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Soil N testing to forecast N fertiliser requirements of wheat crops: N Decision Trial results

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Executive summary

Soil N testing to forecast N fertiliser requirements of wheat crops: N Decision Trial results

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There is increasing pressure on growers to improve nitrogen (N) management practices that increase N use efficiency and reduce the risk of N losses to the wider environment. The best approach to achieve this is to match N supply (soil and fertiliser N) to crop N requirements while minimising the oversupply of N fertiliser. A key to the success of this approach is testing for mineral N and potentially mineralisable N (PMN) at the start of the main growing season and forecasting how much of the PMN will be released (via mineralisation) during the primary growing season.

The objective of this project was to evaluate whether soil test data (mineral N, potentially mineralisable N and Quick N) can be used to improve N fertiliser forecasting that better matches N supply with the N demand of autumn sown dryland and irrigated wheat crops. The aim is to enhance the profitability and environmental performance of these crops, without penalising grain yield. The industry guideline for autumn sown feed wheat is to supply 25 kg of N (initial soil mineral N plus applied N) per tonne (t) of target grain yield. Here we report results from two trials conducted at the Foundation for Arable Research's (FAR's) Arable site at Chertsey where wheat was grown under either dryland or irrigated conditions (2021/22 season). Five different N management treatments were applied to each trial:

- the full industry guideline N rate applied as fertiliser (25 kg N/ha per t of target grain yield),
- the full rate adjusted down for the initial soil mineral N content,
- the full rate adjusted down for the initial soil mineral N content plus the predicted supply of N from mineralisation,
- the N fertiliser recommendations derived from the Quick Test Mass Balance Tool based on quick N testing at growth stages (GS) 32 and 39, after an initial application of starter fertiliser, and
- nil (zero) N fertiliser.

The overall conclusion from these trials is that accounting for both the initial mineral N and the predicted in-field N mineralisation (Treatment 3) when making fertiliser N input decisions can improve N use efficiency and reduce the costs and emissions associated with fertiliser use while still achieving the target yield. Soil testing for topsoil mineral N and PMN at the start of the primary growing season is essential to achieving this objective. This method seems to work well where the yield potential of a crop (given actual conditions for crop growth) closely matches the target yield. In situations where the yield potential of a given crop exceeds the target (i.e. the target yield substantially underestimates the

realised yield), the lower fertiliser rate (adjusted for mineral N and mineralisable N) may not be sufficient to achieve the yield potential.

The trial results have demonstrated that N mineralisation and to a lesser extent (in this case) the initial mineral N content of the soil can be important sources of N for crop uptake. The benefits of soil N testing were apparent despite relatively low to moderate amounts of soil N supply (initial mineral N plus mineralised N) in both trials. We would expect the benefits to be even greater where soil N supply was higher and, consequently, made up a greater proportion of the total crop N demand. Further research is needed to refine the methods and verify this assumption.

Although Quick N testing during the growing season closely matched the laboratory measured nitrate concentrations, the trial results suggest that the recommendations generated by the Quick Test Mass Balance Tool underestimate the amount of fertiliser N needed to achieve the yield potential of both irrigated and dryland wheat crops, at least under the conditions of these trials. Further work is needed to develop N management tools that combine the soil N testing and prediction methods described in this report with estimates of crop N demand that improve N fertiliser forecasting to meet crop production targets while minimising the cost and environmental impacts of excess N fertiliser use.

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1 Introduction

Improved fertiliser management is critical to the economic and environmental sustainability of New Zealand's agricultural production systems. Effectively forecasting fertiliser nitrogen (N) need requires the ability to predict the supply of plant-available N from soil and the demand for that N during crop growth. The N released by mineralisation of soil organic matter (SOM) can contribute a large amount of plant-available N and varies widely depending on soil type and land use history (ranging from <40 to >300 kg N/ha/y). Accurately predicting the supply of N from mineralisation is one of the greatest limitations to: 1) correctly forecasting the amount and timing of N fertiliser N needed to meet, but not exceed, crop demand and 2) minimising the risk that excess N may be lost from arable and vegetable production systems via nitrate leaching and/or gaseous emissions.

The New Zealand Institute for Plant and Food Research Limited (Plant & Food Research) has developed a new soil test for measuring the amount of N a soil is capable of mineralising under optimal conditions (i.e. the Potentially Mineralisable N [PMN] test) (Curtin et al. 2017). Trial results from the *Mineralisable N to improve on-farm N management* project (Sustainable Farming Fund project number 405891) indicate that the PMN test, combined with information on the soil type and weather, can be used to predict the in-field N mineralisation over the growing season of typical spring/summer grown arable and vegetable crops.

The next step in applying the PMN test to improve N fertiliser forecasting is to evaluate whether the predictions of in-field N mineralisation (based on a PMN test) can be used to better match the supply of N from soil and fertiliser to the demand for N by individual crops. The aim is to achieve the target crop yield, with less total N fertiliser applied and less residual mineral N in the soil at the end of the growing season. The benefits of reducing N fertiliser inputs, where the N supply from mineralisation is known, may include lower fertiliser cost, increased profitability, and reduced risk of N losses (including both N_2O emissions and N leaching).

The objective of this project was to evaluate whether soil test data (mineral N, PMN and Quick N) can be used to improve N fertiliser forecasting that better matches N supply with the N demand of autumn sown dryland and irrigated wheat crops. The aim is to increase the profitability and reduce the environmental losses from these crops, without penalising grain yield.

2 Materials and methods

The Wheat N Decision Trials were established in April 2021 on a shallow free-draining Chertsey silt loam soil at FAR's Arable site at Chertsey. The two trials were conducted simultaneously, one managed under dryland (rainfed) conditions and the other with irrigation. The dryland and irrigated trials were positioned approximately mid-way along the length of columns 1 and 2 at the Chertsey site, respectively. The trial site had a history of mixed-arable cropping and had been maintained under unimproved grass for two years prior to establishment.

The grass at the trial site was sprayed off in March 2021 and the soil was ploughed followed by secondary cultivation in mid-April. A feed wheat crop ('Graham') was sown (150 plants/m^2, 15 cm row spacing) on 22 April 2021.

Samples for basic soil fertility test analyses were collected from the top 15 cm of soil at each trial site on 3 August, 2021. The results of these analyses are given in Table 1. No nutrients other than N (as outlined below) were applied to the trial sites at sowing or as a side-dressing during crop development.

Table 1. Surface soil (0–15 cm) properties measured at the dryland and irrigated trial sites in August 2021.

