for new wheat varieties (Sadras and Lawson, 2013), expanded to other regions worldwide (Sadras and Angus, 2006; Patrignani et al., 2014), and applied to other grain crops (Grassini et al., 2009; Grassini et al., 2011a,b). Further, water-limited yield potential (Y_W) derived with French and Schultz (1984a,b) or more refined models, is used to benchmark actual yield and identify yield gaps in rainfed cropping

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Table 1
Summary of experiments for benchmarking yield against crop nitrogen status in South Australia. GSR: growing season rainfall (April–October). Exp. 4 was embedded in and used the protocol of the National Variety Trial (NVT). Coordinates of locations and soil types (Isbell, 1996) are: Hart (34°S, 138°E, Dermosol), Turretfield (35°S, 140°E, Chromosol), Roseworthy (34°S, 139°E, Calcarosol), Wolseley (36°S, 141°E, Vertosol), Wanbi (35°S, 140°E, Calcarosol), Pinnaroo (35°S, 141°E, Chromosol).

Exp.	Year	Location	GSR (mm)	Sowing date	N rate ($kg\,ha^{-1}$)	Variety[a]	Comments/other treatments
1	2015	Hart	399	30/04 26/05	0, 60 (split at sowing and tillering)	Axe, Mace, Trojan, Scout, Cobra, Spitfire	Factorial combining 2 seasons, 2 sowing dates, 2 N rates, 6 varieties
	2016	Hart	630	17/05 02/06			
2	2014	Hart	448	16/05	0, 60 (at sowing), 120, 180[b], 240 (split at sowing and tillering)	Axe, Mace, Trojan, Scout	Factorial combining 4–5 N rates and 4 varieties; rainfed in 2014; 2 water regimes in 2015 and 2016: rainfed and irrigated
	2014	Turretfield	347	30/06			
	2015	Roseworthy	235	26/05			
	2016	Roseworthy	459	02/06			
3	2014	Hart	448	12/05	0, 80 at sowing; 40 or 80 at tillering; 80 (as Entec® urea) at tillering, NDVI-based tactical treatment applying 25–77 $kg\,N\,ha^{-1}$	Mace	Factorial combining 3 seasons, 6 N treatments and 2 previous crops (canola, pulse: lentil in 2014, field pea in 2015 and 2016)
	2015	Hart	399	03/05		Mace	
	2016	Hart	630	02/05		Trojan	
4	2014	Wolseley	239	17/06	83	*All 3 seasons:* Axe, Emu Rock, Grenade, Mace, Scout, Shield, Trojan *Additionally in 2014*: Estoc, Gladius, Phantom, Cobra, Corack, Wallup, Wyalkatchem, Yitpi	Subset of varieties in NVT, using the same protocol as main trial
	2015	Turretfield	262	26/05	27 or 42		
	2015	Wanbi	153	21/05	8 or 16		
	2016	Turretfield	498	03/06	48 or 96		
	2016	Pinnaroo	355	17/05	40 or 80		

[a] Variety grade: Australian Hard (Axe, Cobra, Emu Rock, Gladius, Granade, Mace, Phantom, Scout, Shield, Wallup, Yitpi), Australian Premium White (Corack, Estoc, Trojan, Wyalkatchem); source and further information on these varieties: https://grdc.com.au/_data/assets/pdf_file/0022/233068/sowing-guide-2017_lo-res.pdf.pdf.

[b] In 2014 at Hart, an additional treatment was included: 180 kg N ha split at sowing, tillering and stem elongation.

systems (van Ittersum et al., 2013; Sadras et al., 2015). Benchmarks to define a nitrogen-limited yield potential (Y_N) and calculate yield gaps are less developed (Hochman et al., 2013; Sadras et al., 2015).

Relationships between yield and nitrogen uptake could be used to determine Y_N (Hochman et al., 2013; Sadras et al., 2015) but nitrogen uptake is co-regulated by nitrogen availability in soil and potential crop growth rate (Gastal et al., 2015). To account for this, the Nitrogen Nutrition Index (NNI) is calculated as the ratio between the actual shoot nitrogen concentration and the critical nitrogen concentration ($\%N_c$) derived from nitrogen dilution curves that capture the allometric relationship between nitrogen concentration and shoot biomass (Gastal et al., 2015). The NNI can be used to benchmark crop yield at the end of the season, in-season as a diagnostic tool to guide fertiliser management, and as a standard to calibrate other methods to assess crop nitrogen status, including spectral indices (Sadras and Lemaire, 2014).

The parameters of dilution curves have been mostly determined in well-watered crops and have been considered virtually constant within C3 or C4 species (Gastal et al., 2015). However, $\%N_c$ was lower in water-stressed potato (Belanger et al., 2001) and tall fescue (Errecart et al., 2014) compared to their well-watered counterparts. In wheat, phenological development, water supply and water soluble carbohydrates in shoots all affect the parameters of nitrogen dilution curves (Angus, 2007; Sadras and Lemaire, 2014; Zhao et al., 2014; Hoogmoed and Sadras, 2016). Hoogmoed and Sadras (2018) summarised these effects, and derived robust empirical, stage-dependent$\%N_c$ that partially captures the plant and environmental factors that influence the biomass and nitrogen allometry of current wheat varieties in south-eastern Australia.

Here we use yield-NNI boundary functions to estimate nitrogen-limited yield potential in winter-rainfall regions of Australia. Our aims were to benchmark yield against Y_N, calculate yield gaps, and explore some of their causes. Two sets of experiments were established where nitrogen status was measured (i) at anthesis, for benchmarking of yield, and (ii) at stem elongation, to test the feasibility of using this trait for in-season diagnostic and management.

2. Method

2.1. Overview

We measured yield, quantified crop NNI at stem elongation, anthesis or both, derived boundary functions relating nitrogen-limited yield potential Y_N and NNI, calculated yield gaps as the difference between Y_N and actual yield, and explored the associations between yield gaps and environmental, crop and agronomic factors.

2.2. Sites

The trials for benchmarking yield against NNI at anthesis (experiments 1–5) were located in South Australia, and the trials for benchmarking yield against NNI at stem elongation (experiment 6) were located in Western Australia. In these regions, wheat is the main crop, and is grown in rotation with break crops as summarised in Angus et al. (2015). These environments have a Mediterranean-type climate (di Castri and Mooney, 1973), with winter dominant rainfall, high frequency of small rainfall events, hot dry summer, and with some exceptions, soils with low fertility (Fischer, 2009; Sadras et al., 2016). The most severe, and one of the more frequent drought types in these environments, has an onset about 500 °Cd before anthesis (Chenu et al., 2013). Seasonal rainfall (April–October) was calculated with records from on-site stations where available, or the nearest station of the Australian Bureau of Meteorology (https://www.longpaddock.qld.gov.au/silo/). Seasonal rainfall (+irrigation) during the experiments ranged from 153 to 759 mm in South Australia, and from 178 to 428 mm in Western Australia. For both regions, Dreccer et al. (2017) characterised the photo-thermal regimes and their impact on wheat yield. (2017)

2.3. Experiments 1–5: benchmarking yield against NNI at anthesis in South Australia

A dataset (n = 295) was compiled using three sources: (i)