Excess nitrogen also reduces yield in high yielding wheat crops

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Abstract
Inadequate nitrogen (N) nutrition is regarded as a key reason that Australian rain-fed wheat crops do not achieve their water-limited potential yield. There is a belief that overall N nutrition could be increased without penalty ('N bank' concept). Newer varieties are less likely to experience 'haying-off', and excess N should be recovered in grain protein or at least have minimal yield effect. Results from 23 N experiments in southern Australia (part of the "Hyper Yielding Crops" program), often on fertile sites and/or with high N rates were used to investigate the effects of N applied in excess to wheat in higher yielding seasons.

Nitrogen treatments were effective in 21 of the experiments, at maximum yields ranging between 4.2 and 13.1 t/ha. Fertiliser N use efficiency estimated at the lowest rate averaged 0.26, ranging up to 0.6-0.7 in two Tasmanian experiments. The highest yield responses (12.6 kg grain/kg N) were observed in relatively few experiments, with negative yield responses (to -16.8 kg grain/kg N) common in experiments with yields > 9 t/ha, on both winter and slow-spring cultivars.

Predictor variables that might help forecast nitrogen rates for maximum yield in these environments did not include rainfall, but did include the photothermal quotient between stem elongation and anthesis, the duration of the vegetative period in thermal time, and a negative relationship with soil organic carbon.

Keywords
Haying off, lodging, soil mineral nitrogen, growing season rainfall

Introduction
Fertiliser N applied in excess to high yielding wheat in southern Australia is regarded by some growers (like over-application of fungicide) as an "insurance policy". Some may see waste of the N as a cost, but also that it has value for the subsequent crop. There is some appreciation of potential environmental issues, but little regard for any yield penalty apart from awareness of the need to manage lodging. This study collates N experiments that were part of the Hyper Yielding Crops program (2016-2023) to draw conclusions on the rate and nature of yield penalty to excess N in southern Australia.

Grower attitudes in high-yield environments may be a consequence of exposure to low- and medium-rainfall N agronomy. Inadequate N nutrition has been regarded as a key element of the 'yield gap' between actual and water-limited yields (Hochman and Horan 2018). Excess applications are recognised as necessary to stabilise declining soil organic matter. Maintained soil mineral and organic N is the self-regulated source of N in higher yield potential seasons (compared to in-season top-dressing) that is central to the 'N bank' concept (Smith et al. 2019). The profitability of these practices depends on yield reductions being minimal when N is in excess.

Excess N applied to spring wheat in low yield environments increases pre-anthesis growth, and in turn grain number and water use. Besides potential reduced post-anthesis water use and photosynthesis, assimilate fixed in late tillers is not retranslocated to grain (van Herwaarden et al. 1998b, a). The result is more, much smaller grains, with higher protein (although protein remobilisation also reduces). Increased grain size in recent cultivars (Flohr et al. 2018) may counteract that. In high yield environments, the sink for productive N storage in the RUBISCO protein is limited, and the plant uses protein in stem tissue to store the additional N required for high grain yields (Pask et al. 2012). Protein synthesis consumes assimilate (Bhatia and Rabson 1976) and appears to compete with grain set, with minimal increase in grain number above the yield maximising N rate, and poor remobilisation of storage protein (Pask 2009).

Methods
Experiments
Wheat N fertiliser response experiments were conducted in the high rainfall zones of mostly eastern Australia between 2016 and 2023 (described in more detail in results compendiums; https://faraustralia.com.au/resource, summarised Table 1). These mostly had 4-8 rates, with split applications

and sometimes timing differences, and a single cultivar. Locations are referred to by state: NSW (Wallendbeen), SA (Millicent), Tas (Hagley), Vic (Gnarwarre) and WA (Frankland River). Experiments were randomised complete block designs with four replicates sown in 12 m x 8 row (0.225 m spacing) plots.

All experiments followed break crops on soils with generally good inherent fertility. Where experiments contained additional treatments (for example manures, late applications, or additional non-N fertiliser), only N fertiliser treatments applied spread throughout the growing season were included. Crops were managed to minimise disease and lodging. Lodging was rated for severity (0-5) and proportion of plot affected (0-100) giving a score of up to 500 on experiments where it was observed.