Soil property	Dryland	Irrigated
Soil pH	6.1	6.3
Olsen P, mg L^{-1}	22	17
K (MAF unit)	5	6
Ca (MAF unit)	9	10
Mg (MAF unit)	6	8
Na (Maf unit)	4	4
CEC (me/100g)	11	12
SO_4-S (mg/kg)	3	2

2.1 Experimental design

The N decision trials conducted under dryland and irrigated management were both composed of 4 blocks, each comprising 5 N management treatments, giving a total of 20 plots that were each 8 m long and 1.65 m wide (centre to centre, including buffers) (Figure 1). No basal fertiliser was applied to the site at sowing or over the winter period until the N management treatments were initiated on 1 September 2021.

Five N management treatments were imposed at both trial sites as follows:

Treatment 1: The full industry guideline rate of N applied as fertiliser (25 kg N/ha per t of target grain yield) without adjustment for initial mineral N. Standard split applications were applied as early N (1 September) and at growth stage (GS) 32 and 39.

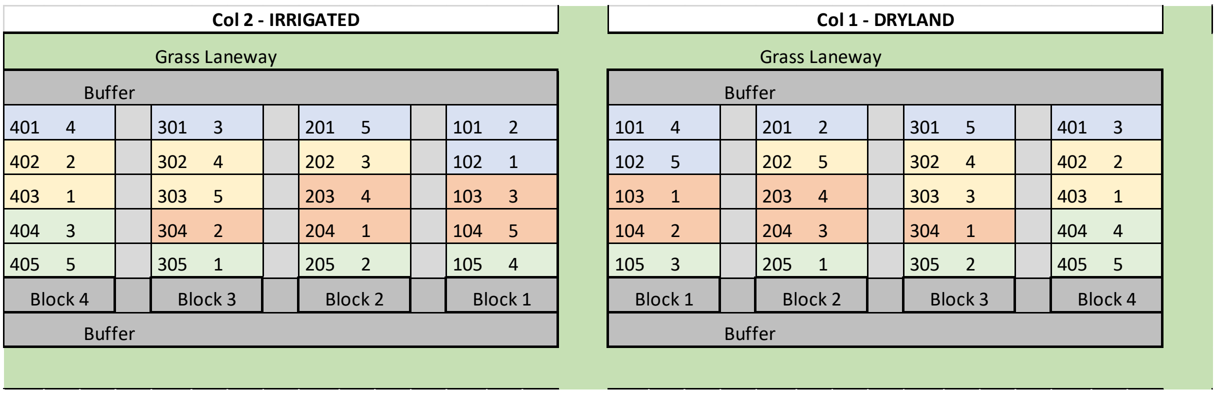
Treatment 2: Treatment 1 rate less the average amount of mineral N in the topsoil (0–30 cm) at the start of the main growing season. The reduction in fertiliser N applied was apportioned across the split applications as per Treatment 1.

Treatment 3: Treatment 1 rate less the average amount of mineral N in the topsoil (0–30 cm) at the start of the main growing season and the predicted amount of N that would be supplied by mineralisation (0–30 cm) during the period of active crop N uptake. The reduction in fertiliser N applied was distributed in proportion to the split applications applied to Treatment 1.

Treatment 4: Early N was applied equivalent to Treatment 2 and the FAR Quick Test Mass Balance Tool was used to forecast the additional fertiliser N required to meet the target yield based on Quick N testing at GS 32 and GS 39.

Treatment 5: Nil (zero) fertiliser N applied. All N for crop uptake was supplied from the initial mineral N plus the N supplied via mineralisation over the growing season.

The target yields for the dryland and irrigated wheat crops were set at 8 and 12 t ha^{-1}, respectively. Treatment 1 was established as the full industry guideline rate of N applied as fertiliser (25 kg N/ha per t of target grain yield), assuming no soil N test data were available and no adjustment was made for soil N supply, resulting in rates of 200 and 300 kg N ha^{-1} applied to the dryland and irrigated crops, respectively. The fertiliser N rates for Treatments 2, 3 and 4 of each trial were established by adjusting the Treatment 1 (full N fertiliser) rate for different measures of soil N supply as outlined above. The following section describes the methods that were followed to obtain these measures of soil N supply and how they were applied to establish the Treatment 2–4 N fertiliser rates. Treatment 5 was included to measure the crop response and N balance in the absence of N fertiliser, where the soil was the sole source of N supplied.



Col 2 - IRRIGATED

Grass Laneway

Buffer

401 4	301 3	201 5	101 2
402 2	302 4	202 3	102 1
403 1	303 5	203 4	103 3
404 3	304 2	204 1	104 5
405 5	305 1	205 2	105 4
Block 4	Block 3	Block 2	Block 1

Buffer

Col 1 - DRYLAND

Grass Laneway

Buffer

101 4	201 2	301 5	401 3
102 5	202 5	302 4	402 2
103 1	203 4	303 3	403 1
104 2	204 3	304 1	404 4
105 3	205 1	305 2	405 5
Block 1	Block 2	Block 3	Block 4

Buffer

Figure 1. The Dogleg row-column design showing the arrangement of nitrogen (N) treatments that was applied to both the Irrigated and Dryland trials in 2021/22. The three-digit numbers are plot numbers and the single-digit numbers are treatment numbers.

2.1.1 Soil N measurements

Ten soil samples (25-mm diameter corer) were collected (3 August 2021) from each block (Two samples per plot) to form a composite sample that was used to determine soil mineral N (0–15, 15–30, 30–50 cm) and hot water extractable organic N (HWEON) (0–15, 15–30 cm) for use in estimating the soil N supply (and, ultimately, establishing the N treatments). Samples were maintained under cool/refrigerated conditions prior to processing. In the laboratory, the field-moist soils were sieved (<4 mm) and mineral N (NH_4-N + NO_3-N) extracted using 2 *M* potassium chloride (KCl). Mineral N in the extracts was determined following standard methods using an automated colorimeter (QuickChem 8000 FIA+, Lachat, Loveland, CO, USA).

