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Mineralisable nitrogen to improve on-farm nitrogen management: Year 2 results

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Executive summary

Mineralisable nitrogen to improve on-farm nitrogen management: Year 2 results

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There is increasing pressure on growers to improve nitrogen (N) management practices and reduce N losses to the wider environment. The best approach to increase N use efficiency is to match N supply (soil and fertiliser N) to crop N requirements. A key to the success of this approach is the ability to predict the amount of N supplied from the mineralisation of soil organic matter during the growing season.

In the 2020/21 growing season, field trials were conducted at four locations (three in Canterbury, one near Bombay, south of Auckland) to validate predictions of N mineralisation using the new hot water extractable organic N (HWEON) test. The test crops (wheat, wheat, broccoli, pak choi) were treated with four rates of fertiliser N, including a zero-N control (treatments replicated four times in a Latin square design). Total crop N uptake was determined and soil N supply was assessed by measuring deep mineral N (at sowing and harvest) and potentially mineralisable N (PMN) using (1) the "gold standard" method (14-week aerobic incubation at constant temperature and moisture; 25°C; 90% field capacity) and (2) the HWEON test.

Nitrogen uptake by the crops in the control (zero N fertiliser) treatments (i.e., all plant available N derived from the soil), ranged from ~77 to 130 kg/ha. Mineralisation accounted for 34–63% of the N supplied by the soil. Based on the amounts of N taken up by the crops in the absence of fertiliser N, and making allowance from changes in deep soil mineral N during the growing season, we calculated that between 25 to 121 kg/ha of mineralised N became available for plant uptake. Results of the 2020/21 trials also showed that there can be significant spatial variability (both vertically and horizontally) in mineral N that may be important to estimating the total soil N supply. Further work is needed to determine how much of the mineral N that exists below 30 cm at the start of the growing season contributes to the N uptake of different crops during their growth. Shallow (0–30 cm) soil mineral N testing would provide a simpler, more practical method that could encourage more growers to routinely measure mineral N for improved fertiliser decision making. Further work is also need to ensure that these methods adequately account for the spatial variability in mineral N at a management unit (e.g. paddock) scale.

Overall, the measurements of mineral N and mineralisable N provided valuable information for interpreting the response of the four crops to fertiliser N additions; however, the interpretation differed somewhat between crops depending on their growth characteristics and N demand. In general, the predicted and measured in-field N mineralisation values followed a similar trend, with values for both approaches being low at the Bombay (broccoli) trial site, moderate at the Lincoln (pak choi) trial site, high at the Southbridge (wheat) trial site and very high at the Leeston (wheat) trial site. However, the

predicted in-field N mineralisation values were consistently higher than the measured values obtained from the N balance calculations for the N0 treatments at each trial site.

The results from the field validation trials conducted over the past 3 years (11 in total) indicate that our predictions of in-field N mineralisation from the PMN test values are very closely related ($R^2 = 0.96$) to the N mineralisation measured from the N0 treatments at each trial site (excluding results from one trial site in 2020/21). However, they also highlight that the predicted in-field N mineralisation was consistently about 25% higher than the measured values. This discrepancy may be due to overestimation of the predicted N mineralisation (perhaps due to the soil moisture function used) or to underestimation of the measured N mineralisation (perhaps due to losses of N that were not accounted for). Although further analysis of existing data may help to resolve this discrepancy, additional research may be needed to ensure the method applied to improve fertiliser N forecasting has an acceptable level of uncertainty. Nevertheless, it is clear that mineralisable N can be a very important source of the N supplied to crops and that testing for PMN coupled with information on soil temperature and soil water content can be used to predict the supply of N from mineralisation over a growing season.

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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) 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 the single greatest limitation to: 1) correctly forecasting the amount and timing of fertiliser N additions 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.

Cropping farmers/growers aim to supply N to their crops in relation to crop demand. While many growers test the soil for mineral N (ammonium [NH_4] and nitrate [NO_3]) at the start of the main growing season (e.g. spring), this does not account for the N that will become available (via mineralisation) during the growing season. Consequently, growers lack the essential information needed to properly forecast the additional (fertiliser) N needed to meet crop demand and, therefore, are more likely to oversupply N to ensure maximum yield. This oversupply is not only an extra cost to the grower (lowering profitability) but also results in surplus N that could be lost through leaching, surface runoff or gaseous emissions.

The New Zealand Institute for Plant and Food Research Limited (PFR) 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). Preliminary trial results indicate that this test, combined with information on the soil type and weather, can be used to predict the in-field N mineralisation over a growing season. The Sustainable Farming Fund project entitled 'Mineralisable N to improve on-farm N management' (Project number: 405891) was initiated in July 2019 to validate these predictions of N mineralisation for a wider range of soils, climates and crops in on-farm trials. The aim is to develop and deliver new knowledge and understanding to growers and other industry stakeholders about the importance of N mineralisation information to improving N management on farms, enabling growers to lift the economic and environmental sustainability of agricultural production systems.

This report describes results from the field validation trials and laboratory analyses conducted in 2020/21.

2 Materials and methods

Field validation trials were carried out at four sites in the 2020/21 project year. The sites were selected to provide a range of soil types in which to evaluate the PMN test. Three of the trials were located on commercial farms, which included two arable cropping farms in mid-Canterbury and one growing vegetable crops near Bombay, south of Auckland. One other trial was established on a research farm near Lincoln with a history of mixed arable and vegetable cropping. Other factors considered when assessing site suitability included soil uniformity, land use and cropping history, the location of irrigation and spray tramlines and practical considerations of the host farms/growers. A brief summary of the four trials is as follows:

Wheat (Southbridge): This trial was established on a deep imperfectly-drained Taitapu silt loam soil on Matt McEvedy's commercial arable cropping farm near Southbridge. The crops on this farm are routinely established with minimum tillage practices. The trial paddock had been under continuous conventional to minimum tillage cropping for many years; the most recent main crops being beans (2019/20), ryegrass seed (2018/19), wheat (2017/18), radish seed (2016/17) and peas (2015/16).

Wheat (Leeston): This trial was established on a moderately deep poorly-drained Leeston silt loam soil on Simon Osborne's commercial arable cropping farm (home block) near Leeston. This farm has been under continuous arable cropping using no-tillage management for more than 40 years. The most recent main crops produced on the paddock selected for this trial were linseed (2019/20), ryegrass seed (2018/19) and peas (2017/18).

Broccoli (Bombay): This trial was established on a deep, moderately well drained Morrinsville granular clay loam at Sutherland Produce's commercial vegetable production property near Bombay. The farm and paddock selected for this trial had been under continuous vegetable production for several years prior to initiating this trial. The most recent crops grown prior to this trial were broccoli (summer 2020), lettuce (summer 2019), broccoli (summer 2018), lettuce (autumn 2017) and broccoli (summer 2016).

Pak Choi (Lincoln): This trial was established on a deep, moderately well drained Templeton silt loam soil on PFR's Lincoln A Block Research Farm (column A1.1). The paddock selected for this trial had been under continuous arable cropping for many years. The most recent crops grown prior to this trial were oats (spring 2019), ryegrass (autumn 2017 – spring 2019), barley (spring 2016 – summer 2017) and potatoes (2015/16).

The baseline soil fertility varied between the four trial sites. In general, most of the soil fertility indicators at the three Canterbury sites were in the medium to high range, with the exception of low Olsen P and potassium (K) values at the Leeston trial site and high pH and magnesium (Mg) values at the Southbridge trial site. The soil fertility indicators at the Bombay site were all high to extremely high (Table 1). Soil organic matter at the Bombay trial site was moderately low for a granular soil (2.3% total carbon [C]; 0–15 cm) compared with the other sites (4.2 to 2.8% total C) on sedimentary soils.

2.1 Experimental design

At each trial site, the experimental treatments comprised four rates of fertiliser N, each replicated four times in a Latin square design (Figure 1). The N rates, which included a zero-N treatment (N0), differed depending on the N requirement of the crops. The total "recommended" rate of fertiliser N (N2 treatment) was defined based on expert knowledge of each crop type and was intended to match the host farm manager/grower recommended rate for the crop grown at each site. The fertiliser N rates for the N1 and N3 treatments were set at 50% and 150% of the N2 rate, respectively.

The N fertiliser product used at each site varied depending on the recommended practice of the host farm/grower and the practicalities of applying variable N rates and fixed rates of other nutrients as prescribed by the soil test values. The fertiliser was usually applied in either two or three split applications, i.e. “starter” fertiliser, applied at sowing, and either one, two or three side dressings (Table 2). The total amounts of N applied at the N0, N1, N2, and N3 rates, respectively, were:

- Wheat (Southbridge): 0, 47, 98, 147 kg ha^{-1}
- Wheat (Leeston): 0, 84, 168, 252 kg ha^{-1}
- Broccoli (Bombay): 0, 65, 131, 196 kg ha^{-1}
- Pak Choi (Lincoln): 0, 30, 60, 140 kg ha^{-1}

Unfortunately, the third side dressing of N to the trial at Southbridge (wheat) was inadvertently missed, so in this case the N3 rate most closely matches the total grower rate at that trial site.

Nutrients other than N were applied, if required, as indicated by standard soil fertility tests conducted on soil samples (0–15 cm) collected prior to initiating each trial (Table 1) and to broadly align with the host grower’s rates (see Table 2 for details). The fertilisers were broadcast onto the plots and incorporated by secondary cultivation wherever possible.

Table 1. Surface soil (0–15 cm) properties at the four trial sites.

Soil Property	Wheat (Southbridge)	Wheat (Leeston)	Broccoli (Bombay)	Pak Choi (Lincoln)
Soil pH	6.4	6.0	7.9	6.2
Olsen P, mg L^{-1}	22	17	120	24
K (MAF unit)	12	3	32	7
Ca (MAF unit)	15	10	21	10
Mg (MAF unit)	46	20	19	13
Total C (%)	3.4 (1.5)[1]	4.2 (1.9)	2.3 (2.1)	2.8 (2.5)
Total N (%)	0.29 (0.13)	0.42 (0.19)	0.20 (0.19)	0.23 (0.20)
Bulk Density (g cm-3)	1.03 (1.33)	1.15 (1.36)	0.92 (1.10)	1.05 (1.27)

[1] Values in parentheses are the equivalent measurements for 15–30 cm soil.

Block 1		Block 2		Block 3		Block 4	
1	N0	5	N3	9	N1	13	N2
2	N1	6	N2	10	N0	14	N3
3	N3	7	N0	11	N2	15	N1
4	N2	8	N1	12	N3	16	N0

Figure 1. The Latin Square design showing the arrangement of nitrogen (N) treatments that was applied to all four N trials in 2020/21.

Table 2. Nitrogen (N) application rates and timing for the four trials in 2020/21. Other non-N fertilisers applied to each trial site are given in the table footnote.

