Crop Nutrient Decisions in the High Rainfall Zone

Technical Report

Front cover photo: Response of canola to additional P at an omission trial site at Tarrington. Left: canola plot supplied with no additional P at sowing (only N, K, S, Zn, and Cu). Right: supplied with 50 kg P/ha at sowing (with N, K, Zn, and Cu). Background Colwell P 62 mg/kg, whereas responses are not normally expected above 27 mg/kg. Photo 6 July 2016, 7 weeks after sowing.

Authors: Malcolm McCaskill[1], Kerry Stott[2], Brendan Christy[3], Angela Clough[4], Rob Norton[5], Amanda Pearce[6], Charlie Crozier[7], Jade Killoran[8,9], Frank Henry[1], Madeleine Francis[1,9], Aaron Vague[10], Craig Farlow[11]; Craig Henson[12], Terry McLean[3], Debra Partington[1], Jack Edwards[13,14], Julia Severi[13,15], Penny Riffkin[1]

[1]Agriculture Victoria, Hamilton; [2]Agriculture Victoria, Parkville; [3]Agriculture Victoria, Rutherglen; [4]Agriculture Victoria, Ballarat; [5]International Plant Nutrition Institute, Horsham, [6]SARDI, Struan, South Australia; [7]MacKillop Farm Management Group, Padthaway, South Australia; [8]AGF Seeds, Smeaton, Victoria; [9]WestVic Dairy, Camperdown, Victoria; [10]Southern Farming Systems, Inverleigh, [11]Victoria; Incitec Pivot, Geelong North, Victoria; [12]Kelly and Henson, Dunkeld, Victoria, [13]Agriculture Victoria, Horsham, [14]D&J Rural Services Wellington, NSW, [15]Cesar Australia, Parkville.

Contents

EXECUTIVE SUMMARY

Commercial wheat and canola crops in the high rainfall zone (HRZ) of southern Australia typically yield well below the yields that have been achieved in trials that were well supplied by nutrients. A previous report concluded that this was because insufficient fertilizer was applied to achieve the potential yield, and that the main barrier to supplying sufficient nutrients was a lack of confidence that the higher rates required would result in an economic return on investment. This report updates progress from this project (DAV00141) and related projects since the previous report to provide an overview of the nutrient status of phosphorus (P), potassium (K), nitrogen (N), sulfur (S), copper (Cu) and zinc (Zn) in both the soils and wheat and canola crops in the HRZ of south-eastern Australia. It also proposes the future direction of the project to assist growers and advisors in making decisions relating to the optimum application of nutrients to maximize the economic yield potential of wheat and canola.

The project has field, survey, simulation and decision support components. In the field component, a series of nutrient omission trials were established in the south-east of South Australia and the HRZ of Victoria (4 sites in 2015 and 6 sites in 2016). These experiments tested the response of wheat and canola to N, P, K, S, Cu and Zn. The first year (2015) was unusually dry, with a decile 1 growing season rainfall. There were early biomass responses to N and P at most sites, but grain yield responses were only recorded to N at one site, S at one site, and N and P at another. There was evidence that the crops with higher fertilizer rates "hayed off" because of water stress during grain-fill. Rainfall in the second season (2016) is well above average, and there are early biomass responses to P and N at most sites. In both seasons, these responses occurred at soil test values well above the critical levels that were largely developed from low and medium rainfall cropping zones. Whether the 2016 biomass responses lead to higher grain yield will be determined by grain harvests scheduled over the next few months.

In the survey component, samples of soil, grain and plant tissue were collected from farm paddocks to determine the nutrient status of the population relative to critical values in the scientific literature. Soil sample data were also obtained from a commercial soil test laboratory. A clear majority of samples were within the critical levels that had been determined previously. Overall soil fertility appeared to have increased over the past 30 years from that reported in the 1996 National Land and Water Resource audit nutrient database.

In the simulation component, a process-level model of wheat and canola growth developed under a previous project was tested on data from a project on N response conducted by Southern Farming Systems (SFS) in 2013 and 2014. Model predictions conformed closely to the 1:1 line in a year of above average growing season rainfall (2013), but it underestimated grain yields by an average of 30% in a year where growing season rainfall was well below average (2014). This process-level model is therefore a good foundation for the decision support component of the project, providing reliable estimates of the grain yield response of these crops to climate and nitrogen, but is on the conservative side in its estimates under extremely dry seasonal conditions. The model has not, however, been tested on independent data for its response to P, K, S and micronutrients.

In the decision support component, we review and make use of existing tools to showed how the preliminary process-based crop model, production economics and Monte Carlo simulation can be used to examine the profitability and risks associated with single-input usage (N or P, other nutrients unlimiting) under a variable climate. As expected, profit maximising nutrient applications and crop yields are lower in drier seasons or when other nutrients are limiting. The grower could respond tactically as the season evolves by applying N in split applications. P-fertiliser application is best at or before seeding; but growers still have flexibility when considering the uncertain season ahead due to the flat response function at the economic optimum. The results suggest that the unrealised potential of crops in the HRZ can be explained, in part, by the cost of nutrient inputs and the risks associated with variable seasons. The analysis optimises one variable input at a time (e.g. N or P, other inputs held constant). Our intention is to extend the method to a more realistic situation that simultaneously examines multi-variable input response processes (such as N and P or S or K) on wheat and canola yields.

After the harvest of the 2016 growing season, there is one remaining growing season in the project (2017), which will be used to test the consistency of field findings across seasons. The decision support framework will be developed as a mock-up and tested with advisors as part of developing decision support messages from the project.

Project outcome

This report is an output of a project with an overall outcome that by June 2018, agronomists, growers, breeders and scientists will have the knowledge and tools to reliably increase the profitability of wheat and canola production in the high rainfall zones of the Southern and Western grains regions.

The plant nutrition component of the project has a more tightly defined outcome: to equip growers and their advisors to confidently assess crop nutrient demands and limitations, predict yield potential and pay-offs associated with high input use in the HRZ environment.

Project background

Grain production in the high rainfall zone (HRZ) of southern Australia has increased nearly two fold for wheat over the past 20 years from 1.7M t (average 1990-1995) to 3.2M t (2007-2011) and nearly tenfold for canola over the same period (81,000-792,000 t). It is expected that yields will further increase in the HRZ to more closely reflect their predicted potential driving an increase in production per se, increases in area sown and grower returns. Field experiments & modelling in previous projects indicate that crop yields in this agro ecological zone could be further doubled through the introduction of better-adapted wheat and canola germplasm & improved management practices. A review of crop nutrition under a precursor project (DAV00116) drew the following conclusions (Christy *et al.* 2015a, b):

   a) Commercial grain yields in the HRZ are well below potential as indicated by field experimental and modelling studies.
   b) Levels of nutrients applied by growers are generally insufficient to achieve the predicted yield potential.
   c) Soil nutrient deficiencies are widespread in the HRZ as extrapolated from the National Land and Water Resource audit nutrient database (Audit 2001).
   d) Limited reliable research has been conducted into nutrient response in the HRZ and there is insufficient data in the Better Fertiliser Decision for Cropping database to develop nutrient response curves for the HRZ.
   e) A barrier to growers in applying recommended inputs was a lack of confidence in achieving an economic return on investment.

This report is an update of progress toward these objectives under project DAV00141.

Project objectives

By June 2018, growers and advisers will have tools that predict the production and economic response as well as the risks associated with applying the level of inputs needed for wheat and canola crops to achieve their high yield potential in the HRZ of south-eastern Australia.

MILESTONE ACHIEVEMENT

By September 2016, an industry report to growers and researchers that provides an overview of the nutrient status of P, K, N, S, Cu and Zn in soils and wheat and canola crops in the HRZ of south-eastern Australia.

BACKGROUND

A previous project established that commercial grain yields in the HRZ are well below potential primarily because insufficient nutrients are applied (Christy *et al.* 2015a, b). On-farm grain yields are typically only half to a third of yield potential, which is estimated as 4.5 to 11 t/ha for wheat depending on location, and 3 to 5 t/ha for canola. Yield limitations due to germplasm have partially been addressed by the more recent cultivar releases, and further improvements are anticipated through the ideotype components of this project. Fertiliser represents the largest variable cost in high rainfall cropping, but a lack of evidence in achieving an economic return from the investment is a barrier to applying sufficient fertilizer to fulfill yield potential. Limited reliable research has been conducted into nutrient response in the HRZ and there is insufficient data in the Better Fertiliser Decision for Crops database to develop nutrient response curves for the HRZ. It was hypothesized that critical soil test values would be higher in the HRZ because of higher yield potential, compared to the low and medium rainfall cropping zones where the majority of nutrient response experiments have been conducted. This component of the project was therefore designed as a combination of field studies and modelling to better predict the nutrient inputs required to achieve an economic yield potential for wheat and canola in the HRZ of south-eastern Australia.

Field studies include a series of omission response experiments at multiple locations, and a survey approach of soil tests and grain quality collected on commercial properties. Modelling comprises a combination of simulation and economic analysis, and forms the link between field experiments and fertiliser decisions. The preferred approach is to value add to frameworks developed under previous GRDC investments, rather than developing new decision support software.

Field studies

Five sets of field data have been used in the project.

1. A series of 10 nutrient omission experiments were undertaken by this project in 2015 and 2016.

2. A series of N response experiments were established within commercial crops in 2013 and 2014 as part of a project undertaken by Southern Farming Systems, 16 of which were used by this project for model validation.

3. Commercial soil test data for 2015 were made available by the Nutrient Advantage Laboratory to quantify the nutrient status of nearly 5000 commercial paddocks, and were supplemented by an additional 12 samples collected by the project in 2014 in South Australia.

4. Plant tissue samples were collected from 39 farmer crops by commercial agronomists in late winter 2014 and 118 random samples of wheat and canola grain were provided by GrainCorp in 2014 and 2015 for analysis of mineral nutrients.

5. A commercial agronomist based in Dunkeld (Craig Henson) established a series of nutrient strip trials in nine commercial paddocks in the Hamilton area in 2015 to facilitate in-crop management, and project resources were used to quantify grain yield responses.

Seasonal conditions

Growing season rainfall in the seasons contributing to this report at indicative stations in the south-east of South Australia and southern Victoria was above median in 2013, below median in 2014, and in decile 1 at all stations in 2015 (Table 1). Due to the very low rainfall in the 2014 and 2015 seasons, data from those years are unlikely to provide a good test of the hypothesis that higher levels of nutrient input are required than in low and medium rainfall areas to fulfill the climatic potential. Nevertheless, it provides a test of how crops respond to high levels of nutrient in a dry season. At the time of this report (September), rainfall for the 2016 season was well above average and fifth highest on record for Hamilton.

Table 1. Growing season rainfall (April-November inclusive) at Naracoorte, Lake Bolac and Winchelsea during the omission trial experiment (2015) and a series of experiments conducted by Southern Farming Systems (2013-2014), and deciles relative to the 1900-2015 period.

Location	Relevant to sites at…	Year	Rainfall (mm/yr)	Decile
Naracoorte	Bool Lagoon	Average	408	6
	Frances	2013	479	8
		2014	350	3
		2015	262	1
Lake Bolac	Chatsworth	Average	399	5
	Wickliffe	2013	433	7
	Streatham	2014	322	3
	Willaura	2015	260	1
Winchelsea	Inverleigh	Average	466	5
	Ombersley	2013	468	6
	Hesse	2014	314	1
		2015	260	1

Omission trials

To investigate interactions and quantify the magnitude of response to a range of nutrients, a series of omission experiments were established in 2015 and 2016 in south-eastern South Australia and southern Victoria (Fig. 1). The 2015 trials comprised canola at Frances and Inverleigh, and wheat at Bool Lagoon and Chatsworth. In 2016, the trials comprise canola at Bool Lagoon, Hamilton, Tarrington, and Rutherglen, and wheat at Bool Lagoon and Inverleigh. At all sites except Hamilton, a common experimental design was imposed, which consisted of three rates of N in an incomplete factorial combination with other nutrients where either P, K, S, or micronutrients (Cu and Zn) were omitted (Table 2, 3). These treatments were "Nil", "-P", "-K", "-S", "-micros" and "All". Plots were 10 to 20 m long, 1.2 to 2.2 m wide, and sown with a drill width of 0.15 or 0.2 m depending on local sowing equipment. Fertilizer treatments apart from N were deep drilled at sowing. In 2015, this was as a separate pass prior to sowing, while in 2016 fertiliser was applied into a separate chute to a depth of 7 cm, while seed was sown to 2 cm for wheat and 0.5 cm for canola. Treatments were replicated 4 times. The N treatments consisted of a sowing basal (18 kg or 30 N/ha), and in-crop applications in August and early October calculated to achieve either 60% (medium N rate) or 100% (high N rate) of yield potential. The medium and high N rates were calculated in July from mineral N data from soil samples collected prior to sowing, an estimate of mineralization and crop demand estimated from rainfall received since sowing and expected rainfall until the end of the growing season. The lowest rate of N was only used for the nil and all treatments of other nutrients (Table 2). The Hamilton site tested four rates of K (0, 50, 150 and 200 kg K/ha) with two N rates (0, 181 kg N/ha) and four replicates. Sites were selected that were believed to be deficient in at least one nutrient, based on evidence from soil tests, prior strip trials, or had low fertilizer applications in recent years. However, soil samples taken immediately prior to planting indicated that some sites were more fertile than were previously believed, and exceeded critical values from the Better Fertilizer Decisions project for most or all nutrients

Table 2. Portrayal of the common omission trial design, showing the combination included treatments as "Y". 'All' refers to all nutrients (P, K, S, Cu and Zn) minus (-) individual nutrients.

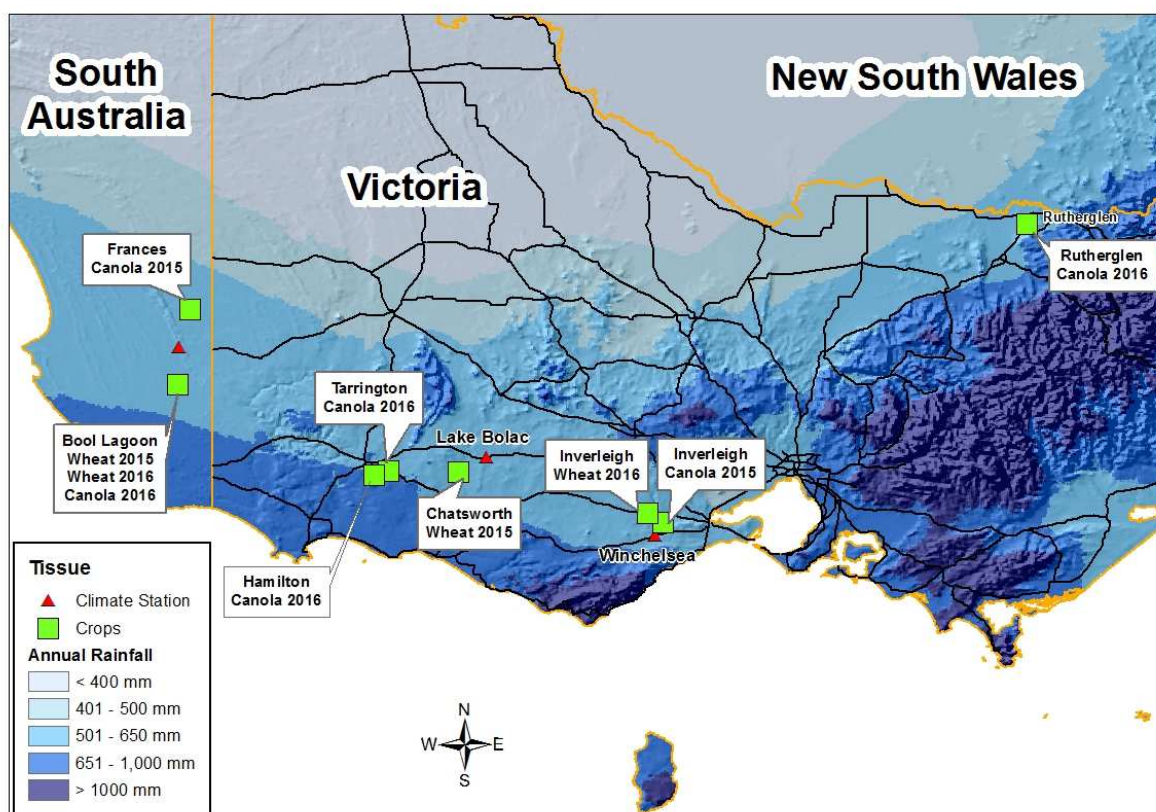| N rate	Treatment					
	Nil	All-P	All-K	All-S	All -Cu & -Zn	All
Low	Y					Y
Medium	Y	Y	Y	Y	Y	Y
High	Y	Y	Y	Y	Y	Y

Fig 1. Location of the omission trials in 2015 and 2016, the location of three long-term climate stations cited in Table 1, and long-term annual rainfall.

