08

FARMLINK RESEARCH REPORT 2020

UTILISING NEW TECHNOLOGIES TO BETTER MANAGE WITHIN-PADDOCK NITROGEN VARIABILITY AND SUSTAINABLY CLOSE THE YIELD GAP IN SOUTHERN NSW

REPORT AUTHOR Eva Moffitt – EM Ag Consulting, eva.moffitt@outlook.com

TRIAL SITE LOCATION Ardlethan, Girral, Rannock, Temora, Thuddungra

KEY FINDINGS

- Moderate to high levels of within-paddock Soil Mineral Nitrogen (SMN) variability were identified across five paddocks (511.4 ha) located in southern NSW within the 2019/20 growing seasons.
- Multiple factors appeared to be driving N variability at each site; including (but not limited to) differences in historic productivity, soil texture/buffering capacities and merging of previous management areas.
- Spatial patterns of 2019 cereal grain protein concentrations as mapped by on-board NIR grain analysers correlated significantly with 2020 pre-sowing Soil Mineral Nitrogen (SMN) levels as measured by 0-60 cm grid deep N sampling at four out of five sites. For these paddocks, both grid SMN and 2019 grain protein% layers were successfully utilised in 2020 as the basis of Variable Rate (VR) N fertiliser applications.
- For the fifth paddock, 2020 wheat yield and protein correlated much more strongly with 2019 wheat protein% than pre-sowing SMN, suggesting 2019 grain protein% would likely have been a good basis for 2020 VR N.
- 2020 canola oil/protein% patterns did not correlate with post-harvest SMN or show any consistent responses to N-rich or nil fertiliser treatments. Rather, there was some indication that climatic conditions (temperature, moisture) may have been more influential in driving canola seed compositions in 2020. Further research is required to determine the potential role (if any) of canola oil/protein% maps in N management.
- While grid deep N sampling appeared to be largely effective in identifying patterns of N variability, it was limited by a number of factors including cost, resolution, the potential for SMN to be present beyond the sampling depth and/or the potential for non-plant-accessible SMN to be present within the sampling depth (e.g., where subsoil constraints exist).
- Grain protein% maps may overcome these limitations through the plant itself indicating the N adequacy of the conditions it experienced. Potential challenges with using this data include variability in protein levels across individual seasons, site-specific effects such as frost and the lack of data continuity across the full rotation.
- Although further research is required on a broader scale, the findings of this project suggest that cereal grain protein% ('N adequacy') maps may constitute a good foundation for allocating N fertiliser in subsequent seasons on a site-specific basis. Results are likely to be improved by the integration of targeted ground-truth deep N soil tests and potentially the use of remotely sensed imagery to fine-tune later season N applications. Where reasonable variability in soil characteristics occurs within a paddock, the use of ECa (e.g., EM38) or soil texture mapping combined with subsoil health testing will also be valuable to understanding N dynamics.

PROJECT PARTNERS

FarmLink change • adapt • prosper

precision agriculture

FUNDING PARTNERS

Australian Government

National Landcare Programme

PROJECT CODE - 4-BA9KC2G

Nitrogen deficiency remains the single greatest factor contributing to the substantial exploitable yield gap present in Australian wheat production and likely other crops (Hochman and Horan 2018; Hunt et al., 2019). As such, for Australian producers to meet ambitious future productivity targets and remain competitive in the global market, it is imperative that shortcomings in nitrogen management are understood and overcome.

While the solution to nitrogen under-fertilisation may appear obvious, the extreme variability in rainfall experienced by Australian growers coupled with the potential agronomic and economic consequences of over-fertilisation (N losses and/or 'haying off') have resulted in the conservative approaches common to the industry today. In addition, increasing social and regulatory pressures on environmental stewardship will demand that any increase in overall N fertilisation occurs in a responsible manner that avoids the potential adverse outcomes of over-fertilisation including nitrate leaching (and associated soil acidification), N runoff and/or increased nitrous oxide (N_2O) emissions.

The sustainable intensification of Australian agriculture will therefore be reliant on achieving a 'sweet spot' where N rates are increased to the point of maximising productivity without being excessive to crop requirements. To meet this goal, there arguably needs to be a transformation within the industry around 'measuring to manage', with current adoption levels being very low of even basic whole-paddock scale deep N soil testing.

Given the commonly high levels of within-paddock variability of factors such as historic productivity (influencing both N removal and N fixation), soil characteristics (e.g., texture, constraints, PAWC), frost and/or waterlogging potential and historic management (e.g., where paddocks have been merged), it is reasonable to assume that substantial variability of soil N levels may also occur. While this would be logical to most growers, the lack of dedicated research and management recommendations around within-paddock N variability in Australian cropping systems has meant that blanket rate N strategies remain the norm.

As ownership of Variable Rate (VR) enabled equipment becomes more commonplace, there is an urgent need for simple, robust methods to quantify and manage N variability across our cropping systems to more effectively match N inputs with yield potential. For maximum adoption, these approaches would ideally also consist of feedback mechanisms that enable growers to evaluate the success/failure of each season, so that learnings could be taken forward over a number of years.

With the recent commercial availability of on-the-go harvester mounted NIR grain analysers, one potential option is the use of geographically referenced cereal grain protein values to map patterns of N deficiency/surplus. The idea of using cereal grain protein concentration as an indicator of N nutrition adequacy has been recognised for many years, with early work from Russell (1963) in South Australia suggesting that yield responses were most likely when wheat grain protein was <11.4%. An analysis of more recent trials in South Australia and Victoria indicates that this general conclusion still appears valid (G. McDonald, published in Unkovich et al., 2020). This review found that when protein was <11.5%, more than 70% of trials analysed had an N response, while when protein was >11.5%, only 32% of the trials had an N response, which was either only marginally positive or in some cases was negative (i.e., yield constraining).

While it has been shown that both varietal and climatic conditions can influence critical grain protein concentrations (Fowler, 2003), a simplified 'rule of thumb' interpretation is that wheat with <11.5% grain protein has had insufficient nitrogen to optimise yield, whereas wheat with >11.5% grain protein has had surplus nitrogen, which has been used to increase protein, often with no economic gain.

This project will explore concepts around within-paddock nitrogen variability with the following aims:

- Quantify the level of within-paddock variability of Soil Mineral Nitrogen (SMN) within five paddocks (511.4 ha) in the FarmLink region of southern NSW
- Examine correlations between SMN and other data layers including cereal and canola protein/oil concentrations, yield and soil properties such as texture and apparent electrical conductivity (ECa)
- Comment on the potential effectiveness of each layer to inform site-specific N inputs, and
- Work with growers and advisors to build capacity in developing VR N applications using the numerous data layers collected, plus assess their success/impact through follow up soil sampling and analysis of grain yield and grain quality layers

Methodology

Paddock Selection, Grain Yield and Grain Quality Data Collection

Candidate paddocks were identified during the 2019 season from a group of eight growers with CropScan 3000H on-board grain analysers installed on their harvesters. These units collect georeferenced moisture, protein and oil percentages in real time using Near Infrared Spectroscopy (NIRS), producing a high-resolution map of grain quality attributes (see Appendix 1 for full description). A single set of certified reference samples for wheat, barley and canola were used to calibrate grain analyser units prior to harvest (November 2019, Mat Clancy from manufacturer Next Instruments). All harvesters were late model CaseIH machines running Pro700 displays. Growers performed grain yield monitor calibrations at the commencement of harvest as per standard procedures outlined by the manufacturer.

Yield and grain quality data were collected from harvesters and imported into Trimble Ag Desktop software (Farmworks) following harvest completion. Five paddocks were selected on the basis of having complete yield and grain quality data coverage in addition to a reasonable level of variability in grain protein levels. Paddocks were located at Ardlethan, Girral, Rannock, Temora and Thuddungra (Figure 1). Yield and grain quality data was cleaned by removing erroneous data points, outliers and overlapping passes on headlands/obstacles. Data was post-calibrated where actual tonnages and delivery dockets were available. The same procedure was undertaken for the five paddocks following the 2020 harvest.

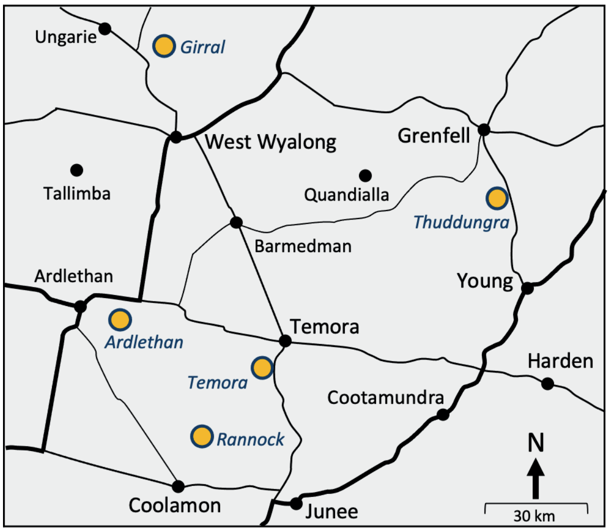


Figure 1: Trial paddock locations in southern/central NSW.

