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PREDICTING IN-FIELD NITROGEN MINERALISATION TO IMPROVE NITROGEN FERTILISER MANAGEMENT OF ANNUAL CROPS

Beare M.H.[1*], Curtin D.[1], Tregurtha C.[1], Gillespie R.N.[1], Qiu W.[1]
Tregurtha R.[1], Arnold N.[2], Cummins M.[3]

New Zealand Institute for Plant and Food Research Limited,
[1] *Canterbury Agriculture and Science Centre, 74 Gerald Street, Lincoln 7608*
[2] *Hawke's Bay Science Centre, 30 Crosses Road, Havelock North 4130*
[3] *Ruakura Science Centre, Bisley Road, Hamilton 3214*
[*] Contact: Mike.Beare@plantandfood.co.nz

Abstract

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 demand. 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. This paper reports progress in developing and verifying a rapid, reliable test of potentially mineralisable N (PMN_{Test}) based on measurements of hot water extractable organic nitrogen (HWEON) and describes the variability in PMN as a function of soil order and land use history. We also describe a method for predicting the amount of N that will mineralised during a crop growing season based on a PMN_{Test} and site-specific soil temperature and water content data. Furthermore, we report results from two N fertiliser rate field trials (with kale and wheat crops), where this method was used to predict the supply of N from mineralisation of soil organic matter under field conditions and the predictions compared to estimates of N mineralisation derived from N balance calculations. These case studies are presented as examples of the significant contribution that N mineralisation can make to the supply of N for crop uptake and to forecasting crop responses to fertiliser N applications.

Introduction

Improved fertiliser management is critical to lifting the economic and environmental sustainability of agricultural production systems. Forecasting fertiliser nitrogen (N) requirements depends on predicting the supply of plant-available N from soil and the demand for that N by crops during their growth. The N released by mineralisation can contribute a large amount of plant-available N (30 – 300 kg N/ha/year) that varies depending on soil type, land use history, and environmental conditions. Accurately predicting the supply of N from mineralisation remains a key limitation to properly forecasting the amount and timing of fertiliser N additions to meet, but not exceed, the requirements of annual crops.

Mineralisation is a microbial process that involves the gradual breakdown of soil organic matter to release mineral N. Predicting N mineralisation in the field requires a measurement of the soil's N mineralisation potential (i.e. the amount released under "optimal" conditions) as well as the ability to predict how environmental conditions (i.e., soil temperature and water content) affect the actual rate of N mineralisation under field conditions.

A soil's potentially mineralisable N (PMN) is best measured using a long-term aerobic incubation in the laboratory, but the procedure is laborious, time-consuming and not suited to routine soil testing. Recently, a simple, practical method to estimate PMN has been developed by Plant & Food Research. This new, rapid test for PMN (PMN_{Test}) was developed based on measurements from a wide range of New Zealand agricultural soils representing different management histories and is now offered by several commercial testing laboratories.

Recent research has focused on predicting how much of the PMN is actual mineralised under field conditions. This paper describes progress in the development of a method to predict in-field N mineralisation from a PMN_{Test} and site specific soil temperature and water content data during crop growth. This includes results from N fertiliser response trails of selected crops that provide evidence to verify the predictions of in-field N mineralisation.

Methods

Soil samples (0-15 cm and 15-30 cm depths) were collected from over 150 sites across New Zealand. These sites were selected to represent the dominant agricultural soil orders (i.e. Allophanic, Brown, Pallic, Gley and Recent) and a wide range of soil textures and soil organic carbon (SOC) contents under arable, vegetable, drystock [sheep/beef] and dairy land uses.

We have previously reported results from laboratory analyses completed on a large number of these soils (130), which found that hot water extractable organic N (HWEON) provides a rapid and reliable (reproducible) test for predicting potentially mineralisable nitrogen (PMN) (Curtin et al., 2017). Details of these methods are given below. Here we report results from a now somewhat large dataset of measurements that verify the relationship between HWEON and PMN and demonstrate how PMN differs between the major agricultural land uses and soil orders of New Zealand.