Crop (Location)	Application	Date	N Treatment (kg N ha^{-1})			
			N0	N1	N2	N3
Wheat (Southbridge)[1]	Starter	Sowing	0	0	0	0
	Side dress #1 (CAN)	22 Sept 2020	0	13	26	39
	Side dress #2 (CAN)	20 Oct 2020	0	36	72	108
	Total		0	49	98	147
Wheat (Leeston)[2]	Starter	Sowing	0	0	0	0
	Side dress #1 (CAN)	2 Sept 2020	0	34	69	103
	Side dress #2 (CAN)	22 Sept 2020	0	35	69	104
	Side dress #2 (CAN)	3 Nov 2020	0	15	30	45
	Total		0	84	168	252
Broccoli (Bombay)[3]	Starter (N Control 75)	27 Nov 2020	0	43	86	129
	Side dress #1 (N Control 75)	22 Dec 2020	0	22	45	67
	Total		0	65	131	196
Pak Choi (Lincoln)[4]	Starter (CAN)	21 Dec 2020	0	15	30	60
	Side dress #1 (CAN)	12 Jan 2021	0	15	30	80
	Total		0	30	60	140

1 No starter N fertiliser was applied to this crop. Superphosphate (285 kg ha^{-1}) and Muriate of Potash (MOP, 52 kg ha^{-1}) were applied to the trial site to match the grower's application of P, K and S. CAN is calcium ammonium nitrate.
2 No base fertiliser was applied to this site and no N fertiliser was applied at sowing.
3 Potash Sulphur Super (142 kg ha^{-1}) and Borate 46 (1.25 kg ha^{-1}) applied on 27 November.
4 Superten 7K (700 kg ha^{-1}) applied on 3 December 2020.

Table 3 provides a brief summary of trial management information. Four trials were all irrigated. The crops were managed using best agronomic practices to control weeds, pests, and diseases. During the growing season, the crops were carefully monitored and herbicides, fungicides, and insecticides were applied when required.

Table 3. Summary of general management information for each trial in 2020/21.

Site	Location	Crop	Cultivar	Plot size	Irrigated	Sowing date	Harvest date
1	Southbridge	Wheat	‘Discovery’	3 x 3 m	Yes	28 April	29 Jan
2	Leeston	Wheat	‘Conquest’	3 x 3 m	Yes	25 April	18 Jan
3	Bombay	Broccoli	‘Brumby’	3 x 1.85 m	Yes	23 Nov	11 Feb
4	Lincoln	Pak Choi	‘Shanghai’	10 x 12 m	Yes	7 Dec	20 Jan

2.2 Soil and plant measurements

2.2.1 Soil temperature and water content

Acclima True TDR-315L sensors (https://acclima.com) were installed at each 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).

2.2.2 Crop production and N uptake

All final crop and soil samples were taken at crop maturity, just prior to commercial harvesting (Table 3). Quadrat samples were taken for yield determination and to measure non-marketable plant components (including crop residues, crowns and roots) from each plot at each trial site. The area harvested from each plot was 1.16 m^2 (1 m x 7 rows) at the Southbridge (wheat) trial, 1.0 m^2 (1 m x 4 rows) at the Leeston (wheat) trial site, and 6 m^2 (1 m x 16 rows) at the Lincoln (pak choi) trial site. The fresh yield and plant component measurements were made from the total plot area (5.55 m^2) at the Bombay (broccoli) trial site.

The plants harvested from the broccoli and pak choi trials were separated into marketable and non-marketable components. In the case of the broccoli trial, the plants were first separated into those with marketable (>122 mm) and non-marketable (undersized, <122 mm) heads. The plants in these two categories were further separated into heads and the remaining aboveground crop residue. The marketable heads included some heads that had exceeded their ideal harvest date but would have been marketable if harvested a little earlier. A representative subsample was taken from each category in each plot to determine the dry weight and for analysis of N concentration (LECO C/N analyser). At the pak choi trial, the plants in each harvested area were separated into marketable and non-marketable above ground components and their total fresh weights recorded. A subsample of each component was removed (0.8–1.4 kg) to determine their moisture content (oven dried at 60°C) and N concentration (LECO C/N analyser). The above-ground components of the wheat crops were separated into grain and non-grain (leaves and stems) components, and their dry weights determined. 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.

2.2.3 Soil N measurements

At trial set-up (prior to N application) and at crop harvest, soil samples for determination of deep mineral N were collected by depth (e.g. 0–15, 15–30, 30–50, 50–70, 70–90 cm) in each plot using a 25-mm diameter corer. Between 6 and 8 cores were taken from each plot and composited by depth. Samples were maintained under cool/refrigerated conditions in transit to the PFR laboratory in Lincoln. 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).

Air-dried samples taken from the N0 plots (0–15 and 15–30 cm depths) at trial set-up were used to determine hot water extractable organic N (HWEON) and hot water extractable C (HWEC), and mineralisable N by both the aerobic (PMN) and anaerobic incubation (AMN) procedures. 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). Anaerobically mineralisable N (AMN) was determined as the amount of ammonium-N (NH_4-N) produced during a 7-day anaerobic incubation at 40°C (Keeney & Bremner 1966). The measurement of AMN was corrected for the concentration of NH_4-N in the pre-incubated soils. Subsamples of soil from some of the trial sites and other archived soils were also analysed for HWEON and AMN by each of the participating commercial laboratories (i.e. Hill Laboratories Limited, ARL and Eurofins) to evaluate the reproducibility of the methods under the projects round robin testing programme.

Potentially mineralisable N (PMN) was measured following the “gold standard” method (i.e. 14-week aerobic incubation at 25°C) described by Curtin et al. (2017). Briefly, samples of air-dry soil (equivalent to 25 g of oven-dry soil) were weighed into plastic vials and de-ionized water was added drop-wise (using an electronic pipette in titrate mode) to adjust soil water content to 90% of field capacity (field capacity defined as water content at -10 kPa; measured using vacuum plates). The soils were incubated at 25°C. To minimize moisture loss during incubation, the vials were covered with Parafilm® (holes were punctured in the film to facilitate aeration). Mineral N was extracted (using 2 M KCl) after 2, 4, 7, 10 and 14 weeks of incubation and determined using an automated colorimeter (QuickChem 8000 FIA+, Lachat Instruments, Loveland, CO, USA). We incubated a sufficient number of sub-samples of each soil to allow one sub-sample to be destructively sampled at each time point. Mineralised N was estimated by subtracting mineral N at the start of the incubation from the amount determined at each incubation interval. Water was added at weekly intervals to compensate for any evaporative losses.

Our previous research (Curtin et al. 2017) showed that there is a close positive relationship between HWEON and PMN measured in a 14 week aerobic incubation. The use of HWEON to predict PMN from this relationship is known as the **PMN test**.

2.3 Predicting in-field N mineralisation

A key objective of the field trials was to compare the in-field N mineralisation predicted from the PMN test with N mineralisation estimated from the N balance calculations derived from the field trial results. These two different approaches to predicting N mineralisation are outlined below.

2.3.1 Predicting in-field N mineralisation from PMN

Potentially mineralisable N (PMN) is taken to represent 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 mineralisation of N under field conditions. Daily soil temperature and water content data were compiled from the Acclima sensors and data loggers installed at each trial site to predict the N mineralised under field conditions over the growing season of each crop. The soil temperature and volumetric water content data obtained for each site can be found in the Appendix (Figures A1–A4). At the two wheat trial sites (Southbridge and Leeston), mean soil temperature during the growing season (September to January) ranged from 8 to 20°C. A narrow range of soil temperatures (15 to 20°C) were recorded at Lincoln under the pak choi crop. The mean soil temperature at the Bombay trial (broccoli) was 2 to 6°C higher than at the Canterbury sites. The soil moisture content fluctuated well within the range of field capacity and wilting point at the four trials. Only at the pak choi trial site did the soil water content briefly exceed field capacity.

For each of two soil layers (0–15, 15–30 cm) at the four trials, the daily N mineralisation potential was calculated as the amount of N mineralised during the 14-week aerobic incubation divided by 98, and expressed as kg N ha^{-1} day^{-1} (measured bulk density values were used to calculate the mass of soil per hectare). These mineralisation potentials are a measure of the daily rate of N mineralisation under "optimum" conditions of temperature and moisture, i.e., 25°C and 90% field capacity water content.

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

$$\text{In-field N mineralisation} = \sum_{i=1}^{n} (\text{Average daily PMN} \times Mt_i \times Mw_i) \qquad \text{(Equation 1)}$$

where n is the number of days in the growing season and Mt and Mw are modifiers calculated from the daily average soil temperature and water content, respectively.

The Lloyd-Taylor equation (Lloyd & Taylor 1994) was used to derive the modifiers of soil temperature measured in the field (Mt). The relationship recommended by Paul et al. (2003) was used to derive the modifiers for water content (Mw). The values for Mt and Mw ranged from 0 (no mineralisation occurs because the soil is too dry or too cold) to 1 (temperature and moisture are optimal).

Note: in predicting in-field mineralisation, values of soil temperature and water content, measured at a depth of 10 cm, were assumed to be applicable to both the 0–15 and 15–30 cm soil layers.

2.3.2 N mineralisation calculated from crop and soil N balance data

In the zero N (N0) treatment (i.e. control, no N applied), the N taken up by the crop was either mineral N present in the soil when the crop was sown or N that mineralised from soil organic matter during the growing season. The contribution of mineralised N to crop N uptake was calculated as:

Mineralised N = Total N uptake + soil mineral N (harvest) – soil mineral N (sowing) (Equation 2)

For this estimate of in-field N mineralisation, it is assumed that losses of N from the soil (leaching or gaseous N losses) during the growing season are negligible (loss of mineral N during the season would result in underestimation of mineralisation).

Mineralisation in the N-fertiliser treatments involves a similar calculation, taking account of the N applied in fertiliser as well:

Mineralised N = Total N uptake + soil mineral N (harvest) – soil mineral N (sowing) - fertiliser N

The estimates of in-field N mineralisation made from the N balance calculations at each trial site were averaged across the four N0 plots.

3 Results and discussion

3.1 Soil N sources

The two primary sources of soil N that contribute to the supply of N for crop uptake during the growing season are the initial mineral N and the mineralised N. The average initial mineral N content of the surface soil (0–30 cm) and entire soil profile (0–90 cm) at each trial site are given in Table 4. The initial mineral N content of the surface soil (0–30 cm) at all four sites was in the low to moderate range (15–45 kg ha^{-1}; Table 4). However, the spatial (plot-to-plot) variability in initial mineral N ranged from relatively low (Bombay) to very high (Leeston) across the four sites (X axis, Figure 2). This variability introduced an additional source of error for validating our predictions of N mineralisation. It also highlighted the challenge of accurately measuring initial mineral for estimating soil N supply.

Overall, there was very poor correspondence between mineral N in the top soil (0–30 cm) and the mineral N measured over the entire soil profile (0–90 cm) (Figure 2). Individually, there was a reasonably close relationship between the top soil (0–30 cm) and soil profile (0–90 cm) mineral N at the Leeston, Lincoln and Southbridge trial sites, but very poor correspondence at the Bombay site. Overall, the mineral N measured in the top 30 cm of soil accounted for between 10 and 87% of the mineral N measured in the top 90 cm. These results are different to our trial results from 2019/20 and the findings of Norris et al. (2019). This raises questions about the adequacy of relying on shallow mineral N testing (0–30 cm) to estimate the stock of plant available N at the start of the growing season. However, it is not clear to what extent the mineral N that exists below 30 cm at the start of the growing season represents a significant source of N for plant uptake, although it is likely that this varies with crop type and soil conditions. This question requires further investigation to provide clear recommendations for mineral N testing to improve fertiliser forecasting. The N balance results from the validation trials discussed below help to shed some light on this question.