Grid Sample Plan Design

Grid soil sampling plans were designed to match the orientation (heading) and location of spreader passes within each of the respective paddocks. Grid cells were 108 m x 108 m (1.17 ha) for four out of five growers who top-dress fertiliser at 36 m (i.e., three spreader passes), and 120 m x 120 m for the remaining grower who top-dresses at 30 m width (i.e., four spreader passes; 1.44 ha grid). Headland areas and any other major obstacles were excluded from the grid. Two paddocks were considerably larger than the budgeted area therefore only part of the paddock was included. The total area encompassed in the study was 511.4 ha (425 grid sites), with individual paddock trial areas ranging from 83.4 ha to 112.0 ha.

EM38 Data Collection and ECa Management Zone Design

EM38 and elevation ground surveying was conducted during January 2020 using a Geonics EM38 unit operated in the vertical dipole, spatially logged via RTK corrected GPS. Soil ECa in milliSiemens per meter (mS/m) was collected on an 18 m swath for the 108 m x 108 m grid and a 24 m swath for the 120 m x 120 m grid. Swaths were orientated to align with the grid sampling plan. Soil moisture conditions were very low (Crop Lower Limit) at the time of surveying.

Data was cleaned and calibrated in ESRI ArcGIS. EM38 and elevation layers were interpreted alongside historic aerial imagery and farmer knowledge to manually create soil type based management zones, a common practice used by a number of local agronomists and precision agriculture service providers. Strategic soil sampling plans were designed for three zones of each paddock consisting of four individual GPS locations (points) per zone.

Soil Sampling

Soil sampling was conducted over two rounds in 2020, pre-sowing (late February-March, following opening rainfall) and post-harvest (early December). Round 1 consisted of both grid and zoned (strategic) sampling, while round 2 only consisted of grid sampling. An earlier round of soil sampling (immediately post 2019 harvest) was cancelled due to extremely hard (dry) ground conditions.

Grid soil sampling consisted of taking five individual subsamples in a 75 m or 85 m diameter (depending on the respective grid size) 'dice' pattern within each cell, segmented into 0-30cm and 30-60cm depths and bulked. Grid samples were analysed for nitrate (NO_3^-), ammonium (NH_4^+), MIR texture (sand/silt/clay%) and MIR Organic Carbon (OC%). Strategic (zone based) samples were also collected at 0-30cm/30-60cm and analysed for NO_3^-, NH_4^+, MIR texture, MIR OC%, pH ($CaCl_2$), Electrical Conductivity (1:5), Chloride and Cation Exchange Capacity (Ammonium Acetate). All soil analysis was undertaken at Australian ASPAC accredited laboratories.

Bulk density (BD) testing was carried out during April 2020. A 3 cm diameter core was taken at two depths (0-30 cm and 0-60 cm) in three zones per paddock. Soils were dried until weights stabilised and density calculated via dry weight (g) / volume (cm^3). Results were interpreted alongside texture data (MIR Particle Size Analysis) to devise a key to estimate BD for each grid cell site at 0-30 cm and 30-60 cm depths according to texture (MIR PSA). Soil Mineral Nitrogen (SMN) was subsequently calculated via:

SMN (kg N/ha) = Total Mineral N (NO_3^- + NH_4^+ mg/kg) x Bulk Density (g/cm^3) x Soil Depth (decimetres)

Data Management

An Inverse Distance Weighted (IDW) interpolation was used in Farmworks software with the 'grid then average base layer' tool to derive yield, protein, EM38 and elevation averages for each grid cell. The search radius used was 50 m (yield, EM38, elevation) and 100 m (protein). Cell sizes to parameterise the interpolation ranged from 8-22 m depending on the nature and noise of the data layer. All further statistical analysis was subsequently performed at the grid cell resolution (i.e., 1.17 ha or 1.44 ha). A minor number of cells were removed as outliers due to confounding effects (e.g., missed fungicide sprays in isolated wet/boggy areas) or where SMN values were greater than 3 standard deviations from the mean and appeared erroneous.

Rainfall

Climatic conditions during 2019 and 2020 were highly contrasting. Decile 1 ('very much below average') rainfall was recorded in 2019 across the study area while Decile 7-9 ('above average') rainfall was recorded in 2020 (BOM, 2021). Average rainfall figures are presented in Table 1.

Soil Attributes

A variety of soil types were encompassed in the study, summarised in Table 2. A higher level of variability was present within the Ardlethan, Girral and Temora sites, while the Thuddungra and Rannock sites were more homogenous in nature. The latter two sites also lacked any obvious subsoil constraints, in comparison to the three former sites where subsoil issues included high pH, high Na% and/or salinity (high EC) in one or more zones.

Table 1: Rainfall totals for 2019 and 2020 seasons measured on-farm or at BOM sites within 10 km of trial paddocks.

	2019			2020		
	Crop	Annual rainfall	GSR (Apr-Oct)	Crop	Annual rainfall	GSR (Apr-Oct)
Ardlethan	Wheat	294	129	Wheat	470	309
Girral	Barley	160	64	Canola	670	420
Rannock	Wheat	-	-	Canola	617	411
Temora	Wheat	310	142	Canola	687	456
Thuddungra	Wheat	301	89	Canola	580	424

Table 2: Soil attributes as collected by strategic sampling of management zones formulated predominantly from ECa surveys (via EM38).

	Zone	Depth (cm)	Texture	CEC cmol/kg	pH $CaCl_2$	Na %	Cl mg/kg	EC (1:5) dS/m	Clay %	Sand %	Silt %	OC %	$CaCO_3$ %
Ardlethan	1	0-30	Loam	6.3	4.8	2.1	10	0.06	21	63	16	0.7	0
		30-60	Clay	20	7.1	6.9	12	0.21	49	34	18	0.3	0
	2	0-30	Clay	33	7.7	11.5	140	0.47	35	51	14	0.9	0
		30-60	Sandy clay	38	8.0	14.2	300	0.64	31	63	5.7	0.3	5.0
	3	0-30	Clay	24	7.3	15.3	130	0.31	52	35	13	0.7	0
		30-60	Clay	42	8.4	17.5	530	0.79	47	43	10	0.3	4.8
Girral	1	0-30	Clay loam	15	6.2	10.2	69	0.17	26	64	9.5	0.6	0
		30-60	Clay	29	7.8	16.0	330	0.47	42	52	6.2	0.2	0
	2	0-30	Sandy loam	5.4	5.2	3.8	28	0.07	18	74	8.1	0.5	0
		30-60	Clay	14	6.8	15.6	42	0.11	41	53	6.8	0.3	0
	3	0-30	Sandy loam	2.8	5.2	1.2	<5	0.04	9.5	85	6	0.3	0
		30-60	SCL	5.6	6.4	7.9	5	0.05	21	76	3	0.2	0
Rannock	1	0-30	Clay loam	6.1	5.1	0.6	12	0.05	26	55	19	0.8	0
		30-60	Clay	9.6	6.4	1.0	8	0.03	40	43	17	0.6	0
	2	0-30	Clay loam	6.4	5.4	0.3	8	0.05	30	55	16	0.7	0
		30-60	Clay	9.3	6.5	0.6	6	0.04	38	46	16	0.4	0
	3	0-30	Clay loam	6.2	5.2	0.6	11	0.05	26	59	15	0.7	0
		30-60	Clay loam	8.6	6.5	1.6	7	0.04	34	49	17	0.4	0
Temora	1	0-30	Loamy sand	5.1	5.0	1.3	22	0.07	7.9	69	23	0.8	0
		30-60	Loamy sand	5.9	6.0	4.4	14	0.04	8.5	68	24	0.4	0
	2	0-30	Loam	7.2	4.9	12.5	52	0.16	12	63	25	1.6	0
		30-60	Clay loam	10	5.4	21.0	70	0.16	26	54	20	0.6	0
	3	0-30	Loam	11	5.4	10.4	40	0.16	19	59	21	1.3	0
		30-60	Clay	19	7.8	18.1	100	0.27	41	44	15	0.3	0
Thuddungra	1	0-30	Loam	2.4	4.9	0.5	8	0.06	10	73	16	0.5	0
		30-60	Clay loam	6.6	6.0	0.5	10	0.04	23	63	14	0.3	0
	2	0-30	Loam	6.2	5.0	0.4	19	0.10	22	62	17	0.7	0
		30-60	Clay loam	7.1	6.1	0.4	5	0.03	32	54	14	0.3	0
	3	0-30	Loam	6.1	5.2	0.8	15	0.07	23	61	17	0.6	0
		30-60	Clay loam	8.0	6.2	0.7	10	0.05	33	50	17	0.3	0

2019 season

Paddocks were managed according to standard farmer practice in 2019. Starter fertiliser (MAP/DAP) was applied at sowing however no urea top-dressing was undertaken due to exceptionally dry conditions (Table 3). One paddock (Thuddungra) had received a Variable Rate chicken litter application prior to sowing (March/April 2019) at an average rate of 3,440 kg/ha (nil – 10,000 kg/ha range) aimed at addressing variable soil Phosphorus levels as determined from 0-10 cm 2 ha grid soil mapping.

