SOIL TESTING FOR INFORMING NITROGEN MANAGEMENT IN NEW ZEALAND CROPPING SYSTEMS

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In New Zealand (NZ) cropping systems, there is often a fine balance between meeting crop nitrogen (N) requirements to maximise production and profitability, and minimising environmental risks associated with an oversupply of N. An important starting point for achieving this balance is to obtain reliable and meaningful estimates of soil nitrogen supply (SNS) for improved forecasting of fertiliser N inputs. In this paper, we review the four soil N tests commonly used to assess SNS in NZ cropping systems, namely the mineral N test, the nitrate 'quick test' (QT) approach, the anaerobically mineralisable N (AMN) test, and the recently developed potentially mineralisable N test (PMN_{Test}). While historical and current best practice recommendations have generally included the assessment of both current mineral N content (i.e. inorganic N) and future N supply (i.e. AMN and recently PMN), uptake of soil N testing appears to be variable, and uncertainty around test selection and application persists. Hence a key purpose of this paper is to provide a synthesis and critique of current soil N testing approaches with a view to facilitating wider adoption of soil N testing across NZ cropping systems. We also address practical questions around test method applications and the implications of more recently developed test approaches on nutrient management recommendations.

Introduction

In New Zealand (NZ) cropping systems, there is often a fine balance between meeting crop nitrogen (N) requirements to maximise production and profitability, and minimising environmental risks associated with an oversupply of N. An important starting point for achieving this balance is to obtain a reliable and meaningful estimate of likely soil nitrogen supply (SNS) for optimising fertiliser N inputs.

There are currently four soil N testing approaches used to inform N management practices in NZ cropping systems including the mineral N test, the nitrate 'quick test' (QT) approach, the anaerobically mineralisable N (AMN) test and the recently developed potentially mineralisable N (PMN) test. While each of these tests has a specific methodology and application, in general the first two (i.e. the mineral N and nitrate QT) are used to quantify N that is immediately available for plant uptake. The latter two (i.e. the AMN test and PMN_{Test}) are used to estimate 'future' N supply from mineralisation of soil organic matter. A fifth test, namely the total N test, is used to quantify total soil N content (i.e. inorganic + organic forms); however, this test is not recommended for crop N management in NZ since only a small proportion of total soil N is available for a crop (Havlin et al 2019).

Historical and current best practice recommendations have generally included the assessment of both current mineral N content (i.e. inorganic N) and future N supply (i.e. AMN and recently PMN). Nevertheless, uptake of soil N testing appears to be variable, and uncertainty around test selection and application persists. In this paper we attempt to provide a consolidated summary of the four main soil N tests used in NZ with a view to facilitating wider soil N test adoption across NZ cropping systems. We also provide recommendations on soil N testing approaches for informing N management decisions, and briefly assess the implications of more recently developed test approaches on N management recommendations. While this paper is focused primarily on soil N testing within annual cropping systems (e.g. arable and vegetable production), the information presented is transferable to other land uses where soil N testing is beneficial (e.g. perennial horticulture).

A brief overview of nitrogen in cropping soils

For the purposes of this paper, we present a simplified N cycle (Figure 1) that highlights the key N pools relevant to N soil testing approaches. The various soil tests used to quantify soil N pools may be grouped into three general categories:

- Tests used to quantify total soil N: Includes the total N test, which represents the sum of organic and inorganic N pools. This test is of limited use for informing N management decisions in cropping systems and is not discussed further in this paper.
- Tests used to quantify inorganic N pools: Includes the mineral N test (sometimes called the 'deep min N' test) and the nitrate quick test (QT). These tests are used to assess plant-available N supply at the time of sampling.
- Tests used to quantify potential N supply: Includes the anaerobically mineralisable N (AMN) test and the potentially mineralisable N test (PMN_{Test}). These tests are used to assess future N supply from mineralisation of soil organic matter.

It is important to highlight that in most cropping soils, the vast majority of soil N (98–99%) is present in stable organic forms with only a smaller sub-pool of this organic N present as 'mineralisable N' or 'potentially mineralisable N'. This is the portion of organic N (generally 1–4%) that is broken down each year to inorganic N through biologically mediated mineralisation processes. Organic matter mineralisation is mediated by soil microbes, occurring most rapidly when soils are warm and moist and is maintained by the return of plant residues and other organic wastes (manures, compost) into the system. Inorganic N is the predominant form of N taken up by plants and is present as the negatively charged nitrate anion (NO_3^-) and positively charged ammonium cation (NH_4^+). In most cropping soils, the amount of inorganic N present at any one time is highly variable, being dependent on the rate of mineralisation, plant N uptake and drainage losses. Inorganic N can also be present in soil in small quantities as nitrite (i.e. nitrogen dioxide, NO_2^-), nitrous oxide (N_2O) or dinitrogen (N_2); however, these forms are not discussed in this paper.