Measurements at all sites included grain yield, final biomass, and harvest index. These measurements were made by hand harvesting two sections within each plot 1 m long and 0.6 to 0.8 m wide comprising the middle 4 rows of the plot, allowing the outer two rows as buffers, giving a total area harvested of 2 m^2 per plot. Mineral analyses were undertaken on grain from the low-N nil treatment and high-N all treatments. At some sites the additional measurements undertaken included oil and protein content at Inverleigh, visual ratings in the vegetative stage for wheat at Bool Lagoon in October 2015 and at Inverleigh in August 2016, and above-ground biomass in canola at Frances on 11 September 2015 and Tarrington on 29 July 2016. The latter included the extractable root mass. Extensive measurements were undertaken at the Chatsworth wheat site at flowering (growth stage 65) on 23 October 2015, which included above-ground biomass, ear density, flag leaf mass and mineral composition of the flag leaves.

At all sites, soil cores were taken prior to planting to a depth of 1.8 m unless rock was encountered at a shallower depth. These samples were taken in each replicate at increments of 0-0.1 m, 0.1 to 0.2 m, 0.2 to 0.4 m 0.4 to 0.6 m, thereafter in 0.4 m increments. Within each replicate three soil cores were taken, which were bulked. Additional 0-0.1 m topsoil samples were taken consisting of 30 cores per replicate. Samples were dried to 40°C for chemical measurements, and 105°C for physical measurements, with additional measurements on topsoil samples of Colwell P and organic carbon. Samples were analysed for pH, EC, nitrate-N, ammonium-N, chloride, available sulfur, and available potassium at the Nutrient Advantage Laboratory in Werribee, which is undertakes the majority of agricultural soil and plant testing in eastern Australia. In accordance with normal laboratory practice, gravel (> 2 mm) was removed prior to testing. Physical measurements on the samples included bulk density, moisture content, gravel (> 2 mm) mass and gravel density. These measurements were needed to convert nutrient concentrations into a quantity per hectare for each soil layer for nutrient balances and modelling.

Statistical analyses were conducted firstly as the overall effect of each nutrient analysed by a design N x P x K x S x micronutrients, where supplied nutrients were indicated in the data as a factor "1" and nutrients not supplied as "0". Analyses were conducted in Genstat 17th Edition using unbalanced analysis of variance and REML. Differences are reported at the 10% significance level.

Table 3. Rates of nutrient (kg/ha) applied in the omission experiments in 2015 and 2016. Rates of N, P, K, S, Cu and Zn were consistent across all sites, whereas in-crop N (applied after sowing) varied from site and year. (For details of the Hamilton design, see text).

Nutrient/site (2015)	2015	Site (2016)	2016
Sowing	kg/ha		kg/ha
N	18,18, 30		30, 30, 30
P	0, 25		0, 50
K	0, 50		0, 50
S	0, 24		0, 20
Zn	0, 1.1		0, 1.1
Cu	0, 2		0, 2
In-crop N			
Bool Lagoon (wheat)	0, 46, 110	Bool Lagoon (wheat)	0, 134, 247
Chatsworth (wheat)	0, 0, 39	Inverleigh (wheat)	0, 63, 236
Frances (canola)	0, 57, 106	Bool Lagoon (canola)	0, 64, 157
Inverleigh (canola)	0, 57, 106	Tarrington (canola)	0, 49,185
		Rutherglen (canola)	0, 229, 366

Results

The 2015 wheat trials at Bool Lagoon and Chatsworth showed an early biomass response to N and P by anthesis, but this did not translate into higher grain yield (Table 4, Appendix A). There was evidence that additional P led to a reduced harvest index and lower grain size, which is consistent with the crop haying off under dry soil conditions during the grain-fill period. The 2015 canola trials showed a strong response in all measured parameters to additional N at Frances and both N and P at Inverleigh. Early results from 2016 indicate a two-fold early biomass response to additional N in canola at Rutherglen, and a strong visual response to N at Hamilton (Fig. 2). There was a response to P of up to 80% in above ground (AGB) and root biomass in canola at Tarrington, 40% in canola at Rutherglen, and 18% AGB in wheat at Inverleigh. There were positive grain yield and HI responses to S in wheat at Bool Lagoon in 2015, but negative responses to S at anthesis in wheat at Chatsworth (2015) and canola biomass (5 leaf stage) at Tarrington (2016). Across all sites, there were only two responses to micronutrients, which were for wheat (grain) at Chatsworth, and did not translate to a higher grain yield, and in canola (biomass) at Rutherglen, which is still at the grain-fill stage at the time of writing. There was one response to K in canola (biomass at the 5-leaf stage in 2016) at Tarrington, for which grain yield results are not yet available. There was a strong early biomass response to N at Rutherglen in 2016.

Pre-sowing soil tests indicate that the 2015 sites all exceeded the currently accepted critical value for all nutrients tested for topsoil (0-10 cm) criteria, except S for canola at Frances and Inverleigh (Table 5). Of the 2016 sites, the Rutherglen canola site is below the critical value for P, and the Bool Lagoon canola below the critical value for S. The Hamilton site is marginal for K relative to the critical value for pasture of 151-182 mg/kg (Gourley et al. 2007), but well above critical value of 40 mg/kg for wheat and 46 mg/kg for canola in the Better Fertiliser Decisions database (Brennan and Bell 2013). Samples of the deeper soil indicated S and K tended to increase down the profile at many sites (Fig. 3). Hamilton was the only site where K levels decreased consistently with depth. Nitrate-N concentrations were highest in the upper 0.4 m of the profile, but ammonium concentrations showed little change with depth apart from Rutherglen where it decreased strongly, and Hamilton where it increased sharply with depth. The relatively high K and S levels at depth are likely to mitigate against responses at most of these sites.

The canola crops in 2016 showed a strong biomass response to additional N at both Rutherglen and Hamilton. A response at Rutherglen is to be expected because of the low mineral N status. However at Hamilton there were 829 kg N/ha in the top 90 cm of the soil profile, of which 133 kg/ha was in the top 10 cm and within the drained zone of the beds. There were clearly processes at the Hamilton site such as waterlogging that restricted the capacity of plants to access stored mineral N.

Chloride concentrations increased strongly at all depths except for Rutherglen. Although rarely deficient as a plant nutrient, Cl is an indicator of how other ions move through the soil. Its accumulation at depth means that other ions would follow the same pathway unless moved or transformed by other processes such as plant uptake, adsorption (which slows ion movement), nitrification ($NH_4 \rightarrow NO_3$) and denitrification ($NO_3 \rightarrow NO_2$ and N_2). Given these chloride profiles, we would expect applied N, K and S to have a high residual value, and only at Rutherglen, would there be a high risk of nitrate leaching downward through the profile and into groundwater.

Grain nutrient concentrations for the Nil and All treatments were generally within reported critical values except P for the wheat crop at Bool Lagoon, K in wheat at both the Bool Lagoon and Chatsworth, and Mn at Bool Lagoon (Table 6). The only canola samples below the threshold were for Cu on the Nil treatment at Frances.

Table 4. Summary of nutrient responses in the omission trials where the probability of the nul hypothesis was less than 10% between the lowest and highest application rate. For detailed statistical analysis refer to Appendix A.

Site	Year	Crop	Parameter	Response (% relative to nil control)				
				N	P	K	S	Cu, Zn
Bool Lagoon	2015	Wheat	Grain yield	-	-	-	13	-
			Harvest biomass	-	10	-	-	-
			Harvest Index	-	-8	-	16	-
			Visual rating October	33	28	-	-	-
Chatsworth	2015	Wheat	Biomass at grain harvest	-	-	-	-	6
			Grain size	-	-4	-	-	-
			Anthesis biomass	5	7	-	-6	-
			Anthesis ear density	-	9	-	-	-
Frances	2015	Canola	Grain yield	47	-	-	-	-
			Harvest biomass	46	-	-	-	-
			September biomass	46	-	-	-	-
Inverleigh	2015	Canola	Grain yield	26	22	-	-	-
			Biomass at grain harvest	16	17	-	-	-
			Harvest Index	5	4	-	-	-
			Oil concentration	-7	2	-	-	-
			Oil yield	17	25	-	-	-
			Protein content	14	-	-	-	-
			Protein yield	53	15	-	-	-
Tarrington	2016	Canola	Biomass 5 leaf stage	na	75	15	-21	-
			Root mass 5 leaf stage	na	80	-	21	-
Inverleigh	2016	Wheat	Visual score August	-	38	-	-	-
Rutherglen	2016	Canola	August biomass	214	40	-	-	19
			August roots	41	32	-	-	18

Notes: "-" not statistically significant; "na" N treatments had not been applied at the time of assessment.

Table 5. Initial soil mineral N (nitrate + ammonium) prior to sowing to a depth of 90 cm, and topsoil (0-10 cm) available P (Colwell), K (ammonium acetate, calculated as equivalent to a Colwell K extract) and S (KCl-40), and critical values at which 95% of maximum yield from the Better Fertilizer Decisions database (Bell *et al*. 2013a, Brennan and Bell 2013, 2013b, Anderson *et al*. 2013).

Site	N	P	K	S
	(kg/ha)	(mg/kg)	(mg/kg)	(mg/kg)
2015				
Bool Lagoon (wheat)	55*	27	1017	8.8
Chatsworth (wheat)	124	53	112	29.5
Frances (canola)	76	32	155	6.7
Inverleigh (canola)	84	58	254	6.8
2016				
Bool Lagoon (wheat)	43*	24	1050	7.2
Inverleigh (wheat)	199	84	290	12.5
Bool Lagoon (canola)	28*	24	1250	6.2
Tarrington (canola)	276	62	210	16.8
Rutherglen (canola)	100	19	280	7.2
Hamilton (canola)	829	90	150	32.0
Critical value (wheat)		22	40	3.1
Critical value (canola)		22	46	7.1

* to a depth of 20 cm for 2015 site and 15 cm for 2016 site, below which is limestone

Figure 2. A strong visual response to N was evident at the Hamilton site on 2 September 2016 under waterlogged conditions, despite 829 kg/ha of mineral N in the top 90 cm of the soil profile. Left: nil N, right 50 kg/ha of in-crop N on 8 August. Both plots received 10 kg N/ha as MAP at sowing, and 150 kg/ha of in-crop K as muriate of potash.
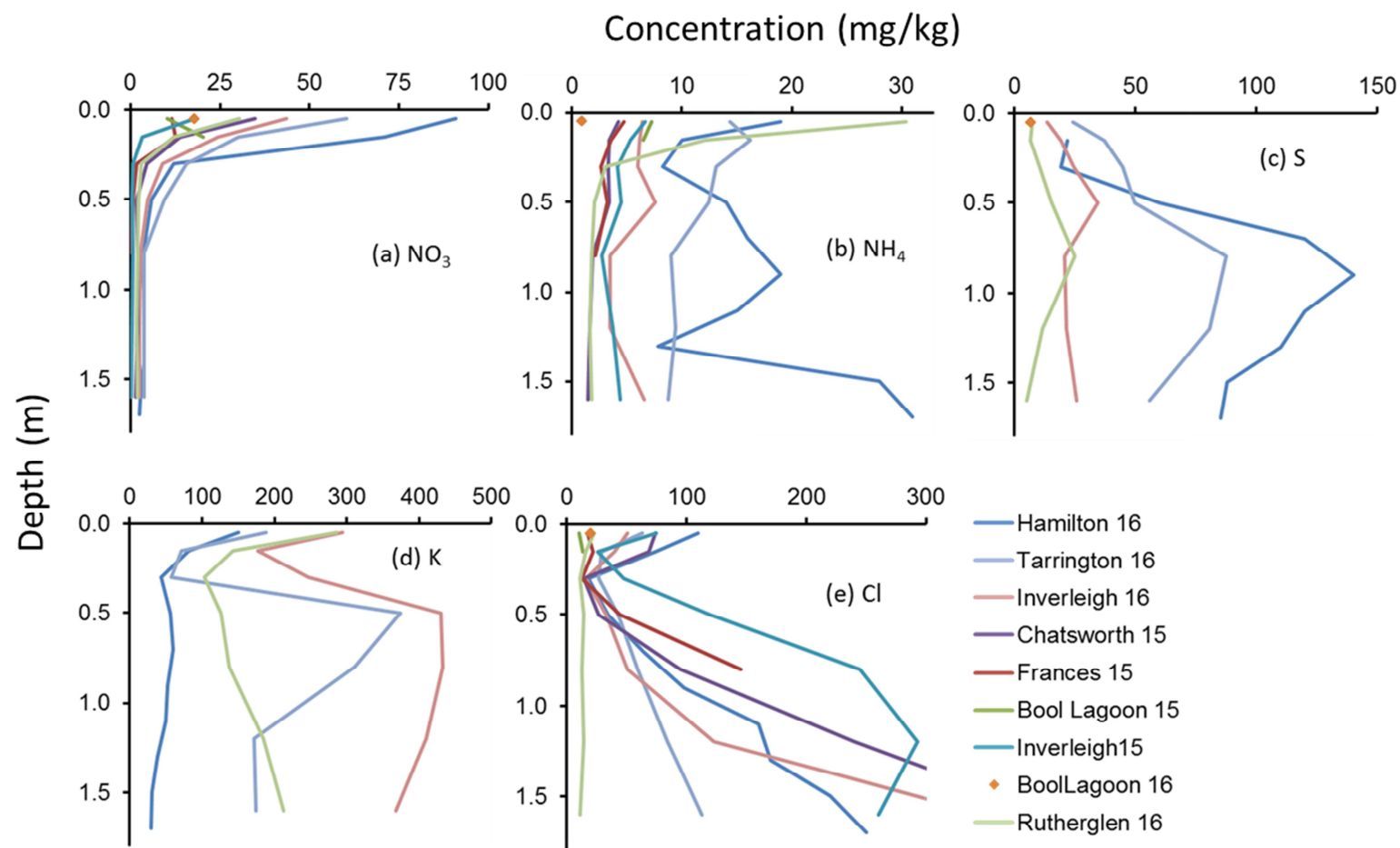
Figure 3. Concentration of (a) nitrate-N, (b) ammonium-N, (c) sulfate-S, (d) plant-available K and (e) chloride for pre-sowing soil sampling on the 2015 and 2016 omission trials.

Table 6: Grain nutrient analysis for the Nil and All treatments from the 2015 omission trials. Values are the mean of 4 plots for each treatment at each site, and are on a dry weight basis except the oil concentration of canola, which is reported on a 6% dry matter basis, and protein in canola, which is oil-free on a 10% moisture basis. Critical values are minimum value for adequate nutrition as sourced from Reuter et al. (1997) and Norton (2014).