3.1.1 Hot water extractable C and N

Hot water extractable organic C (HWEC) and N (HWEON) values ranged from relatively low at the Bombay trial site to very high at the Leeston trial site (Table 4). The HWEON values (89–142 mg kg^{-1}) recorded for the surface soils (0–15 cm) at the Southbridge and Lincoln sites were typical of the values reported for many arable cropping soils In New Zealand but considerably lower than the average values (~200 mg kg^{-1}) reported for continuous dairy pasture soils across New Zealand (Curtin et al. 2017). The very low HWEON values for the Bombay site are undoubtedly due to the loss of soil organic matter over many years of continuous vegetable cropping at this site. In contrast, HWEON in the top soil (0–15 cm) at the Leeston trial site was very high, which can be attributed to the site's history of long-term no-till management and the higher clay content of the Leeston silt loam soil. There were significant quantities of HWEON in the 15–30 cm soils at both the Leeston and Lincoln trial sites, whereas the other two sites had lower values in the deeper layer. As reported previously (Curtin et al. 2017; Beare et al. 2020), there was a very close relationship (R^2 = 0.98) between HWEC and HWEON (Data not shown). This result provides further evidence that HWEC, compared with HWEON, may be used as an equally good predictor of potentially mineralisable N (PMN) (Curtin et al. 2017; Beare et al. 2020) and offers an alternative to HWEON for routine testing to estimate PMN (see Section 3.1.2).

3.1.2 Mineralisable N

Potentially mineralisable nitrogen (PMN), measured in a 14-week aerobic incubation, ranged from 27 to 182 mg kg^{-1} in the 0–15 cm soils and from 30 to 72 mg kg^{-1} in the 15–30 cm soils (Table 5). Like HWEON, the highest PMN values were recorded at the Leeston trial site, which had a history of long-term no-till management, and the lowest values were measured at the Bombay site. The vertical stratification of PMN varied considerably between sites. This result stresses the importance of testing for HWEON to predict PMN in both 0–15 and 15–30 cm soils, because soil organic matter can accumulate below the top 15 cm of soil in arable cropping systems.

Table 4. Initial mineral nitrogen (N), anaerobically mineralisable N (AMN), hot water extractable organic N (HWEON) and hot water extractable C (HWEC) at each of the four trial sites in 2020/21. Values are mean (± SD).

Crop (Location)	Initial Mineral N (kg ha^{-1})		AMN (mg kg^{-1})		HWEON (mg kg^{-1})		HWEC (mg kg^{-1})	
	0–30 cm	0–90 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
Wheat (Southbridge)	16 (9)	54 (15)	90 (8)	36 (8)	142 (5)	49 (7)	1397 (65)	511 (64)
Wheat (Leeston)	25 (22)	31 (25)	128 (24)	32 (8)	240 (6)	82 (16)	2183 (45)	749 (135)
Broccoli (Bombay)	15 (7)	148 (35)	24 (4)	20 (2)	39 (4)	35 (4)	497 (51)	482 (54)
Pak Choi (Lincoln)	45 (12)	69 (14)	54 (3)	51 (6)	89 (6)	76 (13)	995 (67)	875 (136)

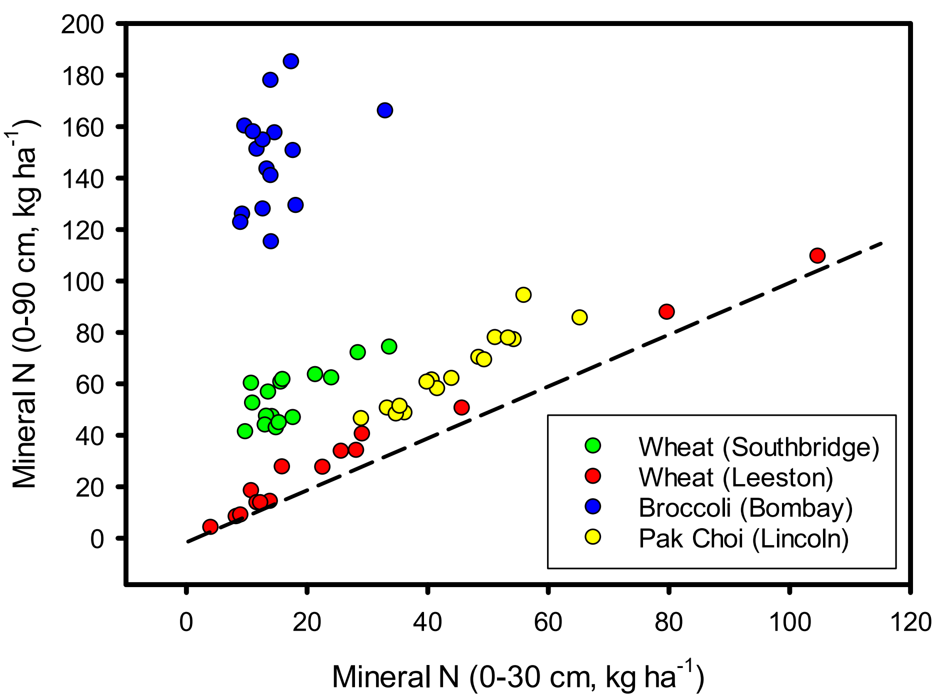

Figure 2. Mineral nitrogen (N) in the top 30 cm of soil compared to mineral N in the top 90 cm of soil at the four trials in 2020/21. The dashed line is the 1:1 line.

In all soils, there was an initial flush (first two weeks) of mineralisation associated with the re-wetting of the air-dried soils at the start of the aerobic incubations (data not shown). The N mineralised in the first two weeks represented between 45 and 62% of the N mineralised over the 14-week incubation. This mineralisation pattern is similar to that observed in previous work (Curtin et al. 2017; Beare et al. 2020). The relationship between HWEON and PMN obtained from the 2020/21 field trials was consistent with data that were used to re-calibrate the HWEON test for predicting PMN (Figure 3; the re-calibration data were obtained from the original 120 sites representing long-term pasture and cropping soils from across New Zealand).

Table 5. The potentially mineralisable nitrogen (PMN) and both the predicted and measured in-field nitrogen (N) mineralisation at each of the four trial sites in 2020/21.

Crop (Location)	PMN (mg N kg^{-1})		In-field N Mineralised (kg N ha^{-1})			
	Measured[1]		Predicted[2]			Measured[3]
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–30 cm	0–30 cm
Wheat (Southbridge)	133 (3.8)	52 (4.3)	88	39	127	94 (5.4)
Wheat (Leeston)	182 (4.3)	72 (10.8)	131	65	196	121 (16)
Broccoli (Bombay)	27 (1.7)	30 (1.8)	18	17	35	25 (2.5)
Pak Choi (Lincoln)	73 (2.7)	67 (7.8)	30	29	59	46 (13)

[1] Measured from the 14-week aerobic incubation, 0–15 and 15–30 cm soils. Values are mean (± SD).
[2] Predicted from equation 1 in Section 2.3.1 for 0–15 and 15–30 cm soils over the growing season.
[3] Derived from the N balance of the N0 treatment (equation 2, Section 2.3.2). Values are mean (± SD).

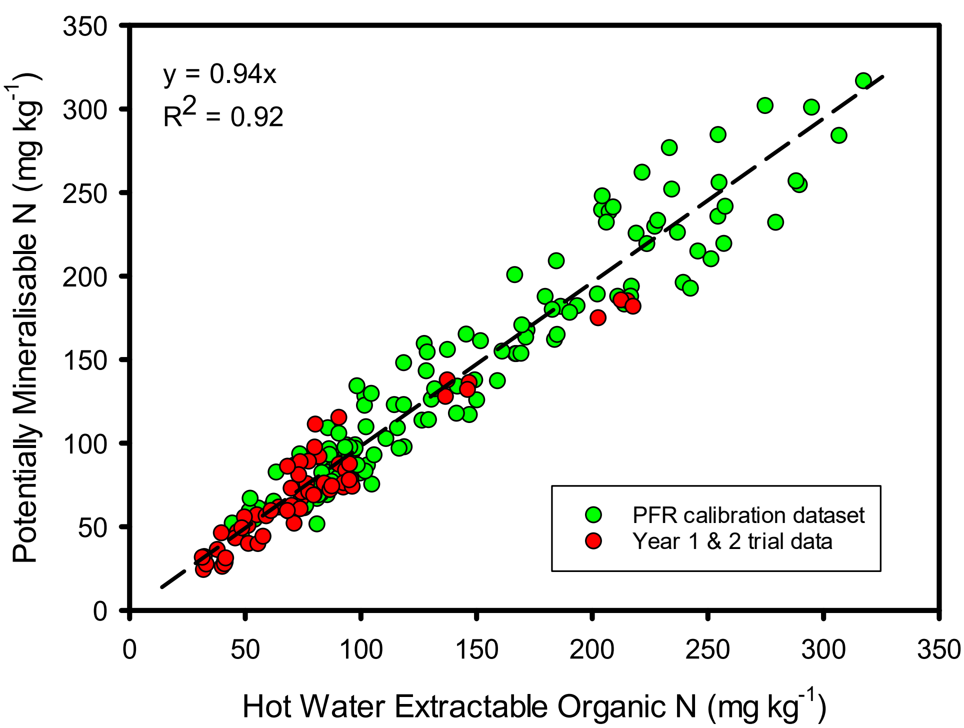

Figure 3. The relationship between hot water extractable organic N (HWEON) and potentially mineralisable nitrogen (PMN) for data obtained from the 2019/20 field validation trials compared with results from the New Zealand Institute for Plant and Food Research Limited calibration dataset.

As reported previously (Curtin et al. 2017; Beare et al 2020), the variability in PMN at the 2020/21 trial sites was much better explained by HWEON (R^2 = 0.81) than AMN (R^2 = 0.62). The results of the round robin testing programme carried out by the four participating laboratories (PFR, Hill Laboratories [Hills], Analytical Research Laboratory [ARL] and Eurofins) have continued to show that the test values obtained from PFR, Hills and ARL are highly reproducible across a broad range of soil HWEON concentrations (Figure 4A). Although initially Eurofin's results were similar to those of the other laboratories, their more recent results have tended to be consistently lower than those of the other three laboratories. They declined the offer to complete re-testing of the samples that fell outside the range of the other three laboratories and have subsequently decided to withdraw from further participation in the round robin testing programme under this project. The results of the round robin testing of AMN demonstrate much greater variability between the four laboratories (Figure 4B). The coefficient of variation for AMN, measured across the four laboratories in the round robin testing programme, ranged from 3 to 58% (mean = 17%), which was considerably wider than the range for HWEON (4-29%, mean = 13%). If the results from Eurofins are excluded, the coefficient of variation for HWEON is much lower (3–23%, mean = 8%)

As discussed in Section 2.3, estimates of the N mineralised under field conditions were obtained by two methods. The predicted N mineralisation was obtained by adjusting the average daily rate of PMN for variation in the daily mean soil temperature and water content over the growing season of each crop (Equation 1). The temperature and soil water content data used to complete these calculations are given in the Appendix (Figures A1–A4). The sum of the predicted N mineralisation for the two sample depths (0–15 and 15–30 cm) was taken as the predicted N mineralisation for the 0–30 cm soil. These predicted N mineralisation values for the 2020/21 trial sites were compared with mineralisation values calculated from the total crop N uptake data, with adjustments for changes in soil mineral N during the growing season (Equation 2).