A series of field trials have also been carried out in Canterbury, Waikato and the Hawke's Bay over the last four years to developed and validate methods for predicting in-field N mineralisation from measurements of PMN and local soil temperature and water content data. The experimental treatments in each trial comprised four rates of fertiliser N, each replicated four times in a Latin square design. The N rates, which included a zero-N treatment (N0), differed depending on the N requirement of the crops (See Figures for N rates applied). 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 farmer/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 soil test values. The N 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. 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 and to broadly align with the host grower's rates. These and other details pertaining to trial management can be found in Beare et al (2020, 2022).

At trial initiation (prior to N fertiliser application) and crop harvest, composited soil samples were collected by depth (e.g. 0–15, 15–30, 30–50, 50–70, 70–90 cm) from each plot for soil N analysis. Field-moist soils were sieved (4 mm) and KCl extractable mineral N (NH_4-N + NO_3-N) determined following standard methods (QuickChem 8000 FIA+, Lachat, Loveland, CO).

Air-dried soil samples (0–15 and 15–30 cm depths) taken at trial initiation were used to determine HWEON and PMN at each trial site. 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) from total N. Potentially mineralisable N (PMN) was measured following the "gold standard" method (i.e. 14-week aerobic incubation at 25°C) as described by Curtin et al. (2017). Mineral N was extracted (using 2 M KCl) after 2, 4, 7, 10 and 14 weeks of incubation and analysed following standard methods. 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.

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), corrected for the initial (pre-incubation) NH_4-N concentration. Subsamples of soil from some of the trial sites and other archived soils were also analysed for HWEON and AMN by Plant & Food Research's soil and environment analytical laboratory and the participating commercial laboratories (i.e. Hill Laboratories Limited, Analytical Research Laboratories) to evaluate the reproducibility of the methods under the project's round robin testing programme.

Acclima True TDR-315L sensors were installed at each site to continuously record soil temperature and moisture. Soil samples (0–15, 15–30 cm) collected at each trial site were used to determine volumetric water content at field capacity (-10 kPa) and wilting point (-1500 kPa). To predict in-field mineralisation, the PMN values, expressed as a daily rate of N mineralisation (kg N/ha/d), were temperature- and moisture-adjusted using scaling factors:

$$\text{In-field N mineralisation} = \sum_{i=1}^{n} (\text{Average daily PMN} \times \text{Mt}_i \times \text{Mw}_i)$$

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 soil temperature (Mt) and water content (Mw) modifiers were derived from the data reported by Lloyd & Taylor (1994) and Paul et al. (2003), respectively.

All final crop and soil samples were taken at crop maturity, just prior to commercial harvesting. Quadrat samples were taken for crop yield determination and to measure non-marketable plant components (including crop residues, crowns and roots) from each plot at each trial site. A representative subsample was taken from each plant component in each plot to determine the dry weight and for analysis of N concentration (LECO C/N analyser).

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 total soil N supply was calculated as:

$$\text{Mineralised N} = \text{Total crop N uptake} + \text{soil mineral N (harvest)} - \text{soil mineral N (sowing)}$$

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 spring/summer growing season of these trials was negligible (loss of mineral N during the season would result in underestimation of mineralisation).

In this paper, we report results from two of these field trials, one for a kale forage crop grown at Lincoln in 2019/20 (cultivar 'Rivage', sown 25 Nov, harvested 11 May 2020, irrigated) and one for a wheat crop grown near Southbridge in 2020/21 (cultivar 'Discovery', sown 28 April, harvested 29 Jan 2021, irrigated). Additional details on these crops can be found in Beare et al (2020, 2022). These case studies are presented as examples of the contributions that N mineralisation can make to the supply of N for crop uptake and the response to fertiliser N applications.

Results and Discussion

Predicting PMN from HWEON

The results of soil analysis from a wide range of soil orders and agricultural land uses across New Zealand verify the close positive relationship between HWEON and PMN measured in the 14-week aerobic incubations, as previously reported by Curtin et al. (2017) and later recalibrated after correcting for incomplete recovery of organic N (Beare et al. 2022)(Figure 1). This relationship can be used to predict the amount of N that can be mineralised from a given soil, under optimal conditions of temperature (25°C) and water content (90% of field capacity) over a 14 week period. Given that mineralisation is measured over this fixed period of time (14 weeks), the pool of potentially mineralisable N (PMN) can be expressed as a rate and corrected for bulk density to a fixed depth, giving units of kg N/ha/day.