Approximately half of each sieved soil sample was air-dried prior to measuring hot water extractable organic N (HWEON) and hot water extractable C (HWEC). The hot water extraction procedure was as described by Curtin et al. (2006) with minor modifications (extraction temperature of 80°C for 16 h; 1:10 soil:water ratio). Total N in the extracts was determined by persulfate oxidation (Cabrera & Beare 1993) and dissolved organic N was estimated after subtracting mineral N (NH_4-N and NO_3-N, determined using an automated colourimeter) from total N. Organic C in the hot water extracts was determined using a Total Organic C analyser (Shimadzu TOC-VCSH). The HWEON method is consistent with the test protocol developed by Plant & Food Research and adopted for commercial testing. The HWEON test values were used to predict each soil's PMN value based on the relationship reported by Beare et al. (2020), recalibrated from data previously reported by Curtin et al. (2017), where:

$$\text{PMN (mg/kg)} = \text{HWEON (mg/kg)} \times 0.964 \qquad \text{(Equation 1)}$$

The PMN can be expressed in units of kg N/ha using the following equation:

$$\text{PMN (kg N/ha)} = \text{PMN (mg/kg)} \times \text{sample depth (cm)} \times \text{soil bulk density (g/cm}^3\text{)} \times 0.1 \qquad \text{(Equation 2)}$$

Where sample depth refers to the sample collected for HWEON analysis and soil bulk density refers to a measurement of soil bulk density under field conditions. PMN can be expressed in units of kg n/ha/day by dividing total PMN (kg N/ha) by 98 days (the length of the incubation period).

The measurements of mineral N, HWEON, and bulk density made in August 2021, just prior to initiating the trials, are reported in Table 2.

Table 2. Soil mineral N, hot water extractable C (HWEC) and organic N (HWEON), soil bulk density and potentially mineralisable nitrogen (PMN) in soil from dryland and irrigated trial sites measured in August 2021.

Trial/Depth	Mineral N	HWEC	HWEON	Bulk density	Mineral N	PMN
Dryland	**(mg/kg)**	**(mg/kg)**	**(mg/kg)**	**(g/cm^3)**	**(kg N/ha)**	**(kg N/ha/d)**
0–15 cm	7.95	765	70	1.21	14.4	1.27
15–30 cm	7.22	768	68	1.27	14.1	1.29
30–50 cm	4.65	ND	ND	1.62	14.5	ND
Irrigated						
0–15 cm	2.76	767	70	1.21	5.0	1.27
15–30 cm	6.72	719	66	1.27	12.8	1.26
30–50 cm	5.19	ND	ND	1.62	17.1	ND

ND = no data (not analysed at this depth).

2.1.2 Predicting in-field N mineralisation from PMN

Potentially mineralisable N (PMN) is taken to represent the pool of N that can be mineralised from a soil under optimal conditions of soil temperature (25°C) and moisture (90% of field capacity) over a 14-week period. Soil temperature and water content are the two most important environmental variables that affect soil microbial activity and the mineralisation of N under field conditions. Annual average daily soil temperature and water content data were calculated from climate data obtained from the Ashburton weather station and used to forecast the in-field N mineralisation over the growing season.

The PMN content (kg N/ha) of these soils was estimated from the HWEON (mg/kg) and bulk density values reported in Table 2 as described previously and divided by 98 to express the PMN in units of kg N ha^{-1} day^{-1} (Table 3).

To predict in-field mineralisation, the daily PMN values were temperature- and moisture-adjusted using scaling factors:

$$\text{Predicted in-field N mineralisation} = \sum_{i=1}^{n} (\text{Average daily PMN} \times Tf_i \times Wf_i) \qquad \text{(Equation 3)}$$

where *n* is the number of days in the growing season and Tf and Wf are scaling factors calculated from the daily average soil temperature and water content, respectively.

The Lloyd-Taylor equation (Lloyd & Taylor 1994) was used to derive the scaling factors for soil temperature (Tf) based on the daily average values calculated from the Ashburton climate data. The relationship recommended by Paul et al (2003) was used to derive the scaling factors for water content (Wf) based on daily average water content values calculated from the same data. The predicted in-field N mineralisation used to estimate the fertiliser N needed in Treatment 3 to meet crop demand was discounted by 20% to account for potential losses of N during the growing season (Table 3).

Whereas it was necessary to use average climate data to forecast the in-field N mineralisation expected for each trial to establish Treatment 3, we also measured soil temperature and volumetric water content on a daily basis throughout the trial to compare the pre-trial with post-trial predictions of in-field N mineralisation. These details can be found in Sections 2.3 and 3.1.

Table 3. The initial mineral N (0-30 cm), potentially mineralisable N (PMN) (0-30 cm) and in-field N mineralisation predicted for the primary period of crop N uptake (August – November) and the entire spring/summer growing season (August – January) for the dryland and irrigated trials at Chertsey.

Trial	Mineral N	PMN	Predicted in-field N mineralisation (kg/ha)	
	kg/ha	**kg/ha/day**	**Aug – Nov**	**Aug – Jan**
Dryland	29	1.28	47	89
Irrigated	18	1.26	57	119

The split applications and total amounts of N fertiliser applied to each of the treatments are given in Table 4. For the irrigated wheat crop, the full industry guideline rate of 300 kg N/ha was applied as fertiliser in Treatment 1, based on a target grain yield of 12 t/ha (at 14% moisture). For Treatment 2, the full N rate was reduced by the total amount of mineral N (18 kg N/ha) in the topsoil (0–30 cm) in August, giving a total of 282 kg/ha of applied N. For Treatment 3, the full N rate was reduced by the total amount of initial mineral N (18 kg N/ha) in the soil plus the amount of N that was predicted to be supplied by mineralisation during the primary period (August through November) of crop N demand (57 kg N/ha), leaving a total of 225 kg/ha of applied N. For Treatment 4, early N was equivalent to Treatment 2 and the Quick Test Mass Balance Tool (QTMB) (https://far-qttool.shinyapps.io/shinyapp/) (Mathers et al. 2020) was used to forecast the additional fertiliser N that was required to meet the target yield based on Quick N testing at GS 32 and GS 39. The total fertiliser N applied in Treatment 4 was 155 kg/ha. Treatment 5 was included to measure the soil N supply and crop performance where no fertiliser N was applied and soil supplied N was the only source of N for crop uptake. Irrigation was applied to the irrigated trial on 29 October 2021 (10 mm), 2 November 2021 (20 mm), 11 November 2021 (20 mm), 16 November 2021 (25 mm) and 7 January 2022 (30 mm), giving a total of 105 mm.

The same approach was used to establish the N fertiliser rates for each of the five treatments in the dryland trial. In this case the full, industry guideline rate of N applied as fertiliser (200 kg N/ha) was reduced to 171, 124 and 95 kg N/ha in Treatments 2, 3 and 4, respectively. As in the irrigated trial, Treatment 5 in the dryland trial received no fertiliser N. No irrigation was applied to the dryland trial.