Crop	Site	Treat	N	P	K	S	Ca	Mg	Mn	Fe	B	Cu	Zn	Protein	Oil
			%	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%	%
Wheat	Critical value		-	0.27	0.50	0.12	-	-	20	-	2.0	2.5	15	-	
	Bool Lagoon	Nil	2.18	0.19	0.43	0.13	0.031	0.10	8	44	2.8	3.9	18	11.5	
		All	2.33	0.21	0.48	0.15	0.034	0.10	7	41	2.4	3.9	20	14.5	
	Chatsworth	Nil	2.23	0.27	0.38	0.13	0.026	0.11	29	51	3.1	1.7	18	12.3	
		All	2.15	0.27	0.37	0.14	0.028	0.12	29	52	3.3	1.3	19	13.9	
Canola	Critical value		1.90	0.35	-	0.36	-	-	10	-	1.0	3.0	15		
	Frances	Nil	2.08	0.69	0.71	0.37	0.450	0.29	33	49	16.8	2.6	35	37.3	41.4
		All	2.27	0.56	0.65	0.42	0.373	0.26	27	40	13.7	3.4	41	43.1	37.9
	Inverleigh	Nil	2.20	0.48	0.94	0.40	0.343	0.32	36	50	13.3	4.5	27	35.9	45.6
		All	2.10	0.47	0.92	0.43	0.308	0.31	28	49	13.5	4.7	33	39.5	42.8

Southern Farming Systems N experiments

In the 2013 and 2014 growing seasons, Southern Farming Systems conducted a series of unreplicated N response experiments in southern Victoria between Willaura and Inverleigh (Fig. 4) (Table 7). This was part of a study on N use efficiency and nitrous oxide release funded by from the Federal Department of Agriculture, Fisheries and Forestry (DAFF) (now Department of Agriculture and Water Resources) to develop on-farm practices that reduce greenhouse gas emissions. Measurements included pre-sowing mineral N concentration (nitrate and ammonium) to a depth of 0.9 m, biomass in October at anthesis, and grain yield. Some N was supplied at sowing as urea, MAP, or DAP, with in-crop application of urea or UAN. In-crop N rates were nil, a grower rate, and one or more N rates calculated from the soil mineral N data. Our analysis focused on eight sites in 2013 and another eight sites in 2014 for which grain yield data were available. To utilize the 0-0.9 m mineral N data for a process-based model (Christy *et al.* 2013), data for bulk density, gravel content and the partitioning of mineral N between layers from the 2016 omission sites at Tarrington and Inverleigh were used to partition the N concentration data (in mg/kg) into quantities of nitrate and ammonium (kg/ha.layer) for layers 0.1 or 0.2 m thick. Daily weather data for the model was obtained from the SILO database (https://www.longpaddock.qld.gov.au/silo/).
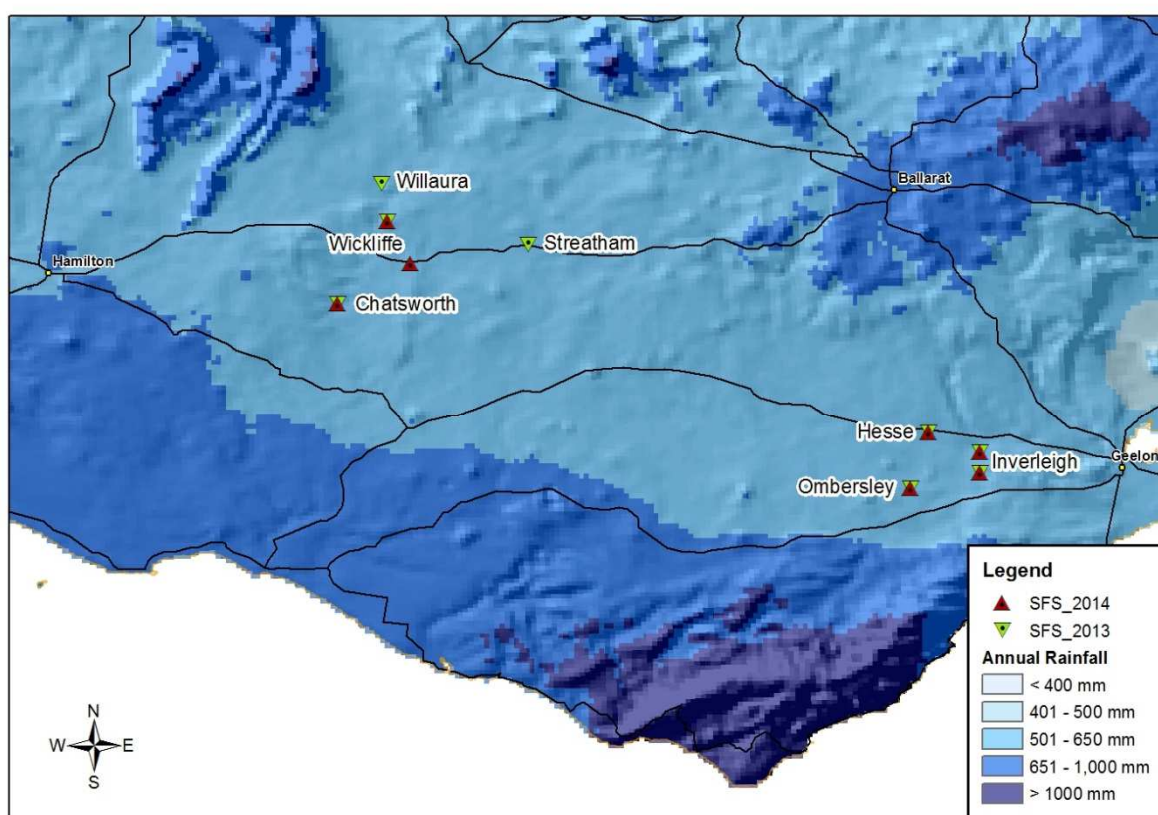
Fig. 4. Location of the Southern Farming Systems N response experiment in 2013 and 2014, and long-term annual rainfall.

Results and Discussion

In the wet year of 2013, there was a positive grain yield response to additional N in six of the eight sites of between 9% and 32% (Fig. 5). The two sites with a negative response had both been sown to barley, and showed a decrease of between 2% and 10%. However, in the dry year of 2014 only half the eight sites showed a positive response to N, with overall responses ranging from a 5% decrease to a 20% increase.

Grain yields predicted by the model of Christy *et al.* (2013) were close to the 1:1 line in 2013 (Fig.6), but in the dry year of 2015 most yields exceeded the 1:1 line by an average of 25%, apart from one site where observed grain yields were over double the model predictions. At this site (Ombersley) the data indicate wheat yields of over six t/ha were achieved with in-crop rainfall of 237 mm, which is unusual. For example, the simpler model of

French and Schultz (1984) would indicate a water-limited potential yield of only 2.5 t/ha. Possible reasons for this discrepancy include rainfall received at the site from an isolated storm that was not detected in the SILO database, stored soil water carried over from the previous crop, or errors in the harvest data. Nevertheless, the model predicted yields and nitrogen responses across a wide range of field sites under a wide range of commercial conditions, and was conservative in that it tended to underestimate yield under dry conditions.

Table 7. Location, variety and in-crop rainfall between planting and harvest for the Southern Farming Systems N response experiments in 2013 and 2014. (Order matches that in Figs 4 and 5).

Year	Location	Crop	Variety	In-crop rainfall
2013	Ombersley	Wheat	Derrimut	318
	Inverleigh 1	Barley	Westminster	305
	Inverleigh 2	Barley	Westminster	372
	Streatham	Barley	Scope	421
	Chatsworth	Wheat	Kellalac	424
	Willaura	Wheat	Lincoln	348
	Hesse	Canola	Gem	313
	Wickliffe	Canola	Thumper	379
2014	Ombersley	Wheat	Derrimut	237
	Inverleigh 1	Wheat	Phantom	260
	Inverleigh 2	Wheat	Derrimut	247
	Chatsworth	Wheat	Revenue	380
	Wickliffe 1	Wheat	Bolac	260
	Hesse	Wheat	Derrimut	227
	Wickliffe 2	Wheat	Derrimut	266
	Wickliffe 1	Canola	Wahoo	231

Commercial soil test data

To quantify the range and distribution of soil fertility levels in the high rainfall cropping zone, data were sought on on-farm fertility. Data were obtained from three sources. Firstly, soil samples were obtained from 12 sites in the south-east of South Australia that were sampled for plant tissue and grain nutrients as reported in the previous section. Secondly, data on pre-sowing mineral N to a depth of 0.9 m were compiled from the 16 Southern Farming Systems N response sites, and the 10 omission sites. Thirdly, commercial soil test data were obtained from the Nutrient Advantage Laboratory. These covered all non-research samples sent to the Nutrient Advantage Laboratory in Werribee in 2015 from high rainfall areas in South Australia, Victoria, Tasmania and southern NSW. Research samples were excluded because they often represented a large number of samples from intensively monitored sites, and were identified as the customer being a research institution such as Agriculture Victoria or Southern Farming Systems. Data were also excluded if the intended crop was neither canola nor a cereal crop (e.g. grain legumes, poppies or pasture hay), but were included if the intended crop was unknown (62% of samples).

Results and Discussion

SA sites: Soil analysis from this first year of field sampling showed that some paddocks in southeast South Australia had low soil nutrient concentrations for S, Cu, Mn and/or Zn, and this is consistent with earlier surveys (Donald and Preston 1975) (Table 8). Most other nutrients in South Australia were adequate according to critical soil test values (Peverill *et al.* 1999; GRDC 2013). Further details are reported by Clough *et al.* (2015).
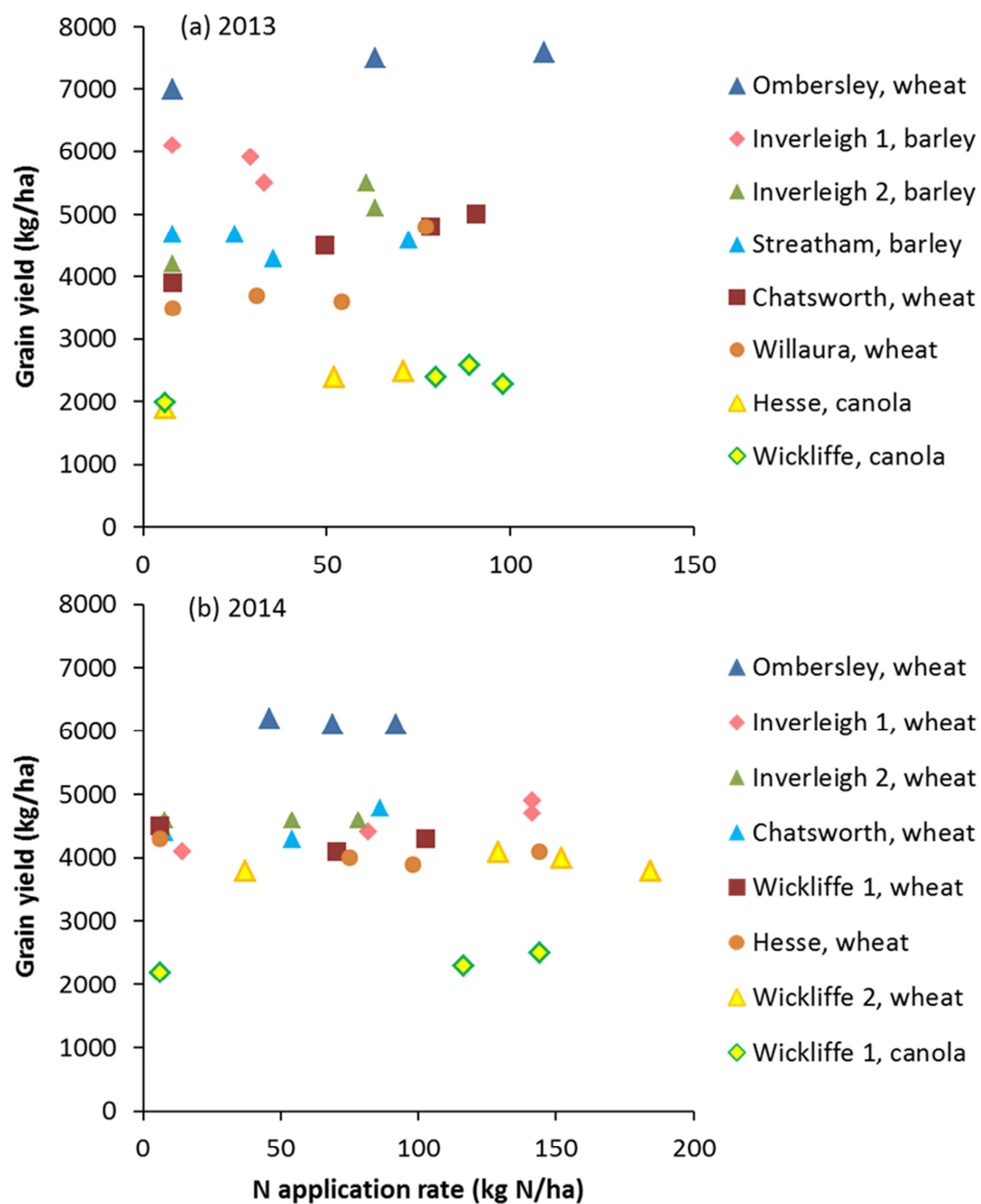
Fig. 5. Response of wheat and canola to N fertiliser in the Southern Farming Systems nitrogen management project in 2014 and 2015. Experiments are denoted by the location followed by the crop.
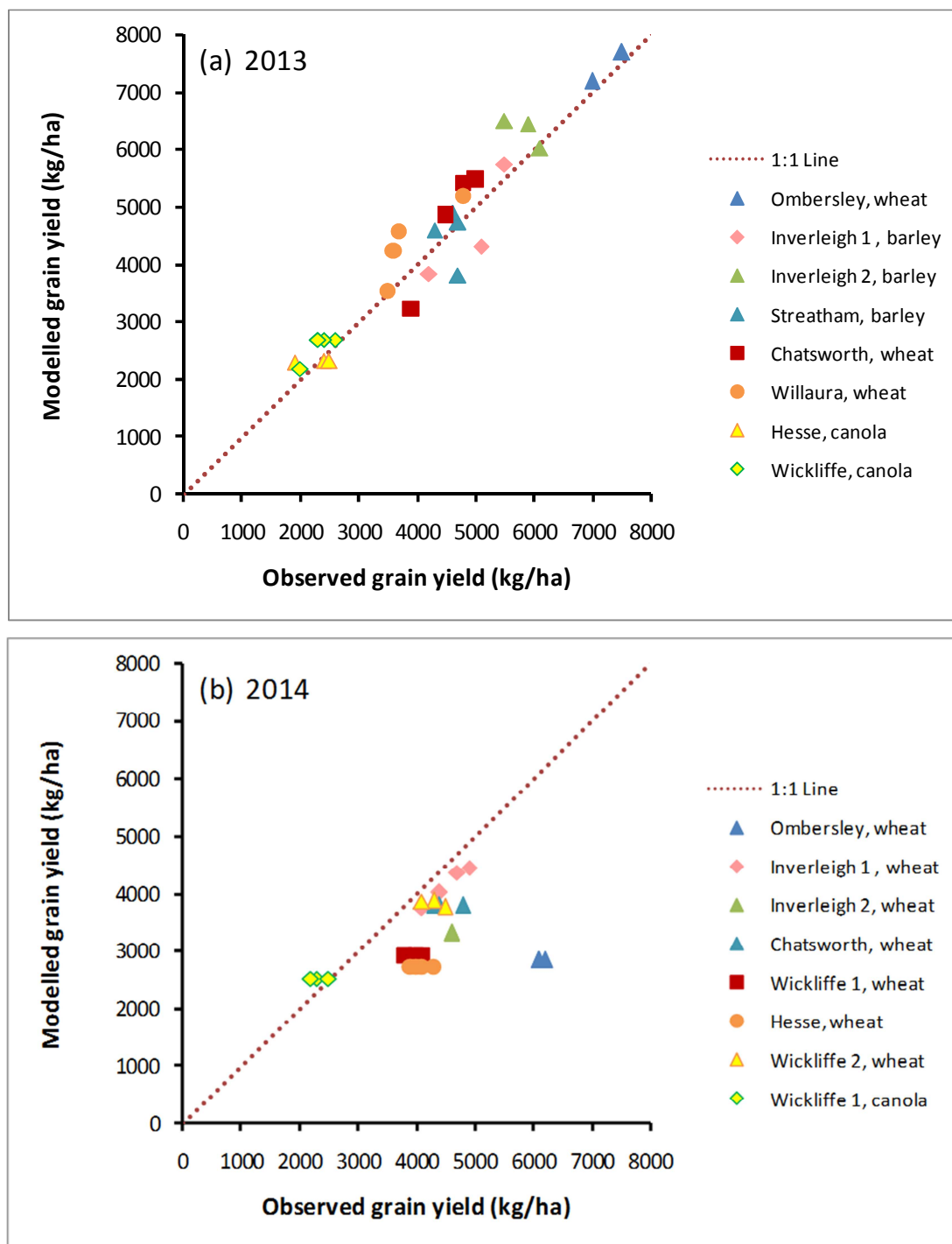
Figure 6. Comparison between grain yield observed in the SFS Nitrogen project and that predicted by the model of Christy *et al.* (2013).

Table 8: Nutrient analysis of soil in southeast South Australia immediately prior to the 2014 cropping season for 0-10 cm (n=12).