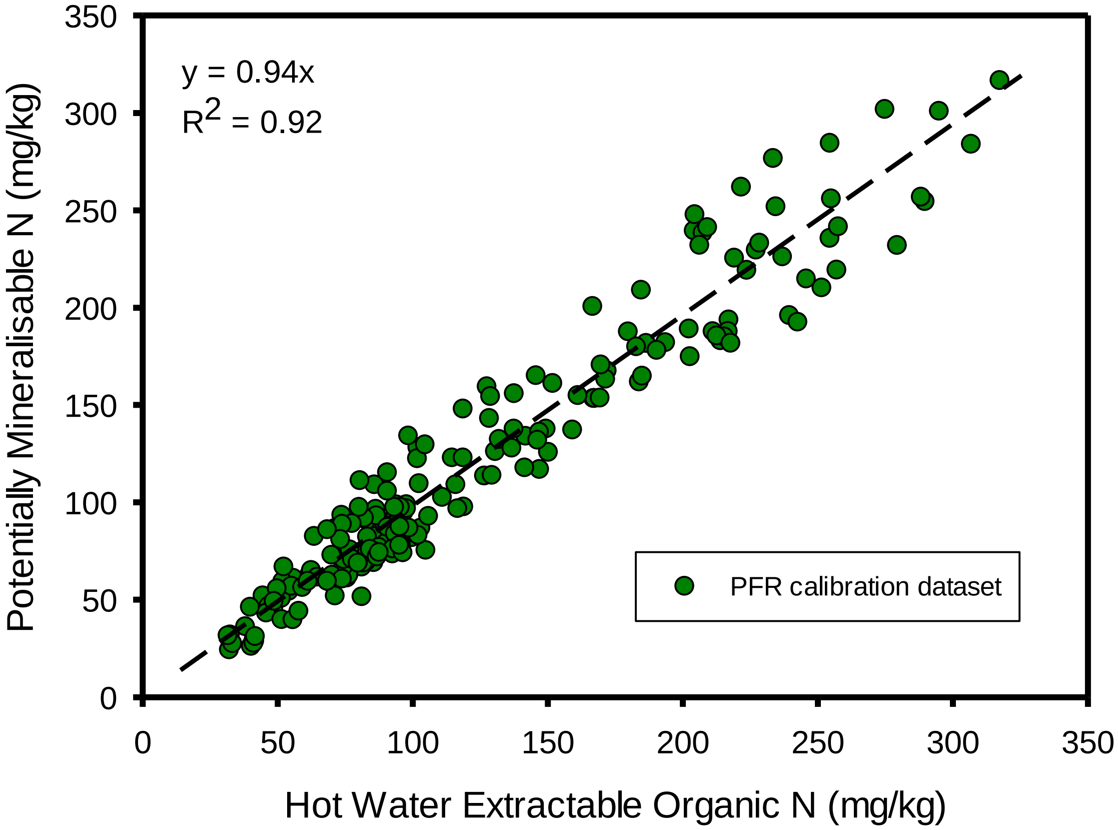

Figure 1. The relationship between hot water extractable organic N (HWEON) and potentially mineralisable nitrogen (PMN) measured on arable, vegetable and pastoral soils (0-15 cm) collected from about 150 sites across New Zealand.

The results of the round robin testing between Plant & Food Research, Hill Laboratories, and Analytical Research Laboratories demonstrate that the HWEON protocol is robust and delivers highly reproducible results (Figure 2A). Verifying the precision of the HWEON test will be important to giving growers and other stakeholders confidence in using the test to inform their soil management decisions. Until recently, the AMN test was regarded as the industry standard commercial test for mineralisable N, though the protocols followed vary between laboratories and the AMN test has not been calibrated against a ‘gold standard” measure of aerobically mineralisable N in New Zealand. The results of our round robin testing showed that the AMN test values obtained from different laboratories vary considerably more than the HWEON test (Figure 2B).