The split applications of N fertiliser in Treatments 2–3 of both trials were apportioned in accordance with the industry guidelines for Treatment 1. The N fertiliser product applied to both trials was SustaiN®.

Table 4. Fertiliser N application rates and timing for each of the five N management treatments of the dryland and irrigated N decision trials (2021/22).

Irrigated wheat		**Fertiliser N applied (kg N/ha)**			
Target grain yield = 12 t/ha	**Treatment No.**	**Early N[1]**	**GS 32[2]**	**GS 39[2]**	**Total N**
Full N fertiliser rate	1	40	174	86	300
Full N – mineral N	2	38	164	81	282
Full N – (min N + Pred N_{min})[3]	3	30	131	65	225
Full N – (min N + QTMB Tool)[4]	4	38	37	80	155
Nil N Fertiliser	5	0	0	0	0
Dryland wheat		**Fertiliser N applied (kg N/ha)**			
Target grain yield = 8 t/ha	**Treatment No.**	**Early N[1]**	**GS 32[2]**	**GS 39[2]**	**Total N**
Full N fertiliser rate	1	40	107	53	200
Full N – mineral N	2	34	92	45	171
Full N – (min N + Pred N_{min})[3]	3	25	66	33	124
Full N – (min N + QTMB Tool)[4]	4	34	23	38	95
Nil N Fertiliser	5	0	0	0	0

[1] Fertiliser applied on 1 September 2021.
[2] N applied at GS 32 and GS 39.
[3] Where min N = mineral N and Pred N_{min} = predicted in-field N mineralisation.
[4] QTMB Tool = Quick Test Mass Balance Tool.

2.2 Soil and plant measurements

2.2.1 Soil temperature and water content

Acclima True TDR-315L or 315H sensors (https://acclima.com) were installed at each trial site to continuously record soil temperature and moisture (sensors were placed horizontally at a depth of 10 cm in 10 plots at each trial site, representing all N treatments). Soil samples (0–15, 15–30 cm) collected at each trial site were used to determine gravimetric and volumetric water content at field capacity (–10 kPa) and wilting point (–1500 kPa). These data were used to calculate the daily relative available water content from the measured soil volumetric water content data collected over the course of each trial, from establishment to crop harvest.

2.2.2 Crop yield and N partitioning

The crop yield attained under each N management treatment of both trials was measured by two methods, quadrat sampling and machine harvesting. The dryland and irrigated crops were harvested on 19 January and 9 February 2022, respectively. At harvest, two quadrat samples were taken from each plot to measure the grain yield and other components (straw, crowns and roots) of the crop. Each quadrat represented a harvested area of 0.225 m^2 (0.5 m x 3 rows) giving a total harvest area of 0.45 m^2 in each plot.

The above-ground components of the wheat crops from the quadrat samples were separated into grain and non-grain (straw) components, and their dry weights determined. Several other measures of cereal crop performance were recorded (e.g. harvest index, tillers/m^2, screenings, one thousand grain weight). Two additional soil/plant samples were collected from each plot (one per quadrat area) to recover the crown and root material for N concentration measurements. A subsample of each dry plant component was ground and analysed for total N (Leco C/N analyser) to calculate the total N uptake of each crop.

After removing the quadrats, NZ Arable completed machine harvesting of each plot and reported the grain yield and grain moisture content. The plot yields reported from the machine harvest were corrected to an area basis after removing the quadrat area from the total area of crop grown (11.55 m^2). The moisture content of the grain was used to correct the grain weight to the grain yield at 14% moisture.

2.2.3 Soil N measurements

As at the start of the trial, soil samples (25-mm diameter corer) were also collected from Treatment 1 and Treatment 5 at GS 32 and GS 39 for mineral N (0–15, 15–30, 30–50 cm) and Quick N (0–30 cm) analyses, respectively. A further and final set of soil samples (0–15, 15–30, 30–50 cm) were taken from each plot (six cores/plot, composited) immediately after crop harvest. The mineral N samples were processed and analysed as described in Section 2.1.1.

2.3 Predicting in-field N mineralisation

The measurements of average daily soil temperature and volumetric water content made during the trials were applied to the PMN values recorded at the start of the trial (Table 1) to compare the estimates of N mineralisation derived from annual average climate data (Table 2) with those derived from edaphic properties measured during the trial.

2.3.1 Predicting in-field N mineralisation from PMN

Daily soil temperature and water content data were compiled from the Acclima TDR soil moisture sensors and data loggers installed at each trial site and used to predict the N mineralised under field conditions over the growing season of each crop. The soil temperature and volumetric water content measured under both trials at this site can be found in the Appendix (Figures A1 and A2). The daily average soil temperature during the growing season (August to January) ranged from 6.3 to 20.5°C. The volumetric water content in the topsoil of the dryland trial varied between 13.7 and 36.9%, whereas the soil volumetric water content of the irrigated trial varied between 17.7 and 35.1%. The higher water contents corresponded with a period of high rainfall in early to mid-December 2021, where the soil water content of both trials approached, but did not exceed, field capacity (37.7% v/v). This led to a period of higher than normal soil water content in the dryland trial; however, differences in soil water content between the dryland and irrigated trials were evident in November and January.

The method to calculate the In-field N mineralisation was the same as that given in Equation 3 (Section 2.1.2) above. However, in this case we compared the use of two different soil water content scaling factors; one based on the relationship between relative available water content and mineralisation as reported by Paul et al. (2003) (and applied in Section 2.1.2) and another based on the same relationship measured in New Zealand soils (Qiu et al. 2022). In both cases, the Lloyd-Taylor equation (Lloyd & Taylor 1994) was used to derive the scaling factors for soil temperature based on the field measurements described above. For predicting the in-field mineralisation, values of soil temperature and water content, measured at an average depth of 10 cm, were assumed to be applicable to both the 0–15 and 15–30 cm soil layers.

2.3.2 N balance calculations

The total amount of N supplied in each treatment was calculated as the sum of the N (kg/ha) in the initial mineral N (0–50 cm), the predicted in-field N mineralisation (0–30 cm) and N fertiliser applied. At harvest, the N recovered (kg/ha) in all of the plant components (grain, straw, crown and root) and the soil mineral N (0–50 cm) were also calculated for each plot.

In addition to these standard measurements, we also calculated the grain yield nitrogen use efficiency (NUE) as follows:

Grain yield NUE = kg/ha grain (at 14% moisture) / total kg N/ha supplied (Equation 4)

where the N supplied includes the initial mineral N, the predicted in-field N mineralisation and the N fertiliser applied.