Analysis

Machine harvest yields and proteins were measured as-is and converted to 12 % moisture basis. Nitrogen harvested in grain (NHarv) was calculated as yield x protein / 5.7. Two-sample Kolmogorov-Smirnov tests (R dgof) were used to estimate the degree of lodging that affected protein – yield relationships for low, medium and high yield experiments. The effectiveness of N treatments was assessed by significant relationships with N yield or protein response in grain, using the best fit of simple quadratic or linear models of N rate and replicate. Confidence interval on the initial response slope was estimated by non-parametric (ordinary) bootstrap (R boot, n=2000).

Yield was fitted to linear or two-segment (R segmented; "bent") models of N rate. Where bent models were significant, the optimum N rate and yield was taken according to slope at lowest, break, or highest N rate. Where not significant, linear model slope was used to select either lowest or highest rate as the optimum.

Cultivar phenology scores (Zadoks) on these or comparable experiments were interpolated to estimate the calendar day for the start of stem elongation (30), mid-flowering (65), and physiological maturity (90). The growing season was broken into fallow (1 Jan – sowing), vegetative (sowing – 30), stem elongation (30 – 65), and grain-fill (65 – 90) periods, for which rainfall + irrigation, radiation, average temperature (base 0°C) and photothermal quotient (PTQ) were calculated from the nearest Silo DataDrill location (https://www.longpaddock.qld.gov.au/silo/point-data/).

Results

There were 23 experiments with three or more N rates, 8 of which had some degree of lodging. Lodging with score >120 significantly affected yield/protein distributions (not shown) and were excluded, or where this left < 7 remaining plots, all plots analysed (SA Accroc 2022, Tas. Manning and Bennett; Table 1). Nitrogen treatments were effective in 21 experiments, mostly (17) on the basis of NHarv. In these experiments the initial slope of the model estimates the fertiliser N use efficiency at the lowest treatment; this averaged 0.26 and was over 0.1 in 13 experiments, ranging up to 0.6-0.7 in two Tas experiments, was negative in the lodged Accroc, and below 0.1 in three more experiments.

Table 1. Details of nitrogen fertiliser experiments including lodging, relevant soil test results, and result of a fit of nitrogen harvest in grain or protein on nitrogen fertiliser rate as a check on the effectiveness of treatments.

State	Sown	Cultivar	Plots (lodged)	OC_{0-10} (%)	N_{0-60} (kg/ha)	Fert. N range (trts) (kg/ha)	Effectiveness check Basis	Slope	(95% CI)	p^2
NSW	21-Apr-20	Accroc	12	1.1	138	154-259 (3)	NHarv	0.121	0.001-0.202	*
NSW	21-Apr-20	Coolah	12	1.1	138	154-259 (3)		0.000	0.000-0.000	
NSW	20-Apr-21	Accroc	20	1.9	59	12-316 (5)	NHarv	0.370	0.272-0.480	*
NSW	20-Apr-21	Rockstar	19	1.9	59	167-432 (5)	NHarv	0.165	0.103-0.217	***
NSW	21-Apr-22	Accroc	28 (9)	2.1	142	0-280 (6)	NHarv	0.206	0.013-0.538	*
NSW	21-Apr-23	Stockade	28	2.6	226	0-280 (7)	NHarv	0.256	0.175-0.332	**
SA	17-Apr-20	Accroc	12	9.8	228	132-172 (3)	Prot	0.008	0.003-0.012	**
SA	12-May-21	Accroc	20	13.5	0	0-240 (5)	Prot	0.003	0.001-0.004	*
SA	21-Apr-22	Accroc	28 (25)	11.0	108	0-280 (7)	NHarv	-0.028	-0.055-0.002	*
SA	11-May-23	Rockstar	28	8.0	253	0-280 (7)	NHarv	0.038	0.021-0.053	***
Tas	06-Apr-16	Manning	18 (18)	2.5	160	60-280 (6)	Prot	0.002	0.000-0.005	*
Tas	06-Apr-17	Relay	16 (2)	2.3	160	0-200 (4)	NHarv	0.726	0.315-1.293	*

