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Updating guidelines for the interpretation of soil organic matter (carbon and nitrogen) indicators of soil quality for state of the environment monitoring (Envirolink project 1801-MLDC132)

Lawrence-Smith E, McNally S, Beare M, Curtin D, Lehto K

April 2018















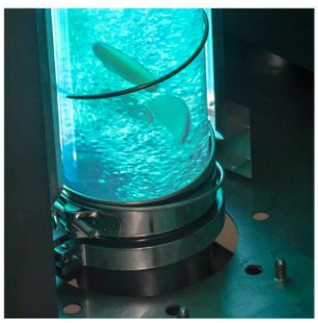


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EXECUTIVE SUMMARY

Updating guidelines for the interpretation of soil organic matter (carbon and nitrogen) indicators of soil quality for state of the environment monitoring (Envirolink project 1801-MLDC132)

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Total carbon (C) and potentially mineralisable nitrogen (N) are included in the seven key soil quality indicators recommended by the National Land Monitoring Forum (Hill & Sparling, 2009) for inclusion in Regional Council State of the Environment (SoE) monitoring programmes.

Recent New Zealand research has resulted in a new method to estimate the maximum amount of C an individual soil can store (i.e. C stabilisation capacity), and an alternative method for predicting the potential of soils to supply plant-available N. Both of these methods were developed for soil samples from 0–15 cm in depth. As the sample depth most commonly used for regional SoE and national land domain reporting is 0–10 cm, the new methods required calibration for this depth. Up to 190 archived soil samples from Regional Council SoE monitoring programmes were used to validate the new methods. The samples represented a range of soil orders (Allophanic, Brown, Gley, Pallic, Pumice, Recent) and included samples from pastoral and cropping land uses. Key findings are summarised below. Recommendations for further work are included in the report.

Soil C stabilisation capacity

- Fine fraction C (FFC) represented 80% of total C in the 0–10 cm soils compared with 85% in the 0–15 cm soils studied by McNally et al. (2017). This difference was expected given particulate organic matter is more concentrated near the soil surface so comprises a greater proportion of total C in shallow soil samples.
- Soil C stabilisation capacity and saturation deficits were calculated for the Council-provided samples using the method of McNally et al. (2017) utilising the FFC proportion appropriate for 0–10 cm. The model coefficients for 0–10 cm depth derived using the Council dataset were similar to the coefficients previously published for 0–15 cm depth.
- Data were interrogated to see if a simpler model (without the need for measured pyrophosphate-extractable aluminium) would be sufficient for application in a SoE context. Extractable aluminium contributed very little to the model fit with the simple model providing a slightly more conservative estimate of the soil C stabilisation capacity.

We recommend SoE soil quality monitoring programmes begin implementing a new indicator of soil C status based on the current concentration of soil C expressed as a percentage of the projected soil C stabilisation capacity (upper limit of soil C stabilisation) of individual soils. This indicator of soil C status could be added to the current suite of soil quality indicators with very little additional analytical cost and time, as it would only require measurements of total soil C concentrations (already included in the suite of recommended soil quality indicators) and measurement of the water content of air-dried soils (as a proxy for soil specific surface area).

The following steps are important to adopting this new indicator of soil C:

1. Develop and apply a consistent methodology for processing all soils and analysing their total C content and air-dried water content. A standardised approach to determining air-dried water content is important to obtaining the correct estimates of the soil C stabilisation capacity. Ideally, this would involve all samples (field moist) being dried using the same methodology (i.e. 25°C) and laboratory. At an absolute minimum, the temperature at which samples were air-dried and the corresponding air-dry water content should be recorded.
2. Review and analyse existing data to establish scientifically defensible and practical target ranges for soil C contents relative to the upper limit of soil C stabilisation for individual soils.
3. Ensure that total C content is measured using the same approach every time (i.e. Dumas combustion and not near infrared (NIR) measurement).

