SPATIAL VARIABILITY OF NITROGEN SUPPLY ASSESSED USING SOIL AND PLANT BIOASSAYS

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Abstract

Knowledge of spatial patterns in soil nitrogen (N) availability is a pre-requisite to delivering more precise N fertiliser management practices at a sub-paddock scale. This study was conducted to quantify spatial variability in soil N mineralisation in a paddock and to identify the chemical or physical soil properties that could help to explain these patterns. Soil samples (0-15 cm depth) were collected from a 30-ha paddock with a history of arable cropping near Otane in Hawke's Bay. One hundred and five individual soil samples collected using a 45 x 45 m grid pattern to determine total N (and C), anaerobically mineralisable N (AMN) and mineral N. A six-month plant bioassay was then run in a greenhouse to quantify the N supplying capacity of the soils (expressed as net N mineralisation, converted to kg N/ha). Indicators of soil N supply across the samples exhibited substantial variability, and net N mineralisation calculated from the bioassay also showed significant spatial variations. Except for mineral N, other N supply indicators showed moderate to strong spatial dependence. The semivariograms for AMN, TN and net N mineralisation were well fitted by spherical and Gaussian models. Correlation of AMN ($R^2=0.32$, $\rho<0.001$) with net N mineralisation was similar to TN with net N mineralisation ($R^2=0.44$, $\rho<0.001$), suggesting that the AMN test did not provide a better estimate of N supplying potential in this study. The relationship between soil texture and indicators of N supply was also examined using 25 samples collected along two perpendicular transects within the paddock, showing TN and net N mineralisation were both positively correlated with clay content ($R^2=0.72$, $P<0.001$ and $R^2=0.48$, $P<0.001$ respectively). This result suggests that textural variation may be a useful factor in identifying potential variability in N supply patterns. Further testing is needed of these observations on a wider range of soils and conditions.

Introduction

Understanding spatial variability of soil N availability at a sub-paddock scale is important for achieving improved N use efficiency. Historically, soil fertility variability within a field has been ignored when making management decisions (Cook and Bramley 1998; Hedley et al. 2004). For example, within-field fertility variability is seldom considered when applying fertilizer, even though it is recognized that uniform, whole-field management may result in inefficient use of nutrient inputs (Johnson et al. 2003). Farmers in New Zealand are under increasing pressure to improve management of nutrients, especially N, to minimise losses to water by leaching and surface runoff. In the future, target nitrate leaching limits may be imposed for different categories of farms in several regions across New Zealand in response to the national policy statement on fresh water management. Adjusting N inputs to take account of within-field variability in N fertility may contribute to the optimisation of N fertiliser management and assist farmers to comply with regulations pertaining to nitrate leaching.

Geostatistical techniques coupled with geographic information system (GIS) technologies have substantial potential to characterise spatial patterns of soil properties at the within-field scale (Zhang et al. 2011). Kriging interpolation methods are a set of geostatistical techniques widely used to explore spatial structure and estimate variation at un-sampled locations (Burgess and Webster 1980; Webster and Oliver 2000). These spatial analysis techniques may contribute to the improvement in N management practice in arable cropping systems.

The main objectives of this study were to (1) quantify small-scale spatial variability of soil N supply potential in a paddock with a history of arable cropping, and (2) identify factors contributing to within-paddock variability in soil N indicators.

Materials and Methods

Site description

The experimental site was a rectangular field (950 m long x 300 m wide; ~30 ha) near Otane, in the Hawke's Bay region of New Zealand (S39°52′, E 176° 40′) that had a long history (> 10 years) of crop production. In the 4 years preceding sampling, the crop rotation included wheat, peas, squash, and barley and winter grass. The site had a flat to gently sloping topography, with average slope gradient <1%. At the time of sampling the paddock had been cultivated and was sown in maize.