Soil analysis	Units	Critical value in 0-0.1 m layer	Min	Average	Max.	StDev
pH (1:5 water)			5.5	7.5	8.6	1.1
pH (1:5 CaCl2)			4.9	7.0	7.9	1.1
Mineral N (NO3 + NH4)	mg/kg		2.7	22.7	85.0	23.9
Phosphorus (Colwell)	mg/kg	25	23	50	73	15
Sulfate sulfur (KCl-40)	mg/kg	5	4.4	23.6	62.0	21.2
Potassium (Amm-acetate)	cmol (+)/g	0.10	0.3	1.7	4.9	1.5
Copper (DTPA)	mg/kg	0.4	0.3	0.8	1.3	0.3
Manganese (DTPA)	mg/kg	5	0.9	3.9	8.8	2.7
Zinc (DTPA)	mg/kg	0.4	1.1	3.5	12.0	3.3

SFS and Omission site compilation: Mineral N to a depth of 0.9 m ranged from 28 to 829 kg N/ha, with a median of 84 kg N/ha for the omission sites and 192 kg N/ha for the SFS sites (Fig. 7). The lowest values were at Bool Lagoon, where it was not feasible to sample below 0.15 to 0.2 m because of limestone below this depth.
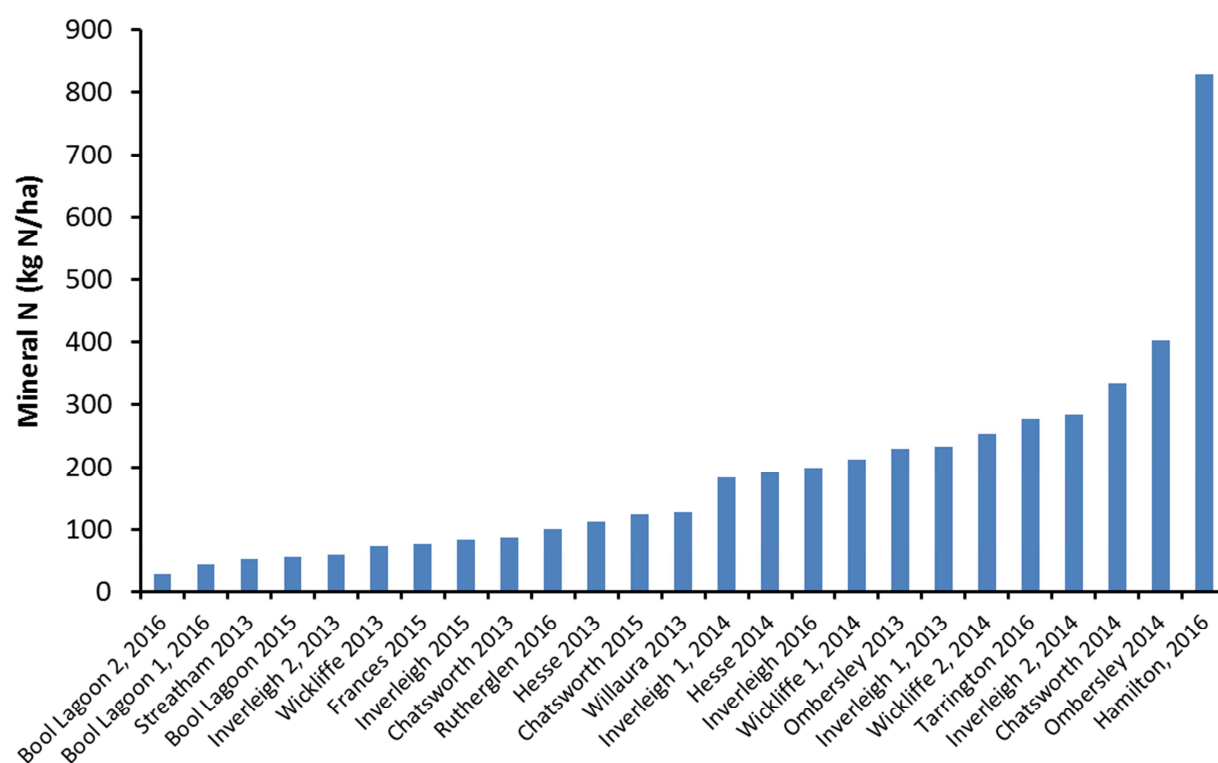
Fig. 7. Distribution of mineral N (nitrate + ammonium) 0-0.9 m depth in the Southern Farming Systems trials (2013 and 2014), and the omission trials (2015 and 2016).

Nutrient Advantage: Of the samples submitted, the majority exceeded critical values from the Better Fertiliser Decisions project database of Colwell P > 22 mg/kg for wheat and canola (Bell *et al.* 2013a,b), Olsen P > 15 mg/kg for pasture (Gourley *et al.* 2007), Colwell K > 161 mg/kg for pasture on (Gourley *et al.* 2007), available S (KCl) > 7.1 mg/kg for canola (Anderson *et al.* 2013), Cu (DTPA) > 0.4 mg/kg and Zn (DTPA) > 0.4 mg/kg (Table 9).

Table 9. Summary of the number of numerical distribution of non-research soil tests undertaken by the Nutrient Advantage Laboratory during 2015, and the percentage exceeding the critical levels from the Better Fertilizer Decisions Project (see text for values and references).

Test	Region	n	Lower quartile	Median	Mean	Upper quartile	% > critical
Colwell P (mg/kg)	NSW - Central	2208	20	33	42	50	69
	SA - North and West	239	31	43	46	57	89
	SA - South East	149	25	36	40	47	79
	Tasmania	82	33	53	185	75	89
	Vic - Central & W Gipp	486	33	54	82	84	89
	Vic - Eastern	25	35	57	80	115	96
	Vic - South West	605	36	55	62	77	90
Avail K (mg/kg)	NSW - Central	2201	240	360	385	500	88
	SA - North and West	169	268	420	471	633	91
	SA - South East	149	150	270	323	463	73
	Tasmania	83	123	170	316	283	52
	Vic - Central & W Gipp	620	220	310	346	410	88
	Vic - Eastern	30	150	190	266	370	63
	Vic - South West	609	170	250	311	393	76
S-KCl (mg/kg)	NSW - Central	1988	3.7	5.8	10.5	9.1	37
	SA - North and West	147	5.8	8.7	14.2	13.0	65
	SA - South East	155	5.6	7.5	19.0	14.0	52
	Tasmania	74	7.3	12.0	15.6	17.0	78
	Vic - Central & W Gipp	563	8.5	13.0	31.9	22.0	84
	Vic - Eastern	26	9.6	15.0	28.7	31.0	81
	Vic - South West	653	8.4	12.0	16.9	17.3	83
Cu (DTPA) (mg/kg)	NSW - Central	1308	0.51	0.88	1.05	1.30	100
	SA - North and West	173	0.39	0.78	0.91	1.33	100
	SA - South East	131	0.25	0.32	0.43	0.48	100
	Tasmania	33	0.41	0.99	0.96	1.43	100
	Vic - Central & W Gipp	579	0.70	1.00	1.28	1.40	100
	Vic - Eastern	9	0.43	0.94	0.96	1.45	100
	Vic - South West	551	0.44	0.72	0.91	1.00	100
Zn (DTPA) (mg/kg)	NSW - Central	1308	0.41	0.67	1.17	1.20	75
	SA - North and West	173	0.83	1.40	1.80	2.30	96
	SA - South East	131	0.82	1.40	2.13	2.00	91
	Tasmania	33	1.30	1.70	1.99	2.15	97
	Vic - Central & W Gipp	579	0.80	1.30	2.29	2.40	97
	Vic - Eastern	9	2.28	4.30	6.32	6.83	100
	Vic - South West	551	0.52	0.83	1.61	1.40	87

These samples are not a random sample of paddocks, but represent a sample biased toward those serviced by commercial agronomists, but nevertheless represent the target group of land managers for decision support. Across the high rainfall cropping zone of the South-East of South Australia and southern Victoria, 89-96% of the 2015 samples exceeded the critical value of 22 mg/kg for Colwell P, whereas a comparable analysis of 1989-99 samples from the high rainfall cropping zone found only 60-80% of samples exceeded the critical value (Audit 2001). This is therefore evidence that the P status of cropping soils in the high rainfall zone has increased over the last 20 years.

Plant tissue and grain samples from commercial crops

To determine whether plant tissue or grain nutrient concentrations were indicative of deficiencies, and quantify the export of nutrient in product, plant tissue samples were taken from commercial crops in 2014 and grain samples in 2014 and 2015. The tissue samples were taken from southeast South Australia and southwest Victoria from April to August 2014 with sites ranging from Frances to Inverleigh (Fig. 8). All samples were analysed for nutrients tissue samples (39) were taken in both South Australia and Victoria from three wheat cultivars (cv. Revenue, Bolac and Derrimut) at Growth Stage (GS) 31 and triazine-tolerance canola at Growth Stage 3.3 (bud first visible) by sampling youngest fully emerged leaves. Leaves were collected from at least 100 wheat or canola plants in July and August at each site. Grain samples of the same wheat cultivars and canola type were taken from two sources. The first source was the crops sampled for tissue analysis in southeast South Australia. The second source was grain from 49 farms in the target region that delivered to GrainCorp® receival sites at Geelong and Naracoorte in 2014, and a further 82 farms in 2015 (Fig. 9). All tissue and grain samples were digested in nitric-perchloric acid followed by mineral determination on an inductively coupled plasma (ICP) spectrophotometer for B, Ca, Cu, Fe, Mg, Mn, P, K, Na, S, Z, N, Mo at the Nutrient Advantage Laboratories, Werribee.
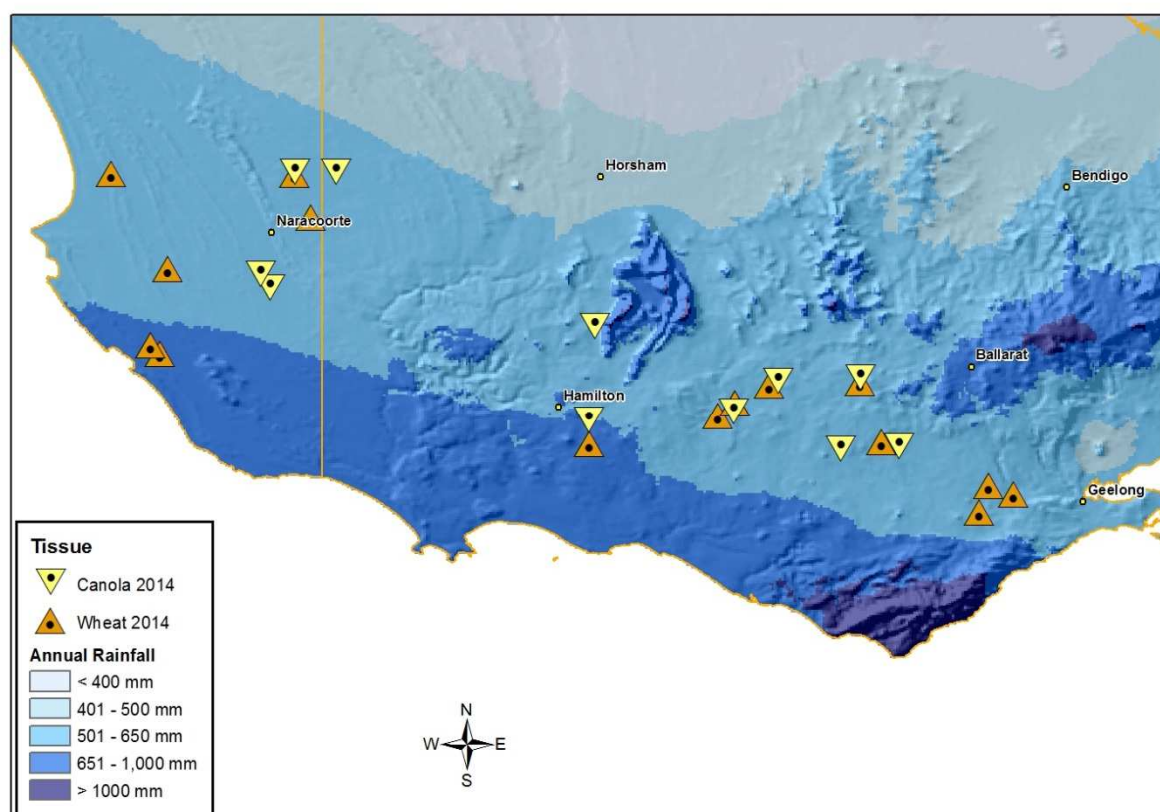

Fig 8. Location of sites where samples of plant tissue were collected at Growth Stage 31 in wheat or Growth Stage 3.3 in canola in 2014
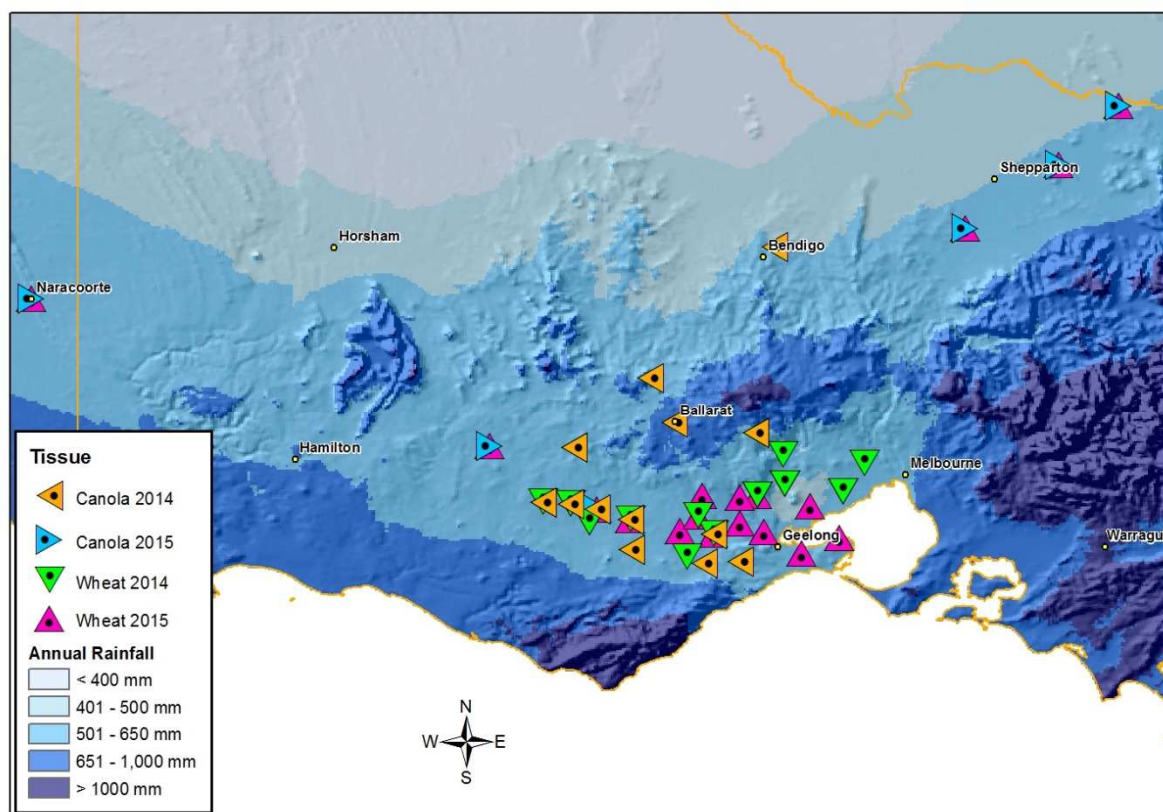
Fig 9. Location of sites from which grain samples were taken in 2014 and 2015.

Results and discussion

The nutrient concentrations of canola at 'first bud visible' (Stage 3.3) were generally above the reported critical values, although some crops tested had micronutrients applied either with fertiliser or as foliar supplements. Nutrient concentrations in wheat at GS31 were generally above critical values for major nutrients although several had low concentrations of B, Mg, Cu and Zn (Table 10).

Grain was sourced from GrainCorp® and this was provided as a sample of grains from a random cross-section of grain enterprises in the region including growers operating low and high input systems. Grain nutrient concentrations were within the adequate range for most nutrients in most paddocks although copper concentrations in canola (1.6 – 3.2 mg/kg) were at the lower end of the range whilst P and K concentrations in wheat were often below critical values proposed in Reuter *et al.* (1997) (Table 11). Wheat from South Australia had Ca concentrations nearly 4 times higher than samples from Victoria, and nearly 2.5 times the B concentration. Nevertheless, these differences were based on only four wheat samples from South Australia. Canola from South Australia was 27% lower in Fe and 31% higher in Cu. For all other nutrients, the differences were less than 20%.

These differences would relate mainly to geology, with the majority of the crop in South Australia grown on limestone that is high in Ca, whereas in southern Victoria many of the crops are grown on soils derived from basalt.

Table 10: Nutrient analysis of wheat tissue at GS31 (n = 23) and canola tissue at 'first bud visible'(n = 16) sampled during the 2014 cropping season. Critical values are minimum value for adequate nutrition as sourced from Reuter et al. (1997).

		N	P	K	S	Ca	Mg	Na	Mn	Fe	B	Cu	Zn	Mo
	unit	%	%	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Wheat	Critical value	3.50	0.30	2.40	0.15	0.21	0.15	-	15.0	-	5.0	3.0	20.0	0.1
	Min.	3.70	0.23	2.50	0.26	0.13	0.08	0.01	37.0	57.0	2.3	1.1	13.0	0.1
	Average	5.24	0.38	3.84	0.39	0.30	0.14	0.04	93.9	99.0	4.0	5.0	27.6	0.6
	Max.	6.70	0.56	4.80	0.52	0.50	0.22	0.07	230.0	180.0	7.9	9.4	71.0	3.5
	StDev	0.85	0.10	0.62	0.08	0.11	0.04	0.02	44.9	29.7	1.3	2.4	14.9	0.8
Canola	Critical value	5.30	0.32	2.80	0.47	0.14	0.21	-	-	-	22.0	4.0	22.0	-
	Min.	6.20	0.64	2.90	0.70	0.57	0.22	0.06	25.0	78.0	27.0	3.0	27.0	0.2
	Average	7.26	0.84	3.33	0.83	0.95	0.33	0.24	50.3	154.5	32.3	5.4	52.9	0.4
	Max.	8.30	1.20	3.80	0.99	1.20	0.49	0.44	93.0	670.0	39.0	7.4	82.0	1.3
	StDev	0.66	0.13	0.28	0.07	0.21	0.06	0.11	19.9	145.7	3.7	1.5	13.2	0.3

Table 11: Grain nutrient analysis for wheat in South Australia (n = 4) and Victoria (n = 50) and canola in South Australia (n = 26) and Victoria (n = 38) sampled during the 2014 and 2015 cropping seasons. All values are on a dry weight basis except the oil concentration of canola, which is reported on a 6% dry matter basis. Critical values are minimum value for adequate nutrition as sourced from Reuter *et al.* (1997) and Norton (2014).