2.3.3 Other performance metrics

The fertiliser cost associated with each of the treatments was calculated assuming a current price (1 June 2022) of $1,289/t (SustaiN®). The greenhouse gas emissions (kg CO_2-e/ha) associated with the fertiliser applied to each treatment were estimated using the He Waka Eke Noa Emissions protocol (Calculation tools and reports – He Waka Eke Noa) and FAR’s emission calculator (E-Check), which applies the New Zealand methodology for calculating agricultural greenhouse gas emissions (Sangster, Gibbs & Morrow, 2022).

3 Results and discussion

3.1 Predicting in-field N mineralisation

As discussed above, PMN represents the pool of N that can be mineralised from the soil under optimal conditions of soil temperature (25°C) and moisture (90% of field capacity) over a 14-week period. Soil temperature and water content are the two most important environmental variables that affect soil microbial activity and the release (mineralisation) of N from the PMN pool under field conditions. We used average daily soil temperature and soil volumetric water content (0–10 cm) data derived from the Ashburton weather station (17.7 km from the trial site) to forecast how much N would be mineralised over the growing season based on the PMN estimated from the HWEON tests conducted at the start of the growing season. Historic climate data are needed to predict the amount of N that is expected from mineralisation over a growing season. It can also be useful to compare the N mineralisation predicted from historic weather data to the mineralisation predicted from the soil temperature and water content measured under the actual conditions of crop growth.

Although the soil temperature modifier (Lloyd & Taylor 1994) used in our predictions of N mineralisation is widely accepted, we have previously highlighted the potential to improve the soil moisture modifier, given the variability in the data reported by Paul et al. (2003). We have recently reported (Qiu et al. 2022) results from a small number of soils in New Zealand that suggest that the relationship between soil volumetric water content and N mineralisation may be somewhat different for New Zealand soils.

Table 5. The predicted in-field N mineralisation (kg N/ha) based on historic weather station data and measured soil temperature and water content data, using either the Paul et al (2003) or Qiu et al (2022) water content relationship for N mineralisation.

Trial/Period	Weather Station Data[1]	Measured Data	
	Wf_1 (80%)[2]	**Wf_1 (80%)[2]**	**Wf_2 (100%)[3]**
Irrigated	-------------------------------------- (kg N/ha) -----------------------------------		
Aug – Nov	57	72	73
Aug – Jan	119	108	111
Dryland	-------------------------------------- (kg N/ha) -----------------------------------		
Aug – Nov	47	52	59
Aug – Jan	89	71	82

[1] Annual average daily soil temperature and water content derived from data obtained from the Ashburton weather station.

[2] Wf_1 (80%), scaling factor for soil water content where the estimate is based on the Paul et al (2003) relationship, assuming 80% of the N mineralised was available for crop uptake.

[3] Wf_2 (100%), scaling factor for soil water content where the estimate is based on the Qiu et al (2022) relationship, assuming 100% of the N mineralised was available for crop uptake.

The results presented in Table 5 compare the predictions of in-field N mineralisation derived from the Ashburton weather station to the predictions made from the measured soil temperature and water content data at the trial site. For the weather station data we report the in-field N mineralisation predicted using the Paul et al. (2003) soil water content scaling factors (Wf_1) assuming 80% of the N mineralised was available for crop uptake. The Wf_1 (80%) values were used in Treatment 3 of both trials to forecast the N fertiliser applications needed to meet crop demand. Table 5 also reports what we predicted for in-field N mineralisation from the measured soil temperature and water content data using the Paul et al. (2003) soil water content modifier (Wf_1, 80%) and using the Qiu et al (2022) soil water content scaling factors (Wf_2) without any correction for potential N losses (i.e. no discounting).

Overall the predictions of in-field N mineralisation using these three methods were reasonably comparable. Interestingly, the predictions from the measured data for the period between August and November tended to be higher than those based on the weather station data, possibly due to slightly higher than average soil temperatures during this period. Although rainfall was somewhat higher than normal during the December period, the N mineralisation predicted for the irrigated trial was still about 32 kg N/ha greater than the dryland trial over the entire spring/summer crop production period, from August to crop harvest. However much of the additional N mineralisation occurred in January, during crop senescence, when we assumed crop N uptake was low or nil.

3.2 Crop performance, costs and environmental indicators

The effects of the N management treatments on crop production, environmental performance and the costs of fertiliser are given for the irrigated and dryland trials in the following sections.

3.2.1 Irrigated wheat trial

There were significant effects of the N management treatments on all of the crop performance indicators measured in the irrigated trial (Table 6). The grain yields obtained by both machine harvest and quadrat harvest methods were comparable and very close to the target yield (12 t/ha) set for this wheat crop. There were no significant differences in the grain yields measured in Treatments 1–3 despite Treatments 2 and 3 receiving 6% and 25% less fertiliser N, respectively than Treatment 1. Although the N concentration (%) in the grain of Treatment 3 was slightly lower than that of Treatments 1 and 2, where higher rates of N fertiliser were applied, there were no significant differences between the three harvest index values. The grain yield and grain N concentration (%) in Treatment 4 averaged about 22% and 9% lower, respectively than Treatments 1–3.

Table 6. Crop performance indicators for each of five N management treatments of the irrigated N Decision Trial.

Irrigated treatments		Nitrogen fertiliser	Machine yield	Quadrat yield	Harvest index	Grain nitrogen
No.	**Description**[1]	**kg N/ha**	**t/ha**	**t/ha**	**%**	**%**
1	Full N rate	300	12.0	11.7	55.2	2.07
2	Full N – min N	282	12.0	11.6	55.4	2.09
3	Full N – (min N + Pred N_{min})	225	12.0	12.1	56.6	2.00
4	Full N + QTMB Tool	155	9.2	9.4	56.8	1.86
5	Nil N Fertiliser	0	5.6	5.4	52.0	1.50
LSD	5%		0.7	0.8	2.0	0.07

[1] where “Full N” refers to the full fertiliser N rate, “min N” is mineral N, “Pred N_{min}” is the predicted in-field N mineralisation and “QTMB” refers to the Quick Test Mass Balance tool.

The grain yield, grain N concentration (%) and harvest index measured in Treatment 5, where no fertiliser N was applied, were 46%, 73%, and 93%, respectively of the average values measured from Treatments 1–3.