Soil sampling and analysis

Samples (0–15 cm) were collected at regular intervals on a grid where sample points were separated by 45 m across the paddock and 45 m along the paddock (a total of 105 samples). Sub-samples were sieved (<4 mm) prior to chemical analysis. Mineral nitrogen (NH_4^+ and NO_3^-) was extracted in 2 *M* KCl and measured on a flow injection analyser (QuickChem 8000 FIA+, Lachat Instruments, Loveland, CO) using standard colorimetric techniques (Keeney and Nelson 1982). Anaerobically mineralisable N (AMN) was determined as the amount of ammonium-N produced during a 7-day anaerobic incubation at 40^{o}C (Keeney and Bremner 1966). Total soil C (TC) and N (TN) were determined using a LECO CNS2000 analyser. Particle size distribution was determined by separating three fractions (>50, 5–50, and <5 µm equivalent diameter) by sieving and gravity sedimentation (Gee and Or 2002) after dispersing 25 soil samples using an ultrasonic vibrator (20 g soil in 60 mL deionised water; 60 s sonication; power output 64 J s^{-1}).

A six-month plant bioassay was conducted to quantify the capacity of the soils to supply N via mineralisation. In a glasshouse, oats (*Avena sativum*) was grown to maturity in pots containing 1.5 kg of soil. Pots were watered every 1-3 days depending on evapotranspiration losses. Fertiliser N was not applied, so that all N taken up was derived for soil N (mineral N in the soil when oats were sown and N that mineralised during crop growth). Total N uptake by oats (including roots) was determined and the contribution of mineralised N was estimated after adjusting for initial and final soil mineral N.

Statistical analysis

Statistical parameters (including mean, standard deviation, coefficient of variation [CV], Kolmogorov Smirnov normal distribution test, skewness and kurtosis) were obtained with Rstudio. Geo-statistical analyses were conducted using GS$^+$7.0 (Gamma Design Software, LLC, Plainwell, MI). Spatial analysis and mapping of N availability indices and organic matter were carried out using ArcGIS 9.2 (ESRI Inc.).

Geostatistics has been widely used in spatial studies of soil characteristics (Trangmar, Yost, and Uehara 1985). Semivariogram analysis is the key method to evaluate spatial variability. In this case study, empirical semivariogram values for soil N availability indicators were obtained using the equation [$Equation$ 1]:

$$\gamma(h)=\frac{\mathbf{1}}{\mathbf{2N(h)}}\sum_{\mathbf{i=1}}^{\mathbf{N(h)}}[\mathbf{Z(Xi)}-\mathbf{Z(Xi+h)}]^{\mathbf{2}} \qquad (1)$$

where $\gamma(h)$ is the sample semivariance between all observations $Z(Xi)$, Z is the measured value at a particular location, *N(h)* represents the number of paired data at the distance h, and *(h)* is the lag distance that separates the total numbers of data pairs. The semivariogram can be fitted using spherical, exponential, or Gaussian models (*Eqs* 2–4), respectively:

$$\gamma(h)=\begin{cases} C_0+C\left[\frac{3h}{2a}-\frac{h^3}{2a^3}\right], & h\le a \\ C_0+C, & h>a \end{cases} \qquad (2)$$

$$\gamma(h)= C_0+C\ [1\text{-exp}(-\frac{h}{a})] \qquad h\geq 0 \qquad (3)$$

$$\gamma(h)= C_0+C\ \{1\text{-exp}\ (-\frac{h^2}{a^2})\} \qquad h\geq 0 \qquad (4)$$

where C_0 is the nugget, C+ C_0 is sill, and a is the correlation length.

The semivariance generally increases with increases in sample separation distance, before reaching an asymptote at a distance *a* (the range value). Samples separated by distances greater than *a* are considered to be spatially independent whereas, within the range, samples show greater similarity when they are nearer to each other. Variance that exists at a scale shorter than the field sampling distance is found at zero lag distance and is known as the nugget variance (C_0). The nugget variance reflects the uncertainty associated with sampling errors or smaller-scale variability. The partial sill (C) is the variance caused by factors such as parent material variability, and vegetation and topographic differences.

Results and Discussion

Classical statistics of soil N indicators

Although the paddock had an even topography (average slope gradient <1%) and had been managed uniformly for many years, substantial variability was observed in all measures of soil N availability (CV ranged from 14% for TN to 47% for net N mineralisation; Table 1). Estimates of net N mineralisation from the plant bioassay covered a very wide range (10 to 220 kg/ha), but about two-thirds (65%) of samples were within ± 20 kg/ha of the mean value of 93 kg/ha (Table 1). The wide range of values observed for net N mineralisation indicates that there was substantial within-paddock variability and, consequently, it may be possible to improve N use efficiency by subdividing the paddock into management units with differing N supply potential.