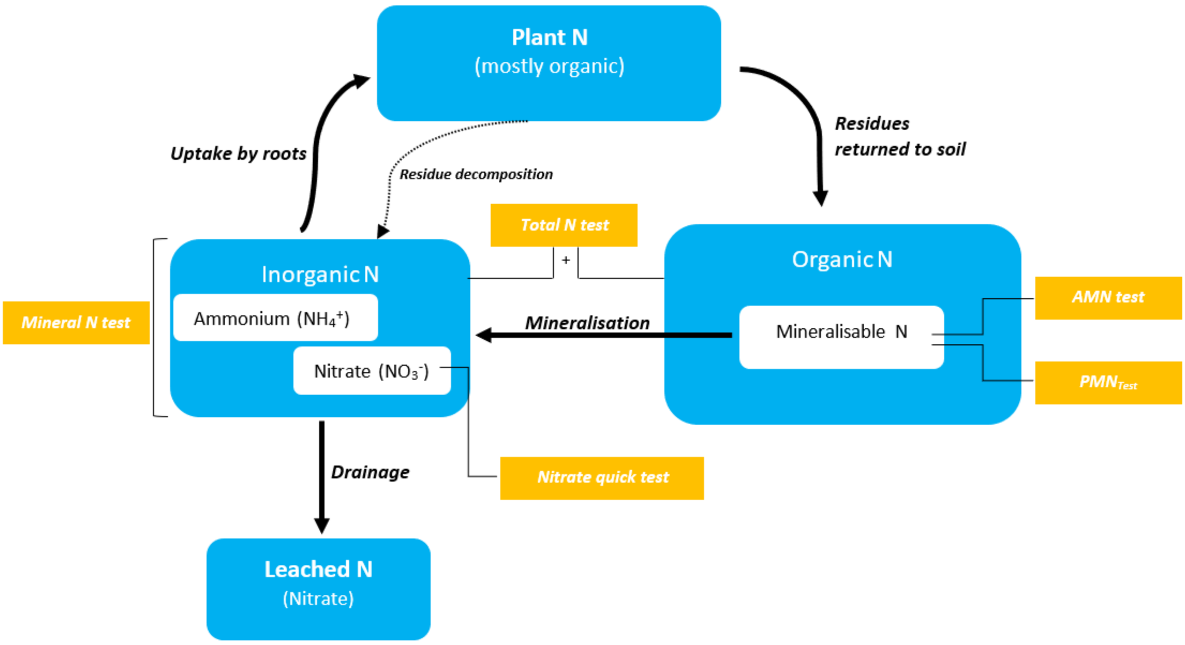

Figure 1. Simplified soil nitrogen (N) cycle and tests used to quantify soil inorganic and organic N pools (adapted from Reid & Morton 2019). AMN = anaerobically mineralisable N, PMN = potentially mineralisable N.

Inorganic soil nitrogen tests

The Mineral Nitrogen Test

Overview

The mineral N test, sometimes referred to as the 'deep mineral N test', is the standard method for assessing soil inorganic N supply. The test measures inorganic N present as nitrate-N (NO_3-N) and ammonium-N (NH_4-N) and represents the N available for crop uptake at the time of sampling. Nitrate-N is usually the predominant form of inorganic N (>90%) in most well-aerated soils, except under conditions of prolonged saturation (high soil moisture contents can inhibit nitrification) or where urea or ammonium-based fertilisers have been applied recently. It is important to highlight that soil inorganic N concentrations are dynamic in space and time, and are affected by several factors including previous crop management, the soil organic matter content and its decomposition rate, crop N uptake, N fertiliser use, waterlogging and drainage through the soil profile. Understanding these factors is important for the correct application of the mineral N test for N management decisions.

Sampling and analysis

Soil sampling and processing recommendations for the mineral N test are detailed elsewhere (e.g. in Knight 2006) and not discussed further here. The procedure for analysis of soil mineral nitrogen is well documented and consists of extraction with 2 M potassium chloride (KCl), filtration of the extract and analysis by colorimetry (Keeney & Nelson 1982). Analysis is conducted on field-moist samples sieved to <4 mm. The test is offered by the three main commercial soil testing laboratories in NZ – Hill Laboratories, Analytical Research Laboratories (ARL) and Eurofins.

Test application

In NZ, mineral N test results are typically used to inform N management decisions either directly through mass balance type approaches or indirectly through input into crop models.

In the mass balance approach, seasonal N fertiliser requirements are calculated as a function of crop N demand and soil N supply according to the following equation:

N fertiliser requirement = Crop N demand – soil inorganic N supply – soil organic N supply

Using this approach, soil inorganic N supply would be determined using the mineral N test, or the nitrate QT as a proxy for inorganic N, while future N supply from mineralisation of organic N would be estimated from an AMN test or the PMN_{Test} or crudely approximated based on the management history of the site.