Overall, these results indicate that the N supplied by the initial mineral N in the soil plus the predicted in-field mineralisation (Treatment 3) was sufficient to meet the demand of this irrigated wheat crop, despite a 25% (75 kg N/ha) reduction in N fertiliser applied and without penalising the yield. Although the N concentration (%) in the grain of Treatment 3, where 25% less fertiliser N was applied, was slightly less than the higher N treatments, the difference was of little practical significance.

The reduction in fertiliser N applied to Treatment 3 also resulted in other benefits, including improved grain yield N use efficiency, lower fertiliser cost and a reduction in emissions to the environment (Table 7). The amount of mineral N remaining in the soil profile (0–50 cm) of Treatments 2 and 3 at harvest was 71% and 47% of the mineral N recovered in Treatment 1, where the full industry guideline rate of N (300 kg/ha) was applied as fertiliser. There were no significant differences in the mineral N remaining at harvest between Treatments 3, 4 and 5, suggesting that further reduction in applied N had no benefit (in this case) for reducing the risk of N losses due to leaching after crop harvest. The actual losses of N post-harvest will of course depend on the selection and management of the next crop and the weather (especially rainfall) during the subsequent autumn/winter period.

Table 7. Nitrogen use efficiency, costs and environmental performance indicators for each of five N management treatments of the irrigated N Decision Trial.

Irrigated treatments		**Nitrogen Fertiliser**	**Residual Mineral N**	**Grain Yield NUE**[2]	**N Fert. Cost**	**Emissions**
No.	**Description**[1]	**kg N/ha**	**kg N/ha**	**kg grain/kg N**	**$/ha**	**kg CO_2-e/ha**
1	Full N rate	300	64.0	26.2	842	1460
2	Full N – min N	282	47.6	27.2	793	1373
3	Full N – (min N + Pred N_{min})	225	33.6	32.5	632	1096
4	Full N + QTMB Tool	155	28.7	31.4	434	752
5	Nil N Fertiliser	0	28.3	37.2	0	0
LSD	5%		11.1	2.8		

[1] where “Full N” refers to the full fertiliser N rate, “min N” is mineral N, “Pred N_{min}” is the predicted in-field N mineralisation and “QTMB” refers to the Quick Test Mass Balance tool.
[2] NUE, nitrogen use efficiency. See equation 4 for calculation of grain yield NUE.

The greater amounts of residual mineral N remaining in the soil profile of Treatments 1 and 2 at harvest were also reflected in a significantly lower grain yield N use efficiency (i.e. yield/total N supplied, kg/ha/kg N supplied) than in Treatments 3, 4 and 5, where less (or nil) N fertiliser was applied. The highest grain yield nitrogen use efficiency was recorded where no fertiliser N was applied. The benefits of testing for initial mineral N and forecasting N mineralisation to reduce fertiliser inputs was also reflected in the fertiliser cost saving and lower estimated emissions from the fertiliser applied to Treatment 2 and 3 compared with Treatment 1. The N fertiliser costs for Treatments 2 and 3 were $49/ha and $210/ha lower, respectively than Treatment 1 (the full fertiliser N rate). The estimated reduction in greenhouse gas emissions from fertiliser was of course directly proportional to the fertiliser reduction in Treatments 2 and 3 compared with Treatment 1, amounting to approximately 87 and 364 kg CO_2-e/ha less than in Treatment 1. The costs and emissions associated with fertiliser were lower again in Treatment 4 and nil in Treatment 5, where the grain yields were much lower than those targeted.

Overall, the results of this trial showed that adjusting the N fertiliser applied for the amount of initial mineral N plus the predicted in field predicted mineralisation can significantly improve the nitrogen use efficiency of an irrigated wheat crop. It can also reduce the post-harvest risk of N leaching losses and the cost and emissions associated with fertiliser use, without yield penalty, compared with where the full industry guideline rate of N is applied as fertiliser. Adjusting the full rate for the initial mineral N content only (Treatment 2), resulted in higher cost and emissions associated with fertiliser use and lower N use efficiency, with no benefits for grain yield or quality.

3.2.2 Dryland wheat trial

As in the irrigated trial, there were significant effects of the N management treatments on all of the crop performance indicators measured in the dryland trial (Table 8). With the exception of Treatment 4, the grain yields obtained by both machine harvest and quadrat harvest methods were comparable. However, in contrast to the irrigated trial, the grain yield recorded in Treatment 1 (full industry guideline N rate) was about 2 t/ha higher than the target yield (8 t/ha) set for this crop. Although there was no substantial difference in the grain yield recorded for Treatments 1 and 2, where the highest rates of N fertiliser were applied (170–200 kg N/ha), the grain yield in Treatment 3, where fertiliser N was reduced by 27–38%, was about 10% lower than Treatments 1 and 2. The yield reduction in Treatment 3 ranged from 0.6 to 1.2 t/ha. Similarly, the N concentration in the grain from Treatment 3 was about 7% lower than for Treatments 1 and 2. There was no significant difference in the harvest index measured in Treatments 1–3. The grain yield and grain N concentration (%) in Treatment 4 averaged about 27% and 12% lower, respectively than Treatments 1 and 2. The grain yield, grain N concentration (%) and harvest index measured in Treatment 5, where no fertiliser N was applied, were 53%, 71%, and 89%, respectively of the average values measured in Treatments 1 and 2.

Table 8. Crop performance indicators for each of five N management treatments of the dryland N Decision Trial.

Dryland treatments		Nitrogen Fertiliser	Machine Yield	Quadrat Yield	Harvest Index	Grain Nitrogen
No.	**Description[1]**	**kg N/ha**	**t/ha**	**t/ha**	**%**	**%**
1	Full N rate	200	10.2	10.1	53.3	1.89
2	Full N – min N	171	9.6	10.0	54.5	1.84
3	Full N – (min N + Pred N_{min})	124	9.0	9.0	52.8	1.73
4	Full N + QTMB Tool	95	7.9	7.8	51.8	1.64
5	Nil N Fertiliser	0	5.4	5.4	48.1	1.33
LSD	5%		0.4	0.9	1.7	0.08

[1] where “Full N” refers to the full fertiliser N rate, “min N” is mineral N, “Pred N_{min}” is the predicted in-field N mineralisation and “QTMB” refers to the Quick Test Mass Balance tool.

