Nitrogen dynamics in high-yielding wheat and canola crops

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Abstract
Wheat and canola crops in the high rainfall zone (HRZ) and medium rainfall zone (MRZ) are constrained by nitrogen (N), which is the largest variable cost. As part of a larger study of within-paddock variability, observations of soil N and crop growth were made at 130 monitoring positions in four commercial paddocks within the Victorian HRZ and the Wimmera (MRZ) in 2019. Measurements were made of the recovery of ^{15}N labelled urea by the crop, water table depth and reduction-oxidation state. Crop demand for N was much larger than pre-sowing mineral N within the rooting depth, and growth was reliant on in-crop N mineralisation and fertiliser application. Water tables and anoxic conditions that can facilitate denitrification occurred at both the HRZ and MRZ sites. Spatial variation in the Normalised Difference Vegetation Index (NDVI) the following year was of a scale better managed by in-crop sensors on spreading equipment than by zone alone as a way of evening out N distribution across the paddock.

Keywords
Denitrification, Sentinel, NDVI.

Introduction
Insufficient nitrogen (N) has been identified as the first limiting factor in the production of wheat and canola in the Victorian medium rainfall zone (MRZ) and the high rainfall zone (HRZ) (Armstrong et al. 2019). Since the cost of N is also the largest variable cost in grain production, optimizing the rate of N application is a key to increasing the profitability of grain production. Three distinct strategies are available to producers in choosing N application rates – (i) a single rate of N is applied to the entire paddock; (ii) a separate rate is applied to pre-defined management zones; or (iii) the application rate is adjusted in real time by data from crop sensors mounted on spreading equipment. The first option is suitable for paddocks of low spatial variability, while in the second option paddocks are normally divided into three management units based on soil type or drainage. In the third option the management unit is limited to the swath width of the spreader (typically 30-40 m) so the scale of management is therefore a grid of 30-40 m, and smaller-scale variation cannot be managed. This is at a scale where satellite imagery can provide data on the above-ground development of the crop. For example, Sentinel-2 satellite imagery has a pixel size of 10x10 m.

This paper reports spatial variation of soil mineral N and plant N uptake in three commercial paddocks in the MRZ and one paddock in the HRZ to determine whether the scale of variation is more conducive to management by zone or a grid based on the spreader swath width.

Methods
Four paddocks of high spatial variability were selected and managed as part of the normal commercial operation of each farm in 2019 (Table 1). Three of the paddocks were sown to wheat (at Nurrabiel, Wallup and Wickliffe) and one to canola (Nurcoung). Within each paddock, 30-40 sampling points were established, and most measurements made within 5 m of these points. Sampling included pre-sowing mineral N (May), root depth by the core break method, and crop biomass that corresponded to times when wheat was at mid tillering (July/Aug), booting (Sep/Oct), anthesis (Oct) and maturity (Nov/Dec). Profile soil samples to 1.2 m consisted of 2-3 cores 4 cm in diameter that were bulked, dried at 40°C and analysed for nitrate and ammonium, and other chemico-physical properties. Crop samples were taken from two areas of 1 m length x 2 rows wide and were 0.45-0.75 m^2 in area. These samples were analysed separately for total N. At three of the paddocks, soil cores were collected immediately prior to the 2020 crop and analysed for mineral N. At a subset of 9-12 monitoring points, bottomless metal boxes 53 x 30 cm were inserted, and ^{15}N-enriched urea applied in place of in-crop urea supplied by the farmer (Wallace et al. 2020). These areas were sampled separately at the end of the season to determine the fate of ^{15}N into plant and soil components. Unaccounted for ^{15}N was presumed to have been lost by volatilisation, denitrification or leached below the measurement

depth, which was 60 cm at Wickliffe and 40 cm at the MRZ other sites. At the Wickliffe site, the depth of the perched water table was logged adjacent to three of the ^{15}N study sites, and the reduction/oxidation state logged at depths of 5, 15, 25 and 43 cm using platinum electrodes. Depth to water table data are presented from the wettest and driest of these sampling points, and the period when the redox potential at 5 cm was less than 350 mV (i.e., anaerobic), which is the redox potential at which nitrate replaces oxygen as the electron acceptor in biological reactions, thereby causing denitrification (Patrick et al. 1996).