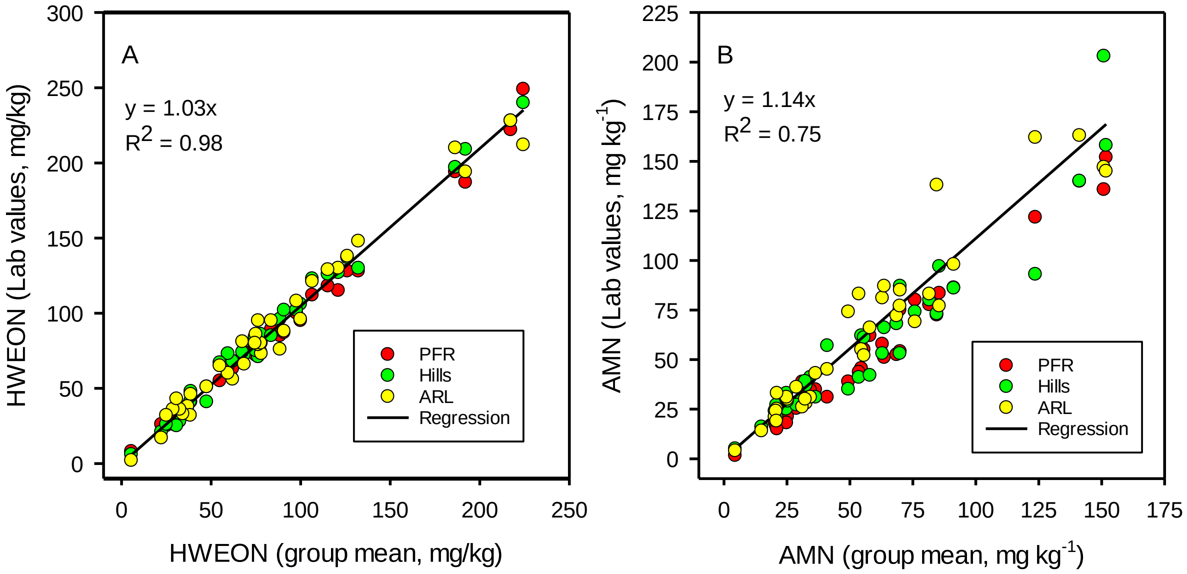

Figure 2. Result of the round robin analyses comparing the individual laboratory results for A) hot water extractable organic nitrogen (HWEON) and B) anaerobically mineralisable N (AMN) to those of the group means for each analyses completed as of November 2021.

Table 1. Mean (± SD) values of potentially mineralisable N (PMN, mg/kg) for different soil order and continuous land use combinations obtained from soils (0-15 cm) collected at approximately 150 sites across New Zealand.

Soil Order	Dairy	Drystock	Arable crop	Vegetable crop
Allophanic	216 ± 38	213 ± 48	ND	105 ± 18
Brown	189 ± 60	179 ± 52	91 ± 28	45 ± 15
Pallic	293 ± 70	227 ± 51	84 ± 20	69 ± 13
Gley	211 ± 51	158 ± 9	116 ± 29	76 ± 13
Recent	231 ± 47	171 ± 43	93 ± 25	81 ± 12

The results of measurements made on soils from approximately 150 sites across New Zealand indicate that PMN is affected by both soil classification (i.e. soil order) and land use history (Table 1). On average, continuous arable and vegetable cropping soils tend to have PMN values that range from 20 to 50% of those at long pasture sites. The PMN in drystock (sheep/beef) pasture soils tended to be 5 to 25% lower than those under dairy pasture, potentially due to differences in pasture dry matter production and N fertiliser inputs. Variation in the PMN values measured in different soil order x land use categories are affected by management history and can be important to forecasting the amount of N that will be mineralised under field conditions, given local climatic conditions.

N balance field validation trials

Results of N balance field trials carried out over the last several years have demonstrated the importance of N mineralisation to the supply of N for crop uptake and provided evidence to verify the methods described above for predicting N mineralisation under field conditions. The following examples from trials conducted with kale (2019/20) and wheat (2020/21) crops grown in Canterbury help to illustrate the range of responses observed.

Table 2. Potentially mineralisable N (PMN) and both the predicted and measured in-field N mineralisation at the kale and wheat crop trial sites.