Ability of soil to supply N

- Four indicators were evaluated for their ability to predict N mineralisation potential as assessed by a 14-wk aerobic incubation: Hot-water-extractable N (HWN), Anaerobically-mineralisable N (AMN), Total N and Particulate organic matter N (POM-N).
- The two best indicators of potentially mineralisable N (PMN) were HWN and AMN, which explained 87 and 92% of the variation in PMN, respectively.
- HWN is faster to measure than AMN, and the available evidence suggests analysis of HWN is more repeatable than AMN, thereby making HWN the preferred indicator of a soil's ability to supply N.

We recommend SoE soil quality monitoring programmes begin implementing HWN as a new indicator of the capacity of soils to supply plant-available N (i.e. PMN). The following steps are important to adopting this new indicator of PMN:

1. Develop and apply a consistent methodology for processing soils and analysing HWN and hot-water-extractable C (HWC). Plant and Food Research has well established protocols and technical expertise in HWN and HWC testing. The commercial laboratories have expressed a strong interest the HWC and HWN tests and we have offered to share our expertise with them. We would be able to offer one or both of these tests for Regional Council SoE monitoring until such time that one or more of the commercial labs is able to offer the tests.
2. Review and analyse existing data to establish scientifically defensible and practical target ranges for HWN relative to values obtained for appropriate benchmark soils.

In addition to the above, we recommend Councils introduce a quality control system whereby a subsample from a known homogenous soil is analysed alongside all other samples, consistent across regions and analysis years to ensure greater confidence in trends over time and consistent methodology across all New Zealand monitoring sites. It would be advantageous for Councils to archive a subsample of soil from each SoE monitoring site where this is not already being done.

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1 INTRODUCTION

The New Zealand Institute for Plant and Food Research Ltd (PFR), in collaboration with other research providers, has recently developed new methods to estimate the maximum amount of carbon (C) that individual soils can store (i.e. C stabilisation capacity). This allows the current C content of a soil to be expressed as a function of its maximum C stabilisation capacity, rather than an arbitrary target value. The methodology was developed for soil samples from 0–15 cm depth and focused on pasture and arable cropping land uses in eight key agricultural regions of New Zealand.

PFR has also developed a reliable and rapid test to predict the quantity of potentially mineralisable N in soils, based on a measurement of hot-water-extractable organic N (HWN). Similarly, the methodology was developed for soil samples from 0–15 cm depth and included many of the same pasture and arable cropping sites used in the soil C stabilisation study.

Total C and potentially mineralisable N (PMN) are included among the seven key soil quality indicators recommended by the National Land Monitoring Forum (Hill & Sparling, 2009) for inclusion in Regional Council monitoring programmes. Total soil C content is routinely measured by Dumas combustion, though is increasingly being measured using near infrared (NIR) measurement in some laboratories. In New Zealand, the commercially available anaerobically-mineralisable N (AMN) test is routinely used as an indicator of PMN, although AMN has not, until recently, been calibrated against other more direct measures of PMN or validated for use in N management under field conditions.

Uptake and use of the new methods described above for routine State of Environment (SoE) monitoring requires that they are tested and calibrated for 0–10 cm soils, the sample depth most commonly used for regional SoE and national land domain reporting. Marlborough District Council, together with members of the Land Monitoring Forum and staff from PFR, were successful in obtaining an Envirolink Advise Grant in order to achieve this. A total of 190 archived soil samples from SoE monitoring sites across New Zealand were analysed for this purpose.

This report briefly describes the relevant research advancements and our calibration of the proposed new indicators for Regional Council application on 0–10 cm soil samples. It also includes recommendations for future work and guidelines to improve practical interpretations of the indicators.

2 SOIL C STABILISATION CAPACITY

2.1 Introduction

Soil C is a key soil property and plays an important role in many ecosystem services. Maintaining soil quality relies on adequate soil C levels. It is now generally accepted that soils have a finite ability to store stable C, which is known as the C stabilisation capacity or upper limit. This capacity varies depending on the physical and chemical characteristics of individual soils. The ability to determine whether a soil is near this upper limit is important in identifying soils that a) have lost significant quantities of soil C, b) are vulnerable to C loss or c) have the ability to gain additional soil C.