Overall, the predicted and measured in-field N mineralisation values followed a similar trend, with values for both approaches being low at the Bombay (broccoli) trial site, moderate at the Lincoln (pak choi) trial site, high at the Southbridge (wheat) trial site and very high at the Leeston (wheat) trial site. Nevertheless, the predicted in-field N mineralisation values were consistently higher than the measured values obtained from the N balance calculations for the N0 treatments at each trial site (Table 5, see detailed results in Section 3.2). On average, the predicted in-field N mineralisation at three of the four trials (i.e. Southbridge, Lincoln and Bombay) was about 30% higher than the measured values; however, the N mineralisation predicted from PMN at the Leeston trial site was about 60% higher than the N mineralisation measured from the crop/soil N balance data.

The measured versus predicted in-field N mineralisation data obtained from 11 field validation trials conducted over last 3 years (between 2018/19 and 2020/21) are plotted in Figure 5. Excluding the results from the Leeston (wheat) trial, these data indicate that our predictions of in-field N mineralisation from the PMN test values are very closely related (R^2 = 0.96) to the in-field N mineralisation measured from the N0 treatments at each trial site. However, our results also indicate that the predicted in-field N mineralisation is consistently about 25% higher than the values measured (estimated), based on the N balance calculations of the field trial data.

The difference between these two methods may be due to overestimation of the predicted N mineralisation or underestimation of the measured N mineralisation. The soil water function that is used to predict the in-field N mineralisation from a PMN test is the most likely factor affecting an overestimation of the predicted N mineralisation. Additional laboratory experiments are underway to evaluate and modify (if necessary) the soil water content function used in our predictions.

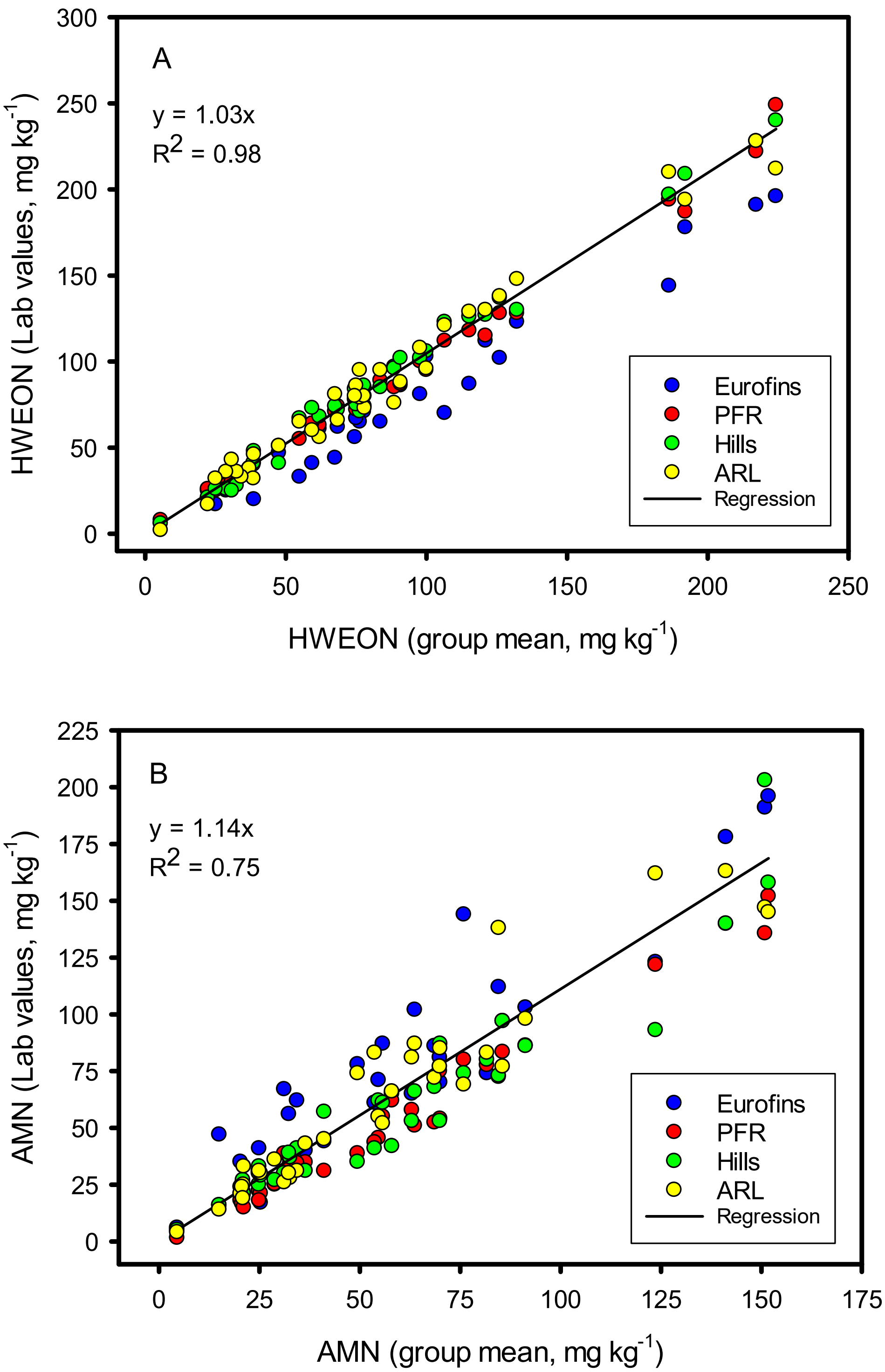

Figure 4. Result of the round robin analyses comparing the individual laboratory results for A) hot water extractable organic nitrogen (HWEON) and B) anaerobically mineralisable N (AMN) to those of the group means for each analyses completed as of November 2021. The regression analyses exclude the results from Eurofins.

Alternatively, the simple N balance approach for measuring N mineralisation may be underestimating the in-field N mineralisation by excluding any losses of N that may occur over the growing season. Our N balance approach assumes that any loss of N during the spring/summer growing seasons are very low, primarily because soil water content rarely exceeds field capacity and therefore the risk of N leaching losses is low. However, in some cases significant quantities of mineral N reside deep in the soil profile at the start of the growing season and may be transported below the depth of final mineral N sampling during the growing season. Gaseous losses of N (especially N_2 and N_2O) could also account for some underestimation of the in-field N mineralisation using our simple N balance approach.

The reasons for the large discrepancy between the predicted and measured in-field N mineralisation at the Leeston (wheat) trial site are not known. They may be due to errors introduced by high spatial variability in deep mineral N (across replicated plots) or errors in the measurements of soil temperature and moisture at this trial site. Alternatively, they may be the result of greater N immobilisation by the soil microbial biomass due to the return of C-rich crop residues at the soil surface in this continuous no-tillage management system. We are conducting a field validation trial on another long-term no-tillage farm in year 3 (2021/22) to see if we find similarly large discrepancies between predicted and measured in-field N mineralisation under no-tillage management at that site.

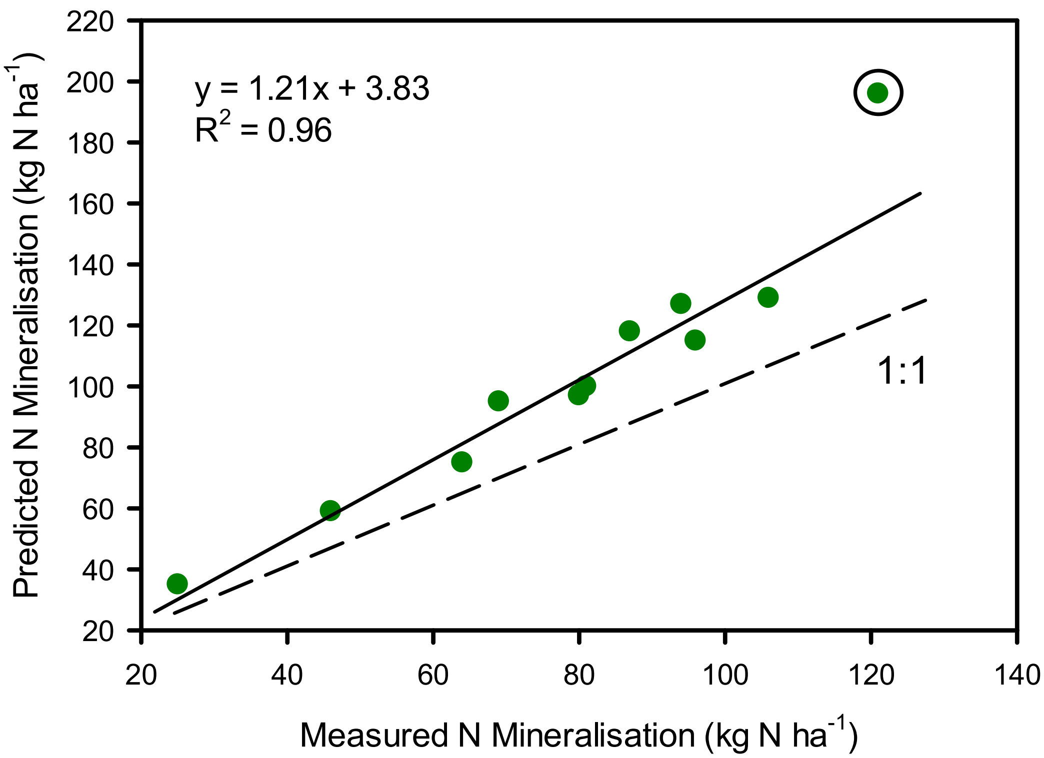

Figure 5. The relationship between measured (from nitrogen (N) balance calculations) and predicted (from potentially mineralisable nitrogen (PMN) test values) in-field N mineralisation derived from result of eleven different field trials conducted over 3 years (between 2018/19 and 2020/21). The solid line is the fitted linear regression (excluding the circled value) and the dashed line shows the 1:1 relationships.

3.2 Crop yield, N balance and N use efficiency

The following sections summarise the crop yield, N balance and N use efficiency results from the four fertiliser treatments at each of the four trial sites.

3.2.1 Wheat (Southbridge)

In the absence of fertiliser additions (N0 treatment), the wheat crop at this trial site yielded nearly 8.1 t ha^{-1} of grain (at 14% moisture) and the total N uptake by the crop (above-ground and roots) was about 50 kg N ha^{-1} less than the N supplied by the initial soil mineral N (dotted line) plus the predicted N mineralisation (dashed line) (Figure 6A). Whereas the crop's grain yield increased markedly between the zero and the middle rate of fertiliser N (N2, 98 kg N ha^{-1}); there was a smaller, but significant (p>0.05) increase (1 t ha^{-1}) in grain yield between the 98 and 147 kg ha^{-1} rates of fertiliser N to reach a high of 13.2 t ha^{-1}.