Crop (Location)	PMN (mg N kg^{-1}) Measured [1]		In-field N Mineralised (kg N ha^{-1}) Predicted [2]			Measured [3]
	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–30 cm	0–30 cm
Kale (Lincoln)	77 (6.3)	66 (6.1)	51	43	94	80 (7.2)
Wheat (Southbridge)	133 (3.8)	52 (4.3)	88	39	127	98 (5.4)

[1] Measured from a 14-week 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.

[3] Derived from the N balance of the N0 treatment. Values are mean (± SD).

Kale

The analysis of soils collect just prior to sowing the kale crop at Lincoln showed that there were moderate levels of PMN at both the 0-15 and 15-30 cm sample depths (Table 2). The N mineralised under field conditions at this site was predicted from these PMN values and the daily soil temperature and volumetric water content measured at the trial site over the growing season. In this case the predicted N mineralisation (94 kg N/ha, 0-30 cm soil) was about 17% higher than the N mineralisation that was calculated from the soil-crop N balance.

In the absence of any N fertiliser additions (N0, zero N applied), the kale crop produced nearly 10 t ha^{-1} of dry matter and the total N uptake by the crop (above-ground and roots) was about 20 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 3A). Whereas the crop's dry matter production increased markedly at the low rate of fertiliser N (100 kg N ha^{-1}), further increases in dry matter were relatively small at the medium (200 kg ha^{-1}) and high (300 kg ha^{-1}) rates of fertiliser N and were not significantly different ($p>0.05$) from that at the low N rate.

Despite the small increases in dry matter produced at the medium and high rates of fertiliser N, N uptake by the crop increased linearly ($p<0.001$) with increases in fertiliser N applied. At the highest fertiliser N rate (300 kg ha^{-1}), the total crop N uptake (424 kg ha^{-1}) closely matched the sum of the initial mineral N, the predicted N mineralisation and the N fertiliser applied (427 kg ha^{-1}). A similar correspondence was observed for the other N fertiliser treatments. This difference between dry matter production and N uptake in the response to fertiliser N can be attributed to luxury N uptake, which is a phenomenon that is well known in brassica crops (Fletcher & Chakwizira 2012). It was also reflected in the concentration of N in above-ground dry matter, which gradually increased from 0.88% in the N0 treatment to 0.92%, 1.23% and 1.58% in the 100, 200 and 300 kg N ha^{-1} fertiliser treatments, respectively.

Although the quantity of mineral N remaining in the soil profile at crop harvest tended to increase linearly with increases in fertiliser rate ($p<0.004$), the total amount of residual N was very low, ranging from 6.5 to 13 kg N ha^{-1} in the zero and 300 kg N ha^{-1} treatments, respectively (Figure 3B). The very high capacity of the kale crop to acquire N was reflected in a very high fertiliser N use efficiency (mean = 1.05) and a high total N use efficiency (mean = 0.95).

Overall, these results suggest that the dry matter gains from increasing fertiliser N additions above 100 kg N ha^{-1} were small; however, the crop was effective at mopping up residual N at higher rates of N, lowering the risk of subsequent N leaching from residual mineral N. The results also showed that our prediction of the N mineralised (calculated from PMN and measurements of soil temperature and water content) during this crop pretty closed matched what was measured (estimated) from the soil-crop N balance and that N mineralisation made a significant contribution to the crops N uptake.