Crop	State		N	P	K	S	Ca	Mg	Mn	Fe	B	Cu	Zn	Protein	Oil
		unit	%	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	%	%
Wheat		Critical value	-	0.27	0.50	0.12	-	-	20	-	2.0	2.5	15		
	SA	Min.	1.70	0.13	0.34	0.12	0.03	0.08	26	43	1.8	1.9	22	9.69	
		Average	2.25	0.24	0.45	0.19	0.12	0.14	34	49	5.9	3.1	27	12.83	
		Max.	3.50	0.43	0.69	0.37	0.38	0.28	39	66	17.0	3.8	38	19.95	
		StDev	0.84	0.13	0.16	0.12	0.18	0.10	6	11	7.4	0.9	8	4.80	
	Vic	Min.	1.50	0.17	0.30	0.12	0.02	0.09	18	26	0.5	1.6	12	9.01	
		Average	2.62	0.25	0.38	0.16	0.03	0.11	40	37	2.4	4.5	24	12.61	
		Max.	4.60	0.36	0.44	0.18	0.04	0.14	58	63	5.6	22.0	66	14.82	
		StDev	0.79	0.05	0.04	0.01	0.01	0.01	9	7	1.0	3.3	10	1.36	
Canola		Critical value	1.90	0.35	-	0.36	-	-	10	-	1.0	3.0	15		
	SA	Min.	3.10	0.39	0.67	0.35	0.28	0.25	20	36	12.0	2.0	21	19.59	38.30
		Average	3.98	0.55	0.74	0.43	0.38	0.32	30	59	14.3	4.1	29	24.56	41.39
		Max.	4.80	0.73	0.92	0.48	0.53	0.36	56	110	18.0	13.0	38	28.99	43.40
		StDev	0.42	0.06	0.06	0.04	0.08	0.03	10	18	1.3	2.9	5	2.93	1.52
	Vic	Min.	3.30	0.29	0.53	0.35	0.18	0.23	24	35	11.0	1.6	21	20.90	34.80
		Average	3.78	0.54	0.67	0.41	0.34	0.32	38	88	15.9	3.1	35	23.37	41.41
		Max.	5.40	0.89	1.00	0.52	0.44	0.38	48	510	20.0	9.3	58	30.30	45.50
		StDev	0.39	0.13	0.10	0.04	0.06	0.04	5	88	1.9	1.8	7	2.00	3.29

Commercial nutrient strips

To quantify the magnitude of nutrient responses over and above the rates applied commercially, grain yield was measured on a series of nutrient response strips that had been applied by a local agronomist on six wheat crops and three canola crops between Hamilton and Dunkeld. These strips were neither replicated nor randomized, but capable of providing useful data on responses that could be followed up by other techniques such as soil testing and replicated trials. The strips were intended for in-crop nutrient management. At each site, nutrient treatments were applied to strips 2 m wide at right angles to the sowing and header rows. Treatments were applied in June 2015 included additional N, P, NK and NKP. The N was supplied at 184 kg N/ha as urea, P at 35 kg P/ha as single superphosphate, and K at 200 kg K/ha as muriate of potash. These nutrient applications were additional to fertilizer applied to the commercial crop of 80 kg/ha MAP drilled at sowing and in-crop urea of 100-150 kg urea/ha. Hand harvests were made on 13 and 25 November 2015, comprising 2 quadrats per plot 1 m in length and 4 drill rows wide (1 x 1 m). Soil tests were only obtained from a few of these sites. One of the strip sites (Paddock 4) was used for the 2016 Tarrington omission site, and soil data for this site can be considered typical of the others.

Results and discussion

All the commercial fields showed a dry matter response to additional nutrient applied of between 11 and 54% relative to the nil control (Table 12). However, at three of the nine sites there was a negative yield response to the most complete treatment (NPK), and in the other three, the response was 5% or less. In these cases, the harvest index of the NPK treatment was much lower than for the Nil treatment, which is indicative of the crop haying off due to moisture stress. At many of these sites, effects of the 2015 fertiliser are visually evident in the 2016 crops, which raise questions relating to the residual effects of nutrient applications and indicate that applications (and potential economic benefits) should be considered over multiple years.

Other relevant field studies

A series of N response experiments with wheat was undertaken in the Hamilton area in 2012-2014 by Harris *et al.* (2015, 2016a,b). Grain yields responded negatively to applied N in 2012, which was attributed to a soil high in mineral N and post-anthesis water deficit. There were high losses of N to denitrification when applied at sowing due to a combination of high mineral N, high soil carbon, and waterlogging. There was little response to N applied at sowing, but much better responses and lower losses to top-dressed N, because it coincided with crop demand.

Through the GRDC project, DAN00168 led by Dr Mark Conyers, K response experiments on wheat, canola and barley were undertaken at Worndoo (Lake Bolac) in 2015 as well as sites in the HRZ of southern NSW (Breadlebane). The final results from these experiments are still with NSWDPI but when available will be used where relevant in the DAV00141 project.

Through IPN00003 (Norton 2016), a survey of field fertilizer practices across the southern region was undertaken and this included data on fertilizer use and crop yield over 5 years from 179 fields (45 growers) in the high rainfall zone. Table 9 summarizes the nutrient inputs for cereals, canola and legumes in the HRZ over the period 2010-2014 from the survey fields. From the information provided by the growers and consultants, nutrient balances and nutrient performance indicators were calculated. The mean partial nutrient balances (PNB - amount removed divided by the amount supplied) for N and P in the HRZ were 1.55 and 0.70 respectively. These data were not normally distributed and were generally skewed to the right. This N PNB indicates that there was 50% more N being removed in crop products than supplied from fertilizer and biological nitrogen fixation. Conversely, the P PNB less than one indicates that the P application rates were higher than the P removals, indicating that P was likely to be building up in this region, although no conclusion can be made on the availability of this extra P. The PNB for K was very high, with around 8 times more K removed than applied in this region. No fields in the HRZ were in K balance. Conversely, the S PNB was around 0.6 for the HRZ indicating that nearly twice as much S was applied as was removed. Much of the S was supplied as gypsum, and the distribution on the data on both K and S were also skewed, with only a few farmers using K and S.

Table 12. Grain yield, dry matter and harvest index of 9 wheat and canola fields in the Hamilton-Dunkeld area in 2015 to additional N, P, NK and NPK over and above that provided to the commercial crop. Note that missing cells were not harvested, and in Field 7 responses are compared to the +N treatment.

Field	Crop	Variety	Treatment					Max. response (%)
			Nil	N	P	NK	NPK	
					Grain yield (t/ha)			
1	Wheat	Bolac	6.5	6.0	6.7	6.6	5.7	2
2	Wheat	Bolac	4.6	4.3	5.0	5.3	4.7	13
3	Wheat	Bolac	3.9	3.6	4.4	4.1	4.1	11
4	Wheat	Revenue	5.9	7.1	7.0	6.6	6.2	21
5	Wheat	Revenue	4.1	3.4		4.3	3.2	4
6	Wheat	Revenue	5.0	5.7	5.8	6.1	6.1	22
7	Canola	Edimax		2.2		2.9	2.6	33
8	Canola	Wahoo	3.2	3.6		4.3	3.8	33
9	Canola	Wahoo	1.8	1.9		1.8	1.8	5
					Total dry matter (t/ha)			
1	Wheat	Bolac	14.5	14.5	15.5	16.1	14.9	11
2	Wheat	Bolac	10.3	10.5	11.2	12.6	11.8	23
3	Wheat	Bolac	9.0	9.0	10.2	10.1	10.4	15
4	Wheat	Revenue	12.5	14.2	14.0	14.7	14.5	18
5	Wheat	Revenue	9.2	8.5		10.2	10.0	11
6	Wheat	Revenue	11.4	13.9	13.3	13.6	13.9	22
7	Canola	Edimax		7.6		9.7	8.8	27
8	Canola	Wahoo	8.3	9.6		11.9	10.3	44
9	Canola	Wahoo	6.4	6.5		6.3	9.9	54
					Harvest Index			
1	Wheat	Bolac	0.45	0.41	0.43	0.41	0.38	-5
2	Wheat	Bolac	0.45	0.41	0.45	0.42	0.40	-1
3	Wheat	Bolac	0.44	0.40	0.43	0.41	0.40	-1
4	Wheat	Revenue	0.47	0.44	0.46	0.45	0.43	-3
5	Wheat	Revenue	0.45	0.40		0.42	0.32	-7
6	Wheat	Revenue	0.44	0.41	0.44	0.45	0.44	2
7	Canola	Edimax		0.29		0.30	0.30	5
8	Canola	Wahoo	0.39	0.37		0.36	0.37	-3
9	Canola	Wahoo	0.29	0.30		0.29	0.18	3

Table 13. Nutrient application rates in kg/ha for cereals, canola and legumes (pulse and pasture) for N, P, K and S for the high rainfall zone fields surveyed for the period 2010-2014.

Crop type	Average Yield (t/ha)	kg N/ha	kg P/ha	kg K/ha	kg S/ha
Cereals	4.23	59	18	4	3
Canola	2.15	66	20	8	50
Legumes	2.42	12	14	2	25

It is clear that while the tissue, grain and soil samples from wheat and canola crops in the high rainfall zone are within previously published criteria for nutrient adequacy, substantial additional responses have been obtained, particularly in early part of the growing season. These responses appear to be in the "hidden hunger" phase of crop nutrient response, where deficiencies are not detectable through plant or soil tests, but are expressed in a yield response. Exceptionally dry finishes in the 2014 and 2015 seasons (i.e. decile 1) were not conducive for these early responses being translated into higher grain yield in wheat, but this was not the case in canola. In some cases, the application of additional N led to a reduction in grain yield. At the time of writing (September), above median rainfall in 2016 and seasonal forecasts of above average spring rainfall indicate a season in which crops can express their potential, and be a good test of whether these early responses can be translated into additional grain yield providing crops are not adversely affected by waterlogging. The variability of response with season means that decision-making processes on in-crop N need to account for moisture already in the soil profile, and seasonal forecasts of spring rainfall. While application of P, K and S at sowing develops plant canopy to set up the yield potential, in-crop N is required to fulfill this potential in seasons with sufficient moisture to allow these potentials to be expressed. In dry seasons, there is opportunity to limit further growth of biomass by limiting in-crop N to minimize crop hay-off and ensure sufficient soil moisture to complete crop grain-fill.

Early responses to P would be due to a placement effect, in which P fertilizer placed just below the seed allows seedlings preferential access to readily available P. Plants with good P reserves are more able to tolerate stress such as herbicide damage or waterlogging.

A possible explanation for the early negative responses to S is that the sulfate and phosphate anions compete at the root surface. In our omission experiments, the S was supplied as single superphosphate or sulfate of ammonia. While the P:S ratio of single super (0.8 to 1) is similar to that required for plant growth (1 to 1; Table 10), P is adsorbed onto soil particles much more strongly than S. The solution concentration would then be much richer in S than P, leading to limitations on the amount of P that could be taken up through the root surface, and restricting the uptake of P by seedlings.

DECISION SUPPORT

New pathways to market for decision-making

It is recognized that GRDC has committed substantial recent investment in decision support tools for crop nutrition and therefore this project plans to work with, and complement current projects and tools wherever possible.

Similar to current projects and tools, our focus will be to support strategies (such as the split application of N) that allow farmers to adjust tactically and dynamically to unfolding circumstances; to maximise the higher yields and profits in good years, supported by additional nutrient inputs, and minimize the losses in poor years. Our work will add value by encompassing multiple crop nutrient constraints (N, P, K and S), be specific to HRZ cropping (wheat and canola) and using 'marginal' economic analysis to inform grower's nutrient strategies. Efforts will also be made to capture the potential residual effects of fertiliser applications over multiple years.

Outputs may include links with existing DSS, factsheets, BMP guides, rules of thumb and case studies to demonstrate the approach and identify circumstances that need to apply for the best nutrient decision to be made. These product(s) will be location specific; they also need to be simple to use, relevant, effective, low cost, and user friendly and users will be closely involved in their development (Nguyen *et al.* 2007).

Review of existing decision support systems

The features of a selection of DSS from those listed on the Climate Kelpie[1] and/or GRDC[2] web sites are tabulated in Table 14. The purpose of this tabulation is to help frame our own work, and to identify opportunities to add value to these products.

Most of the DSS listed involve short-run decisions regarding the use of a single fertiliser type, with no other nutrient constraints, where the main benefit of fertiliser application is in the current growing season. Most focus on N, a few on P. For short-run decision-making, the key source of risk is production risk due to unknown

---

[1] http://www.climatekelpie.com.au/manage-climate/decision-support-tools-for-managing-climate
[2] https://grdc.com.au/Resources/Tools/Australian-Grains-Industry-Tools?pg=2&all=0

Table 14. Selected web-based tools to assess the risk and benefits of nutrient use.

Tool & URL	Question the tool answers	Region	Commodities	Nutrient	Technical relationships embedded in tool	Risky variables	Grower input: biophysical parameters	Grower input: economic parameters	Outputs
Nitrogen Fertiliser Calculator	How much N fertiliser is required to reach my target yield?	Queensland and northern New South Wales Applicable at regional rather than paddock scale.	Wheat and sorghum	N	Uses WhopperCropper (since superseded by CropARM) to calculate nitrogen budgets for desired crop yield.	Seasonal risk expressed as season types: poor, poor to moderate, moderate to good and good.	Soil nitrogen, expected planting time, starting soil moisture.	Grain price, fertiliser cost, and other variable costs used to calculate gross margins.	Fertiliser N required and expected gross margins under 4 climate scenarios.
Option$ page (BOERA) on CropPro http://www.croppro.com.au/options.php	What are the economic benefits and risks of implementing various options to manage production constraints.	Southern cropping region	Wheat and canola	Most production constraints	None: relies on the grower's subjective estimate of potential (unconstrained) yields and yield penalties.	Probability distribution for expected yields 'with' and 'without' the production constraint	Grower's estimate of likely crop performance and potential impact (yield penalties) of constraints and mitigation strategies	Additional returns and costs for estimating net benefits of alternative management strategies	Cumulative frequency distributions of net benefits for alternative management strategies, estimates of the average return on investment and probability of breaking even.
WhopperCropper[1] (superseded by CropARM) http://www.armonline.com.au/#/wc	What is the range of yields possible from a given set of inputs?	Qld and NSW, some Vic sites, (but not HRZ). Applicable at regional rather than paddock scale.	Wheat and canola in southern Australia and all major winter and summer crops in northern Australia	none	600,000 pre-run APSIM (www.apsim.info) yield simulations.	Seasonal risk generated from 100 years of weather data expressed as 4 season types based on 'phases' of the Southern Oscillation Index (SOI).	Soil water-holding capacity, soil water at sowing, time of sowing, N fertiliser rate, crop maturity type, sowing density.	none	A range of yields displayed as individual yield results (time series) or in various types of probability graphs (e.g. boxplots, and cumulative frequency distributions).

Tool & URL	Question the tool answers	Region	Commodities	Nutrient	Technical relationships embedded in tool	Risky variables	Grower input: biophysical parameters	Grower input: economic parameters	Outputs
NitrogenARM http://www.armonline.com.au/#/ncalc	What is the fertiliser N required and GM for my target yield?	Qld and NSW	Sorghum, wheat	N	Yield response to total crop N supply under 4 climate scenarios from *CropARM*. Nitrogen fertiliser application rates are based on the difference between the demand and supply of nitrogen for the targeted yields.	Seasonal risk (as above)	Low N and high N strategy	Grain price, fertiliser cost, and other variable costs for calculating gross margins.	Yields and gross margins for the two nitrogen regimes (high and low) for the four season types.
Yield and N calculators spreadsheet available from Jeff Baldock (CSIRO)	What is the N required for the targeted yield and grain protein?	Dryland regions in southern Australia with annual rainfall lass than 500mm	Cereal and canola	N, P	Estimate water limited potential yields and the amount of nitrogen required to attain these yields using various factors (protein to N conversion factors, the N harvest index and N use efficiency).	Seasonal risk expressed as rainfall deciles.	Soil test data, paddock history, expected growing season rainfall.	none	Attainable yield, N fertiliser requirements and yield penalties for decreasing fertiliser N with and without sufficient P.
Yield Prophet® http://www.yieldprophet.com.au/yp/Home.aspx	Given the seasonal conditions to date, and historic climatic conditions, what is the yield potential of my crop under current management and with unlimited nitrogen supply?	All dryland and irrigated cropping regions. Provides paddock-specific yield forecasts.	Wheat, barley, sorghum, canola and oats.	N	Interface to the crop production model APSIM (www.apsim.info) that models crop growth across a range of weather conditions.	Yield probability forecasting displayed as a cumulative distribution function	Paddock's location, details of its soil including soil type and soil test results, and the details of the current crop including sowing date, crop type and cultivar, rainfall throughout the growing season. Integrates with soil probes.	Grain price, fertiliser cost, and other variable costs for calculating GMs.	Real time assessment of crop yield potential throughout the growing season. Impact of different N fertiliser rates and strategies on yield forecasts, probability of a positive gross margin on fertiliser inputs.