Examples of NZ crop models that require mineral N as an input parameter to initiate scenarios include AmaizeN (Li et al. 2009), the Sirius Wheat calculator (Jamieson et al. 1998; Jamieson & Semenov 2000) and the Potato Calculator (Jamieson et al. 2006).

In addition to its use for N management purposes, the mineral N test can also be used to assess the potential for environmental impact. High soil nitrate-N concentrations at any phase in a crop cycle indicate an increased potential for nitrate leaching, with the risk deemed to be greater on free draining soils and under crops with shallow root systems or low N demand. Mineral N sampling shortly after crop harvest can be a useful way to determine the presence of surplus inorganic N and serve as the basis for implementing N loss mitigation strategies, for example improved in-season N forecasting or the establishment of post-harvest catch crops.

Limitations to routine mineral N testing include analytical costs and intensive soil sampling requirements (especially for deep samples), and alternative approaches such as the nitrate QT (discussed below) and proximal sensing (e.g. Jones et al. 2018; Yeshno et al. 2019) have been suggested as means to address some of these issues. The test is, nevertheless, the established reference method for determining soil inorganic N concentrations and will likely remain in use for the foreseeable future.

The Nitrate Quick Test

Overview

The nitrate QT is an alternative method to the mineral N test for assessing soil inorganic N supply. A key method assumption is that the nitrate anion (NO_3^-) is the dominant form of inorganic N, which is usually the case in most cultivated/well aerated cropping soils, although exceptions can occur, for example, when soils are under prolonged water saturation or fertilisers such as urea or ammonium-based fertilisers have been recently applied. The value proposition for the QT approach over the standard mineral N test relates to the cost of the test (~$1 compared with standard laboratory analyses of $40–50), its ease of use, and ability to generate results within a short time frame (generally <1 h). Hence, useful information for N management or environmental monitoring purposes can be quickly obtained without the need for more costly analytical services.

Sampling and analysis

The reader is referred to the 'Quick Test User Guide' (Mathers et al. 2020) for a full overview of the soil sampling and analytical approach. In brief, analysis is conducted on field-moist soil sieved to <4 mm and extracted with 0.01 M $CaCl_2$ (1:3 soil to solution ratio). Colorimetric test strips (similar to pH litmus paper) are then used to determine the concentration of nitrate (mg/L NO_3-N) in solution and results converted to a gravimetric basis (mg/kg NO_3-N) using soil specific correction factors.

Test application

The nitrate QT approach has been adopted by several growers across a range of different arable/horticulture systems and is typically used to inform N management decisions through mass balance type approaches. The test was initially validated through a Ministry for Primary Industries Sustainable Farming Futures project ('Nitrogen – Measure it and manage it'; 2017–2020), which sought to validate the approach for informing N management decisions across arable and vegetable production systems. Findings from this project demonstrated that significant N savings could be made by quantifying soil inorganic N supply prior to fertiliser applications (base and or side dressings). For example, at 14 of the 18 field trial sites, N fertiliser inputs were reduced by 23–52% without compromising yield and quality (Norris et al. 2019). Good management practice recommends that soil mineral N sampling (QT or mineral N test) be conducted prior to every N application (base or side dressing) to help inform the decision-making process (Mathers et al. 2020).

While the nitrate QT is a cheap and relatively simple method for quantifying the nitrate-N component of soil inorganic N, results do need to be interpreted with some caution due to the semi-quantitative test methodology. In addition, omission of the ammonium-N component of soil mineral N can result in soil inorganic N supply being underestimated. The test is, nevertheless, very useful for monitoring changes in mineral N availability during the growing season, particularly in intensive crop rotations where frequent sampling requirements may limit the use of more expensive mineral N testing.

Mineralisable nitrogen tests

In this section we review the two most widely used tests used in NZ to estimate future N supply from mineralisation of soil organic matter, namely the AMN test and the more recently developed PMN_{Test}. Some background context to mineralisable N tests is provided below.

Background

The decomposition of soil organic matter to release mineral N is commonly referred to as net N mineralisation (N_{SOM}). Nitrogen mineralisation is a soil microbial process that depends on the amount of readily biodegradable (i.e. mineralisable) organic matter in the soil and the environmental conditions (particularly soil moisture and soil temperature) that support its decomposition by microbes (Curtin et al. 2012; Dessureault-Rompre et al. 2015). The two key elements required to predict N_{SOM} under field conditions include 1) a robust and reliable method for measuring the organic nitrogen in soil that is readily mineralisable under "optimal" conditions of soil temperature and water content (this pool of N is commonly referred to as "potentially mineralisable N"); and 2) a method to predict how variations in soil temperature and water content in the field affect the actual rate of N release from the pool of readily mineralisable N. Previous studies on NZ soils have shown that PMN can be a significant source of the mineral N for crop production, ranging from 40 to >300 mg/kg soil (Curtin et al. 2017; Beare et al. 2020, 2022a).