Table 3: 2019 season crop type and N inputs.

	2018 crop	2019 crop	Variety	Sown date	Harvest date	Starter kg N/ha	Topdress kg N/ha	Comments
Ardlethan	Canola	Wheat	Lancer(PBR)	29/04/2019	13-15/11/2019	5.0	0	
Girral	Barley	Barley	La Trobe(PBR)	08/05/2019	07-10/11/2019	7.0	0	
Rannock	Wheat	Wheat	Lancer(PBR)	29/04/2019	25-27/11/2019	7.0	0	
Temora	Wheat	Wheat	Scepter(PBR)	11/05/2019	27-28/11/2019	4.0	0	
Thuddungra	Canola	Wheat	Lancer(PBR)	29/04/2019	13-19/11/2019	10.6	0	VR chicken litter Mar/Apr 2019

Data Analysis

Regression analysis was used to assess the relationship between February 2020 SMN concentrations and a range of parameters including 2019 grain yield, protein%, nitrogen removal, OC%, elevation, texture and ECa (via EM38). Nitrogen removal was calculated using a standard nitrogen-to-protein conversion factor of 5.7 for all grains as per Unkovich et al. (2020) pg. 61. Rearranged, this is expressed as:

N Removal (kg/ha) = Grain Protein (%) x Grain Yield (kg/ha) x 0.00175

2020 season

During the 2020 season, growers and their advisors developed 'best-bet' variable rate urea application plans for each of the trial paddocks. All paddocks also had 'test' cells or strips (rows of cells), where either high, nil or average rates were applied. These strips served as indicators of N responsiveness and as a means to analyse the efficacy of VR urea applications. The various approaches used to devise urea rates are summarised in Table 4, with an explanation of each provided below.

Table 4: 2020 crop types and management information.

	Crop	Variety	Sown date	Harvest date	Target yield (t/ha)	VR 1 strategy	VR 2 strategy
Ardlethan	Wheat	Spitfire PBR	15/05/2020	03/12/2020	2.5	Blanket + N-rich strips	-
Girral	Canola	HyTTec® Trident	25/04/2020	18-19/11/2020	1.8	Unkovich et al. (2020) SMN	-
Rannock	Canola	44Y90 CL	16/04/2020	21-26/11/2020	2.3	Unkovich et al. (2020) SMN	NDVI + mgmt. zone potential
Temora	Canola	InVigor® T4510	25/04/2020	15-18/11/2020	2.3	Unkovich et al. (2020) SMN	NDVI + mgmt. zone potential
Thuddungra	Canola	Diamond	26/04/2020	16-18/11/2020	2.3	2019 protein %	2019 protein %

Unkovich et al. (2020) SMN based method for canola:

Fertiliser N required =
(Crop total N required – N supplied from soil) x 2

where

- Crop total N required = Nitrogen removed per tonne of grain (40kg N/ha) / 0.65 (Nitrogen Harvest Index of 65% in canola including dropped leaves) x target yield
- N supplied from soil = (Soil Mineral N from deep N test + estimated mineralisation) x 0.5 (assumes a 50% extraction efficiency)
- Pre-sowing mineralisation was estimated using the values reported by Angus et al. (2006), pg. 357-8.
- In-season mineralisation was estimated using the Ridge method (0.15 x GSR x OC%) based on typical GSR at each site and estimated OC% (MIR OC% values were not available at the time of top-dressing).
- x 2 assumes 50% fertiliser efficiency

2019 Grain Protein % Method:

At the Thuddungra site, two rounds of VR urea applications were undertaken based on 2019 grain protein percentages. A target average urea rate of 100 kg/ha was selected for the initial application after reviewing deep N results. Rates were varied at 20 kg/ha intervals per 0.5% change in protein (Table 5).

A second VR urea application was undertaken in response to favourable seasonal conditions improving yield potential. The same VR application map was used with urea rates scaled to 0.8x the original map. Total 2020 urea inputs were roughly equivalent to a target yield of 2.3 t/ha as per the Unkovich et al. (2020) method.

NDVI + Management Zone Potential:

Top-up VR urea applications were also applied at the Temora and Rannock sites in response to favourable seasonal conditions. Satellite NDVI imagery (Sentinel-2, https://eos.com/landviewer/) was used to approximate biomass and asses variability. Rates were subsequently assigned in a tactical manner aimed at maximising productivity based on the growers' understanding of estimated yield potentials across soil zones.

Blanket + N-rich strips

At the Ardlethan site, conflicting patterns observed between 2019 protein and pre-2020 sowing SMN resulted in a lack of confidence to undertake a VR urea application. Instead, a blanket rate of 80 kg/ha urea was applied across the trial including two double rate N-rich strips (160 kg/ha urea). Each strip was 120 m wide (i.e., one row of grid cells).

2020 nitrogen inputs across all sites are summarised in Table 6.

Data Analysis

Linear regression analysis was used to assess the relationship between a range of attributes including post-harvest (December 2020) SMN, 2020 yield/protein/oil/N removal, ECa, texture, elevation and OC%.

At the Ardlethan site, where no VR strategy was implemented, 2019 protein and pre-sowing SMN was also compared against 2020 harvest results to comment on which pre-season layer was a better predictor of 2020 yield and protein. The responsiveness of N-rich strips was assessed by pairing each cell along the N-rich strip with an immediately adjacent non N-rich cell and calculating their yield and protein difference. The magnitude of response could then be assessed against other attributes for that location, such as pre-sowing SMN.

The efficacy of VR approaches was assessed through comparing the Coefficient of Variability (standard deviation divided by mean) across pre- and post-VR data layers (e.g., pre-sowing SMN vs. post-harvest SMN; 2019 harvest vs. 2020 harvest). Test-strips/test-cells were excluded from this analysis.

Table 5: Urea rates at the Thuddungra site for 17/06/2020 application, based on 2019 grain protein concentrations

Protein %	Urea (kg/ha)	Protein %	Urea (kg/ha)	Protein %	Urea (kg/ha)
12.5 - 13	200	14 - 14.5	140	15.5 - 16	80
13 - 13.5	180	14.5 - 15	120	16 - 16.5	60
13.5 - 14	160	15 - 15.5	100	> 16.5	40

Table 6: 2020 fertiliser inputs across the five sites. Values in paratheses are min/max urea rates only applied in test strips/cells.

		Variable Rate Urea 1 (kg/ha)				Variable Rate Urea 2 (kg/ha)				Starter/ Early Fert (kg N/ha)	Average Total Fert (kg N/ha)
		Date	Average	Min	Max	Date	Average	Min	Max		
Ardlethan	Wheat	3/08/2020	104	80	80 (160)	-	-	-	-	5	53
Girral	Canola	16/06/2020	155	50	250 (350)	-	-	-	-	5.5	77
Rannock	Canola	21/06/2020	137	50	200 (250)	3/08/2020	135	115	175	19.3	144
Temora	Canola	17/06/2020	143	60	240	5-6/08/20	98	80	140	4	115
Thuddungra	Canola	17/06/2020	103	40 (0)	180 (250)	5/08/2020	84	32 (0)	144 (250)	10.8	96

Results and discussion

2019 season

Below average yields and above average grain protein concentrations were recorded across NSW in 2019 due to extremely low (decile 1) rainfall. 'Haying off' occurred across some zones of the trial paddocks to varying severity. Table 7 contains a summary of 2019 harvest results and post-harvest (Feb-Mar 2020) 0-60 cm SMN. Low levels of mineralisation are estimated to have occurred between harvest 2019 and soil sampling due to very dry conditions.

Soil Mineral N levels as measured by 0-60 cm deep N testing in February/March 2020 had a significant positive correlation with 2019 cereal grain protein% at four out of five sites (Table 8; Figure 2a). The site that did not show a strong correlation (Ardlethan) had considerably lower (however still variable) protein% levels (average 8.3%) and SMN (average 46 kg N/ha) compared to the other sites. Protein levels at this site had a significant correlation with numerous other factors however; including EM38 (ECa 0.5/1.0), sand%, clay% and OC%. Strategic soil sampling at this site revealed two main soil zones were present – a lower CEC loam over clay (zone 1; higher protein) and a higher CEC clay possessing a sodic and saline subsoil (zones 2 and 3; lower protein). It is possible that the more hostile subsoil conditions in zones 2 and 3 are limiting root exploration and N extraction compared to zone 1 where additional N may have been accessed below 60 cm depth. Interestingly, a negative correlation was observed between OC% and protein, which does not support an interpretation that variability in mineralisation may be responsible for the trends observed. It is however possible that differences in soil physical, chemical and biological properties may be impacting the many complex N transformation processes which determine net mineralisation (e.g., as observed by Akhtar et al. 2012 on saline soils).