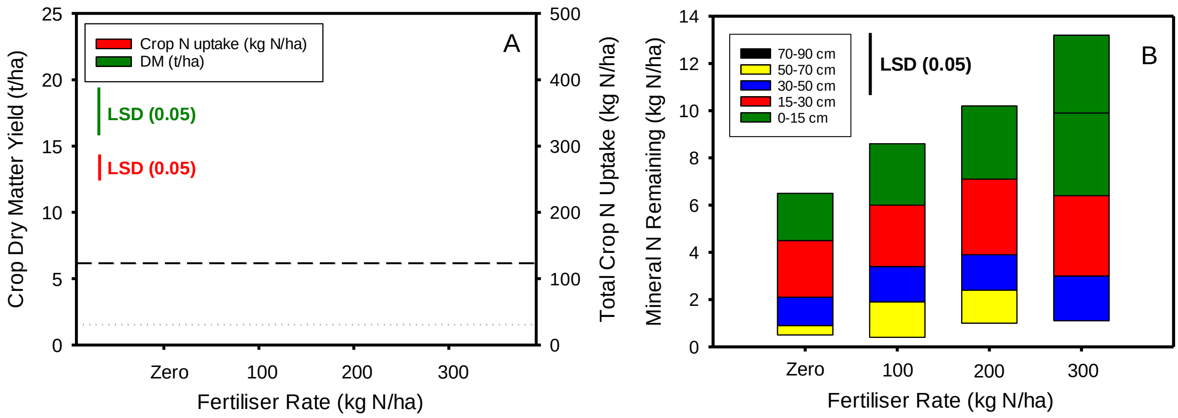

Figure 3. Effects of the fertiliser treatments (kg N/ha) on A) the total above-ground dry matter production and total crop N uptake and B) the vertical distribution and total soil mineral N remaining at harvest of the kale crop at Lincoln, 2019/20. The dotted line in A) is the initial soil mineral N 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.

Wheat

The PMN measured in the 0-15 cm soil at the wheat trial site was considerably higher than that measured at the Kale trial site but about 20% lower that the kale site at the 15-30 cm soil depth (Table 2). The predicted N mineralisation (127 kg N/ha, 0-30 cm soil) was higher than that predicted for the kale site and about 25% higher than the N mineralisation that was calculated from the soil-crop N balance. Nevertheless, the predicted N mineralisation at both trials sites (and others not reported here) indicates that N mineralisation can contribute significantly to the supply of N for crop uptake and these predictions on N mineralisation broadly agree with the estimates of N mineralisation derived from the N balance calculations.

In the absence of fertiliser additions (N0 treatment), the wheat crop at this trial site yielded nearly 8.1 t ha^{-1} of grain 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 4A). Whereas the grain yield increased markedly between the zero and middle rate of N fertiliser (N2, 98 kg N ha-1); there was a smaller, but significant ($p>0.05$) increase 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 small increase in grain yield at the highest N fertiliser rates, 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 4B).

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. 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.

Overall, the results of our N balance calculations indicate that N mineralisation made an important contribution to the total N uptake of the crop and to achieving the maximum grain yield at the highest N fertiliser rate, with no increase in the amount of residual mineral N remaining in the soil. 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 N mineralisation when forecasting crop fertiliser N requirements.

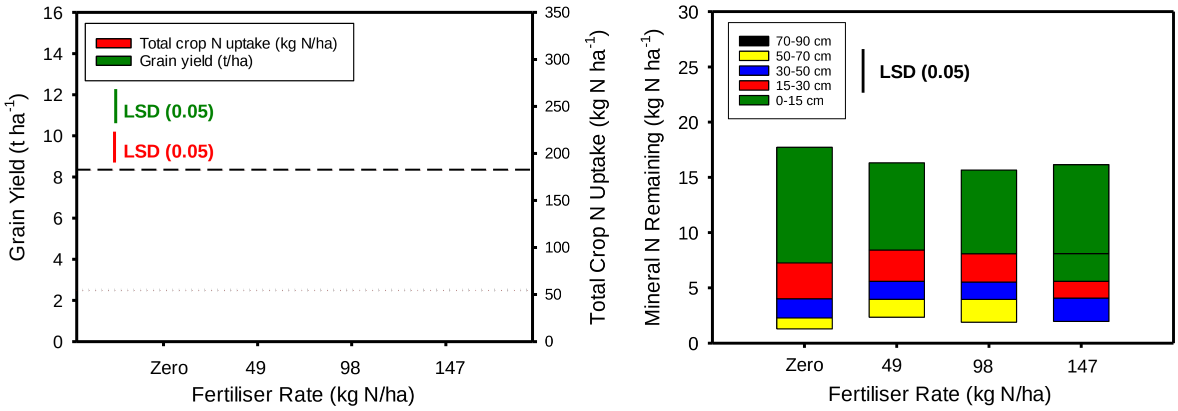

Figure 3. Effects of the fertiliser treatments (kg N/ha) on A) the total above-ground dry matter production and total crop N uptake and B) the vertical distribution and total soil mineral N remaining at harvest of the wheat crop at Southbridge (2020/21). The dotted line in A) is the initial soil mineral 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.

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