Overall, the results from Treatments 1 and 2 indicate that the yield potential of the dryland wheat crop was about 2 t/ha greater than the target yield, so it is not surprising that we recorded a lower crop yield in Treatment 3, where 25% (76 kg N/ha) less N fertiliser was applied than in Treatment 1 (the full N rate). The soil temperature and water content during the spring/early summer growing season of this crop were reasonably good, creating a greater demand for N to support the crop yield potential. Whereas the total N supplied by soil (initial mineral N plus mineralisable N = 76 kg N/ha) and fertiliser to Treatments 1 and 2 (247–276 kg N/ha) was sufficient to meet the crop demand where the yield potential was higher than the target, the total N supplied to Treatment 3 (200 kg N/ha) was not sufficient to achieve the higher yield potential of Treatments 1 and 2.

In contrast to the irrigated trial, the amount of residual mineral N remaining at harvest was very low and there were no significant treatment effects (Table 9). This result is consistent with the suggestion that crop demand for N was high compared with N supply, particularly in Treatments 3–5 where the N fertiliser applied was much lower (or nil) compared with Treatments 1 and 2. In general, the grain yield nitrogen use efficiency (i.e. yield/ total N supplied, kg grain/kg N supplied) decreased as the N applied from fertiliser increased. The average grain yield N use efficiency of the fertiliser treatments was 34 kg grain/ha per kg N supplied, which was higher than the N use efficiency of the irrigated crop (Treatments 1–4) and is consistent with the suggestion that N supply may have limited the yield of this crop, particularly in Treatments 3 and 4. The grain yield nitrogen use efficiency of Treatment 5, where nil N fertiliser was applied, was higher than the other treatments, as was observed in the irrigated trial.

Despite the yield penalty noted in Treatment 3, the benefits of adjusting fertiliser inputs for mineral N and mineralisable N were apparent in the cost saving and lower estimated emissions from fertiliser applied to Treatments 2 and 3 compared with Treatment 1. The N fertiliser costs for Treatments 2 and 3 were $79/ha and $213/ha lower, respectively than Treatment 1 (full fertiliser N rate). Similarly, the estimated greenhouse gas emissions from fertiliser were ≈138 and 370 kg CO_2-e/ha less, respectively than Treatment 1. However, it is worth noting that the savings in fertiliser costs achieved in Treatments 2 and 3 were outweighed by the returns expected from the additional grain yield ($348–$696/ha) achieved in Treatment 1 (at $580/t feed wheat grain), based on the machine harvest data. The costs and emissions associated with fertiliser were lower again in Treatment 4 and nil in Treatment 5, where the grain yields achieved were much lower than the target.

Table 9. Nitrogen use efficiency, costs and environmental performance indicators for each of five N management treatments of the dryland N Decision Trial.

Dryland treatments		Nitrogen Fertiliser	Residual Mineral N	Grain Yield NUE[2]	N Fert cost	Emissions
No.	**Description[1]**	**kg N/ha**	**kg N/ha**	**kg grain/kg N**	**$/ha**	**kg CO_2-e/ha**
1	Full N rate	200	12.3	31.1	561	973
2	Full N – min N	171	9.7	33.8	482	835
3	Full N – (min N + Pred N_{min})	124	13.9	36.1	348	603
4	Full N + QTMB Tool	95	15.2	35.5	268	464
5	Nil N Fertiliser	0	10.7	42.9	0	0
LSD	5%		NS	4.4		

[1] where “Full N” refers to the full fertiliser N rate, “min N” is mineral N, “Pred N_{min}” is the predicted in-field N mineralisation and “QTMB” refers to the Quick Test Mass Balance tool.
[2] NUE, nitrogen use efficiency. See equation 4 for calculation of grain yield NUE.

Overall, results of the dryland N decision trial showed that adjusting the N fertiliser applied for the initial mineral N plus the predicted in-field N mineralisation improved the nitrogen use efficiency and reduced the cost and emissions associated with fertiliser use compared to where the full industry guideline rate of N was applied as fertiliser. However, in this case, the grain yield achieved in Treatments 1–3 exceeded the target yield (8 t/ha) by 1–2 t/ha. If we assume that an average of 25 kg N/ha per t grain yield is needed to meet crop demand, then the total N supplied from soil (76 kg/ha) and fertiliser (171–200 kg/ha) in Treatments 1 and 2 was sufficient to meet the demand of the grain yield achieved (10 t/ha, ≈250 kg N/ha). However, due to the lower input of N fertiliser, the total N supplied from soil (76 kg/ha) and fertiliser (124 kg/ha) in Treatment 3 was not sufficient to achieve the same grain yield as in Treatments 1 and 2 (10 t/ha, ≈250 kg N/ha). This would explain the 1 t/ha lower yield in Treatment 3 compared with Treatments 1 and 2. However, if the target grain yield had been set higher (e.g. 10 t/ha) and the N fertiliser rate in Treatment 3 adjusted accordingly (i.e. 174 kg N/ha) to match the estimated total N demand of the crop (i.e. 250 kg N/ha), then it seems likely that Treatment 3 would have achieved an equivalent yield to Treatment 1, but with comparable fertiliser cost and emission reductions to those measured in the trial.

It is useful to note that the grain yield achieved in Treatment 5 (nil fertiliser N applied) of both the irrigated and dryland trials was very similar, although the N concentration in the grain and residual mineral N in the soil at harvest of the dryland trial was lower than the irrigated trial. This result suggests that N supply was the main limitation to the yield achieved in the dryland trial, while the higher predicted in-field N mineralisation under irrigation facilitated greater uptake of N in the grain as well as more mineral N in the soil profile at harvest.

4 Conclusions

The overall conclusion from these trials is that accounting for both the initial mineral N and the predicted in-field N mineralisation when making fertiliser N input decisions can improve N use efficiency and reduce the costs and emissions associated with fertiliser use while still achieving the target yield. Soil testing for topsoil mineral N and PMN at the start of the spring/summer growing season is essential to achieving this objective. This method seems to work well where the yield potential of a crop (given actual conditions for crop growth) closely matches the target yield. In situations where the yield potential of a given crop exceeds the target (i.e. the target yield substantially underestimates the realised yield), the lower fertiliser rate (adjusted for mineral N and mineralisable N) may not be sufficient to achieve the yield potential.

The results of these trials have shown that N mineralisation and to a lesser extent (in this case) the initial mineral N content of the soil can be important sources of N for crop uptake. The benefits of soil N testing were apparent despite relatively low to moderate amounts of soil N supply (initial mineral N plus mineralised N) in both trials. We would expect the benefits to be even greater where soil N supply was higher and, consequently, made up a greater proportion of the total crop N demand. Further research is needed to refine the methods and verify this assumption.