Of the remaining four paddocks, grain protein% correlated with SMN more strongly than any other variable measured. Importantly, areas of the paddock with the lowest protein% coincided reasonably well with areas of low SMN (e.g., see Figure 3 and Figure 4 examples). This occurred both in paddocks of lower overall protein% (Rannock, Temora) and in those with very high protein% levels (Thuddungra, Girral). On the other end of the spectrum, areas within the paddock with very high protein concentrations did not necessarily always coincide with the highest SMN values (e.g., northern zone in Figure 4). In the two main instances this occurred (Temora and Girral sites), these zones were in low lying areas with at least average SMN levels and it is likely they were impacted by frost. These localised effects demonstrate the importance of paddock and seasonal knowledge when interpreting protein and other data patterns.

Table 7: 2019 harvest and Round 1 (Feb-Mar 2020) 0-60 cm SMN summary (grid n = 58 to 96).

		Ardlethan	Girral	Rannock	Temora	Thuddungra
2019 Dry Yield (kg/ha)	Average	1,297	1,091	1,257	1,535	1,773
	Min	699	298	438	489	1,019
	Max	1,560	1,841	2,104	2,378	2,792
	CV	11%	35%	32%	31%	20%
2019 Protein %	Average	8.3	17.4	11.7	13.4	15.3
	Min	6.7	15.9	10.0	10.1	14.0
	Max	11.9	18.4	13.5	15.4	16.8
	CV	14%	4%	7%	10%	4%
Feb/Mar 2020 0-60 cm SMN (kg N/ha	Average	46	94	95	67	127
	Min	27	29	52	22	55
	Max	70	213	199	162	285
	CV	24%	43%	25%	39%	30%
0-30 cm : 30-60 cm SMN	(ratio)	1.9	1.7	2.2	2.5	3.0

Table 8: Pearson correlation coefficients (r) for Round 1 soil results, 2019 harvest and EM38/elevation attributes. Values in bold are significant at P < 0.0001. *Variable Rate chicken litter application performed pre-sowing 2019 at Thuddungra site only.

Variables		Ardlethan	Girral	Rannock	Temora	Thuddungra
Feb/Mar 2020 0-60 cm SMN	2019 Protein%	0.17	**0.49**	**0.59**	**0.51**	**0.67**
	2019 Dry Yield	0.09	-0.02	0.05	0.16	**-0.55**
	2019 N removal	0.22	0.06	0.16	0.32	**-0.47**
	Elevation	0.11	-0.36	0.28	0.19	**-0.46**
	ECa (0.5)	-0.32	0.17	-0.07	0.33	0.19
	ECa (1.0)	-0.34	0.19	0.19	**0.41**	0.24
	0-60 cm sand%	0.18	**-0.40**	-0.12	**-0.42**	-0.09
	0-60 cm clay%	-0.20	0.36	-0.03	**0.50**	0.02
	0-30 cm OC%	0.23	**0.47**	**0.44**	0.32	0.39
	Manure rate*	-	-	-	-	**0.66**
2019 Protein %	2019 Dry Yield	-0.21	**-0.55**	0.25	-0.21	**-0.65**
	Elevation	-0.11	**-0.74**	**0.45**	-0.09	**-0.52**
	ECa (0.5)	**-0.72**	0.27	-0.24	0.23	0.05
	ECa (1.0)	**-0.69**	0.30	0.13	0.33	0.13
	0-60 cm sand%	**0.66**	**-0.71**	-0.11	-0.30	-0.19
	0-60 cm clay%	**-0.71**	**0.72**	-0.01	0.30	0.20
	0-30 cm OC%	**-0.56**	**0.67**	0.20	0.07	0.33
	Manure rate*	-	-	-	-	**0.69**
2019 Dry Yield	Elevation	**0.64**	0.48	**0.66**	**0.80**	**0.72**
	ECa (0.5)	0.19	**-0.60**	-0.01	0.26	-0.12
	ECa (1.0)	0.09	**-0.63**	0.05	0.26	-0.22
	Manure rate*	-	-	-	-	**-0.59**

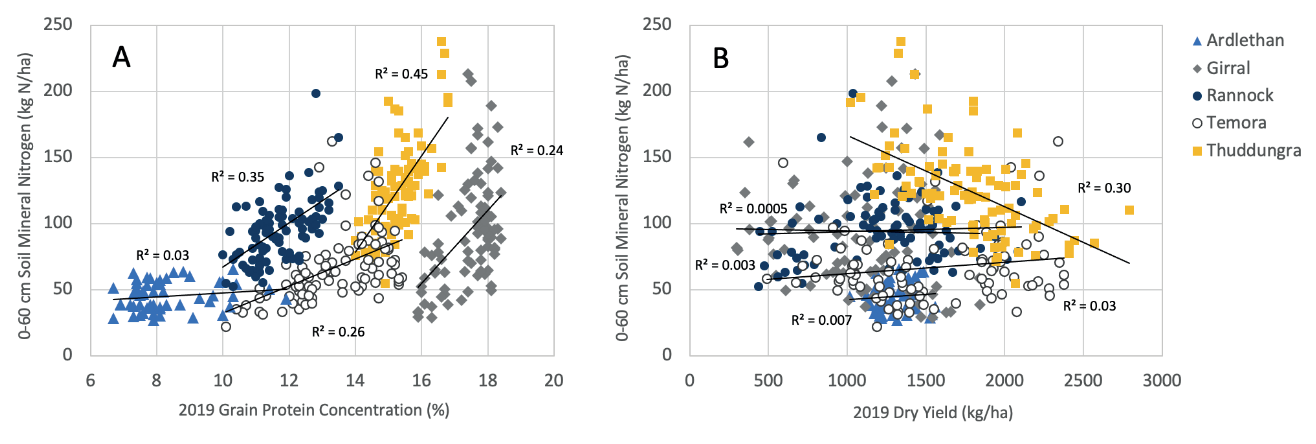


Figure 2: 0-60 cm Soil Mineral N (kg N/ha; sampled Feb-Mar 2020) versus 2019 cereal harvest results, (a) Grain Protein Concentration and (b) Dry Yield. (Girral = barley, rest = wheat).

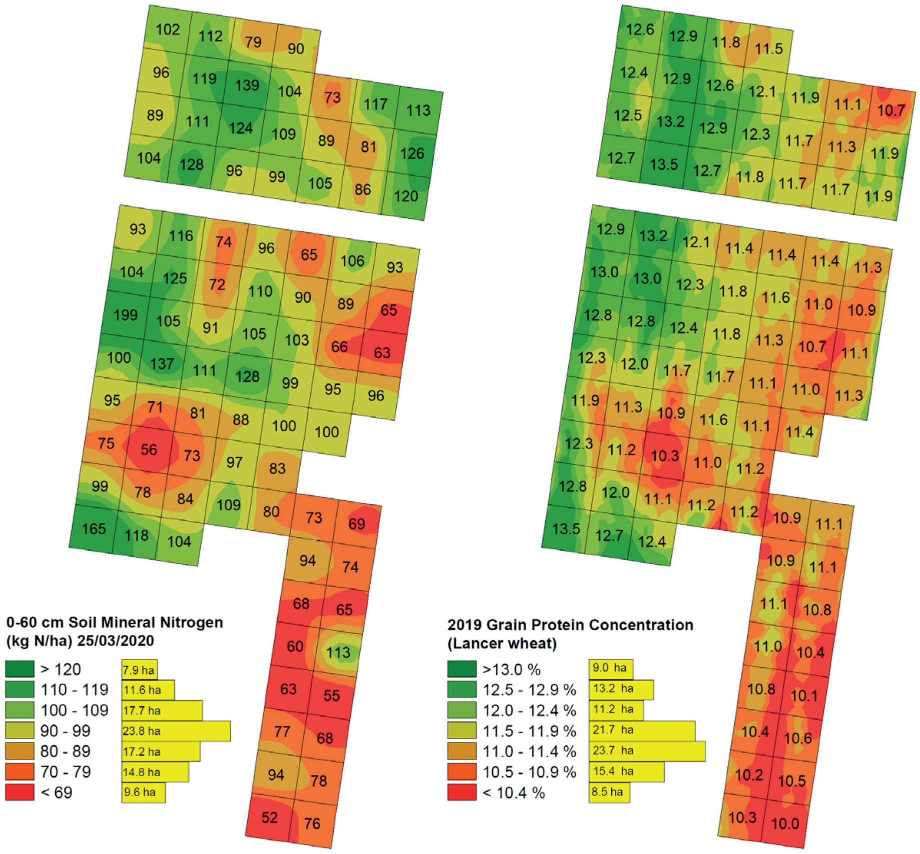


Figure 3: Rannock site 0-60 cm SMN (kg N/ha) sampled 25/03/2020 (left) and 2019 wheat protein% (right). Pearson correlation coefficient = 0.59, P < 0.0001). The missing section between the two blocks is the location of an old fenceline which was excluded from the sampling plan. Each cell size is 108 x 108 m, total area = 102.7 ha.