Despite the smaller increase in grain yield at the highest rate of fertiliser N, N uptake by the crop increased linearly (p<0.001) with increases in fertiliser N applied. The total crop N uptake (287 kg ha^{-1}) at the highest fertiliser N rate accounted for about 87% of the total N supplied (329 kg ha^{-1}) from the initial mineral N (54 kg ha^{-1}), the predicted N mineralisation (127 kg ha^{-1}) and the N fertiliser applied. The total amount of residual mineral N remaining in the soil at harvest was relatively small (Mean = 17 kg N ha^{-1}) and did not differ significantly between treatments (p=0.578; Figure 6B). Because the amount of residual mineral N was low and most of it was recovered in the top 30 cm of the soil, the risk of post-harvest N leaching losses was also very low.

The high N uptake by the crop and the low residual mineral N at harvest was reflected in a very high fertiliser N use efficiency (mean = 1.08) and a high total N use efficiency (Table 6). The latter actually increased gradually from 0.72 (kg N uptake per kg N supplied) in the N0 treatment to 0.88 at the highest fertiliser N rate, which indicates that total N use efficiency improved somewhat with the addition of fertiliser N within the range of the applied fertiliser rates.

The difference between grain yield and N uptake in the response to fertiliser N can be attributed both to a gradual increase in plant component dry matter (grain, straw and roots) and an increase in N concentration in each component. Grain accounted for largest proportion of the total N uptake (70-76%) and the N concentration in grain increased from 1.32% in the N0 treatment to 1.93% at the highest N fertiliser rate (N3,147 kg N ha^{-1}). The average grain yield per unit of N supplied (i.e. initial mineral N + mineralisable N + fertiliser N) decreased slightly from 46 kg grain kg N^{-1} ha^{-1} at the lowest fertiliser rate to 40 kg grain kg N^{-1} ha^{-1} at the highest rate.

Overall, the results of our N balance calculations indicate that mineralisable N made an important contribution to the total N uptake of the crop and to achieving the maximum grain yield (13.2 t ha^{-1}) at the highest N fertiliser rate, with no increased risk of N leaching losses after harvest. The high (N3) rate of fertiliser applied in this trial closely matched the total amount of N fertiliser applied by the grower at this site. It is interesting to note that the industry recommended rate of N fertiliser for this soil (with initial mineral N of 54 kg N ha^{-1}) and a target grain yield of 13 t ha^{-1} is 270 kg N ha^{-1}, which is about 120 kg N ha^{-1} greater than was applied to this crop. This demonstrates the value of including predictions of mineralisable N when forecasting crop fertiliser N requirements.

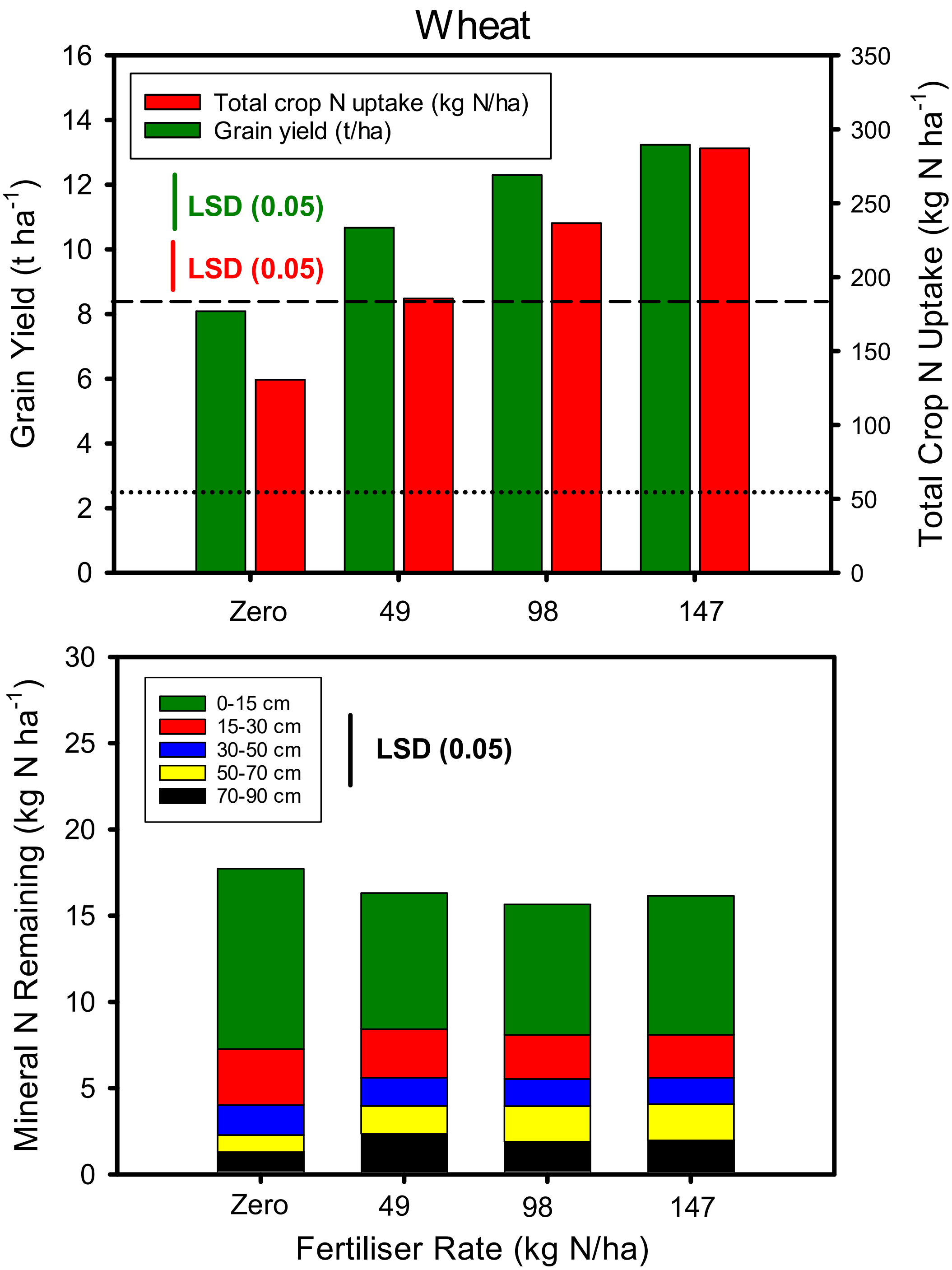

Figure 6. Effects of the fertiliser treatments on A) the total grain yield and total crop nitrogen (N) uptake and B) the vertical distribution and total soil mineral N remaining at harvest of the wheat crop at Southbridge in January 2021. The dotted line is the initial soil mineral N content (kg N ha^{-1}) and the dashed line is mineral N plus the predicted in-field N mineralisation (kg N ha^{-1}) plotted on the right hand y-axis.

Table 6. Indicators of nitrogen (N) use efficiency calculated for the four fertiliser rates applied to each of the four test crops in 2020/21.

Crop (Location)	Fertiliser N rate (kg N/ha)	Fertiliser N Use Efficiency [1] (kg N/kg N)	Total N Use Efficiency [2] (kg N/kg N)	Crop Yield N Response [3] (Yield/kg N)
Wheat (Southbridge)	0	-	0.72 (0.02)	45 0.8)
	49	1.12	0.81 (0.04)	46 (2.1)
	98	1.08	0.85 (0.04)	44 (0.8)
	147	1.07	0.88 (0.04)	40 (1.6)
	LSD (0.05)[4]		0.08**	2.0**
Wheat (Leeston)	0	-	0.49 (0.07)	23 (3.5)
	84	0.91	0.61 (0.03)	27 (0.4)
	168	0.87	0.66 (0.06)	26 (1.7)
	252	0.88	0.70 (0.03)	23 (0.6)
	LSD (0.05)		0.06***	3.3^{ns}
Broccoli (Bombay)	0	-	0.70 (0.03)	179 (9)
	65	0.60	0.68 (0.03)	172(19)
	131	0.28	0.53 (0.02)	122 (18)
	196	0.20	0.44 (0.02)	104 (11)
	LSD (0.05)		0.03***	15***
Pak Choi (Lincoln)	0	-	0.53 (0.08)	236 (41)
	30	0.43	0.51 (0.02)	190 (22)
	60	0.57	0.54 (0.05)	187 (14)
	140	0.41	0.47 (0.06)	131 (24)
	LSD (0.05)		0.12^{ns}	55**

[1] Fertiliser N Use Efficiency = (Crop N uptake $_{fert}$ – Crop N uptake $_{zero}$)/fertiliser N rate.
[2] Total N Use Efficiency = Crop N uptake/Total N supplied (i.e. initial mineral N + mineralisable N + fertiliser N). Values are mean (± SD).
[3] Crop Yield N Response = Crop yield/total N supplied (i.e. initial mineral N + mineralisable N + fertiliser N); Crop yield was expressed as follows for each crop: wheat (kg grain ha^{-1}); broccoli (marketable head count ha^{-1}); pak choi (kg marketable fresh weight ha^{-1}). Values are mean (± SD).
[4] Linear probability; * <0.05, **<0.01, *** <0.001, ns = not significant.

3.2.2 Wheat (Leeston)

The average grain yield (5.1 t ha^{-1} at 14% moisture) and total N uptake (108 kg N ha^{-1}) of the wheat crop in the N0 treatment at the Leeston trial site were both considerably lower than the N0 treatment at Southbridge (Figure 7A). This was surprising given the high N mineralisation (196 kg N ha^{-1}) predicted for this site. The total N uptake by the N0 crop (grain, straw, crowns and roots) was about 110 kg N ha^{-1} less than the N supplied by the initial soil mineral N (dotted line, 22 kg N ha^{-1}) plus the predicted N mineralisation (dashed line) (Figure 7A). Whereas, the crop's grain yield increased markedly between the zero and N2 rate of fertiliser N (168 kg N ha^{-1}), there was a smaller, but significant (p<0.05) increase (0.9 t ha^{-1}) in grain yield between the N2 and N3 rates of fertiliser N (168 vs 252 kg ha^{-1}) to reach a high of 10.7 t ha^{-1}.

In contrast to the yield, N uptake by the crop increased linearly (p<0.001) with increases in fertiliser N applied. The total crop N uptake (332 kg ha^{-1}) at the highest fertiliser N rate (N3) accounted for about 70% of the total N supplied (470 kg ha^{-1}) from the initial mineral N, the predicted N mineralisation and the N fertiliser applied. The total amount of mineral N remaining in the soil at harvest was somewhat higher than following the wheat crop at Southbridge and increased from 36 kg N ha^{-1} in the N0 and N1 treatments to 66 kg N ha^{-1} in the N3 treatment (Figure 7B). Because the soil at this site was relatively deep and had finer texture, the risk of postharvest N leaching was probably relatively low. However, a much higher percentage (41%) of the residual mineral N (28 kg N ha^{-1}) was recovered in 30–90 cm layer of the N3 (252 kg ha^{-1}) treatment than in the lower N treatments.