How to practically quantify PMN and then relate this to in-field mineralisation has been the focus of much research, both in NZ and internationally, partly because the "gold standard" method for measuring PMN is time consuming and costly to undertake. The test requires a lengthy incubation period (typically 98 days) at optimal soil temperature (e.g. 25°C) and soil water content (e.g. 90% of field capacity) (Stanford & Smith 1972). Research efforts have, therefore, tended to focus on the development of rapid test methods for predicting PMN that are suitable for routine commercial testing (Curtin & McCallum 2004; Curtin et al. 2017; Franzluebbers et al. 2000; Keeney & Bremner 1966; Ros et al. 2011; Sharifi et al. 2007; Schomberg et al. 2009). In NZ, the two most common commercial laboratory methods used for estimating the amount of potentially mineralisable N in soil are the AMN test and the more recently developed PMN_{Test}. These tests are discussed in more detail below.

Anaerobically Mineralisable Nitrogen (AMN) test

Overview

The most widely used proxy test for PMN in NZ is the AMN test, which was originally proposed by Bremner and his co-workers at Iowa State University (Keeney & Bremner 1966; Waring & Bremner 1964). The test measures the amount of ammonium-N produced during a 7-day anaerobic (waterlogged) incubation of soil. In NZ, the AMN test has been widely used on arable soils, but not on pastoral soils.

Sampling and analysis

AMN, like many other soil N tests, can be spatially variable at a paddock scale (Qiu et al. 2016) so the collection of a representative sample is important to the outcome. In most cases, the recommended sampling depth for AMN has been 0–15 cm (Francis & Curtin 2002; Reid & Morton 2019), which is the usual sampling depth for soil fertility testing in arable and vegetable cropping systems. However, there is evidence that significant quantities of AMN can also occur in 15–30 cm soil, particularly in annual cropping systems where the topsoil has been mixed with tillage.

The AMN test involves a 7-day anaerobic soil incubation (1:2 soil:solution ratio) followed by extraction with 2.5 M KCl and analysis of NH_4-N in the supernatant. Compared with aerobic incubation methods, the AMN test has several features that make it more attractive for routine use including a relatively short (7 days) incubation period, and the requirement to measure NH_4-N only (NO_3^- is not produced in soil under anaerobic conditions). Over time, further changes have been introduced by some laboratories intended to shorten the reporting timeline and/or reduce analytical costs. For example, near infrared spectroscopy (NIRS) is used by Hill Laboratories as a rapid alternative to the incubation procedure for determination of AMN (Hill Laboratories Technical note (b)). Some commercial testing laboratories do not correct their AMN test values for the initial (pre-incubation) NH_4-N content of soil, which can introduce additional variability into the test results. Given the variation in test methods, it is perhaps not surprising that the AMN test is known to suffer from poor analytical precision. In addition, variable reporting notations between commercial soil testing laboratories (e.g. PAN in kg/ha vs AMN in µg/g) can further confound result interpretation.

Test application

The AMN test has a long history of use in NZ, and a substantial amount of data have accumulated to allow soils to be divided into broad categories (low, medium, high) based on the test value (Table 1). It should be noted that these categories are based solely on the distribution of measured values and not on any independent measure of the N mineralised under aerobic conditions or the N requirements of crops. AMN is strongly influenced by paddock management history, with long-term pastures having substantially higher values than cropped soils (arable or vegetable) (Curtin et al. 2017). Translating an AMN value to a prediction of the N fertiliser requirement of NZ crops remains a challenge, as discussed below.

Table 1. Classification of anaerobically mineralisable N (AMN) into "very low", "low", "medium", "high", and "very high" categories (Hill Laboratories Technical note (a)).

Level	***AMN***	***"Available N"*** [1]
	mg/kg	***kg/ha***
Very low	< 35	<50
Low	35-50	50-150
Medium	50-80	150-250
High	80-240	250-350
Very high	> 240	>350

[1] This is sometimes termed 'potentially available N' or PAN.

A key factor limiting the application of AMN as a soil N fertility test is the absence of both appropriate calibration data for some crops (and pastures) and the independent validation of resulting recommendations under NZ conditions. Reid and co-workers have provided fertiliser recommendations for a range of vegetable crops based on AMN (or AMN plus mineral N) test results (Reid & Morton 2019; Reid et al. 2018). Many (but not all) of their recommendations are based on empirical modelling of crop responses to different fertiliser rates at trial sites where AMN and mineral N were measured (Jamieson et al. 2001; Reid et al. 2018; Reid et al. 2020). The recommendations reported by Reid and Morton (2019) represented the first genuine attempt to account for differences in soil N supply (including N mineralisation) when forecasting the fertiliser N requirements of different crops. Their recommendations are based on empirical relationships between crop yield and a combination of measured AMN values and fertiliser N applied. They do not involve relationships between crop N content and yield, nor attempt to estimate crop N uptake. An important limitation of this approach is that, taken in isolation, yield forecasts made this way do not specifically address how much residual N may be left at harvest and the associated risk of N losses. To reduce the risks from this, the published recommendations contained supplementary information on methods to reduce the risks of nitrate leaching. Reid et al. (2020) identified a need for a "better method of forecasting N mineralisation than the AMN test provides – or at least a reliable way to estimate what portion of the AMN value will be mineralised over the lifetime of a particular crop". Furthermore, they highlight that forecasting methods that ignore N mineralisation probably underestimate the amount of residual N remaining in the soil, which represents a risk to achieving compliance with environmental regulations.