Table 1. Summary of the four paddocks monitored. Values shown are the mean of all sampling points and the 5% lsd for differences according to zone in parentheses. Parameters where there were significant differences at the 5% level are shown as - for P < 0.01, * for P < 0.05, ** for P < 0.01 and * for P < 0.001.**

	Nurcoung	Nurrabiel	Wallup	Wickliffe
Average annual rainfall (mm)[1]	441	483	392	581
Decile of Apr-Oct 2019 rainfall	4	4	5	4
Study area (ha)	50	48	128	37
Crop 2019	Canola	Wheat	Wheat	Wheat
Grain yield (kg/ha)	2787 (534)-	2448 (544)-	3809 (687)	6588 (750)***
Grain protein (%)	24.1 (1.69)	14.7 (0.99)	9.6 (0.84)-	9.8 (0.72)**
Rooting depth (cm)	81 (6)**	106 (8)***	98 (6)**	104 (5)
Pre-sowing N[2] 2019 (kg N/ha)	87 (36)	41 (17)	58 (17)	129 (30)
As above to 20 cm (kg N/ha)	43 (15)	18 (8)	34 (8)	59 (19)-
N application (kg N/ha)	63	128	38	100
Mid-tillering biomass N (kg N/ha)	109 (18)	73 (11)***	53 (10)*	37 (11)
Booting biomass N (kg N/ha)	101 (25)	125 (21)	109 (24)	98 (20)
Anthesis biomass N (kg N/ha)	126 (34)	109 (19)*	79 (14)	116 (22)
Grain N (kg N/ha)	111 (23)	61 (12)	62 (11)	112 (17)***
Stubble N (kg N/ha)	62 (16)	77 (11)***	47 (9)	49 (7)***
^{15}N in plant (%)	39 (14)	34 (45)	57 (18)-	40 (7)***
Unaccounted for applied ^{15}N (%)	35 (10)	41 (37)	19 (21)-	35 (11)***
Pre-sowing N[2] 2020 (kg N/ha)	51 (37)*		29 (17)	73 (18)***
As above to 20 cm (kg N/ha)	22 (14)		13 (7)	36 (12)***
Crop 2020	Wheat	Clover	Faba beans	Canola

[1]1970-2019 for the nearest grid point in SILO gridded data (https://www.longpaddock.qld.gov.au/silo/)
[2]Nitrate + ammonium N to the depth of rooting measured at each sampling point

For each paddock three management zones were identified using the Fuzzy K-Means clustering algorithm implemented through the Cluster package in R open source statistical software. Variables used in the clustering include elevation, EM38h, EM38v, EM31, gamma radiometrics (K, U & Th), and two data sets of the Normalised Difference Vegetation Index (NDVI) from the Sentinel 2 satellite collected close to peak biomass in August and September of 2019. At Nurcoung and Nurrabiel these zones were closely aligned to soil texture, Wallup to subsoil salinity and at Wickliffe to topography. Normalised Difference Vegetation Index (NDVI) was calculated for each paddock throughout 2019 and 2020, using all available Sentinel-2 cloud-free images. Water height measurements were extended to all sites in 2020, and redox measurements to Nurrabiel. However, 2020 data on N dynamics are not presented here.

Results and Discussion

At all sites N in the crop increased progressively from mid tillering to harvest, except for the wheat crops at Nurrabiel and Wallup where there was a decrease in biomass N between booting and anthesis that was associated with leaves senescing and dropping (Table 1). Crop demand for N was much larger than the soil stores of mineral N within rooting depth, and growth was reliant on mineralisation and in-crop N application. The strongest effect of zone on N dynamics was at Wickliffe, where the mid-slope zone had higher pre-sowing mineral N, booting biomass N, grain yield, grain N, grain protein, stubble N, and soil mineral N in 2020 than the upper or lower zones. Plant uptake of ^{15}N was significantly less in the lower zone (18%) than in the upper (44%) or mid-slope (30%) zones, while equivalent quantities of unaccounted for ^{15}N were 58%, 24% and 30% respectively. This loss of N can be attributed to a longer period with high water tables and anaerobic conditions in the lower zone that can facilitate denitrification (Figure 1a). At Nurrabiel there was significantly more N in the crop in the high-clay zone at mid-tillering, anthesis and in the stubble (Table 1). Across the MRZ sites there was no significant effect of zone on plant or unaccounted for urea ^{15}N. Nevertheless, an average of one third of applied ^{15}N was unaccounted for, similar to previous studies on MRZ cropping systems (Wallace et al. 2020). Observations of depth to water the following year (2020) showed short periods of high water tables, despite the lower average rainfall in this environment. Redox potential observations indicated that anaerobic conditions could occur even before water tables develop (Fig 1b). Poor internal drainage of these soils may limit internal water redistribution and aeration, providing conditions conducive to denitrification.