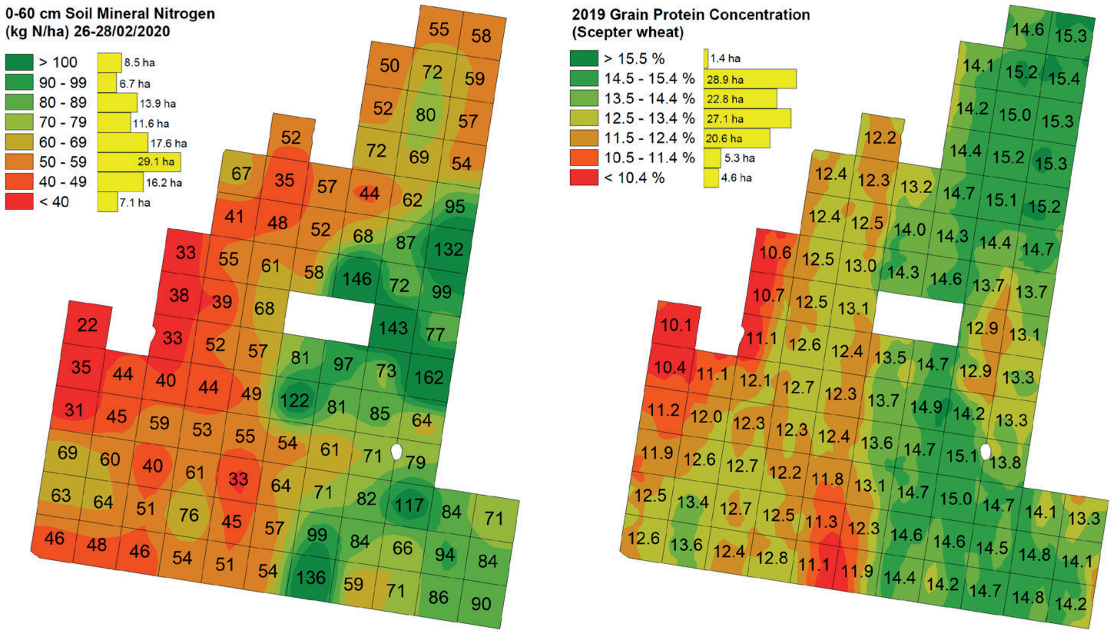


Figure 4: Temora site 0-60 cm SMN (kg N/ha) sampled 26-28/02/2020 (left) and 2019 wheat protein% (right). Pearson correlation coefficient = 0.51, P < 0.0001). The far north of the paddock is a low-lying area that yielded very poorly and was most likely severely impacted by both moisture stress and frost in 2019. Each cell size is 108 x 108 m, total area 110.7 ha.

Feb/Mar 2020 SMN levels did not correlate significantly with 2019 dry yield or N removal at four out of five sites (Figure 2b). The one exception was the Thuddungra site, where lower yields coincided with areas of higher SMN. This appears to be related to the VR chicken litter application undertaken just prior to sowing, with manure rates also correlating negatively with dry yield and positively with SMN and protein%. Of note, all five paddocks displayed a significant positive correlation between dry yield and elevation. This is possibly explained by the impact of frost which was noted across a number of the trial site locations and exacerbated by dry conditions in 2019.

No consistent relationship was observed between SMN and ECa or texture attributes across the five trial sites, however some significant correlations existed on individual sites. At Girral and Temora, SMN correlated negatively with 0-60 cm sand% (i.e., sandier soils had lower SMN). Sandier areas also had a consistent negative correlation with 0-30 cm OC% (r = -0.30 to -0.79; p < 0.0001 at all sites except Rannock).

Organic Carbon% consistently had a positive correlation with SMN, however the strength of the relationship was variable and not always significant. It is possible that this relationship may have been stronger if soil sampling had been delayed until later in the season following rainfall (i.e., Autumn mineralisation).

Previous management history appeared to be a key driving factor of N variability for at least three sites (Girral, Rannock and Temora), with noticeable differences observed between areas that were previously fenced separately, despite some of these changes being made up to 15 years prior.

2020 season

2020 seasonal conditions were highly contrasting to 2019, with wetter and cooler conditions prevailing and a relatively soft finish. 2020 dry yields exceeded yield targets across all study sites, therefore residual N levels were relatively low in most areas. Harvest results and post-harvest SMN levels are summarised in Table 9:

Table 9: Summary of 2020 harvest results and post-harvest (December 2020) SMN. Ardlethan = wheat, all other sites = canola. Results exclude outliers and test cells/strips. *Girral site suffered considerable hail damage after windrowing which impacted both the overall yield and yield patterns. Temora site also suffered some hail damage which may have disproportionately reduced yield in the southern part of the paddock where the crop was more mature/brittle.

		Ardlethan (non N-rich)	Ardlethan (N-rich strips)	Girral	Rannock	Temora	Thuddungra
2020 Dry Yield (kg/ha)	Average	2,569	3,202	2404*	3,352	2,600*	3,798
	Min	2,002	2,739	1,759*	3,093	2,117*	3,234
	Max	3,465	3,805	2,857*	3,582	2,891*	4,359
	CV	14%	10%	11%*	3.5%	7.7%*	6.2%
2020 Protein %	Average	8.3	10.0	22.9	21.6	22.2	22.2
	Min	7.4	9.1	22.1	20.3	20.6	20.9
	Max	9.5	11.5	24.0	23.3	23.3	23.8
	CV	7.2%	6.7%	1.8%	2.9%	2.7%	2.8%
2020 Oil %	Average	-	-	41.8	43.9	43.3	41.8
	Min	-	-	39.8	41.5	41.5	39.9
	Max	-	-	43.0	46.1	45.8	43.3
	CV	-	-	1.6%	2.3%	2.5%	1.8%
Post-harvest 0-60 cm SMN (kg N/ha)	Average	26	29	35	36	52	59
	Min	19	19	14	23	17	31
	Max	34	50	70	65	121	92
	CV	16%	26%	27%	19%	36%	25%
0-30 cm : 30-60 cm SMN	(ratio)	1.6	1.7	1.9	2.1	1.5	2.2

Ardlethan site (wheat)

At the Ardlethan site, where a VR nitrogen strategy was not implemented, there was a significant positive correlation between 2019 protein% and 2020 protein% for both the N-rich strip areas (n = 15, r = 0.81, P < 0.001) and non N-rich strip areas (n = 40, r = 0.73, P < 0.0001; Figure 5a). 2019 protein% also correlated significantly with 2020 dry yield at lower urea rates (r = 0.83, P < 0.0001) however not at higher fertiliser levels (r = 0.37, ns; Figure 5b). No significant correlations were observed between pre-sowing 0-60 cm SMN and 2020 yield or protein, nor post-harvest (residual) SMN and 2020 yield or protein. There was also no strong/consistent evidence of additional residual SMN in the N-rich strip cells, suggesting the fertiliser efficiency was high and the crop was most likely N-constrained.

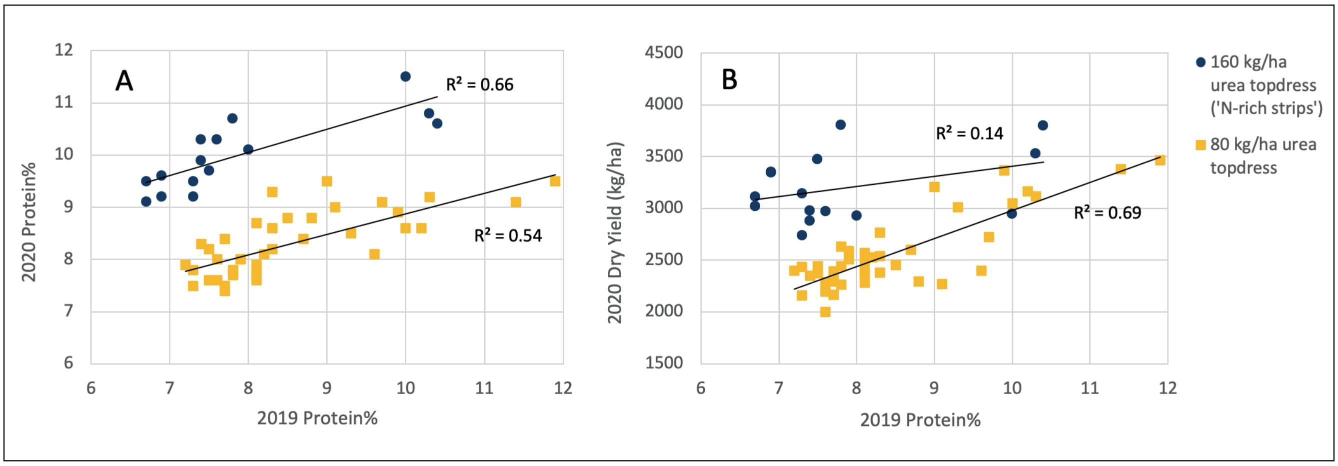


Figure 5: 2019 wheat (cv. Lancer(PBR)) protein% versus 2020 wheat (cv. Spitfire(PBR)) a) protein% and b) grain yield at the Ardlethan site. Each point represents one 120 x 120 m grid cell. N-rich strips n = 15, non N-rich strips n = 40.