Potentially Mineralisable Nitrogen test (PMN_{Test})

Overview

The PMN_{Test} was developed as an alternative to the AMN test with a view to providing a more rapid, reliable, and cost-effective method for predicting PMN based on the gold standard method, and a verified method for predicting in-field N mineralisation from a measure of PMN. The test approach is based on work of Curtin et al. (2017) and Beare et al. (2020, 2022a, 2023) which demonstrated the utility of hot water extractable organic N (HWEON) as a reliable proxy for the 'gold standard' measure of PMN (i.e. HWEON reflects the water-soluble component of the soil organic matter that is readily mineralisable by soil microbes). For commercial testing purposes, the use of HWEON multiplied by a coefficient to estimate the N mineralisation potential of soil is known as the PMN_{Test}.

Sample analysis

The methods for measuring HWEON are well established and well suited to routine commercial testing. A commercial testing protocol for HWEON was developed under the recently completed Sustainable Farming Fund (SFF) project entitled 'Mineralisable N to Improve On-farm N Management', building on the methods described by Curtin et al. (2017), which were adapted from the earlier work of Curtin et al. (2006) and Ghani et al. (2003). The commercial testing protocol is now in use by the three main commercial testing laboratories (Hill Laboratories, Analytical Research Laboratories and Eurofins). In brief, the test involves extracting the soil with distilled water (1:10 soil to solution ratio) at 80°C for 16 h. Filtered extracts are then analysed for mineral N and total persulfate-oxidizable nitrogen (TPN) and hot water extractable organic N calculated by difference.

Test application

The current calibration of the HWEON test for predicting PMN is based on data from 225 samples collected from a wide range of arable, vegetable, and pastoral sites across NZ:

PMN (mg/kg) = 0.964 x HWEON (mg/kg) ($R^2 = 0.95$)

Although most of the testing was carried out on 0–15 cm deep soil samples, recent research has identified that significant quantities of PMN can, in some cases, be recovered in 15–30 cm soil samples obtained from cropping sites. There is no evidence to suggest that the relationship between HWEON and PMN differs depending on soil type, land use (e.g. pasture vs cropping) or sample depth (0–15 vs 15–30 cm).

Round robin testing was also completed by three laboratories (Plant & Food Research, Hill Laboratories and ARL) participating in the SFF project to evaluate the precision of the HWEON test. The results of that testing showed improved analytical precision compared with the AMN test approach with reproducible values achieved across a broad range of soil HWEON concentrations (Figure 2).