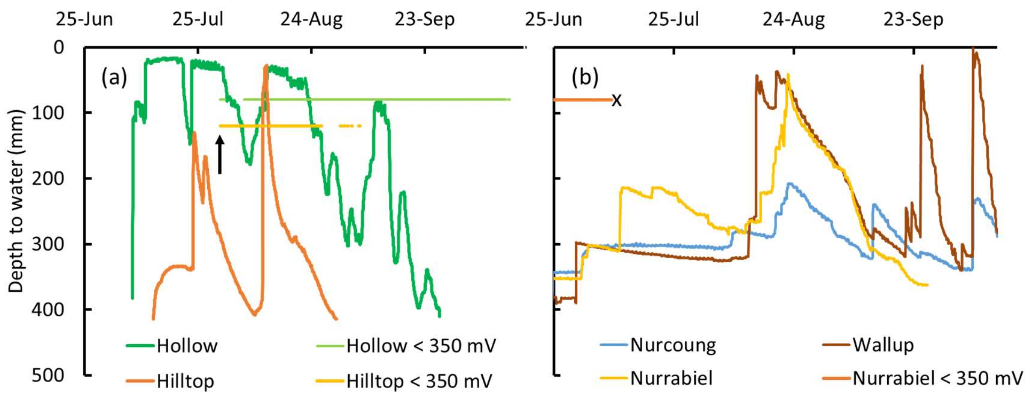

Figure 1. (a) Depth to the perched water table at Wickliffe in a hollow and hilltop in 2019, showing the installation date for redox sensors (arrow) and duration of a redox potential of < 350 mV (anaerobic) at 5 cm depth as a horizontal line; (b) depth to water at the wettest location in each of the MRZ sites in 2020, and redox potential at Nurrabiel until equipment was damaged (x).

By the start of the 2020 season the quantity of mineral N in the paddocks sampled had approximately halved, but since the 5% lsd was virtually unchanged the relative variation had increased. The growth of non-legume crops was therefore heavily dependent on applied N and the risk of low-N patches within the crop had increased. The Wickliffe paddock was sown to canola on 10 April and the northern half spread with 150 kg/ha of urea on 25 May 2020. A satellite image five days later shows a relatively uniform NDVI in the northern half but areas of low NDVI in the southern half (Figure 2a). An earlier image shows the entire site with a pattern similar to the southern half (data not shown). This variation was only partially related to management zone, and was of a scale that could be managed by sensors on a spreader (e.g., 40 x 40 m). The entire paddock eventually received 400 kg/ha of urea and yielded 4.9 t/ha of canola grain. The Nurcoung site was sown to wheat on 4 May and spread with 150 kg/ha of urea on 10 June. By 17 July, areas of low NDVI were evident on the satellite image (Figure 2b). Again, this variation was only partially related to zone, and would be better managed by sensors on a spreader. The crop received no further N application and yielded 3.8 t/ha of wheat.

Conclusion

There are many processes that can increase the spatial variation of N within a paddock, one of which is losses such as denitrification. While some of this variation can be managed by varying inputs according to pre-defined zones, in-crop N application is one of the few inputs where technology has been developed that can vary inputs at a finer scale. The evidence presented here indicates that there may be sufficient benefits to justify investment in sensor-based N application to reduce the spatial variability in soil mineral N caused by spatially-varying processes such as denitrification.

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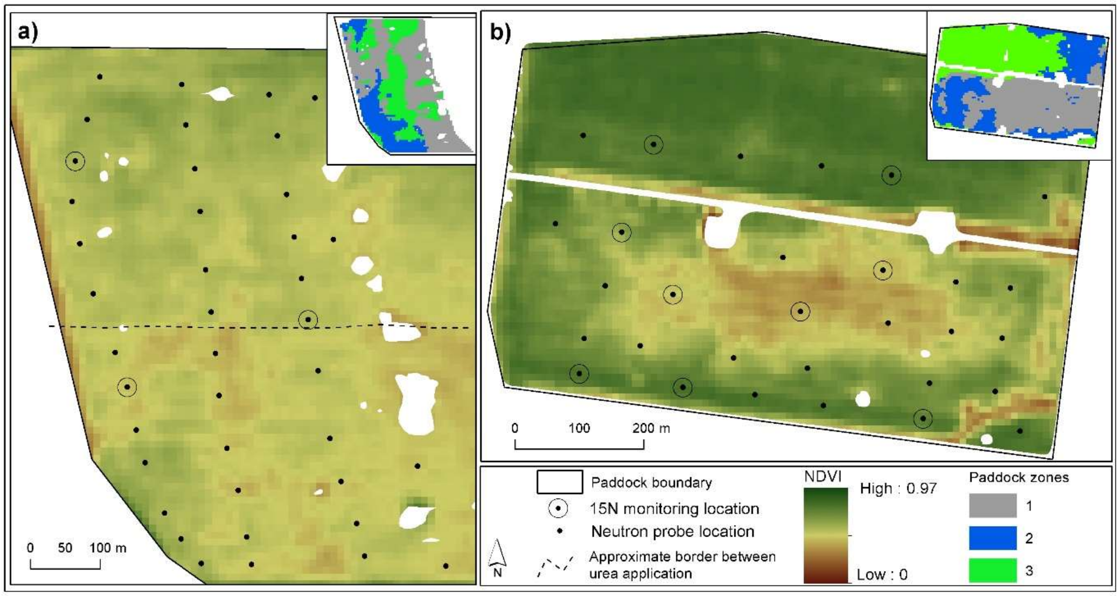

Figure 2. Sentinel-2 satellite NDVI image for a) canola crop at the Wickliffe paddock on 30 May 2020, 5 days after the northern half of the site (dashed line) had received 150 kg/ha of urea, and b) wheat crop at the Nurcoung paddock on 17 July 2020. Inset maps show designated paddock zones for both sites.

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