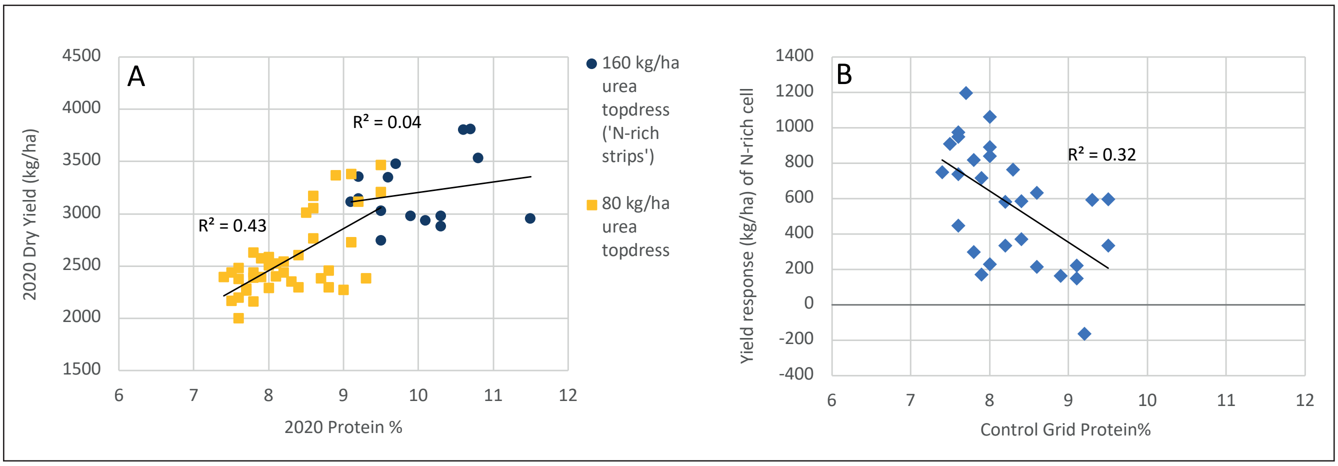


Figure 6: Wheat (cv. Spitfire(PBR)) yield and protein% trends at the Ardlethan site in 2020. (a) Dry yield versus protein% (n = 55 120 m x 120 m grid cells). (b) Yield response to N-rich strips (160 kg/ha urea) versus the control (80 kg/ha urea), plotted against protein% of the control. Data points in Figure 6b are pairs of immediately adjacent cells located on and off the N-rich strip (n = 29).

Ardlethan site (wheat)

Of the other parameters measured, apparent electrical conductivity (ECa 0.5/ECa 1.0) also correlated reasonably strongly with both 2020 protein% and yield at this site (r = -0.66 to r = -0.74, P < 0.0001). As occurred in 2019, lower protein values were associated with higher ECa values (i.e., the western clay zone with sodic/saline subsoil). This zone was also associated with lower yields and greater N-responsiveness in 2020. While these results suggest that using ECa to create management zones for VR N fertilising would have been valid in this example, it is worth considering that subsequent deep N sampling to assign rates to these zones would have most likely returned relatively homogenous results, given the reasonably poor correlation between ECa and 0-60 cm SMN. It is however possible that deep N patterns may have differed if sampling was delayed until later into the year (e.g., May) or the depth of sampling was increased (e.g., to 1.2 m).

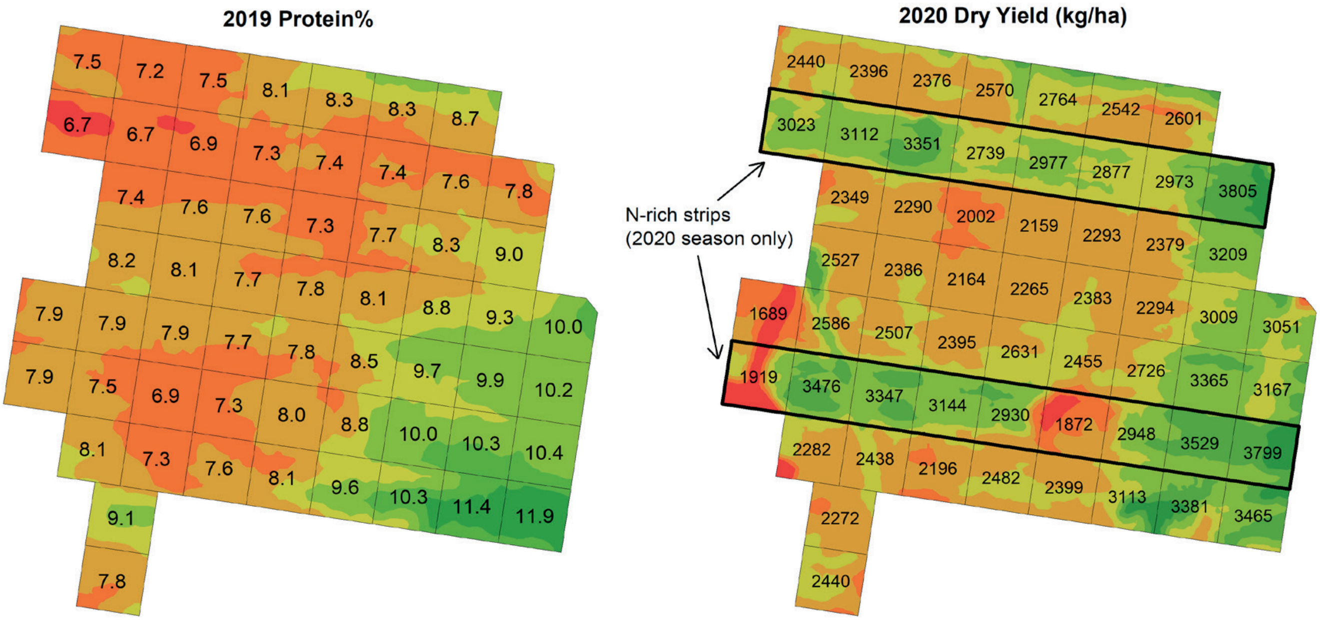


Figure 7: 2019 wheat (cv. Lancer(PBR)) grain protein (left) and 2020 wheat (cv. Spitfire(PBR)) dry yield at Ardlethan, with locations of N-rich strips shown. Note the greater yield response to additional N in areas of lower 2019 protein%.

Girral, Rannock, Temora and Thuddungra sites (canola)

Assessment of Variable Rate Applications

Across the four sites that implemented VR applications in 2020, all recorded substantial decreases in variability of dry yield and protein% compared to 2019 (see Tables 7 & 9 CV% values). It is difficult however to determine the proportion of this decrease that can be attributed to site-specific N management versus the decrease in variability which may be expected due to more favourable seasonal conditions.

Post-harvest (residual) SMN levels were also less variable, with SMN generally being much lower across the board compared to pre-sowing SMN (where both very low and very high zones were often present). The full extent of the decrease in variability was likely partially masked by the more recent fertilisation creating some 'noise' in residual SMN results, with a minor number of very high NO_3^- or NH_4^+ cells being removed as outliers.

Given the substantial drawdown on SMN levels due to crop yields exceeding targets, another consideration is that SMN levels may have 'flat-lined' in 2020, which would result in low, even levels. A review of 'N-rich' strips/cells that were embedded into the VR applications at Rannock and Thuddungra however demonstrated that in neither case was there a positive yield response to additional N. At both sites, excess residual SMN was identified in the soil profile under N-rich treatments, indicating that the higher rates applied were excessive to plant requirements. The extra ability of the crop to

Girral, Rannock, Temora and Thuddungra sites (canola)

produce yields above targeted rates could be related to a number of factors, such as 1) the conservative approach of calculating N rates via Unkovich (2020) whereby soil supply is only assumed 50% available and fertiliser supply 50% efficient, 2) the potential for greater mineralisation than budgeted due to the wet season and 3) the potential for additional SMN to have been accessed below 60 cm depth, particularly following a number of dry (low N removal) years.