Although Quick N testing during the growing season closely matched the laboratory measured nitrate concentrations, the trial results suggest that the recommendations generated by the Quick Test Mass Balance Tool underestimate the amount of fertiliser N needed to achieve the yield potential of both irrigated and dryland wheat crops, at least under the conditions of these trials. Further work is need to develop N management tools that use soil N test values to better match the N supplied by soil (i.e. initial mineral N plus in-field N mineralisation) and fertiliser to crop demand under different environmental conditions.

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6 References

Beare MH, Curtin D, Tregurtha C, Gillespie R, Qiu W, Arnold N, McDougall S, Dellow S 2020. Mineralisable nitrogen to improve on-farm nitrogen management: year 1 field trials report. A Plant & Food Research report prepared for: Ministry for Primary Industries and project partners. Contribution to Milestone No. 83146. Contract No. 37307. Job code: P/441011/01. PFR SPTS No. 20254.

Cabrera ML, Beare MH 1993. Alkaline persulfate oxidation for determining total nitrogen in microbial biomass extracts. Soil Science Society of America Journal 57: 1007–1012.

Curtin D, Beare MH, Lehto K, Tregurtha C, Qiu W, Tregurtha R, Peterson M 2017. Rapid assays to predict nitrogen mineralization capacity of agricultural soils. Soil Science Society of America Journal 79 (3): 858–863.

Curtin D, Wright CE, Beare MH, McCallum FM 2006. Hot water-extractable nitrogen as an indicator of soil nitrogen availability. Soil Science Society of America Journal 70: 1512–1521. DOI:10.2136/sssaj2005.0338.

Lloyd J, Taylor JA 1994. On the temperature-dependence of soil respiration. Functional Ecology 8(3): 315–323.

Mathers D, Norris M, Hunt A, Dellow S, Liu J and Trolove S 2020. The Nitrate Quick Test Mass Balance Tool – User Guide. https://www.far.org.nz/articles/1231/quick-test-mass-balance-tool-user-guide.

Paul, KI, Polglase, PJ, O'Connell, AM, Carlyle, JC, Smethurst, PJ, Khanna, PK 2003. Defining the relation between soil water content and net nitrogen mineralization. European Journal of Soil Science 54 (1), 39-47.

Qiu W, Curtin D, Hu W, Beare MH 2022. Sensitivity of organic matter mineralisation to water availability: role of solute diffusivity and the “Birch effect”. Soil Research (In Press).

Appendix

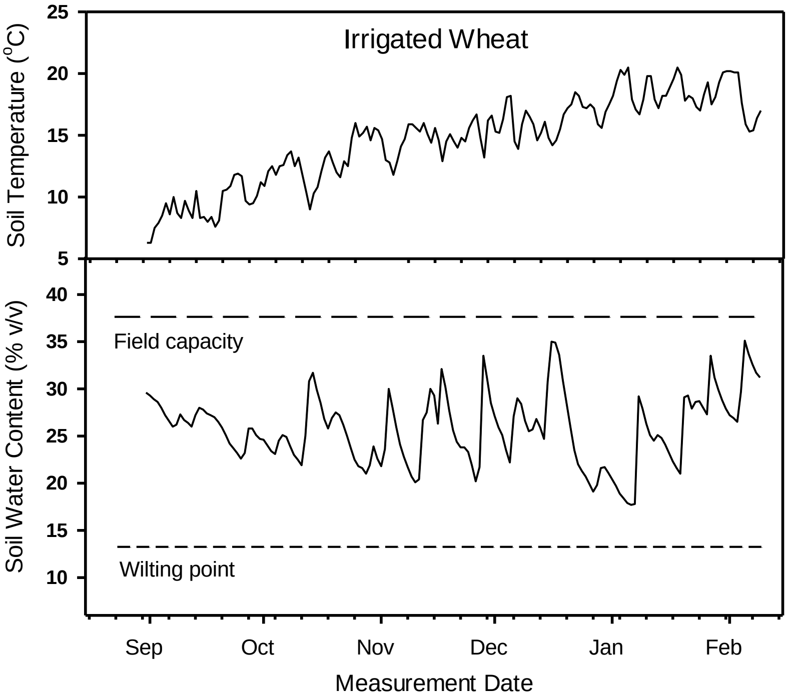

Figure A1. Soil temperature and volumetric water content measured under the irrigated wheat crop (Chertsey), 2021/22.

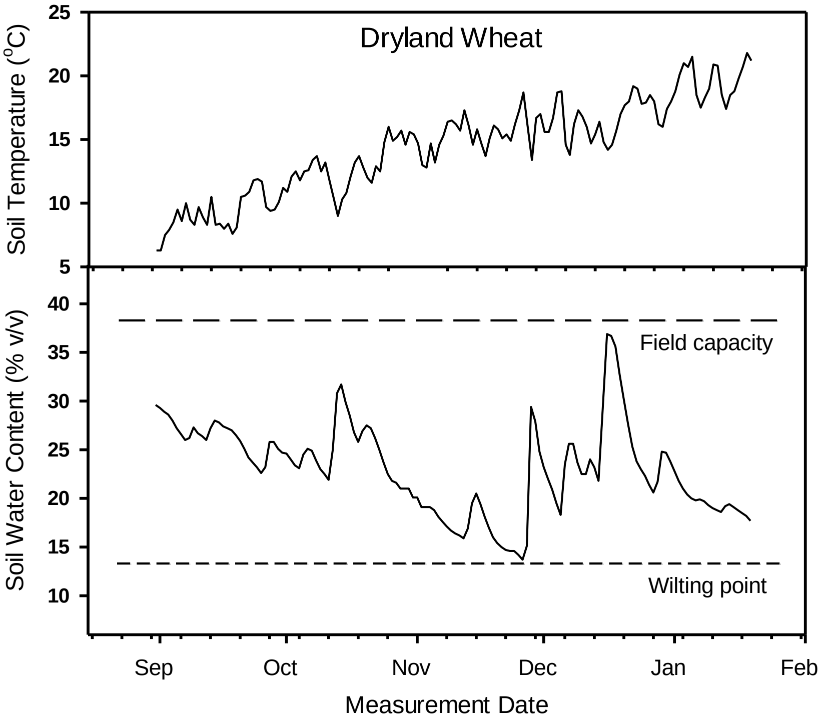

Figure A2. Soil temperature and volumetric water content measured under the dryland wheat crop (Chertsey), 2021/22.

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