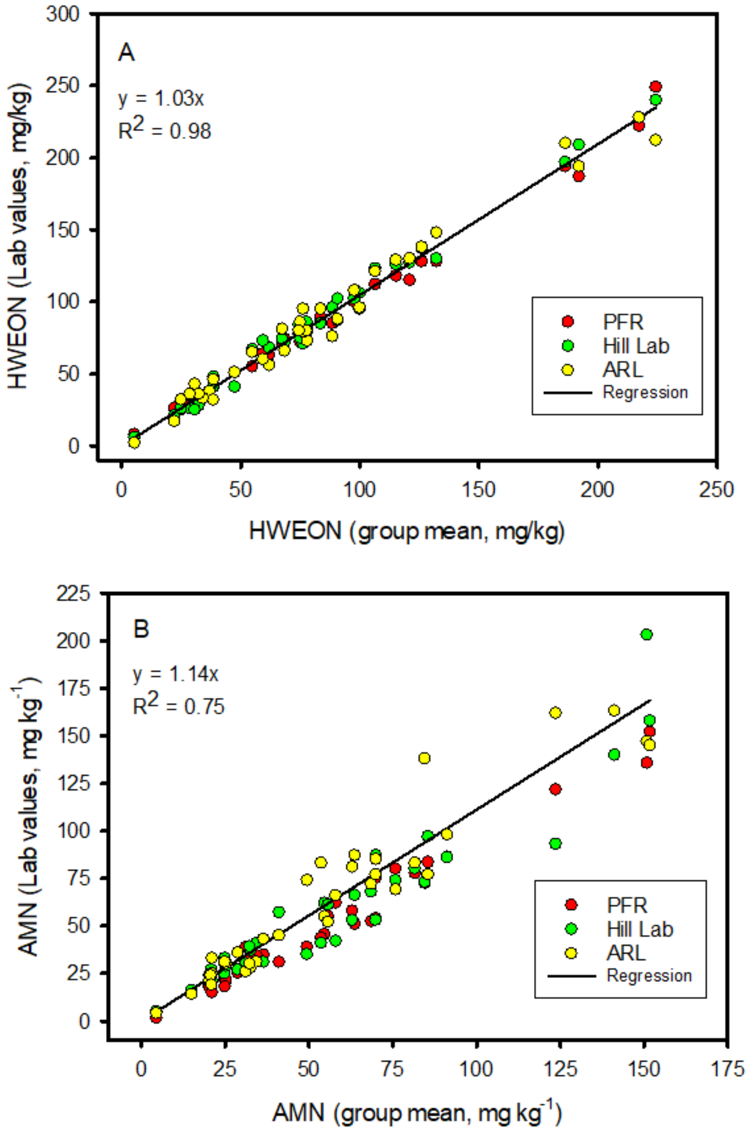

Figure 2. Result of the round robin analyses comparing the individual laboratory results for A) hot water extractable organic nitrogen (HWEON) and B) anaerobically mineralisable N (AMN) to those of the group means for each analysis completed as of November 2021 (Beare et al. 2022a).

PMN derived using the equation above represents the amount of N that can be mineralised from the soil over a 98-day incubation period under optimal conditions of soil moisture and temperature. To account for in field edaphic factors, the daily rate of PMN (calculated from the 98-day incubation period and expressed as kg N/ha/day) is adjusted for the average soil temperature and water content (under field conditions) on each day of the growing season. The predicted daily N mineralisation values are then summed over the period of interest (e.g. a month or growing season) to predict the accumulated net N mineralised. This is referred to as in-field net N mineralisation (N_{SOM}):

$$\text{Predicted } N_{SOM} = \sum_{i=1}^{n} (\text{Average daily PMN} \times St_i \times Sw_i)$$

where n is the number of days in the period of interest (e.g. a month or growing season), PMN is a measure of the N mineralisation potential (kg N/ha/day) and S_t and S_w are scaling factors calculated from algorithms relating soil temperature and soil water content to N mineralisation, respectively. These algorithms were developed and validated as part of the SFF field trial programme and have been incorporated into the recently published 'Guidelines for Soil Nitrogen Testing' (https://www.plantandfood.com/en-nz/article/soil-nitrogen-testing-and-predicting-nitrogen-supply). The guidelines allow the grower or fertiliser consultant to adjust the PMN_{Test} value from the commercial laboratory for the period of crop growth and local climate conditions to predict the in-field N mineralisation. Field studies across a range of arable crops have validated this method for predicting in-field N mineralisation (Beare et al. 2020, 2022a, 2023). Further trials on wheat crops have demonstrated how the PMN_{Test} and the method for predicting in-field N mineralisation can be used to inform N fertiliser decisions under NZ conditions (Beare et al. 2020b). Adoption of the PMN_{Test} will likely increase over the coming years as the approach is integrated into decision support tools and test guidelines disseminated more widely, although some further work is still required to verify the approach for other crops (including perennial crops) and across a wider range of soils.

Selection of a potentially mineralisable N test and application to nutrient management guidelines

With two potentially mineralisable N tests currently available in the NZ soil testing market, a primary question is 'which test to use'. Building on the discussion above, we recommend the PMN_{Test} is used where possible for the following reasons: 1) it has demonstrably better analytical precision than the AMN test; 2) it has been calibrated against the "gold standard" measure of aerobically mineralisable N; and 3) a method for predicting in-field N mineralisation from a PMN_{Test} and regional soil/climate factors has been developed and validated. In contrast, the AMN test lacks reproducibility, it is conducted under anaerobic conditions that do not reflect typical field conditions and has not been calibrated against the "gold standard" measure of aerobically mineralisable N, and there is no existing method for predicting in-field supply of N from an AMN test that accounts for difference in soil type and climate. An exception would be the work undertaken by Reid and colleagues, which represents the first genuine attempt to account for differences in soil N supply, derived from soil N results, to forecast the fertiliser N requirements of different crops.

The adoption of PMN testing does not have any immediate implications for recommendations generated using the three well-known crop models; AmaizeN (Li et al. 2009), the Sirius Wheat calculator (Jamieson et al. 1998; Jamieson & Semenov 2000) and the Potato calculator (Jamieson et al. 2006). These models are initialised using starting soil mineral N concentration data and soil type/texture 'drop downs', which define the amount of organic N available for mineralisation. This information in conjunction with local climate data is used to predict daily N mineralisation for N forecasting purposes. These models could be modified to include a PMN_{Test} input for more accurate predictions of in-field N mineralisation, noting that the current models incorporate a limited number of NZ soils and assume a fixed PMN pool (i.e. changes in land management/cropping history are not accounted for). Regarding other models, Plant & Food Research has recently provided guidance to OVERSEER Limited on how the PMN_{Test} and method for predicting in-field N mineralisation could be applied in the Overseer model. Furthermore, the method for predicting in-field N mineralisation from a PMN_{Test} and local climate data has been included in a prototype N balance tool that has been developed by the Sustainable Vegetable Systems (SVS) programme (Sustainable Vegetable Systems (SVS) – Agrilink) and is currently undergoing testing.