Although the fertiliser N use efficiency (mean = 0.89) of the crop was relatively high, on average the total N use efficiency was much lower than at Southbridge (Table 6) owing to the high N mineralisation (196 kg N ha^{-1}) predicted at this site. As at Southbridge, the total N use efficiency increased gradually, from 0.49 kg N uptake per kg N supplied in the N0 treatment to 0.70 at the highest fertiliser N rate, indicating that total N use efficiency improved with the addition of fertiliser N.

The differences in grain yield and N uptake in response to fertiliser N can be attributed both to a gradual increase in plant component dry matter (e.g. grain, straw, roots) and an increase in N concentration in each component. Grain accounted for the largest proportion of the total N uptake (65-68%) and the N concentration in grain increased from 1.69% in the N0 treatment to 2.34% at the highest N fertiliser rate (N3). The average grain yield per unit of N supplied (i.e. initial mineral N + mineralised N + fertiliser N) was much lower than at Southbridge and decreased slightly from 27 kg grain kg N^{-1} ha^{-1} at the lowest fertiliser rate (N1) to 23 at the highest N rate (N3). The lower yield and N uptake at this site compared to the Southbridge site, at comparable rates of fertiliser N, may be due to cultivar differences or the wider row spacing used at this site.

Overall, the results of our N balance calculations indicate that N mineralisation made a significant contribution to the total N uptake of the crop, although only about 50% of the total N supplied from the initial mineral N and mineralised N was taken up by the N0 wheat crop. The reasons for this relatively low apparent recovery of N are not known, but may be due to overestimation of mineralised N at this site or unaccounted for losses of N. The medium rate of N fertiliser (N2) applied in this trial matched the grower applied rate at this site. In this case, the industry recommended rate of N fertiliser for this soil (with initial mineral N of 22 kg N ha^{-1}) and a target grain yield of 10.7 t ha^{-1} is 245 kg N ha^{-1}, which is about 78 kg N ha^{-1} greater than was applied to this crop. Although some additional grain yield (0.9 t ha^{-1}) was achieved at a rate that more closely matched the industry recommended rate, this also resulted in much more residual mineral N (66 kg N ha^{-1}) in the soil profile at harvest.

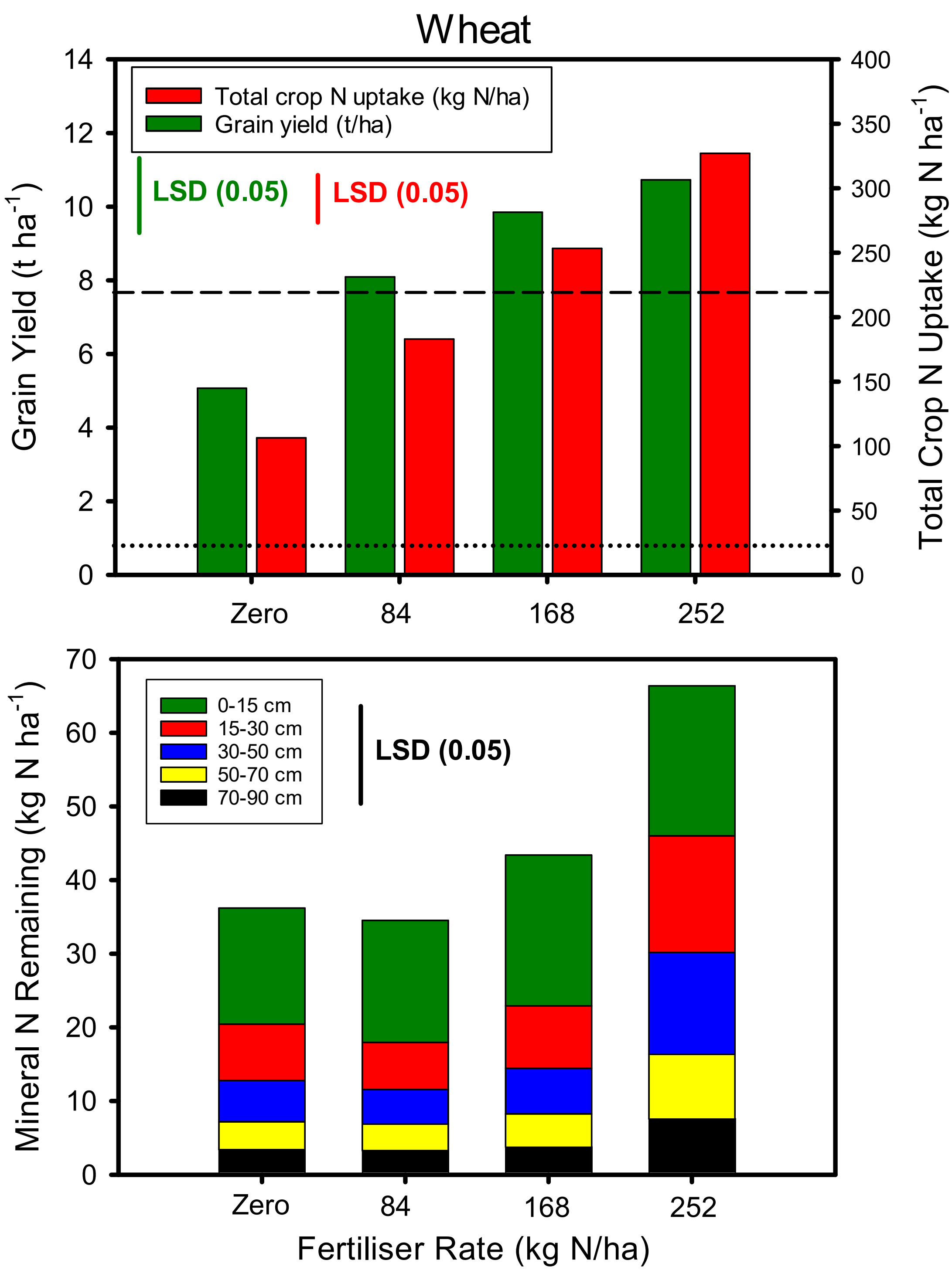

Figure 7. Effects of the fertiliser treatments on A) the total grain yield and total crop nitrogen (N) uptake and B) the vertical distribution of soil mineral N remaining at harvest of the wheat crop at Leeston In January 2021. The dotted line is the initial soil mineral N (kg N ha^{-1}) and the dashed line is mineral N plus the predicted in-field N mineralisation (kg N ha^{-1}) plotted on the right hand y-axis.

3.2.3 Broccoli (Bombay)

Compared to the N0 treatment, the addition of fertiliser N at this site increased the yield of marketable heads by about 22% to an average of 40,200 heads ha^{-1} (p<0.05; Figure 8A). However, there were no significant differences in the number of marketable heads harvested from the three N fertiliser treatments (N1 to N3). Furthermore, there were no differences in the total N recovered in marketable heads (78 kg N ha^{-1}) or non-marketable crop residues (81 kg N ha^{-1}). Although N fertiliser addition increased the total N uptake in the crop (mean = 167 kg N ha^{-1}) compared to the N0 treatment (129 kg N ha^{-1}) where no fertiliser N was applied, there were no significant differences in the total N uptake across the three fertiliser N treatments.

Although the predicted N mineralisation at this site was very low (35 kg N ha^{-1}), probably due to a history of continuous intensive cropping, the initial mineral N (at planting) was relatively high (148 kg N ha^{-1}). This high initial mineral N was undoubtedly due to a carryover of residual N from previous crops. The total crop N uptake in the N0 treatment (129 kg N ha^{-1}) accounted for ≈ 70% of the total N supplied from soil (i.e. initial mineral N plus N mineralisation), which averaged 183 kg N ha^{-1} (Figure 8A). Although the N supplied by the soil over the growing season was more than sufficient to meet the N demand of the highest yielding crop, a low rate of fertiliser N was required to achieve the yield potential. This is probably because much of the initial mineral N was located deeper in the soil profile (e.g. 110 kg N ha^{-1} was below 50 cm depth) where it was largely inaccessible to the growing crop.

The reasonably strong crop response to N fertiliser at the lowest N rate (N1, 65 kg N ha^{-1}) was reflected in a medium value for fertiliser N use efficiency (0.60 kg N kg^{-1} N applied) at that rate. However, as there was no difference in total crop N uptake at higher fertiliser N rates, the fertiliser N use efficiency was much lower in the N2 (0.28 kg N kg^{-1} N applied) and N3 (0.20 kg N kg^{-1} N applied) treatments. The yield and total N uptake of the crop per unit of total N supplied were similar in the N0 and N1 treatments, however both measures indicated a significant decline in total N use efficiency at higher rates of fertiliser N (p<0.001), which is consistent with the decline in fertiliser N use efficiency.

Although the broccoli crop in the N0 treatment removed 70% of the N supplied from the soil, about 44 kg N ha^{-1} remained in the soil profile as mineral N at harvest and a further 25 kg N ha^{-1} was unaccounted for. As there was no difference in the crop N uptake across the three fertiliser rates, both the amount of residual mineral N remaining at harvest and the unaccounted for N increased with increasing rates of fertiliser N applied (p<0.003; Figure 8B). The residual mineral N increased significantly (p<0.001) from about 44 kg N ha^{-1} in the N0 fertiliser treatment up to 73 kg N ha^{-1} at the highest fertiliser N rate (N3, 196 kg N ha^{-1}). On average, about 40% of the residual mineral N was recovered in the soil between 50 and 90 cm depth, suggesting an increased risk of N leaching after harvest. The unaccounted for N gradually increased from 10 kg N ha^{-1} in N0 to 139 kg N ha^{-1} at the highest fertiliser N rate (N3 treatment). The unaccounted for N was most likely lost through leaching or gaseous emissions. The former is consistent with the high amount of mineral N that was located below 50 cm in the soil profile at the start of the growing season and the vertical distribution of mineral N at harvest. These losses may have been associated with two high rainfall events that occurred early in the crop growing season (November and December) (see Appendix, Figure A3).