Tool & URL	Question the tool answers	Region	Commodities	Nutrient	Technical relationships embedded in tool	Risky variables	Grower input: biophysical parameters	Grower input: economic parameters	Outputs
Crop Phosphorus Model (WA) https://www.agric.wa.gov.au/crop-phosphorus-model	What is the rate of P fertiliser and corresponding gross margin?	WA	Wheat, lupins and canola.	P	Response functions relating crop yield in current year to applied P.	Production function parameters (yield potential and initial soil P) grain price and fertiliser price.	Potential yield, Colwell P (0-10cm), PBI, P content of fertiliser.	Grain price and price per tonne of fertiliser. The future economic benefit of any carry-over has not been included.	Graphical representation of yield and GM for a range of applied P.
Deep placement of P calculator (Zull et al 2015)	How much P should I apply, and how often?	12 northern grains regions.	9 rain-fed crops, i.e. wheat. Case study presented for Goondiwindi region for a 'short' rotation (3 year) and a 'long' rotation (7 year).	P	Uses APSIM to estimate crop yields and damages (yield penalties) for 2 levels of PAWC x 3 season types when Colwell-P <10mg/kg and fallow mineralization.	Seasonal risk generated from over 100 years of weather data expressed as three basic season types: 'dry start', 'no stress', 'later stress'.	Region, soil PAWC, soil tests, crops/rotations,	Discounted cash flow analysis over multiple years: variable costs, farm gate grain prices, deep-P application costs, MAP and Urea prices, additional capital, financial discount rate.	Optimal application rate; average real net gain ($/ha/yr); risk of different decisions ($) (expected, worst, best, breakeven); IRR (%); probable pay-back period.
Dairy N-Advisor http://vro.agriculture.vic.gov.au/dpi/vro/vrosite.nsf/pages/nitrogen-advisor	Is your N fertiliser application profitable for your current grazing rotation?	national	Dairy pasture	N	Based on predicted pasture response functions determined from nearly 6,000 nitrogen fertiliser experiments undertaken across southern temperate Australia over the past 40 years	Seasonal risk: subjective assessment of better, most likely and worse outcomes.	Pasture DM consumption calibrated to paddock for current rotation	Exact profit maximising level of N determined by equating marginal returns to marginal costs. Requires equivalent market price for pasture consumed and price of N.	N applied and pasture DM consumed at profit maximizing N rate, and rate of return on last $ invested in N.

Table 15. Factors involved with short and long-term nutrient decisions.

Short-term decisions	Long-term decisions
Main benefit in current season	Benefits for many seasons
Unknown season type or yield but known starting moisture	Unknown season type or yield and unknown starting water after first season
Fixed crop $ (can contract)	Unknown future crop prices
Good knowledge of response functions	Poor knowledge of response functions
Fixed fertiliser prices at application	Fixed fertiliser prices at time of decision
Assume no other nutrient constraints	Unknown future fertiliser prices
	Time value of money and inflation ($$$ in the ground v in the bank)

Source: Zull *et al.* (2015)

seasonal outcomes (Table 15). Unknown future crop and fertiliser prices are more relevant to longer-term decision-making where the benefits accrue over many seasons. Hence, tools have a heavy focus on modeling the response of yield to applied nutrient under variable seasonal conditions. This modelling typically involves calculating the potential wheat and canola yields using models such as APSIM or the pre-run APSIM simulations embedded in Whoppercropper/CropARM. Users are required to provide information specific to their own circumstances, such as 'background' soil fertility (N and P status of the soil), sowing date, and available soil moisture at time of sowing and rainfall during the growing season. Potential yields are estimated using the mass-balance approach. For N (by way of example), this involves:

- Predicting the 'water limited' achievable or target yield
- Estimating fertiliser required to achieve the yield target (total N demand).
- Deducting N inputs from non-fertiliser sources (mineral N at sowing, in-crop mineralisation).
- Compensating for N losses to leaching and surface runoff.

Only one of the DSS reviewed, the Option$ page on CropPro, relies solely on the grower's subjective evaluation of yields, as it does not embody any response functions or estimates of yield penalties.

Some of the DSS make use of auxiliary information such as the SOI index (WhopperCropper) and real-time input from soil water probes (Yield Prophet®). Factoring in the seasonal forecast is done manually from sources such as 'The Break' newsletter, the soil moisture probe network maintained by DEDJTR and the farmer co-operators, CliMate, and the Bureau of Meteorology's POAMA (the Predictive Ocean Atmosphere Model for Australia). In mid-2017, the Bureau will be releasing the ACCESS – S model, which has more regional detail and more frequent outlooks than POAMA.

The economic analysis is an addendum to the biophysical modelling. It typically involves gross margin analysis, i.e. an estimate of the gross returns less the associated variable costs. Best practice economic analysis is to apply 'marginal analysis' which is concerned with how the addition of another unit of the variable input, such as N or P, will change the economic well-being (add to profits) of the business. The economic decision rule to maximise profit is to apply the input up to where the revenue from an extra kilogram of nutrient applied just exceeds its cost. Mathematically, this is equivalent to equating the derivative of the production function to the inverse price ratio (Bishop and Toussant 1958). The price ratio is the price of the input 'delivered and spread', divided by the net price of the cereal 'ex farm' at the time of harvest. This profit maximising rule assumes full information, no constraints on capital, and all other inputs held constant. The Dairy N-Advisor is an example of the application of marginal analysis in the dairy industry.

Only one DSS that involves the deep placement of P in northern cropping regions (Zull *et al*, 2015), accommodates time in decision making for nutrients that persist (and decay) in the soil over multiple years. It is normal practice for any nutrient left in the soil at end of the planning horizon to be ignored, as the tools are meant to be used in a stepwise fashion through time. This means that after the end of the planning horizon, new soil tests are undertaken and the situation reviewed.

It follows from the previous discussion that linkages with other projects and tools may include:

- Providing meta-data and pre-run yield simulations for Whoppercropper/CropARM/NitrogenARM and for any future DSS.
- Providing new functionality, defined in the broader sense – e.g. to include response functions, yield penalties and case studies, to the Option$ calculator on CropPro.
- Incorporating seasonal climate risk information and outlooks.

The building-blocks that we have on-hand to prototype our method are CAT (Catchment Analysis Tool, version 8.4.5) and Excel®. A graphical outline of the approach is shown in Figure 10, with potential linkages to pre-existing projects and tools shown by the dashed lines.
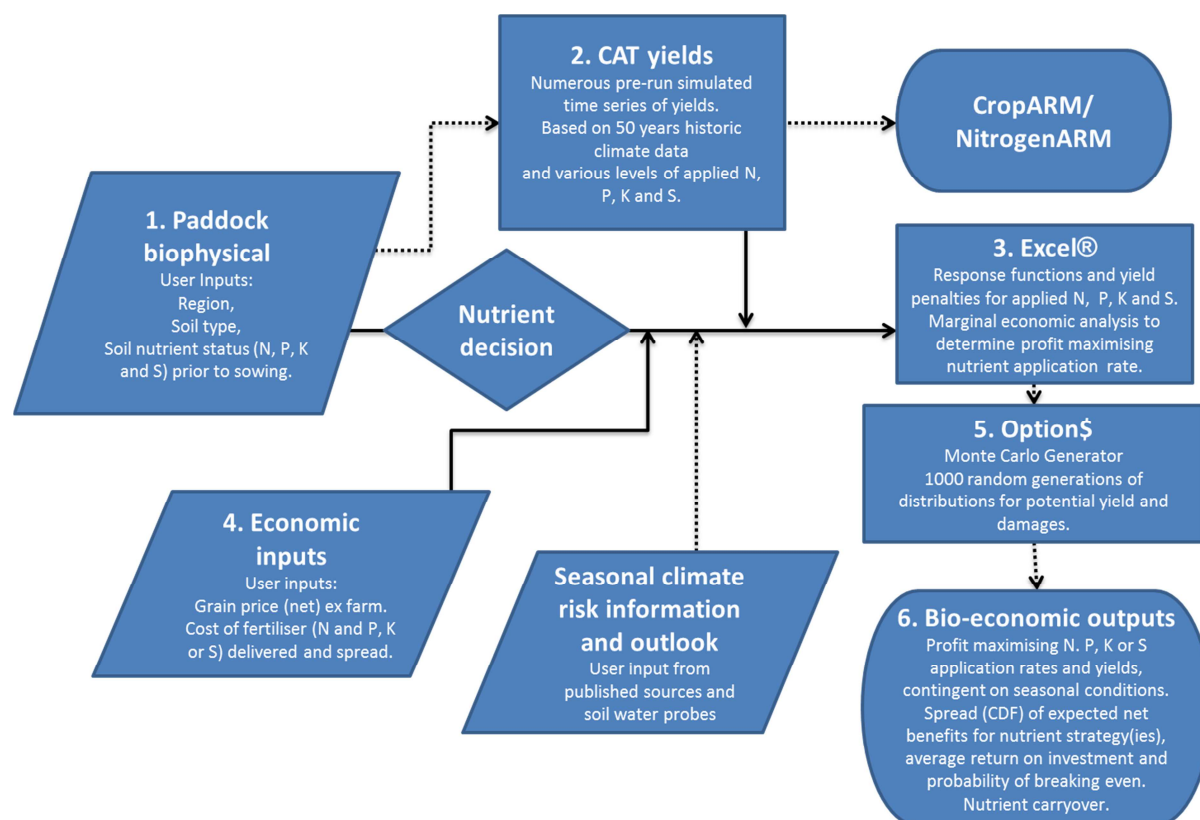

Fig. 10. Schematic of the bio-economic framework showing possible links (dashed lines) to existing tools

The key building blocks for our analysis are numbered from 1-6.

- The starting point (#1) is defining the paddock biophysical properties relevant to the study area that are tractable in the biophysical modelling of yield outcomes. These include soil properties prior to sowing such as the availability of N, P, K, S and micronutrients.
- CAT modelling (#2), using location-specific climate and soil nutrient status, provides sufficient data points to estimate response functions that exhibit the diminishing marginal returns necessary for economic analysis. Response functions are required for three basic season types: 'poor', 'normal', and 'good' years based on quartiles of consecutive yield outcomes.
- The "Solver" add-in in Excel® (#3) is used to fit the response functions to modelled yield data from CAT. As an interim measure, we use an exponential Mitscherlich function with an asymptotic plateau (after Hannah et al. 2016). Parameter values were found that minimised the sum of the squared differences ($\sum\chi^2$) between the yield values generated by CAT and those predicted from the Mitscherlich function.

We assumed no substitution possibilities between nutrients in the production of grains. Yield penalties or 'damages' were derived from the response functions for use in the Option$ calculator.

- For calculating the net benefits, only the costs and benefits that change with the nutrient treatment are considered (#4); these being (1) the expected farm-gate grain price on a per ton basis, and (2) the cost of fertiliser on a per hectare basis. We exclude the benefits and costs of other treatments or other variable costs because these cannot be recovered; i.e. they are "sunk". For simplicity, the cost of soil testing, nutrient carry-over and the (opportunity) cost of additional capital for fertiliser purchases (as represented by the overdraft rate) were not included in the analysis.

- The precise 'best bet' level of fertiliser to use is each season type is calculated using Excel® (#3) by equating the derivative of the response function to the inverse price ratio (i.e. the cost of the nutrient divided by the grain price) (Bishop and Toussaint, 1958). Note that the economic analysis as it is currently formulated deals with one fertiliser type at a time, assuming other nutrients are unlimiting.

- The Option$ calculator is used to examine the variability (risk) around the net benefits for specified nutrient strategies (#5). These are calculated from hundreds of Monte Carlo simulations, with each simulation using yields drawn at random from the triangular probability distributions for potential yields and yield penalties.

- The range in net benefits for the nutrient strategy is presented as a cumulative distribution function (CDF) (#6). Where multiple scenarios are being explored, the scenario with a CDF that lies further to the right is the one that makes more efficient use of that capital (and is said to be 'stochastically dominant', Hardaker et al. 2004). The Option$ calculator also provides estimates of the average return on investment and probability of breaking even.

Prototype of decision-making process

By applying the method to two case studies, we demonstrate how it can be used to equip growers and their advisors to confidently assess crop nutrient demands and limitations, predict yield potential and pay-offs associated with high input usage in the HRZ environment. The scenarios use expected crop and fertiliser prices and modelled fertiliser response functions.

Scenario 1 (Christy *et al.* 2016)

Three farmers collaborating on the Nutrient Omission Field Experiments meet to compare the soil nutrient status of their paddocks. They intend to plant canola, and ponder, "If I don't address my P, K or S nutrient deficiencies, how would this impact my in-crop N-decision?"

Assumptions: Yield responses of canola to applied N while constraining P, K and S were derived from CAT modelling for the three locations at Inverleigh (Victoria), Hamilton (Victoria) and Naracoorte (South Australia). At these locations, soil nutrient status was analysed from soil tests of four paddocks within each location sown to canola. The model was run over 50 years, using location specific climate, with additional N applied as urea in two split applications totaling 200 kg N/ha, 100 kg N/ha and 0 kg N/ha at first bud and start of flowering. Mineral N and soil water were reset each year at planting (the former to 140 kgN/ha); there was no carry-over between seasons. For each of the three locations, five scenarios were considered being: unlimited P, K and S status to determine the yield response to N; with the other four scenarios based on the actual soil tests to determine N response limited by P, K and S soil status.

Results: The average yield response with unlimited P, K and S suggests that a risk-neutral producer would maximise profits by applying sufficient N to produce yields of 4900, 5900 and 5200 kg ha^{-1} at Inverleigh (Figure 11), Hamilton (Figure 12) and Naracoorte (Figure 13), respectively. The difference in yields between the three sites can be attributed to growing season rainfall with Inverleigh being the lowest and Hamilton the highest.

When the actual soil nutrient status for each of the four sites was taken into account, the N responsiveness of canola decreased. At all locations except for Hamilton, the soil P, K and S status of a site decreased the optimal yield and N application rate; at Hamilton, the soil test levels were not limiting. It is not financially viable for the growers to chase a higher yield by applying more N than the profit maximising rate; the reason being that beyond this point, the grower would be losing money with each additional unit of N applied.

This decrease in yield potential demonstrates how soil nutrient status other than N impact negatively on yield potential, and hence reduces the economically optimum N application rate. This new plateau shows that there is a limit to which in-season N application can raise yield, when it is constrained by the status of other nutrients. Whether it pays to ameliorate these deficiencies is another question (see Scenario 2).

Fig. 11: Profit maximising yield and N application rates for canola with unlimited P, K and S and for the four sites at Inverleigh. Risk-neutral producer. Soil nutrient status for each site shown in Table.

Legend:
— Hamilton (P, K S not limited)
– – – Hamilton (Site1)
– – – Hamilton (Site2)
– – – Hamilton (Site3)
– – – Hamilton (Site4)

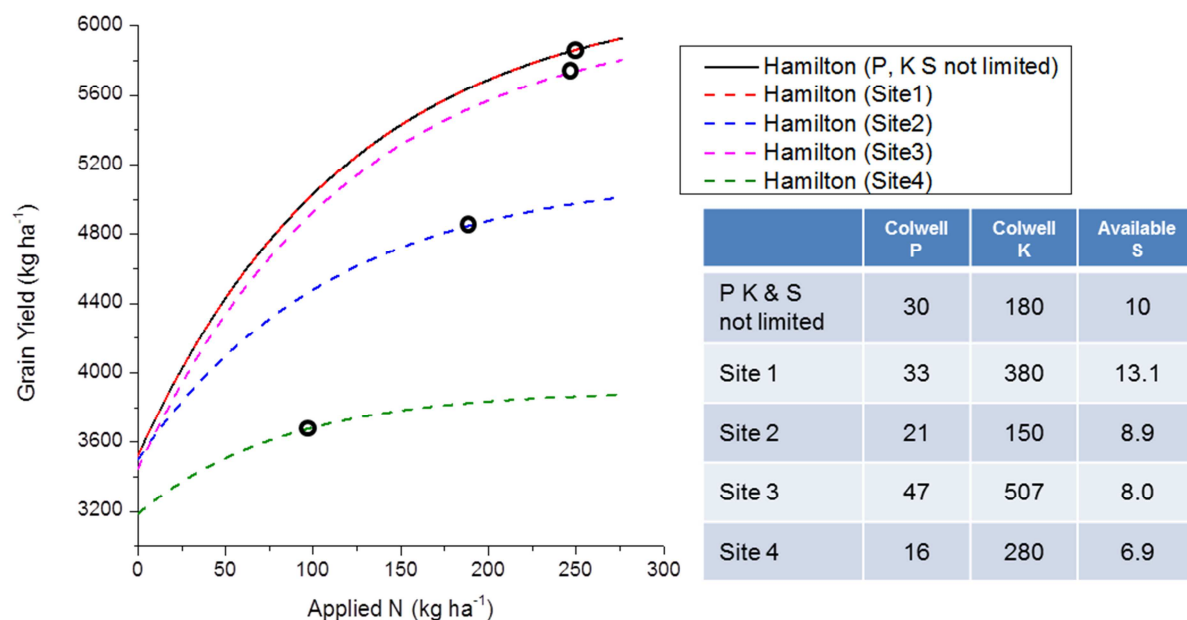|	Colwell P	Colwell K	Available S
P K & S not limited	30	180	10
Site 1	33	380	13.1
Site 2	21	150	8.9
Site 3	47	507	8.0
Site 4	16	280	6.9

Fig. 12: Profit maximising yield and N application rates for canola with unlimited P, K and S and for the four sites at Hamilton. Risk-neutral producer. Soil nutrient status for each site shown in Table.