With regard to the 'nutrient management for vegetable crops in New Zealand' guidelines (Reid & Morton 2019), three rather different situations exist.

1. For cabbage, beetroot, broccoli, cauliflower, lettuce, onions, silverbeet and spinach, N fertiliser recommendations were calculated using critical nutrient dilution curve theory to determine how much N the crops would need to take up to attain a specific yield potential. For these crops, N application rates are based on the soil N supply required (termed 'Soil Available N (kg N/ha)') to achieve the potential yield. Although, it is often assumed that the AMN test (also termed Available N) provides an accurate measure of the soil N supply, there is considerable evidence to indicate that this is not the case. However, the guidelines could be updated to recommend that the 'soil available N' is determined from a prediction of in-field N mineralisation (based on the more accurate PMN_{Test}) and a mineral N test at the start of the growing season. Further field trials are needed to verify the fertiliser recommendations for these crops, given potential differences in the methods used to estimate 'soil available N' and that the critical nutrient concentrations used were based mostly on overseas experimental work. Note that the 'Soil Available N (kg N/ha)' terminology used in the guidelines is somewhat confusing because it is similar to the term 'Available N supply', which is a derivate of the AMN test used by Hill Laboratories. We recommend that this terminology is clarified in future guideline updates to avoid confusion.

2. For beans, buttercup squash, carrots, sweet corn, and tomatoes, N fertiliser recommendations were calculated using the PARJIB model (Reid 2002). This used measurements from multiple field sites to model the yield response of crops with different yield potentials to differences in N supplied from fertiliser and soil (using the AMN

technique). It did not involve measurements of plant N uptake, only yield response to differences in N fertiliser applied. It is not a simple matter to replace AMN with PMN_{test} values in these cases. Updating the recommendations to account for this change will require field experiments with at least some of the crops, because the PARJIB model relies on empirically derived relationships between estimates of N supply and how close a crop will come to achieving its potential yield.

3. For potatoes, N fertiliser recommendations were calculated using the Potato Calculator, and cross checked against a PARJIB calibration. The Potato Calculator was initialised with measures of soil mineral N to 60 cm depth. However, as noted above, the Potato Calculator does not explicitly account for the soil N supply from N mineralisation to generate its recommendations.

We suggest that future work should focus on testing and validating the method for forecasting the N fertiliser requirements of different crops based on the PMN_{Test} and predictions of in-field N mineralisation. This would involve field trials with different crops where the treatments include applied fertiliser N rates that are adjusted for soil N supply (from mineral N and mineralisable N) to meet the projected crop N demand based on a target yield. These trials would serve to both verify the best practice method(s) and demonstrate the benefits of their use to farmers and industry representatives, including the potential to reduce excess N use and the associated cost and risk of N losses to the environment.

Recommended soil N test approaches for improved N management

Best practice recommendations for N forecasting are based on reliable estimates of both current and future N supply (soil and fertiliser) along with an estimate of crop N demand based on a realistic target yield. To this end, and assuming some prior knowledge of crop N demand, we recommend the approach of Beare, Curtin and colleagues (Beare et al. 2022b, 2023 and Guidelines for Soil N Testing), which is to measure for topsoil (0–30 cm depth) mineral N and PMN at the start of the main growing season of individual crops. For many crops this is in the early spring or summer just prior to planting/sowing. Early spring testing also applies to autumn/winter sown cereal crops that typically receive little or no applied N at sowing. Using mineral and PMN testing to forecast the fertiliser N requirements of winter grown vegetable crops is more challenging due to the increased risk of N losses from both soil N supply and fertiliser where drainage is typically higher in the winter period. In combination, the mineral N and PMN tests provide the best estimate of soil N supply by accounting for both the initial mineral N content of the soil and the predicted in-field N mineralisation over the course of the growing season. The mineral N test is a well-established method, while guidelines for the PMN_{Test} and application are now widely available and easy to apply. We recommend the use of the nitrate QT as a tool for monitoring changes in mineral N availability during the growing season, especially prior to in-season N applications (i.e. side dressing) – these can be readily ‘fine-tuned’ using QT results.