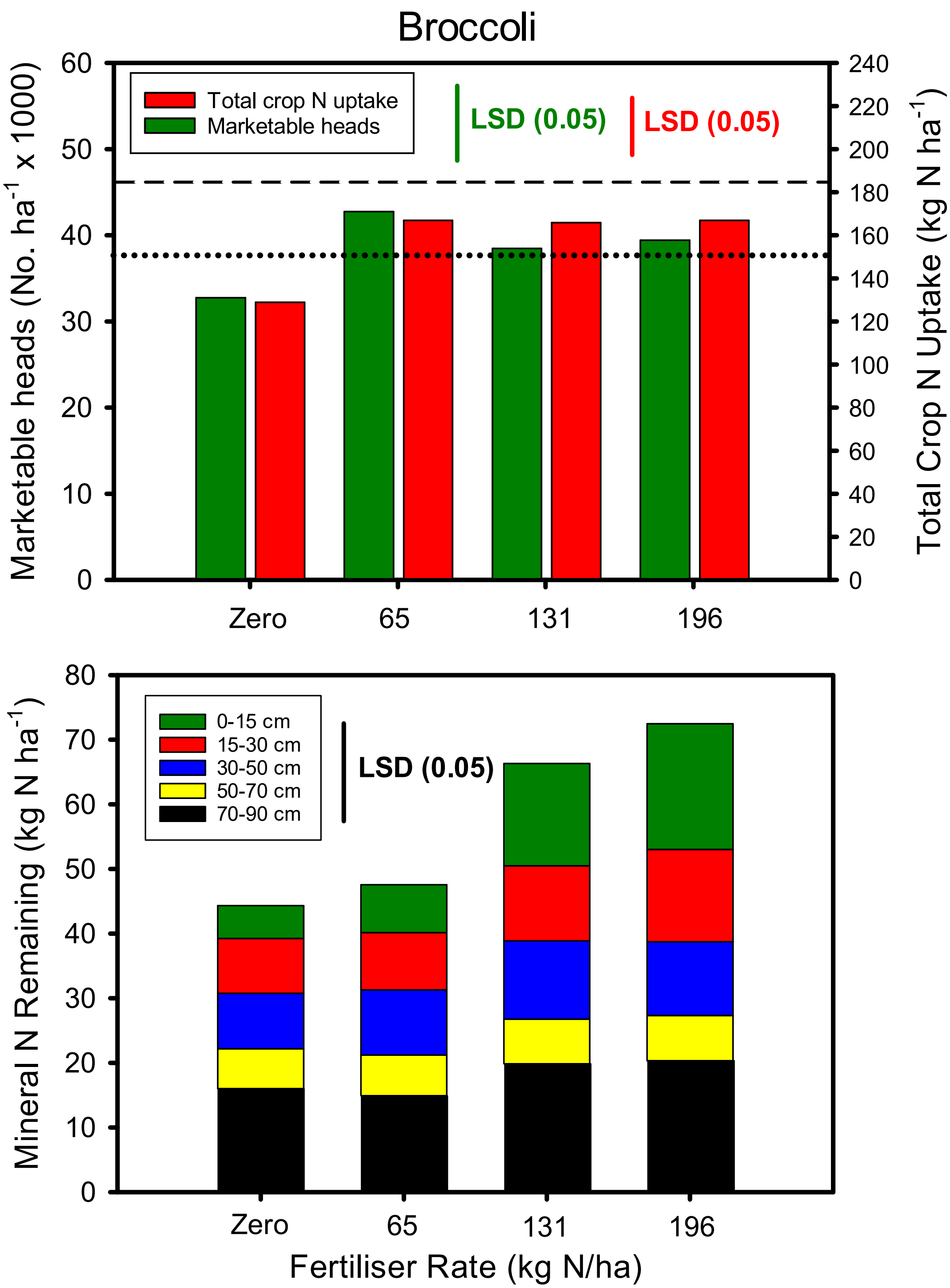

Figure 8. Effects of the fertiliser treatments on A) the yield of marketable heads and total crop nitrogen (N) uptake and B) the vertical distribution of soil mineral N remaining at harvest of the broccoli crop at Bombay in February 2021. The dotted line is the initial soil mineral N (kg N ha^{-1}) and the dashed line is the mineral N plus predicted in-field N mineralisation (kg N ha^{-1}) plotted on the right hand y-axis.

3.2.4 Pak choi (Lincoln)

The pak choi N mineralisation validation trial at Lincoln was carried out in collaboration with the Sustainable Vegetable Systems (SVS) project. There was no statistically significant difference (p=0.642) in the marketable fresh yield of the pak choi crop (mean = 36 t ha^{-1}) in response to the fertiliser N treatments (Figure 9A). However, there was a difference (p=0.002) in the total N uptake of the crop (i.e. marketable + non-marketable residues + root N), which increased steadily from about 77 kg N ha^{-1} in the N0 treatment, where no fertiliser N was applied, to 134 kg N ha^{-1} in the N3 treatment, where 140 kg fertiliser N ha^{-1} was applied over the growing season. The difference in the marketable fresh yield and N uptake response to fertiliser N can be attributed to luxury N uptake, similar to that observed in other brassica crops (Fletcher and Chakwizira, 2012). Luxury uptake was also reflected in the marketable crop N concentration, which increased (p<0.001) from 2.55% in the N0 treatment to 3.13%, 3.35% and 4.64% in the 30, 60 and 140 kg N ha^{-1} fertiliser treatments, respectively.

The mineral N at the start of the growing season averaged 88 kg N ha^{-1}, but varied considerably across the trial site from 60 to 126 kg N ha^{-1}, in part due to variable quantities of mineral N deeper in the soil profile. For the purposes of this project, we assumed the average of 88 kg N ha^{-1} was a good reflection of the initial mineral N available to the crop at planting. The predicted N mineralisation for this crop was relatively high (59 kg N ha^{-1}), given the short duration of this crop (44 days). In absolute terms, the N supplied by the soil (initial mineral N + mineralised N; 147 kg N ha^{-1}) was more than sufficient to meet the demand of even the highest yielding crop treatment. However, in contrast to other crops, the total N uptake by the pak choi crop in the N0 treatment accounted for a relatively small proportion (52%) of the soil N supplied (Figure 9A).

As with crop N uptake, the amount of residual mineral N remaining at harvest increased with the amount of fertiliser N applied (p=0.008). Residual mineral N in the soil profile (to a depth of 150 cm in this case) was about 53 kg N ha^{-1} where no (zero) N fertiliser was applied, increasing up to 148 kg N ha^{-1} at the highest fertiliser N rate (N3) (Figure 9B). Most of the difference in residual mineral N between N fertiliser treatments was associated with the top 30 cm of soil. Although plot-to-plot variability in the mineral N measurements was very high, our N balance calculations indicate that, on average, only about 15 kg N ha^{-1} was unaccounted for at harvest in addition to the quantities of mineral N remaining in the soil profile at harvest. Although very small, this unaccounted for N may be attributed to some leaching of mineral N deeper in the soil profile or perhaps overestimation of the N mineralisation.

Overall, the fertiliser N use efficiency of this pak choi crop (mean = 0.47 kg N kg N^{-1} applied) was low compared to the two wheat crops and the N1 treatment of the Broccoli crop (Table 6). There was no clear trend in fertiliser N use efficiency relative to the N fertiliser rates applied. The average total N use efficiency of the pak choi crop (0.51 kg N kg N^{-1} supplied) was also lower than the Leeston wheat (0.61 kg N kg N^{-1} supplied) and Bombay broccoli (0.59 kg N kg N^{-1} supplied) crops and considerably lower than the Southbridge wheat crop (0.81 kg N kg N^{-1} supplied). There was no significant difference between the N fertiliser treatments (p=0.634) in total N use efficiency owing to a large increase in N concentration in the marketable crop with increasing fertiliser rate that may be attributed to luxury consumption of N. As noted previously, there was no significant difference in the market fresh yield of the pak choi crop across the four N fertiliser treatments, which meant that the market fresh weight (MFW) per unit of N supplied declined markedly with increasing N fertiliser additions, from 236 kg MFW kg N^{-1} supplied in the N0 treatment to a low of 131 kg MFW kg N^{-1} supplied in the N3 fertiliser treatment.

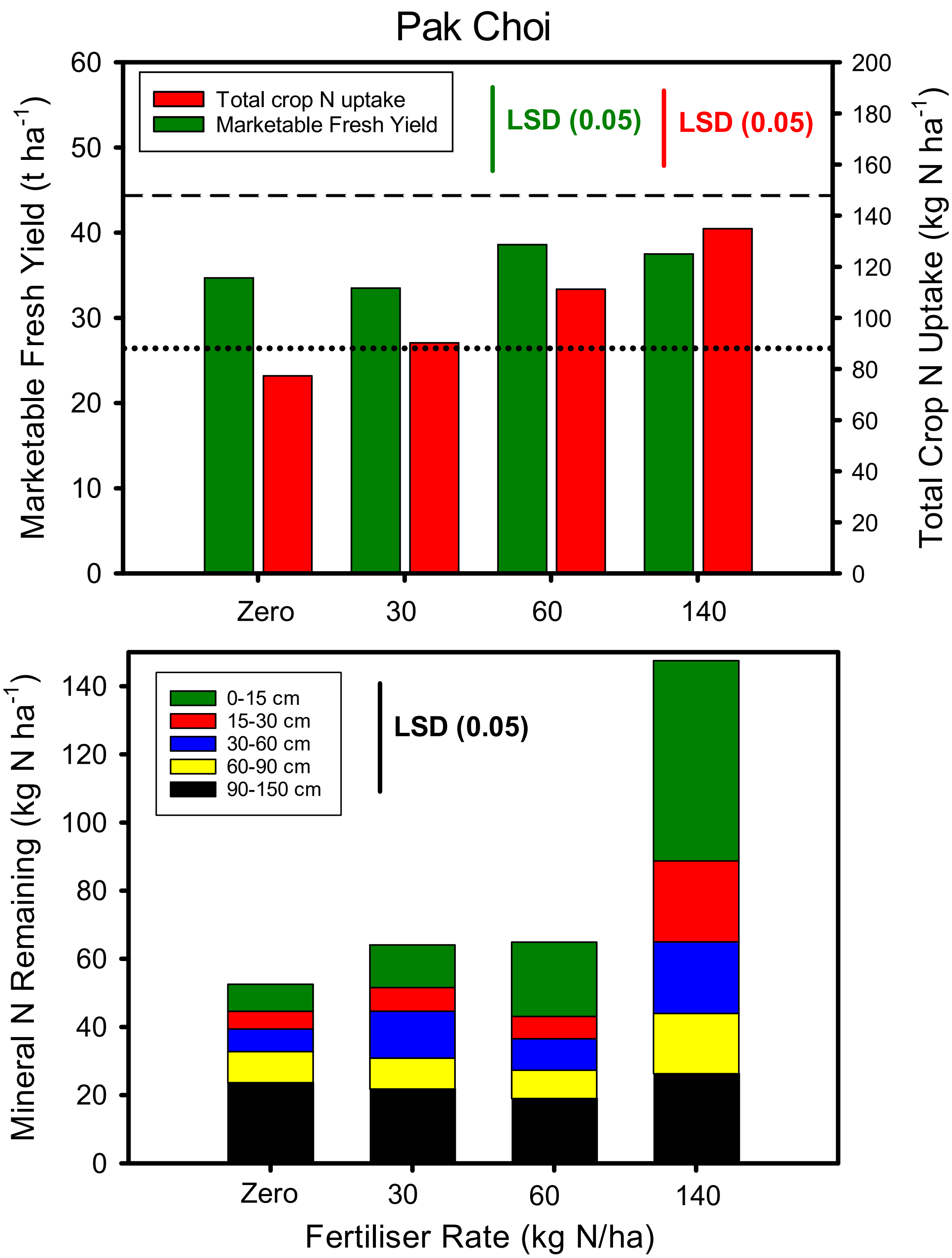

Figure 9. Effects of the fertiliser treatments on A) the total market fresh yield and total crop nitrogen (N) uptake and B) the vertical distribution and total soil mineral N remaining at harvest of the Lincoln pak choi crop in January 2021. The dotted line is the initial soil mineral N content (kg N ha^{-1}) and the dashed line is mineral N plus predicted in-field N mineralisation (kg N ha^{-1}) plotted on the right hand y-axis.