Legend:
— Naracoorte (P, K S not limited)
– – – Naracoorte (Site1)
– – – Naracoorte (Site2)
– – – Naracoorte (Site3)
– – – Naracoorte (Site4)

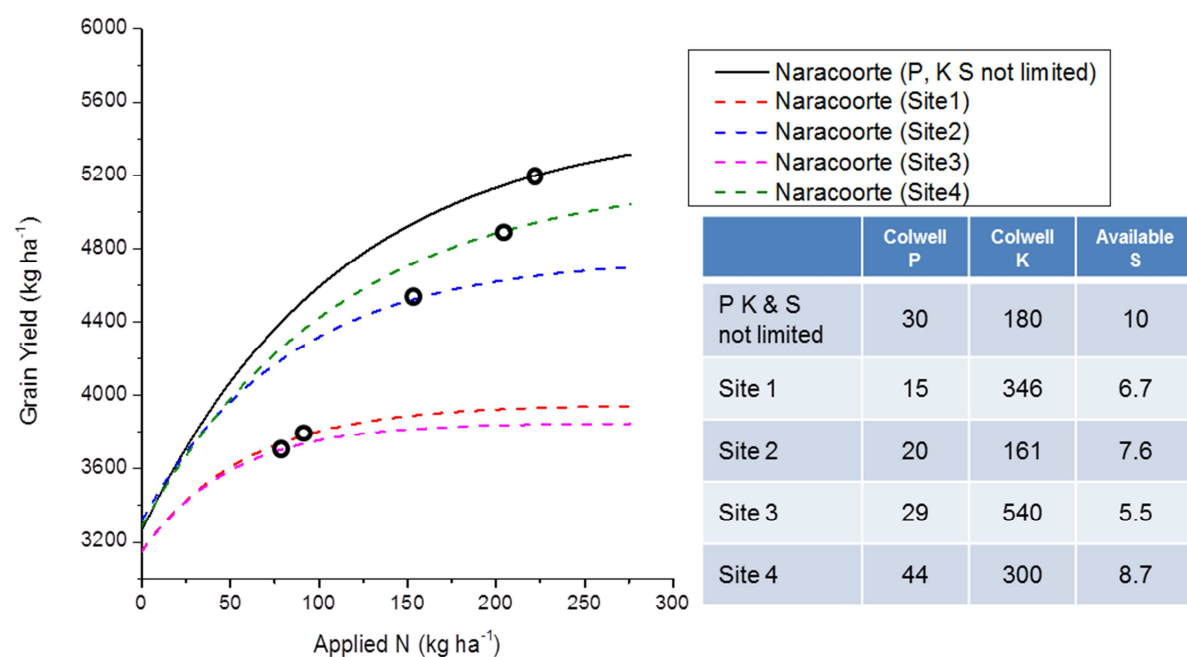|	Colwell P	Colwell K	Available S
P K & S not limited	30	180	10
Site 1	15	346	6.7
Site 2	20	161	7.6
Site 3	29	540	5.5
Site 4	44	300	8.7

Fig. 13: Profit maximising yield and N application rates for canola with unlimited P, K and S and for the four sites at Naracoorte. Risk-neutral producer. Soil nutrient status for each site shown in Table.

Scenario 2 (Stott *et al*. 2016)

"My soil is low in P (10mg/kg Colwell-P), and I intend to apply nutrients to maximise my profits from growing wheat on the expectation of a good seasonal outcome. I will split my N in case the season doesn't pan out well, but what is the likelihood that I will break even on my P investment?"

Assumptions: Yield responses to applied N and P were derived for a case-study paddock at Inverleigh in Victoria for three season types: 'poor', 'normal' and 'good' years. Season types were based on quartiles of consecutive yield outcomes from CAT modelling. Inverleigh is one of the trial sites in the Nutrient Omission Field Experiments currently being conducted by Agriculture Victoria in collaboration with Southern Farming Systems (SFS) and MacKillop Farm Management Group (MFMG).

CAT was run using 50 years of climate data and three nutrient scenarios, which involved initial P set at 'low' (Colwell P 10 mg/kg soil), 'marginal' (20 mg/kg) and 'sufficient' (30 mg/kg) and other nutrients unlimiting. In translating soil P levels to applied P, we assumed that 2.7 kg P/ha is required to raise soil test values by 1 mg P/kg soil (Burkitt et al. 2001; Burkitt et al. 2002). Mineral N and soil water were reset each year at planting (the former to 160 kgN/ha); there was no carry-over between seasons.

Data derived from analysis of the modelled grain yields in Excel® were used to inform the Option$ calculator on CropPro (Figure 15). The Option$ calculator was used to evaluate three P application decisions taking into account the seasonal risk. The three P decisions are the profit-maximising P rates in 'poor', 'normal and 'good' years (Figure 14).

The Option$ calculator relies on the grower's subjective estimates of potential yields and yield penalties, and uses Monte Carlo simulation to generate cumulative distribution functions (CDF) of the net benefits of the alternative mitigation strategies. Instead of using gross margins, only the costs and benefits that change with the P treatment are considered when calculating the net benefits of the various P treatments; these being (1) the expected farm-gate wheat price, and (2) the cost of P fertiliser delivered and spread. The Option$ calculator leaves crop and fertiliser prices static, but these variables could be subjected to sensitivity analysis by changing them one at a time; which we have not done due to space limitations.

Results: The case-study paddock at Inverleigh was shown to have high yield potential, estimated at 9.0 t/ha in good seasons with profit maximising applications of P and other nutrients non-limiting. In good seasons, it is financially viable for the grower to chase this high yield by addressing P fertility with 51 kg P/ha. In less benign seasons, profit maximising P applications and yields are lower. Profit maximising yields fall to 6.8 t/ha in normal years and 2.4 t/ha in poor years, with the associated profit maximising P rates falling to 45 kg P/ha and 16 kg P/ha, respectively.

With an unknown seasonal outcome, the best-bet P decision made by a risk-neutral producer at or before seeding, would be to apply 45 kg P/ha (pie chart, Figure 13). This is the best-bet outcome on 52% of occasions, and would achieve expected yields in good, normal and poor years, respectively, of 8.9, 6.8 and 2.6 t/ha. Decision-makers appear to have a wide margin for error; even in good years it is seldom worth the added cost of increasing the P rate to 51 kg P/ha from 45 kg P/ha, as both rates are located on the flat part of the P response curve (Pannell 2006). The second-best option is to apply a more modest 16 kg P/ha, as the lower returns achieved in poor years would be more than offset by lower P-fertiliser costs.
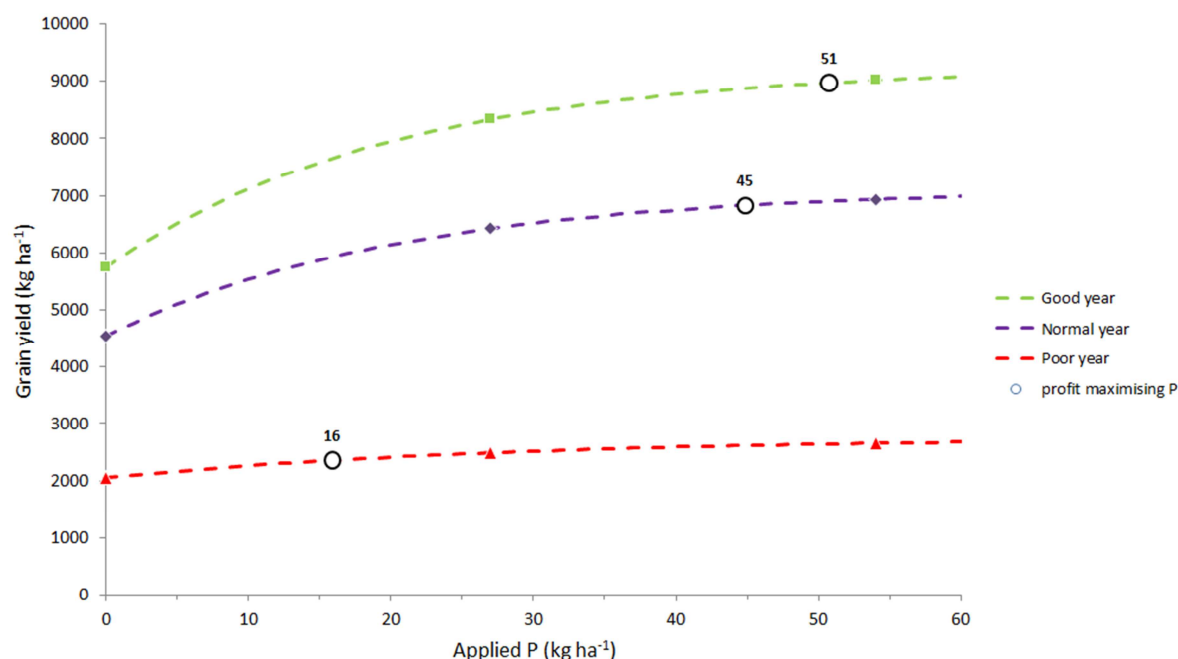
Fig. 14. Profit maximising P application rates (open circles) for wheat at the Inverleigh trial site by three season types. Solid shapes show modelled data points.

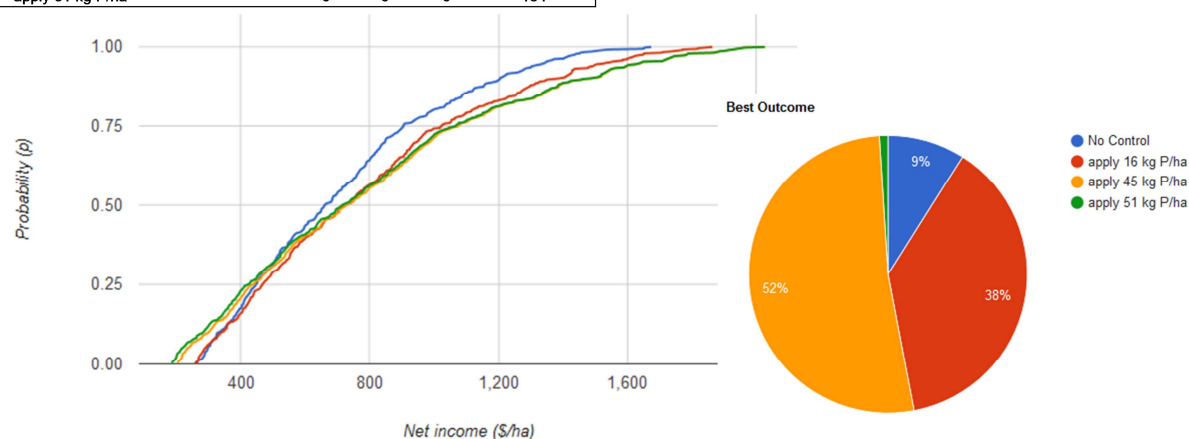| Option$ calculator inputs	Seasonal Conditions			P expenditure ($/ha)
	Poor	Normal	Good	
Probability of seasonal outcome (%)	25	50	25	
Wheat price, net, on-farm post-harvest ($/t)	256	256	256	
Wheat yield at profit maximising P (t/ha)	2.4	6.8	9.0	
Yield penalty with 'low' initial soil P (10mg/kg Colwell-P) (%)				
- do nothing (control)	22	34	36	0
- apply 16 kg P/ha	11	14	15	62
- apply 45 kg P/ha	1	1	1	163
- apply 51 kg P/ha	0	0	0	184

Fig. 15. Best outcome and net income CDF for the decision to apply 16, 45 or 51 kg P/ha with unknown seasonal outcomes. The CDF shows the probability (y-axis) that net income ($/ha) would be less than or equal to a particular value (x-axis).

Residual value

At a meeting with commercial agronomists in February 2015, there was support for including an estimate of the residual value of fertilizer. This was because if the agronomist recommended fertilizer applications that were not required in the current season because of an unexpectedly early finish, there would be a saving in fertilizer costs in the following season. To develop such a relationship for P, data from the Hamilton Long-term Phosphate Experiment were assembled comprising Olsen P in autumn, P applied and Olsen P the following autumn (Cayley and Kearney 1999 and unpublished). These were converted to an equivalent Colwell P value using a site-specific calibration $Colwell = -1.40 + 2.15\ Olsen$. Export as product and accumulation in sheep camp areas were estimated as between 1.1 and 2.2 kg P/ha.yr depending on soil fertility and stocking rate (McCaskill and Cayley

2002). The following relationship was developed by linear regression from 230 cases over 12 years between 1979 and 2002:

$$P_1 = 1.122 + 0.8315P_0 + 0.1324P_{net} + 0.00439P_{app}$$

where P_0 (mg/kg) is the initial Colwell P in the first autumn, P_{net} (kg/ha) is the P applied less export, and P_1 (mg/kg) Colwell P the following autumn. This relationship accounted for 94% of variation, and is illustrated in Figure 16.
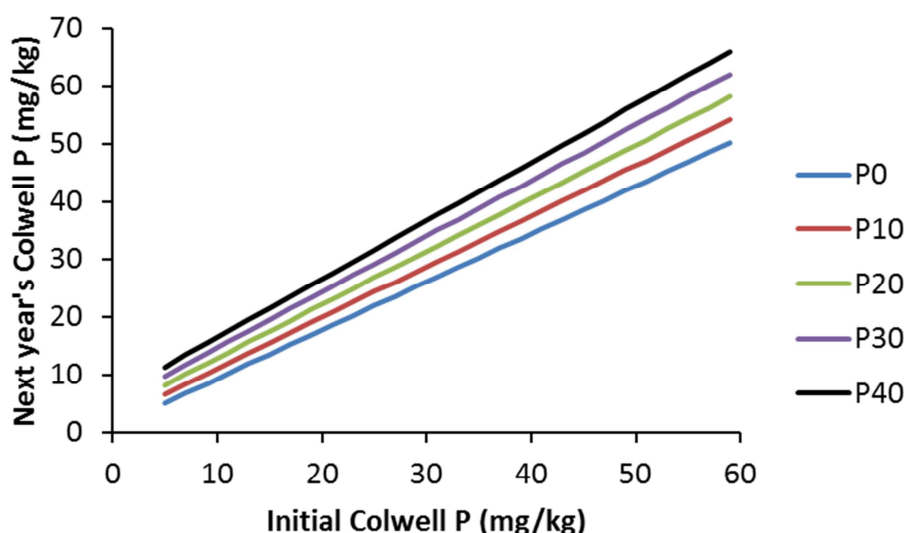

Fig. 16. Relationship between Colwell P in the first autumn, with that in the following autumn, as a function of net P accessions (application less export in crop or livestock) of nil (P0) to 40 kg P/ha (P40).

The relationship allows the residual value of applied P to be accounted for in decision support, but is based on a pasture site. Similar relationships will be sought using data from a long-term crop nutrient study at Dahlan, and for other nutrients from measurements at the start and end of season on the omission trials. We have not yet undertaken decision scenarios that incorporate residual value.

Nascent messages

With only one complete year of field results, it is too early in the project to develop conclusive findings. Nevertheless, the following messages are developing.

1. There is a response to P banded at sowing that is additional to the soil test value, leading to early P responses. Under water limited conditions, these early responses do not follow through to grain yield, but will be tested in the 2016 and 2017 seasons of this project.

2. Responses to P early in the season are additional to those embodied in the Better Fertiliser Decisions project, the CAT model, and the relationships used in the current version of the economic model.

3. There is a negative effect of S at sowing. The preferred fertiliser at sowing should be MAP. Should S be required it should be applied as gypsum or single super before the crop, or sulphate of ammonia in-crop.