Table 1. Descriptive statistics of soil nitrogen (N) indicators at the experimental site in Hawke's Bay, New Zealand.

Soil properties	Min.	Max.	Mean	Std Dev.	CV%	Skewness	Kurtosis
Mineral N (µg/g)	20	109	58	17	29	0.538	0.639
AMN (µg/g)	38	176	112	30	27	-0.205	-0.145
TN (g/kg)	1.6	3.2	2.4	0.3	14	0.078	-0.327
Net N mineralisation (kg /ha)	10	225	93	43	47	0.551	0.494

AMN = anaerobically mineralisable N, TN = Total N

Geostatistical analysis of soil N indicators

In geostatistical methods, a normal distribution for the variables is required to avoid distortions of the data and low levels of significance (Webster and Oliver 2001). In this study, the Shapiro-Wilk test (sample size <2000) was used to check for normality of the data. The *P* values of TN, mineral N and AMN were more than 0.05, indicating that the data were normally distributed; however, the N mineralisation data were not and required transformation. After Box-Cox transformation ($\lambda=0.75$) the mineralisation data passed the normality test ($P=0.37$).

The nugget variance (C_0) as a percentage of sill variance (C_0+C) provides a measure of spatial dependence that can be classed as strong (<25%), moderate (25–75%), or weak (>75%). Except for mineral N, indicators of N supply showed moderate to strong spatial dependence and the semivariograms were well fitted using either the spherical or Gaussian models (Table 2).

Table 2. Geostatistical parameters for soil nitrogen (N) indicators at the experimental site in Hawke's Bay, New Zealand.

Soil properties	Semi var. model	Nugget C_0	Sill C_0+C	Range α (m)	Nugget/Sill (%)	Spatial dependence	R^2
Mineral N	N	N	N	N	N	N	0.16
AMN	Spherical	515	1031	418	50	moderate	0.70
TN	Gaussian	0.07	0.15	368	46	moderate	0.97
Net N mineralisation	Gaussian	628	1109	925	17	strong	0.96

AMN = anaerobically mineralisable N, TN = Total N

Spatial distribution of soil N indicators and implications for management

Spatial distribution maps for AMN, TN and net N mineralisation were obtained by ordinary kriging (Zhang et al. 2011) based on the semi-variogram parameters (Webster and Oliver 2000). Spatial distribution mapping of mineral N was achieved by the inverse distance weighting (IDW) interpolation method (Figure 1). AMN values showed a distinct spatial trend, with the largest values in the upper-middle northern and the lowest values in the southeast area of the paddock. A similar pattern was observed for TN and net N mineralisation, with the high values again in the northwest of the paddock. Unlike the other variables, mineral N did not show a clear spatial trend (Figure 1). The spatial distribution of TN showed a stronger correlation to net N mineralization ($R^2=0.44$, $P<0.001$) than did AMN ($R^2=0.32$, $P<0.001$). This indicated that AMN did not provide a better estimate of N supplying potential at a within-paddock scale (Figure 2). The wide range of values observed for net N mineralisation indicates that the supply of N to plants via mineralisation differs considerably within the paddock and, consequently, N use efficiency could be improved by subdividing the paddock into management units for N application. The range value, which indicates the distance beyond which sampling points are independent of each other, was as large as 925 m for net N mineralisation and ranged between 368 to 418 m for the TN and AMN.