These recommendations assume that a high priority is placed on soil N testing as a key to improving N management decisions. For most crops, sampling to 30 cm is recommended for pre-season N forecasting purposes because mineralisable N is found predominantly in the top

30 cm of soil, while mineral N that exists below 30 cm at the start of the season is not a reliable source of N for crop uptake because of the risk of N loss, e.g. leaching. The recommendation to sample to 30 cm and determine both mineral N and PMN from the same sample is an attempt to minimise the effort and cost required to obtain the essential soil N tests for reliable fertiliser N forecasting and, thereby, encourage wider adoption by farmers. Field studies (Beare et al. 2020, 2022a, 2023) have demonstrated that pre-season sampling to 30 cm is generally sufficient for N forecasting purposes across a range of crops. Note that shallower sampling (i.e. 0–15 cm) may be more appropriate for shallow rooting crops (e.g. leafy greens) or very shallow soils (i.e., soils over gravels or stones). Sampling the 30–60 cm depth can have merit for deep rooting annual or perennial crops in environments where N leaching losses during the growing season are unlikely. While we don't discourage 'deep' mineral N testing (i.e. >30 cm depth), the reality is that sampling to this depth requires considerable effort, which is rarely undertaken by growers and consultants. Such efforts (if they exist) may be better applied to obtaining more samples for improved spatial resolution in the 0–30 cm depth.

Finally, the recommendations supplied above are considered fit for purpose in contexts where N applications are constrained to a single crop within an application time frame of less than about six to eight months. This would include most arable crops and forage crops and even some perennial horticulture crops such as kiwifruit.

For more intensive vegetable production rotations characterised by short-duration crops with multiple N applications, a more intensive N soil sampling programme is recommended. In these contexts, annual PMN testing (0–30 cm) (autumn or spring) should be undertaken to establish background organic N supply levels (often low in continuously cropped soils). Ideally soil inorganic N supply should be quantified prior to each application of N, using the mineral N test (0–30 cm), or the nitrate QT where cost and analytical time constraints preclude mineral N testing. If using the Reid and Morton (2019) guidelines, we recommend that the soil N testing approaches outlined there continue to be used, including the use of the AMN test, which is required for the correct interpretation of these guidelines, until further work has been completed to update the guidelines based on the PMN testing and forecasting methods. These existing guidelines may eventually be superseded by the adoption of tools like the SVS nutrient budgeting tool, which incorporates PMN testing and forecasting methods and is currently undergoing prototype testing.

Summary and conclusions

The end goal of soil N testing is to enable informed N management decisions with a view to maximising production and profitability, while at the same time minimising environmental risks and costs associated with an oversupply of N. This paper has sought to provide an overview of the four main soil tests used in NZ to quantify soil inorganic N pools (mineral N test and the nitrate QT) and N supply from mineralisation of soil organic matter (AMN test and the recently developed PMN_{Test}). Each of these tests has a specific methodology and application based on the pool of N being measured, and to ensure that test results are fit for purpose, it is essential that the correct soil sampling methods, storage, processing and analytical protocols are followed.

Key recommendations in relation to the application of these tests include:

- Where possible, we recommend that the PMN_{Test} be used to estimate 'future' N supply from mineralisation of soil organic matter. Not only does the PMN_{Test} have demonstrably better analytical precision than the AMN test, but the test has been calibrated against an independent measure of N mineralisation. Furthermore, a method for predicting the supply of N from mineralisation based on a PMN_{Test} and local soil and climate factors has been developed and validated.
- For most annual crops (arable and vegetable), testing of mineral N and PMN on topsoil (0–30 cm depth) samples collected at the start of the spring/summer growing season is appropriate. These two tests currently provide the best estimate of soil N supply by accounting for both initial mineral N and predicted in-field N mineralisation over the course of a growing season. Where a crop's N requirements to achieve a target yield are known, these predictions can be used to forecast the additional fertiliser required to meet that demand.
- Where the Reid and Morton (2019) guidelines are followed, the soil N testing approaches outlined there should continue to be used, including the AMN test, which is required for the correct interpretation of these guidelines. These may eventually be superseded by guidelines and tools that are based on the PMN_{Test}, such as the Sustainable Vegetable Systems nutrient budgeting tool currently undergoing prototype testing.
- For all practical purposes, soil testing for mineral N and PMN at the start of the growing season and predicting in-field N mineralisation following the Guidelines for Soil N Testing should also be applicable for perennial crops, though testing and field validation of these methods for perennial crops is lacking and should be the focus of future research. Further work is also needed to determine the most appropriate soil testing depth, especially for the mineral N content of the soil.
- For all crops, the nitrate QT or frequent mineral N testing should be used to monitor changes in mineral N availability during the growing season, especially prior to in-season N applications (i.e. side dressing).

Further work is required to test and validate the method for forecasting the N fertiliser requirements of different crops based on a PMN_{Test} and prediction of in-field N mineralisation. This would involve trials where the treatments include applied fertiliser N rates that are adjusted for soil N supply (from mineral N and mineralisable N) to meet the projected crop N demand based on a target yield. Collectively, data from these trials could be used to update existing nutrient management guidelines and/or modify models to better account for infield N mineralisation based on mineral N and PMN tests.

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