Tas	06-Apr-17	Relay[1]	24 (3)	2.3	160	0-280 (6)	NHarv	0.535	0.186-0.932	*
Tas	05-Apr-18	Bennett	12 (8)	2.0	0	160-240 (3)		0.000	0.000-0.000	
Tas	05-Apr-18	Relay	12	2.0	0	160-240 (3)	Prot	0.012	0.002-0.018	*
Tas	04-Apr-19	Relay	28	1.9	85	0-384 (7)	NHarv	0.281	0.136-0.463	*
Tas	29-Apr-21	Accroc	16	2.2	131	10-291 (4)	NHarv	0.629	0.343-0.977	*
Tas	28-Apr-22	Relay	28	2.0	165	0-280 (7)	NHarv	0.046	0.014-0.077	*
Tas	26-Apr-23	Stockade	28	1.9	110	0-280 (7)	NHarv	0.148	-0.042-0.294	*
Vic	25-Apr-20	Accroc	12	2.4	104	150-220 (3)	NHarv	0.224	0.070-0.365	**
Vic	28-Apr-22	Accroc	28 (12)	2.4	173	0-280 (7)	NHarv	0.090	0.004-0.151	**
Vic	29-Apr-23	Cesario	28 (7)	2.4	118	0-280 (7)	NHarv	0.265	0.072-0.420	*
WA	29-Apr-23	Mowhawk	18	2.8	83	110-156 (5)	NHarv	0.320	0.171-0.509	**

1. Treatment with a third (Nov 2) split, vs two in the remainder. 2. * <0.05, ** <0.01, *** <0.001

Estimated maximum yields (at the optimum N rate) ranged between 4.2 and 13.1 t/ha (Table 2). Few experiments had a significant positive yield response below the optimum (up to 12.6 kg grain/kg N); relatively more had negative responses above the optimum (up to -16.8 kg grain/kg N). The high positive response to final N increments in Mowhawk 2023 was observed in some replicates across the dataset. Negative responses were typically observed at high yields (>9 t/ha), but also some low yield experiments, and in high yield spring wheat (Stockade, Tas 2023).

Table 2. Estimates of optimum nitrogen fertiliser rate from segmented linear ("bent") or linear models, with estimates of yield at the optimum rate, and slope(s) of the yield/nitrogen relationship.

State	Sown	Cultivar	Model	Optimum N		Max Yield		Slope 1		Slope 2	
				(kg/ha)	se	t/ha	95% CI	kg/kg N	se	kg/kg N	Se
Tas	06-Apr-17	Relay[1]	Bent	280.0		13.1	12.4-13.7	8.6	±2.8	1.6	±3.5
Tas	06-Apr-17	Relay	Bent	110.4	±32.3	12.8	11.8-13.7	12.6	±4.3	-11.9	±11.1
Tas	06-Apr-16	Manning	Bent	60.0		12.1	11.6-12.3	-2.2	±1.7	-4.3	±6.1
Tas	29-Apr-21	Accroc	Bent	221.2	±16.3	11.8	11.1-12.4	12.2	±1.5	-16.8	±7.6
Tas	26-Apr-23	Stockade	Bent	120.0	±32.0	11.5	11.0-11.9	1.3	±2.3	-8.1	±2.3
Tas	04-Apr-19	Relay	Bent	0.0		11.1	10.9-11.6	-1.5	±0.8	-5.6	±2.1
NSW	21-Apr-20	Accroc	Linear	259.0		10.1	9.6-10.5	0.0	±0.0	0.0	±0.0
Tas	05-Apr-18	Relay	Linear	160.0		10.0	9.6-10.5	0.0	±0.0	0.0	±0.0
Vic	25-Apr-20	Accroc	Linear	150.0		9.9	9.3-10.5	0.0	±0.0	0.0	±0.0
NSW	20-Apr-21	Accroc	Bent	241.0		9.6	8.9-10.3	10.8	±2.0	4.4	±8.6
Tas	28-Apr-22	Relay	Linear	0.0		9.5	8.9-10.1	1.1	±3.4	-3.4	±3.3
SA	12-May-21	Accroc	Bent	0.0		9.5	9.3-10.8	-1.9	±2.6	-15.7	±6.9
SA	11-May-23	Rockstar	Linear	280.0		8.9	8.7-9.0	0.5	±0.5	1.6	±3.0
NSW	20-Apr-21	Rockstar	Bent	357.0		8.2	7.5-9.0	4.2	±2.7	10.4	±9.3
NSW	21-Apr-23	Stockade	Linear	280.0		8.2	7.8-8.6	2.7	±2.3	-1.6	±2.2
NSW	21-Apr-22	Accroc	Bent	88.4	±23.3	7.5	6.9-8.1	0.6	±3.4	-12.8	±2.7
SA	17-Apr-20	Accroc	Linear	172.0		7.4	6.7-8.0	0.0	±0.0	0.0	±0.0
Vic	28-Apr-22	Accroc	Linear	0.0		7.1	6.7-7.5	0.1	±1.5	-3.5	±5.5
Vic	29-Apr-23	Cesario	Linear	0.0		5.9	5.4-6.4	1.7	±2.9	-3.2	±3.4
WA	29-Apr-23	Mowhawk	Bent	110.0		5.1	4.5-5.0	-12.6	±7.0	24.4	±14.7
SA	21-Apr-22	Accroc	Bent	97.1	±60.2	4.2	3.7-4.7	1.2	±3.0	-3.2	±1.4