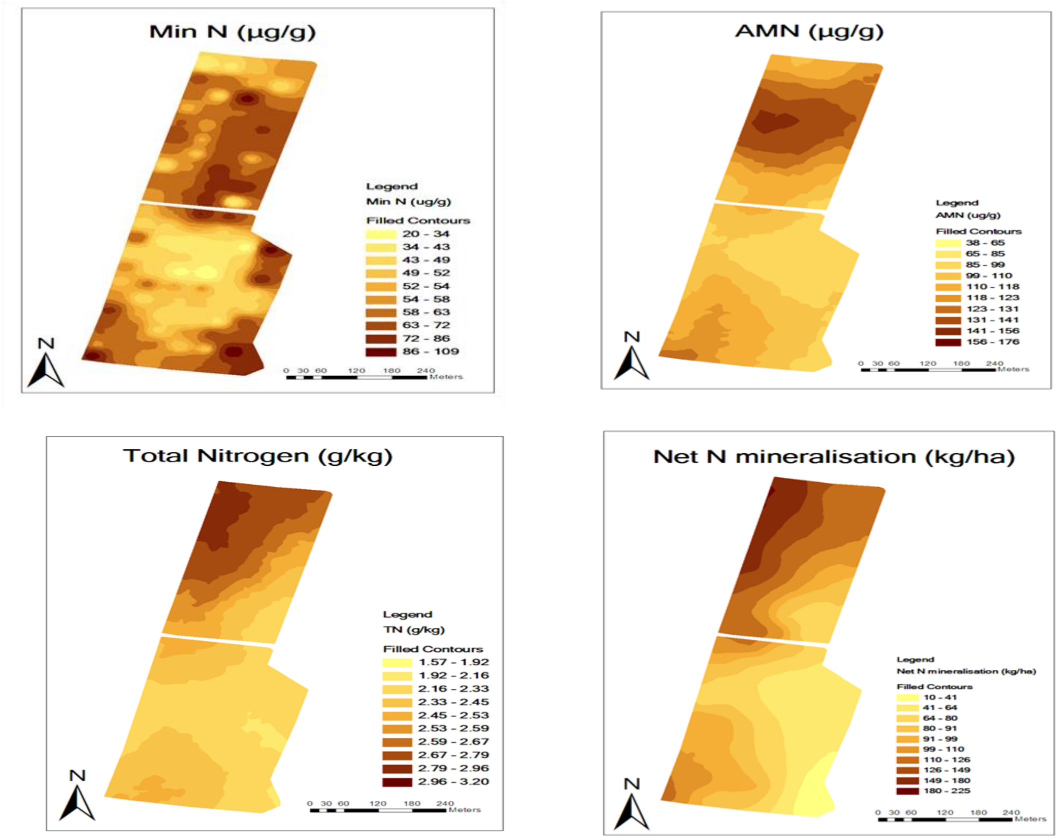

Figure 1. Spatial patterns of soil nitrogen (N) indicators at the experimental site in Hawke's Bay, New Zealand. AMN = anaerobically mineralisable N.

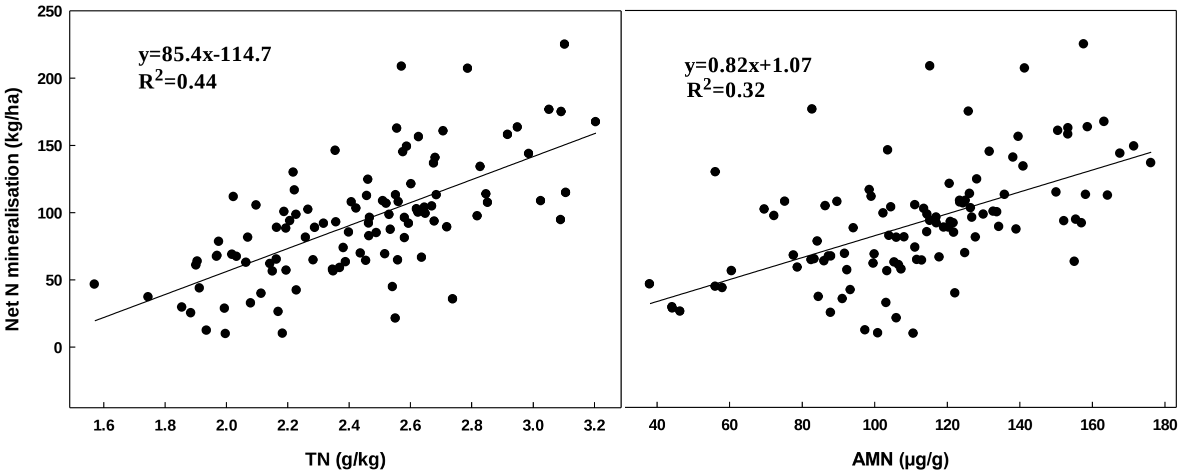

Figure 2. Relationship between soil total nitrogen (TN), anaerobically mineralisable N (AMN) and net N mineralisation over six-month bioassay using oats.