4 Conclusions

Results from the year 2 field validation trials provide further evidence that both mineral N and mineralisable N can be important sources of N for crop uptake. The amount of PMN measured at the four trial sites was consistent with the average quantities of PMN reported by Curtin et al. (2017) for the surface (0–15 cm) of arable and vegetable cropping soils across New Zealand. The results also showed that significant quantities of PMN can occur in the 15–30 cm layer of cultivated (cropping) soils and therefore this represents an important source of mineralisable N that may affect the supply of plant available N over the crop growing season. As reported previously (Curtin et al. 2017), both HWEON and HWEC were found to be good indicators of PMN. Initial comparative analyses by the participating commercial laboratories and Plant and Food Research indicated that HWEON analysis can be completed with a relatively high degree of precision, which is greater than that typically found for AMN. Some exception were noted from the more recent results from Eurofins.

In contrast to the results from 2019/20, there was very poor correspondence between mineral N in the top soil (0–30 cm) and the mineral N measured over the entire soil profile (0–90 cm) across the four trials undertaken in 2020/21. Overall, the mineral N measured in the top 30 cm accounted for between 10 and 87% of the mineral N measured in the top 90 cm. This result raises questions about the adequacy of relying on shallow mineral N testing (0–30 cm) to estimate the stock of plant available N at the start of the growing season. Further work is needed to determine how much of the mineral N that exists below 30 cm at the start of the growing season contributes to the N uptake of different crops during their growth. Shallow (0–30 cm) soil mineral N testing would provide a simpler, more practical method that could encourage more growers to routinely measure mineral N for improved fertiliser decision making. Further work is also need to ensure that these methods adequately account for the spatial variability in mineral N at a management unit (e.g. paddock) scale.

Measurements of mineral N and mineralisable N provided valuable information for interpreting the response of the four crops to fertiliser N additions; however, the interpretation differed somewhat between crops depending on their growth characteristics and N demand. Overall, the predicted and measured in-field N mineralisation values followed a similar trend, with values for both approaches being low at the Bombay (broccoli) trial site, moderate at the Lincoln (pak choi) trial site, high at the Southbridge (wheat) trial site and very high at the Leeston (wheat) trial site. However, the predicted in-field N mineralisation values were consistently higher than the measured values obtained from the N balance calculations for the N0 treatments at each trial site.

Overall, the results from the field validation trials (11 in total) conducted over the last 3 years indicate that our predictions of in-field N mineralisation from the PMN test values are very closely related (R^2 = 0.96) to the in-field N mineralisation measured from the N0 treatments at each trial site (excludes results from the Leeston [wheat] trial in 2020/21). However, they also highlight that the predicted in-field N mineralisation is consistently about 25% higher than the values measured (estimated) from the N balance calculations of the field trial data. The difference between these two methods may be due to overestimation of the predicted N mineralisation (perhaps due to the soil moisture function used) or to underestimation of the measured N mineralisation (due to losses of N that were not accounted for). Although further analysis of existing data may help to resolve this discrepancy, additional research may be needed to ensure the method applied to improve fertiliser N forecasting has an acceptable level of uncertainty. Nevertheless, it is clear that mineralisable N can be a very important source of the N supplied to crops and a PMN test coupled with information on soil temperature and water content can be used to predict the supply of N from mineralisation over a growing season.

Although the calculated fertiliser N use efficiency of the two wheat crops evaluated in 2020/21 was very high, the total N use efficiency of these crops was much lower when we accounted for all of the N supplied by the soil. The industry recommended rate of N fertiliser for these two crops was 78 and 120 kg N ha^{-1} higher than that applied to achieve maximum grain yield (13 and 11 t ha^{-1}, respectively). The fertiliser N use efficiency of the broccoli and pak choi crops was considerably lower than that of the wheat crops, as was their total N use efficiency. There was a tendency for both efficiency metrics to decline with increases in N fertiliser rate. Although the broccoli crop yield did respond to a low rate of N fertiliser, there was no significant effect of N fertiliser on the yield of the pak choi crop. Furthermore, the yield of both crops did not significantly increase with increasing rates of N fertiliser. In both of these cases, the N supplied by the soil (i.e. the initial mineral N and the N mineralised over the growing season) provided most of the N needed to meet crop requirements.

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Appendix

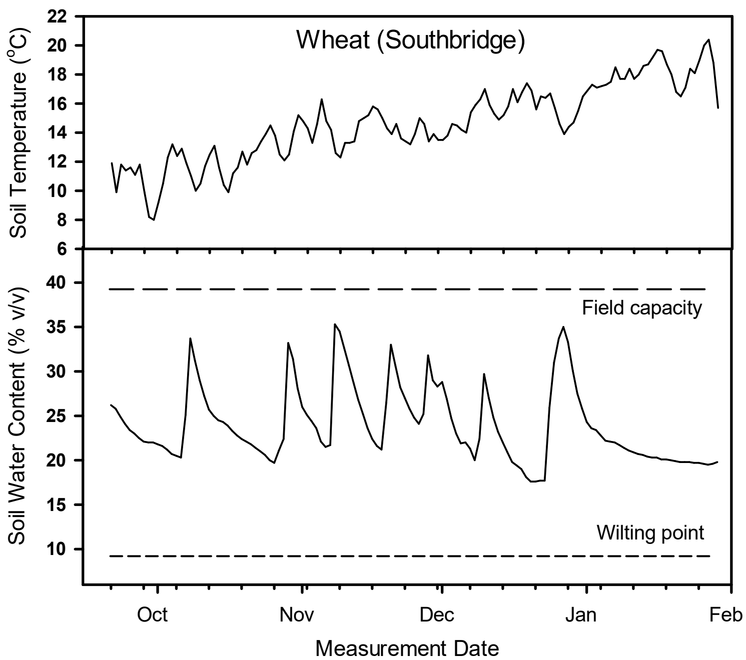

Figure A1. Soil temperature and volumetric water content at the wheat trial site (Southbridge), 2020/21.

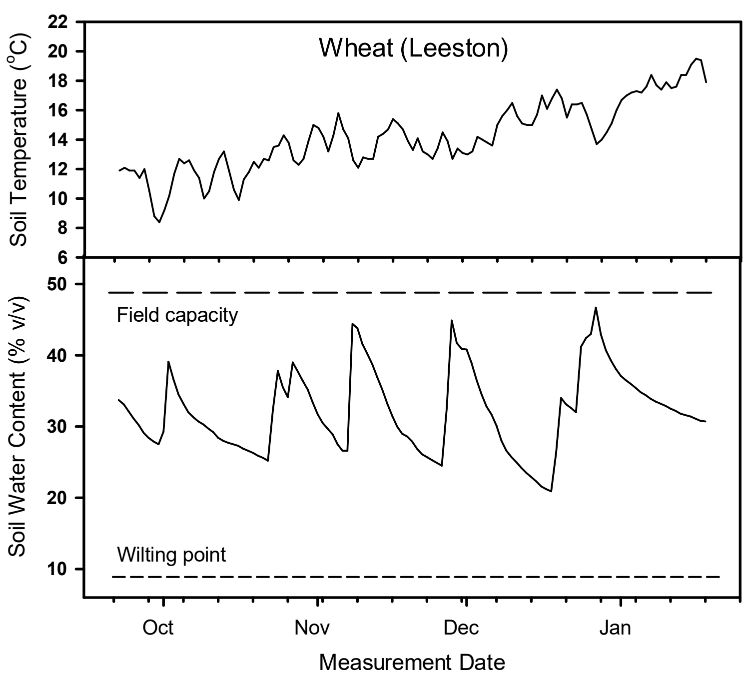

Figure A2. Soil temperature and volumetric water content at the wheat trial site (Leeston), 2020/21.

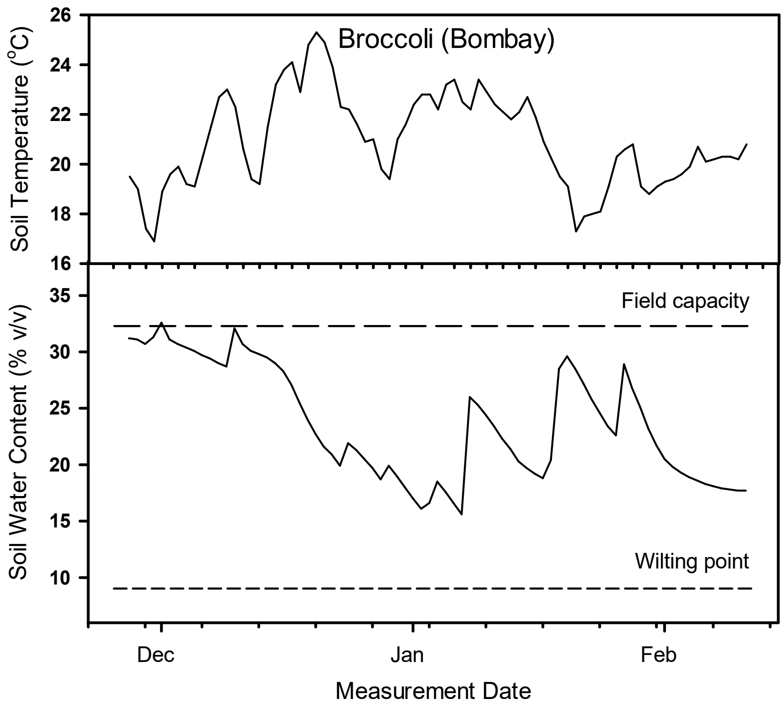

Figure A3. Soil temperature and volumetric water content at the broccoli trial site (Bombay), 2020/21.

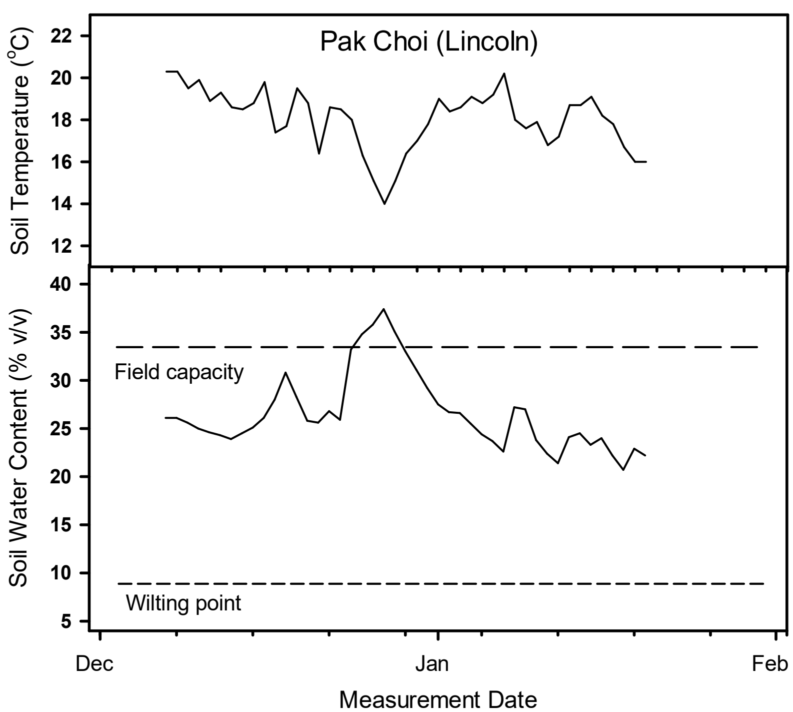

Figure A4. Soil temperature and volumetric water content at the pak choi trial site (Lincoln), 2020/21.

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