1. Treatment with a third (Nov 2) split, vs two in the remainder.

Many predictor variables were explored to find relationships that might help to forecast N rates (N_{Fert}) for maximum yield (Yld_{Max}). Combinations of rainfall in various periods, soil mineral (N_{0-60}) and N_{Fert}, and organic carbon (OC) proved non-significant (not shown).

Average PTQ during stem elongation (PTQ_{SE}) was a significant predictor of Yld_{Max} in this dataset, and the sites contained some high OC levels (relative to rainfall-limited environments). Linear models of $OC^{0.5}$ (creating a semi-asymptotic relationship) and thermal time for the vegetative phase (TT_{Veg}) were significant, albeit with some significant environmental correlation (-0.49 between PTQ_{SE} and $OC^{0.5}$, -0.64 between TT_{Veg} and N_{Fert}) and inflation of variance estimates (up to 3.5 for TT_{Veg}, and 3.7 for N_{Fert}):

$$Yld_{Max} = -6.86\ (\pm 2.93) + 3.14\ (\pm 1.91) \times PTQ_{SE} + 0.0117\ (\pm 0.0028)\ TT_{Veg} - 3.21\ (\pm 0.76)\ OC^{0.5} + 0.0127\ (\pm 0.0056)\ N_{0\text{-}60} + 0.0144\ (\pm 0.0047)\ N_{Fert}$$

where Yld_{Max} is in t/ha (12% moisture basis), PTQ_{SE} is in MJ/°C, TT_{Veg} is in °C days (>0°C base), $OC^{0.5}$ is in $\%^{0.5}$, and $N_{0\text{-}60}$ and N_{Fert} are in kg N/ha. Adjusted R^2 0.79, $p<0.001$.

The coefficients imply TT_{Veg} is either a proxy for mineralisation or a contribution to yield (eg. via increased carbohydrate/N stored prior to stem elongation). The coefficient of 0.0117 equates to an extra tonne of yield per 85°C days. Soil OC reduces Yld_{Max}; this may relate to waterlogging, or other inhibitions to mineralisation/growth in high OC soils. The coefficients were similar even with OC >5% excluded. The coefficients on N_{Fert} and $N_{0\text{-}60}$ imply 70 – 79 kg N required per tonne of grain approaching Yld_{Max}. Pending further understanding, these rates need to be considered together with the other coefficients in this model, and its fit to relatively fertile sites.

The analysis has been done in terms of Yld_{Max}; given the relatively high site fertility (and variation between replicates, and high variability at very high N rates), it was difficult to fit an asymptotic model that would allow for a price-sensitive break-even yield calculation. At $250/t grain price, the higher responses of 12.6 kg grain/kg N allow for N priced up to $3.15/kg N (~$1450/t urea). The negative yield responses equate to a loss of at least $4 grain/kg N applied, in addition to the cost of the fertiliser.

The negative responses had similar magnitude to those observed in high yield environments with winter wheat (Pask et al. 2012) and medium yield environments with spring wheat (van Herwaarden et al. 1998b, a). Some of the steeper decreases paralleled the assimilate requirement for protein synthesis of 15 kg glucose per kg N, although the average slope of the "decrease" experiments of Pask et al. and Herwaarden et al. was about 5 kg grain per kg excess N (not shown).

Conclusion

Crops yielding > 9 t/ha were likely to decrease in yield as more nitrogen was applied than required for maximum yield on relatively fertile sites, and this applied to spring as well as winter cultivars. At most the rate was similar to the assimilate cost of storing additional nitrogen: 15 kg per kg N, possibly exceeding 1 t/ha. In about half of the experiments a lesser rate was observed, and the cost of over-applied urea would be the main penalty. Growers of high-yield potential crops need to be particularly cautious about over-applying nitrogen, and applying low- and medium-rainfall agronomy concepts to estimate nitrogen requirements.

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