Of the small number of grid cells that were considered 'very low' in post-harvest SMN (< 25 kg N/ha), all were located in areas that had been identified as having very low pre-sowing SMN levels. In these instances, although high rates of synthetic fertiliser were applied, it is logical to assume that these soils would have a poor ability to bridge any 'shortfall' between target and actual yields through mineralisation and/or N reserves below 60 cm depth. Despite these areas likely being somewhat N constrained during 2020, it is reasonable to conclude that the level of N constraint would have been much higher in the absence of the VR N approach. These areas will probably require additional N inputs to continue over a number of seasons to rebuild N levels.

Another outcome which supports the effectiveness of the VR N approach was the lack of a significant or consistent correlation between fertiliser N supply and dry yield at any of the four sites (r = -0.27 to 0.24). Given the considerable range in N fertiliser rates across each site (including some very low rates, e.g., 50 kg/ha urea), a positive correlation might be expected if N rates had been inadequate. There was also no significant correlation between fertiliser N supply and post-harvest 0-60 cm SMN (r = -0.35 to 0.20). If N supply had been excessive to crop requirements, greater residual SMN may have been expected where higher rates had been applied.

On balance, it therefore appears that all four VR applications undertaken in 2020 were at least reasonably (and potentially highly) successful in both maximising productivity across the site while concurrently minimising oversupply of N and its associated potential economic and environmental impacts. Ongoing monitoring of yield and cereal grain protein% results across these sites would be beneficial to further assess the efficacy and longevity of variable rate strategies.

Patterns of Variability

Across the four canola sites, there was no consistent correlation between post-harvest 0-60 cm SMN and any other attribute; including pre-sowing SMN, 2020 canola dry yield, protein%, oil%, N removal, fertiliser rates, elevation or soil characteristics (ECa, sand/clay%; Table 10, Figure 8).

Table 10: Selected Pearson correlation coefficients (r) for Round 2 soil sampling (December 2020) and harvest attributes (canola paddocks only). Values in bold are significant at P < 0.0001.

Variables		Girral	Rannock	Temora	Thuddungra
December 2020 0-60 cm SMN	Feb/Mar 2020 SMN	0.24	0.12	-0.06	-0.19
	2020 Dry Yield	-0.15	0.27	0.27	-0.11
	2020 Protein %	-0.14	0.00	-0.17	-0.26
	2020 N removal	-0.17	0.21	0.25	-0.18
	Elevation	-0.28	0.16	**-0.45**	0.07
	ECa (0.5)	-0.08	-0.07	**-0.41**	0.20
	ECa (1.0)	-0.09	0.08	-0.38	0.18
	Total fertiliser N	-0.35	-0.17	0.20	0.17
2020 Protein %	2020 Dry Yield	-0.06	-0.04	**-0.66**	0.38
	Elevation	**0.49**	**0.50**	**0.58**	0.39
	ECa (0.5)	0.17	0.34	0.07	**-0.61**
	ECa (1.0)	0.03	0.36	0.12	**-0.63**
	Total fertiliser N	0.44	-0.02	**-0.46**	0.10
2020 Dry Yield	Elevation	-0.01	**0.47**	**-0.64**	**0.71**
	ECa (0.5)	0.03	-0.28	-0.13	-0.41
	ECa (1.0)	0.25	0.12	-0.09	-0.48
	Total fertiliser N	0.24	-0.27	0.18	0.13

Girral, Rannock, Temora and Thuddungra sites (canola)

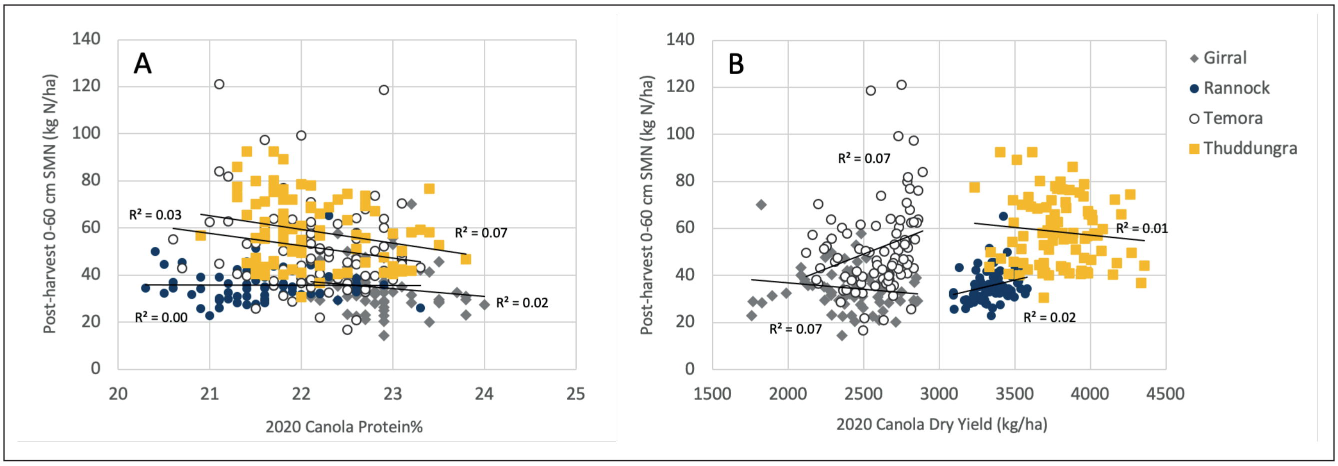


Figure 8: Post-harvest 0-60 cm Soil Mineral N (kg N/ha; sampled December 2020) versus 2020 canola harvest results, (a) Seed Protein Concentration and (b) Dry Yield. Protein and oil concentrations were highly inversely correlated. Note, yield at both Girral and Temora sites were impacted by hail events.

Canola yield correlated significantly with elevation at three out of four sites however the relationship was not consistent. At Thuddungra and Rannock, yields were higher at higher elevations, while at Temora, yields were higher at lower elevations (Table 10). Conversations with growers suggest that these trends are reasonably common yield patterns related to variability in soil type and microclimate. At Rannock and Temora, this knowledge was used in conjunction with in-season NDVI imagery to devise ‘tactical’ top-up N applications targeting maximum yields.

Canola oil% and protein% were strongly inverse to each other across the four trial sites however did not show consistent correlations with any other attribute except elevation (Table 10). Across all sites, protein% was higher (i.e., oil was lower) at higher elevations, or more accurately, at higher landscape positions (e.g., hilltop areas versus troughs or slopes).

For at least the Temora and Thuddungra sites, hilltop areas were substantially faster in terms of crop maturity compared to the remainder of the paddock (at least +7 days). This could be related to light interception, temperature (higher cumulative degree days), soil depth, moisture availability, minor frost effects or a combination of factors. It is possible that similar factors are also responsible for the differences observed in protein/oil%. Walton et al. (1999) and Pritchard et al. (2000) both found that higher oil concentrations (and lower protein%) were correlated with cooler spring temperatures and higher spring rainfall. It is therefore plausible that minor temperature and moisture gradients within a paddock (such as between hilltops and troughs) could influence the spatial patterns of oil/protein%.

Uppal et al. (2019) further found that the critical period sensitive to heat stress (resulting in a substantial decline in oil%) is from 50% flowering to mid pod formation. This suggests that differences in plant maturity alone could influence oil/protein% patterns if particular weather events were to occur at or near this critical period. Spatial differences in plant maturity at the time of windrowing could also impact on the patterns of canola seed quality components, as premature windrowing has been shown to result in lower oil concentrations (e.g., Hertel, 2013).

A number of studies also demonstrate a clear relationship between decreasing oil% (increasing protein%) with increasing N fertiliser rates (e.g., Brennan 2016). This effect was not observed in the current study except perhaps at the Girral site, where elevated protein% values appear to roughly coincide with the location of an N-rich strip. At Thuddungra and Rannock however, there was no protein/oil response whatsoever when comparing N-rich strips to adjacent non N-rich strip cells (even at rates of nil versus 500 kg/ha urea at the Thuddungra site). These results suggest that the effect of N rates on oil and protein concentrations may vary according to seasonal (climatic) conditions, with more work required to understand these potential interactions.

Conclusions

The results of this project have shed considerable light on both the level of N variability and efficacy of various approaches to managing such variability within a small selection of broadacre cropping paddocks in southern NSW.

The level of variability identified in pre-2020 sowing grid deep N testing suggests there may be substantial production upside to N management at the sub-paddock scale. It also calls into question the appropriateness of using paddock-scale deep N sampling to quantify N levels at least in the current examples, where the process of bulking cores from large areas would have masked the presence of both N constrained and N excessive areas.

The inconsistency observed between trial sites in regard to using soil characteristics (e.g., texture or ECa) to zone for N management can be explained by considering the wide array of differences driving patterns of N variability. Some of these differences were clearly linked to soil type factors, for example; inherent differences in soil nutrition (e.g., OC%), productivity differences related to soil constraints and/or nutrition and differences in N loss processes across different soils (e.g., leaching). In other instances, N variability drivers were entirely separate to soil type factors, such as where previously separate management areas had been merged, historic VR fertiliser applied, or where non soil-type factors were driving sustained differences in productivity (e.g., elevation/frost effects).