4. The majority of N should be applied in-crop, because its efficiency early in the crop life is low and subject to high losses through denitrification, whereas in-crop application achieves a higher N efficiency and allows some control of excessive canopy development in dry seasons.

5. Preliminary bio-economic analysis suggests that the unrealised potential of crops in the HRZ can be explained, in part, by the cost of nutrient inputs and the risks associated with variable seasons. The grower could respond tactically to evolving seasonal conditions during the growing season by applying profit-maximising amounts of N in split applications. P-fertiliser application is best at or before seeding;

however growers still have flexibility when considering the uncertain season ahead thanks to the flat response function around the economic optimum.

These findings will be tested for consistency across years in the subsequent years of the project.

Next steps

To develop a residual value function for soil P that is appropriate to cropping, data will be sought from Incitec-Pivot from the Dahlan Long-Term cropping experiment to develop a relationship between the current soil test level, applied P, nutrient removal, and the soil test level in the subsequent year.

Samples of stubble will be collected at grain harvest from the 2016 omission trials to quantify the potential net removal in stubble.

A mock-up version of the way of thinking about the nutrient use problem and some general conclusions about optimum nutrient usage and least-cost nutrient combinations will be further developed and tested with industry representatives by June 2017. This will involve (1) engaging with growers and their consultants and discussing the scenarios and ways of thinking about the nutrient problem; and (2) exploring more realistic climate-dependent response functions involving pairs of nutrients (e.g. N and P, N and S, N and K) (Heady 1957).

ACKNOWLDEGEMENTS

REFERENCES

[Publications of this project (DAV000141) are indicated by *]

Anderson GC, Peverill KI, Brennan RF (2013) Soil sulphur-crop response calibration relationships and criteria for field crops grown in Australia. Crop and Pasture Science 64, 523-530.

Audit, NLaWR (2001) Nutrient management in Australian agriculture. In 'Australian agricultural assessment. Vol. 1.' (National Land and Water Resources Audit: Canberra, ACT:) Available at http://nrmonline.nrm.gov.au/catalog/mql:892

Bell R, Reuter D, Scott B, Sparrow L, Strong W, Chen W (2013a) Soil phosphorus-crop response calibration relationships and criteria for winter cereal crops grown in Australia. Crop and Pasture Science 64, 480-498.

Bell R, Moody PW, Anderson GC, Strong W (2013b) Soil phosphorus – crop response calibration relationships and criteria for oilseeds grain legumes and summer cereal crops grown in Australia. Crop and Pasture Science 64, 499-513.

Bishop CE and Toussaint WD (1958). *Agricultural Economic Analysis*, John Wiley and Sons, New York.

Brennan RF, Bell MJ (2013). Soil potassium – crop response calibration relationships and criteria for field crops grown in Australia. Crop and Pasture Science 64, 514-522.

Burkitt LL, Gourley CJP, Sale PWG, Uren NC, Hannah MC (2001). Factors affecting the change in extractable phosphorus following the application of phosphatic fertiliser on pasture soils in southern Victoria. Australian Journal of Soil Research 39, 759-771.

Burkitt LL, Moody PW, Gourley CJP, Hannah MC.(2002). A simple phosphorus buffering index for Australian soils. Australian Journal of Soil Research 40, 1-18.

Cayley JWD, Kearney GA (1999) Changes in bicarbonate-extractable phosphorus of a basalt-derived duplex soil associated with applications of superphosphate to pasture grazed by sheep. Australian Journal of Agricultural Research 50, 547-554.

*Christy B, Stott K, McCaskill M, Riffkin P (2016) Canola yield potential limited by nutrient status in the high rainfall zone of Southern Australia. Proceedings of the 19th Australian Research Assembly on Brassicas, Melbourne October 3-6th (accepted).

Christy B, O'Leary G, Riffkin P, Acuna T, Potter T and Clough A 2013. Long-season canola (*Brassica napus L.*) cultivars offer potential to substantially increase grain yield production in south-eastern Australia compared with current spring cultivars. *Crop and Pasture Science* **64**, 901–913.

*Christy B, Clough A, Riffkin P, Norton R, Midwood J, O'Leary G, Stott K, Weeks A, Potter T (2015a). Managing crop inputs in a high yield potential environment – HRZ of southern Australia. (The State of Victoria Department of Economic Development, Jobs, Transport & Resources), Available at http://anz.ipni.net/article/ANZ-3232

*Christy BP Riffkin PA, Clough A, Norton R, Stott K, O'Leary GJ (2015b) Crop yield potential limited by nutrient status in the high rainfall zone of Southern Australia. "*Building Productive, Diverse and Sustainable Landscapes*". Edited by T. Acuña, C. Moeller, D. Parsons and M. Harrison. *Proceedings of the 17th Australian Agronomy Conference 2015*, 21 – 24 September 2015, Hobart, Tas. http://www.agronomy2015.com.au/proceedings

*Clough A, Norton R, Riffkin PA, Partington DL, Christy R (2015) Nutrient status of soils and crops in the high rainfall zone of Victoria and South Australia. "*Building Productive, Diverse and Sustainable Landscapes*". Edited by T. Acuña, C. Moeller, D. Parsons and M. Harrison. *Proceedings of the 17th Australian Agronomy Conference 2015*, 21 – 24 September 2015, Hobart, Tas. http://www.agronomy2015.com.au/proceedings

Donald CM, Prescott JA (1975). Trace elements in Australian crop and pasture production, 1924 – 1974. In:Trace elements in soil-plant-animal systems (Eds DJD Nicholas, AR Egan). Proceedings of the Jubilee Symposium of the Waite Agricultural Research Institute, November 1974, Glen Osmond, South Australia. pp7-37.

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment. 1. The relation between yield, water use and climate. Australian Journal of Agricultural Research 35, 743-764.

GRDC (2013). Crop nutrition fact sheet: Micronutrients. https://www.grdc.com.au/Resources/ Factsheets/2013/11/Micronutrients-and-trace-elements

GRDC (2016). 2016 Farm Gross Margin Guide. https://grdc.com.au/Resources/Publications/2016/01/2016-Farm-Gross-Margin-Guide [Accessed 29 April 2016].

Gourley CJP, Melland AR, Waller RA, Awty IM, Smith AP, Peverill KI, Hannah MC (2007) Making Better Fertilizer Decisions for Grazed Pastures in Australia. Department of Primary Industries, Melbourne.

Hannah MC, Gourley CJP, Chia K and Awty IM (2016). A calibrated model for predicting pasture yield response to nitrogenous fertiliser. 7th International Nitrogen Initiative Conference, Melbourne, 4 -8 December, 2016.

Hardaker J.B, Richardson JW, Lien G, Schumann KD. (2004). Stochastic efficiency analysis with risk aversion bounds: a simplified approach. Australian Journal of Agricultural and Resource Economics, 48(2): 253–270.

Harris R, Armstrong R, Wallace A (2015) Recovery of 15N urea fertiliser applied to wheat under different management strategies, in the High Rainfall Zone of south western Victoria. "Building Productive, Diverse and Sustainable Landscapes". Edited by T. Acuña, C. Moeller, D. Parsons and M. Harrison. Proceedings of the 17th Australian Agronomy Conference 2015, 21 – 24 September 2015, Hobart, Tas. http://www.agronomy2015.com.au/1314

Harris RH, Armstrong RD, Wallace AJ, Belyaeva ON (2016a). Effect of nitrogen fertilizer management on soil mineral nitrogen, nitrous oxide losses, yield and nitrogen uptake of wheat growing in waterlogging-prone soils of south-eastern Australia. Soil Research 54, 619-633.

Harris RH, Armstrong RD, Wallace AJ, Belyeava ON (2016b) Delaying nitrogen fertiliser application improves wheat 15N recovery from high rainfall cropping soils in south eastern Australia. Nutrient Cycling in Agroecosystems 106, 113-128. DOI: 10.1007/s10705-016-9792-z

Heady EO (1957), An econometric investigation of the technology of agricultural production functions. Econometrica 25 (2): 249-268.

McCaskill, M.R., and Cayley, J.W.D. (2000). Soil audit of a long-term phosphate experiment in south-western Victoria: total P, S, N and major cations. Australian Journal of Agricultural Research 51, 737-48.

Nguyen NC, Wegner M, Russell I (2007). Decision support systems in Australian agriculture: state of the art and future development. ABFM Journal 4, 14-21.

Norton, RM (2012). Wheat grain nutrient concentrations for south-eastern Australia. "Capturing Opportunities and Overcoming Obstacles in Australian Agronomy". Edited by I. Yunusa. Proceedings of 16th Australian Agronomy Conference 2012, 14-18 October 2012, Armidale, NSW. http://www.regional.org.au/au/asa/2012/nutrition/7984_nortonrm.ht

Norton RM (2016). Nutrient performance indicators IPN00003 – a scoping study to investigate the development of grains industry benchmarks partial factor productivity, partial nutrient balance and agronomic efficiency of nitrogen, phosphorus, potassium and sulfur. International Plant Nutrition Institute, Horsham, Victoria. 95pp,

Pannell DJ (2006). Flat Earth Economics: The Far-reaching Consequences of Flat Payoff Functions in Economic Decision Making. Review of Agricultural Economics 28, 553–566.

Peverill KI, Sparrow LA, Reuter DJ (1999). Soil analysis: an interpretation manual. CSIRO Publishing, Melbourne.

Reuter DJ, Edwards DG and Wilhelm NS (1997). Temperate and Tropical Crops. In Plant Analysis: An Interpretation Manual. Eds DJ Reuter, JB Robinson. p 83-253. CSIRO Publishing, Melbourne

*Stott K, Christy B, Riffkin P, McCaskill M (2016) Benefits, costs and risks of nutrient use in cropping in the high-rainfall zone of southern Australia. Proceedings 7th International Nitrogen Initiative Conference, Melbourne 4-8 December (accepted).

Zull A, Bell M, Cox H, Gentry J, Klepper K (2015). A bioeconomic framework for phosphorus deep-placement decisions. "*Building Productive, Diverse and Sustainable Landscapes*". Edited by T. Acuña, C. Moeller, D. Parsons and M. Harrison.*Proceedings of the 17[th]Australian Agronomy Conference 2015*, 21 – 24 September 2015, Hobart, Tas. http://www.agronomy2015.com.au/proceedings

APPENDICES

Summary of significant effects of applied nutrients in the 2015 omission trials, and data collected from the 2016 trials until late August. Values separated by different letters are significantly different at the 5% level. For N effects, 2 lsd's are shown. The first is for comparison between the lowest and middle rate, the second for comparisons between the middle and highest rate. This is because the lowest N rate was only applied to the Nil and +all treatments, whereas the middle and highest N rate were applied to all treatments.

Site	Parameter	Response to…	Description of significant differences		5% lsd
Frances (canola)	Grain yield (t/ha, 100 C drying)	N	18 kg N/ha	0.64b	0.163
			95 kg N/ha	0.89a	0.126
			174 kg N/ha	0.94a	
	Biomass – 11 September (kg/ha)	N	18 kg N/ha	2326b	660
			95 kg N/ha	2632b	461
			174 kg N/ha	3396a	
	Harvest Index	Not significant		0.243	
	Biomass at grain harvest (t/ha)	N	18 kg N/ha	2.76c	0.52
			95 kg N/ha	3.62b	0.40
			174 kg N/ha	4.04a	
Bool Lagoon (wheat)	Grain yield (t/ha, 100 C drying)	N, S	18 kg N/ha	3.50a	0.459
			64 kg N/ha	3.05b	0.320
			149 kg N/ha	3.45a	
			0 kg S/ha	3.12b	0.356
			23 kg S/ha	3.55a	
	Visual rating 28 Oct (scored 1-5)	N, P	18 kg N/ha	1.50c	0.334
			64 kg N/ha	1.76b	0.233
			149 kg N/ha	1.99a	
			0 kg P/ha	1.54b	0.260
			25 kg P/ha	1.97a	
	Biomass at grain harvest (t/ha)	P	0 kg P/ha	7.67b	0.396
			25 kg P/ha	8.42a	
	Harvest index	P, S	0 kg P/ha	0.456a	0.0337
			30 kg P/ha	0.421b	
			0 kg S/ha	0.377b	0.0337
			23 kg S/ha	0.439a	

Site	Parameter	Response to…	Description of significant differences		5% lsd
Chatsworth (wheat)	Grain yield (t/ha, 100 C drying)	Not significant	4.32		
	Harvest Index	Not significant	0.41		
	Grain protein (%)	Not significant	13.0		
	Grain weight (g/1000 grain)	P (P = 0.09)	0 kg P/ha	33.2a	1.53
			25 kg P/ha	31.9b	
	Anthesis biomass – 23 October (kg/ha)	N, P S (P = 0.08)	18 kg N/ha	9369b	438
			77 kg N/ha	9807a	
			0 kg P/ha	9033b	534
			25 kg P/ha	9688a	
			0 kg S/ha	10007	534
			23 kg S/ha	9449	
	Ear density – 23 October (ears/m^2)	P	0 kg P/ha	425b	30.3
			25 kg P/ha	463a	
	Flag leaf mass – October (g/m^2)	N	18 kg N/ha	18.7b	1.31
			77 kg N/ha	21.5a	
	Biomass at grain harvest (t/ha)	Micronutrients (P = 0.1)	None	10.6	0.69
			+Cu, Zn	11.2	
Inverleigh (canola)	Grain yield (t/ha, 100 C drying)	N, P	18 kg N/ha	1.34b	0.252
			75 kg N/ha	1.60a	0.173
			146 kg N/ha	1.69a	
			0 kg P/ha	1.38b	0.196
			25 kg P/ha	1.69a	
	Biomass at grain harvest (t/ha)	N, P	18 kg N/ha	5.16b	0.770
			75 kg N/ha	5.72ab	0.527
			146 kg N/ha	6.02a	
			0 kg P/ha	5.12b	0.599
			25 kg P/ha	6.00a	
	Harvest Index	N, P (P = 0.07)	18 kg N/ha	0.279	0.0336
			75 kg N/ha	0.292	0.0199
			146 kg N/ha	0.293	
			0 kg P/ha	0.282	0.0218
			25 kg P/ha	0.294	

Site	Parameter	Response to…	Description of significant differences		5% lsd
	Oil content (% oil at 6% moisture)	N, P	18 kg N/ha	46.04a	0.529
			75 kg N/ha	43.49b	0.362
			146 kg N/ha	42.63c	
			0 kg P/ha	42.39b	0.411
			25 kg P/ha	43.41a	
	Oil yield (t/ha)	N, P	18 kg N/ha	0.690b	0.1248
			75 kg N/ha	0.777ab	0.0853
			146 kg N/ha	0.806a	
			0 kg P/ha	0.652b	0.0970
			25 kg P/ha	0.818a	
	Protein content (%, 6% moisture)	N, P	18 kg N/ha	36.6c	0.844
			75 kg N/ha	40.2b	0.577
			146 kg N/ha	41.9a	
			0 kg P/ha	42.2a	0.656
			25 kg P/ha	40.5b	
	Protein yield (t/ha)	N, P	18 kg N/ha	0.282c	0.0600
			75 kg N/ha	0.386b	0.0241
			146 kg N/ha	0.431a	
			0 kg P/ha	0.358b	0.0467
			25 kg P/ha	0.412a	
Tarrington (canola)	Above-ground biomass at 5 leaf stage, 29 Jul) (kg/ha)	P, S, K (P = 0.06 for K)	0 kg P/ha	328b	81.3
			50 kg P/ha	573a	
			0 kg S/ha	630a	81.3
			23 kg S/ha	499b	
			0 kg K/ha	467a	81.3
			50 kg K/ha	539a	
	Harvestable root biomass at 5 leaf stage, 29 July (kg/ha)	P, S	0 kg P/ha	41.6b	10.7
			50 kg P/ha	74.6a	
			0 kg S/ha	65.4b	10.7
			23 kg S/ha	79.2a	
Inverleigh (wheat)	Visual score 9 August (1-10)	P	0 kg P/ha	5.3b	0.94
			50 kg P/ha	7.3a	

Site	Parameter	Response to…	Description of significant differences		5% lsd
Rutherglen (canola)	Above-ground biomass at 5 leaf stage, 29 Aug) (kg/ha)	N, P, micronutrients (P=0.08 for micros)	30 kg N/ha	974b	423
			122 kg N/ha	1955a	295
			214 kg N/ha	2087a	
			0 kg P/ha	1396b	329
			50 kg P/ha	1949a	
			None	1526a	329
			+Cu, Zn	1819a	
	Harvestable root biomass at 5 leaf stage, 29 Aug) (kg/ha)	N, P, micronutrients (P = 0.1 for micros)	30 kg N/ha	259b	85
			122 kg N/ha	384a	59
			214 kg N/ha	364a	
			0 kg P/ha	289b	66
			50 kg P/ha	382a	
			None	308b	66
			+Cu, Zn	363a	