Correlation between soil N indicators and texture

To examine whether the spatial patterns in soil organic matter and net N mineralisation were related to textural variation, we performed textural analysis on samples collected along a single north-south and a single east-west transect through the paddock. These transects included samples with a wide range of organic matter and net N mineralisation values (total N ranged from 1.97 to 3.11 g/kg and N mineralisation from 42 to 176 kg/ha). The results revealed that there was considerable textural variation within the paddock. For example, the clay content (<5 µm fraction) ranged from 18% to 31%. There was a strong, positive relationship (R^2 = 0.74, $P<0.001$) between TN and the amount of fine (<5 µm) material (Figure 3), reflecting the tendency for organic matter to adsorb onto the surfaces of clay (Hassink 1997; Baldock and Skjemstad 2000). Our results were also consistent with the finding of Baxter & Oliver (2005), who showed that fine-textured areas within fields in Bedfordshire, UK, had greater quantities of organic matter than coarser areas. Soils with more organic matter and finer texture have greater biomass production potential because of their ability to store nutrients and water (Mzuku et al. 2005). There was also a significant correlation between clay content and N mineralisation (R^2 = 0.45, $P<0.001$), presumably because of the tendency for organic matter to increase as clay content increased (Figure 3).

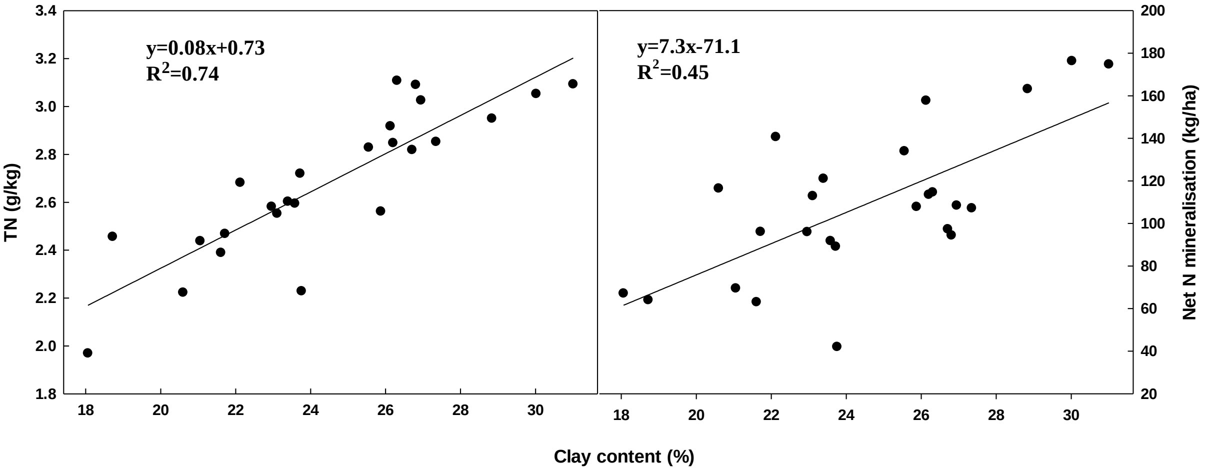

Figure 3. Relationship between soil clay content and soil total nitrogen (TN), net N mineralisation at the experimental site in Hawke's Bay, New Zealand.

Conclusions

Within-field indicators of soil N availability showed significant variability even though the entire paddock had been managed uniformly (i.e. the same fertility practices had been applied to the whole paddock) for many years. AMN, TN and net N mineralisation showed moderate to strong spatial autocorrelation and were well fitted by either a spherical or a Gaussian model. TN showed a stronger correlation to net N mineralization than AMN, suggesting that the AMN test did not provide a better estimate of N supplying potential in this study. Clay content appeared to explain some variability in soil N supply, but other unknown factors were clearly important. Spatial variability should be considered when designing site-specific fertiliser management practices. Improved practical methods for predicting soil N supply are needed to underpin the application of variable fertilizer rate strategies. Further work is needed to test and improve these observations for a wider range of soils and management conditions.

Acknowledgements

Research was funded through the New Zealand Ministry for Business Innovation and Employment Core Funding Agreement with Plant & Food Research under the Value from Variability and Land Use Change and Intensification (LUCI) programmes. We thank Chris Dunlop and Sarah Glasson for technical assistance.

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