The results of this study suggest that both intensive grid deep N sampling and cereal grain protein% ('N adequacy') maps can be effective tools to map and manage these complex patterns of N variability. The ability of canola seed oil/protein% maps to perform this function was not demonstrated, however further research in this area would be beneficial to investigate the potential use (or lack of use) of this data for N management.

While a key advantage of the grid deep N approach was the quantification of actual (rather than relative) N levels, a number of limitations were also identified. Firstly, the substantial expense of such data and the resultant trade-off that must occur between cost and data quality (i.e., spatial resolution, subsample numbers). Secondly, and particularly for deeper rooted species such as canola, the value of SMN present below 60 cm could be substantial and may not necessarily be homogenous across a management area. This could be addressed through deeper soil sampling, however it is unlikely this would be cost-feasible for an intensive (e.g. grid) approach. Lastly, if appreciable soil constraints are present that limit rooting depth (e.g., subsoil salinity), it is possible that SMN may be present within the 0-60 cm depth that is not plant accessible.

Cereal grain protein% maps appear to have the capacity to overcome many of these limitations as the plant itself provides an indication of the N adequacy of the conditions it experienced. While these maps cannot be used for N management within the season of measurement, the stability of N patterns identified in the current study suggests the potential for using this data in subsequent seasons is high. A major advantage of such an approach is that N inputs follow yield potential, rather than necessarily aiming to provide an 'even' N supply. For example, given similar access to N, an area of higher yield potential would theoretically produce lower cereal protein% than a lower yield potential area due to the effects of dilution. Subsequent N inputs would therefore be increased to this area which would facilitate higher yields in the following season.

A further advantage of this system is through the identification of areas for follow up investigation where nitrogen supply has been adequate (i.e., protein >11.5%) and yield has been poor. These areas are likely constrained by another issue (e.g., pH, P), which could be addressed through targeted soil amelioration and/or nutrition. If this was not an economic option, inputs could subsequently be scaled back to match lower yield potentials. Once non-N yield constraints had been addressed and wheat grain protein% levels stabilised around critical values (i.e., 11-12%) a potential 'end goal' may be an N replacement strategy (plus a buffer for losses), with the aim of maintaining an optimal 'N bank' (see Meier et al., 2021) which would serve to both maximise yields and minimise adverse environmental impacts including the rundown of Soil Organic Matter (SOM).

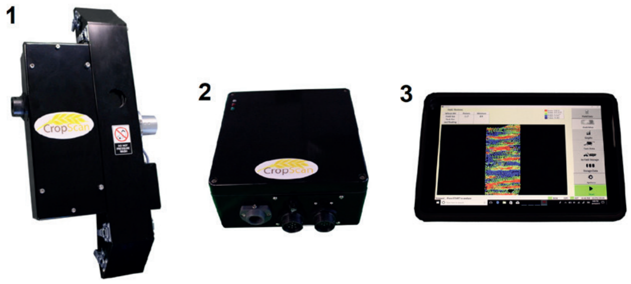
Practically speaking, achieving such a goal is unlikely to occur using wheat protein% ('N adequacy') maps in isolation. At the very least, targeted deep N soil sampling will likely be an ongoing tool used to set baseline N rates for individual seasons. Additionally; EM38/elevation surveying, subsoil health testing, in-season remotely sensed imagery and grower knowledge have all been demonstrated to provide valuable insight into the many interrelated factors that impact upon N dynamics.

Given the immense potential productivity and environmental benefits of improved site-specific N management, considerable scope exists for follow up research on a larger scale to further assess the agronomic and practical potential of this approach.

Appendix

Description of CropScan 3000H (Next Instruments; Sydney, Australia)

The unit consists of three components: 1) sampling head, 2) NIR spectrometer and 3) touch screen computer. The sampling head is mounted on the clean grain elevator, where it collects and isolates a grain sample within its chamber every 8-12 seconds (although at yields <2t/ha cycle times are longer). A tungsten halogen lamp shines light through the stationary sample and into an optical fibre cable which transmits the light back to the NIR spectrometer located in the cabin. Protein, oil and moisture absorb NIR light at different frequencies and the NIR spectrometer uses a diode array detector and a spectrograph to separate the frequencies of light into the NIR spectrum. The in-cabin touch screen PC takes the NIR spectrum and applies calibration models to convert the spectral data into grain quality measurements. The cycle is repeated roughly 5 times per minute, with grain quality data georeferenced using location coordinates from the harvester's GPS. To reduce noise a rolling average is applied, although raw readings are also logged.



Appendix 1: Components of Cropscan 3000H grain analyser: 1) sampling head (mounted on clean grain elevator 2) NIR spectrometer (installed in-cabin and connected via fibre optic cable) and 3) in-cabin touch screen computer.

Acknowledgements

This project is supported by the Department of Agriculture, Water and the Environment, through funding from the Australian Government's National Landcare Program. Research was further supported by Charles Sturt University where the author holds an Adjunct Research Fellow position. APAL agricultural laboratory generously provided in-kind MIR Particle Size Analysis for this project.

The sizeable contribution of the five growers including their time, provision of data, implementing VR applications and modifying harvest plans to suit trial requirements is hugely appreciated. Chris and Broden Holland are particularly thanked for sharing much insight into their experiences with grain quality mapping to date. Thanks to Mat Clancy (Next Instruments) for his technical support throughout the project.

Many thanks to Kirsten Barlow (Precision Agriculture) for assistance in data analysis, interpretation, reviewing this report and acting as a sounding board throughout the project. Thanks also to John Angus (CSIRO) for the helpful discussions around N budgeting in devising VR urea rates.

References

Angus, J. F., Bolger, T.P., Kirkegaard, J.A. and Peoples, M.B. (2006) Nitrogen mineralisation in relation to previous crops and pastures. Australian Journal of Soil Research 44:4, 355-365

Akhtar, M., Hussain, F., Ashraf, M.Y., Qureshi, T.M., Akhter, J. and Awan, A.R. (2012) Influence of salinity on nitrogen transformations in soil. Communications in Soil Science and Plant Analysis 43:12, 1674-1683

BOM (2021) Accessed via *http://www.bom.gov.au/climate/history/rainfall/*

Brennan, R.F. (2016) Effect of time of application and amount of nitrogen fertilizer on seed yield and concentration of oil in canola (Brassica napus). Journal of Plant Nutrition 39:3, 337-347

Fowler, D. B. (2003) Crop Nitrogen Demand and Grain Protein Concentration of Spring and Winter Wheat. Agronomy Journal 95: 260-265

Hertel K., (2013) Canola: the economics and physiology of the timing of windrowing. Accessed via *https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2013/02/canola-the-economics-and-physiology-of-the-timing-of-windrowing*

Hochman, Z. and Horan, H. (2018) Causes of wheat yield gaps and opportunities to advance the water-limited yield frontier in Australia. Field Crops Research 228: 20-30

Hunt, J., Kirkegaard, J., Celestina, C. and Porker, K., (2019) Transformational agronomy: restoring the role of agronomy in modern agricultural research. In: Pratley, J., Kirkegaard, J. (Eds.), Australian Agriculture in 2020: From Conservation to Automation. Agronomy Australia and Charles Sturt University, Wagga Wagga, pp. 373–388.

Meier, E.A., Hunt, J.R. and Hochman, Z. (2021) Evaluation of nitrogen bank, a soil nitrogen management strategy for sustainably closing wheat yield gaps. Field Crops Research 261, 108017

Pritchard F.M., Eagles H.A., Norton R.M., Salisbury P.A. and Nicolas M. (2000) Environmental effects on seed composition of Victorian canola. Australian Journal of Experimental Agriculture 40: 679-685.

Russell JS (1963) Nitrogen content of wheat grain as an indication of potential yield response to nitrogen fertilizer. Australian Journal of Experimental Agriculture and Animal Husbandry 3: 319-325

Unkovich M.J., Herridge D.F., Denton M.D., McDonald G.K., McNeill A.M., Long W, Farquharson, R. and Malcolm, B. (2020) A nitrogen reference manual for the southern cropping region. GRDC publication. Accessed via *https://grdc.com.au/resources-and-publications/all-publications/publications/2020/a-nitrogen-reference-manual-for-the-southern-cropping-region*

Uppal, R.K, Brill, R. and Bromfield, J. (2019) Effect of heat stress on canola grain yield and quality. Accessed via *https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/effect-of-heat-stress-on-canola-grain-yield-and-quality*

Walton, G., Si, P. and Bowden, B. (1999) Environmental Impact on Canola Yield and Oil. In: 'Proceedings of the 10th International Rapeseed Congress'. Canberra, ACT. (Agriculture Western Australia: South Perth, W. Aust.) Accessed via *http://www.regional.org.au/au/gcirc/2/136.htm*