Recent studies have demonstrated that the C stabilisation capacity of 0–15 cm New Zealand soils is related to the specific surface area and extractable aluminium content of the mineral soil (McNally et al., 2017; Beare et al., 2014). They also provided evidence that these factors can be used to predict the upper limit of soil C stabilisation. Most of the current Regional Council soil quality monitoring programmes are based on 0–10 cm soil samples. Therefore, our objective was to derive new model coefficients to predict the upper limit of C stabilisation (and saturation deficits) for a selection of 0–10 cm soils obtained from Regional Council archives. These results will be compared with those of McNally et al., (2017), and a case study presented to describe how this method may be used as an updated tool for soil quality monitoring.

2.2 Methods

2.2.1 Calibration soil samples

Soil sample selection was restricted by the availability of archived samples from Regional Council soil quality monitoring sites. Samples were selected to represent a wide range of soil orders (Table 1), total C concentrations (0.6 to 14 mg g^{-1}) and management practices. Samples were sourced from the archives of the Auckland Regional Council (n=15), Bay of Plenty Regional Council (10), Waikato Regional Council (23), Hawkes Bay Regional Council (27), Taranaki Regional Council (12), Greater Wellington Regional Council (52), Marlborough District Council (42), and Environment Canterbury (9). For the purposes of this report, these samples will be subsequently referred to as the "Council dataset".

Table 1. The number of soil samples provided by participating Regional Councils that represent different soil order and land use combinations.

Soil order	Pasture		Crop			Total
	Dairy	Drystock	Horticulture	Vegetable	Arable	
Allophanic	10	7	5	2	4	28
Brown	10	11	3	3	6	33
Gley	8	9	4	6	9	36
Pallic	8	12	10	3	9	42
Pumice	10	4	0	0	1	15
Recent	8	7	4	10	7	36
Grand Total	**54**	**50**	**26**	**24**	**36**	**190**

2.2.2 Laboratory methodologies

The participating Regional Council's provided air-dry samples of soils that they had held in storage (i.e. archived). Soils were processed (samples sieved <2 mm) and placed in an air-drying cabinet for a minimum of 7 days to standardise air-drying conditions. Air-dried soils were then subsampled to determine particulate organic matter and fine fraction C (FFC), specific surface area, total C, and pyrophosphate-extractable aluminium (Al-p) as follows.

Particulate organic matter and fine fraction C content (FFC)

Particulate organic matter (POM, i.e., organic matter in the >50-µm particle size fraction; (Cambardella and Elliott, 1992; Gregorich et al., 2006)) was separated after dispersion of soil (15 g) by sonication for 45 s with energy equivalent of 64 J s^{-1} (Qiu et al. 2010). Allophanic soils required 2 sonication events to achieve full dispersion of soil. Between each sonication event these samples were placed in a cold water bath (10 min) to dissipate sample heat. Once dispersed, soil was washed on a 53-µm sieve until the draining water was clear. Material retained on the sieve was dried at 60°C, weighed, ground using a mortar and pestle, and a subsample analysed for C and N using a LECO analyser.

The FFC content (<53 µm) was calculated as the difference between total soil C and POM-C.

The ratio of FFC to total soil C (i.e. FFC/TC) was determined for all soils.

Specific surface area

Council-supplied soils were air-dried in a temperature-controlled cabinet at 25°C for 7 days. Air-dried water content of all soils was determined by oven drying a subsample (5–10 g) at 105°C for 16 h. The specific surface area (SA) of soils was calculated as described by Parfitt et al. (2001):

SA (m^2 g^{-1}) = 2 (m^2 g^{-1} soil) * water content of air dry soil (g_{water} g_{soil}^{-1})

To ensure that soils from the Council dataset were not affected by any previous air drying conditions (e.g. temperature and humidity), a subset of soils ('incubation subset' N=54) were rewetted and the surface area determined using the standardised conditions outlined above. The surface area values from this subset were compared to the surface areas determined from the air-dried soils as received from the Councils.

Extractable aluminium

Al-p was measured by the standard method of Blakemore et al. (1987). Briefly, vials containing 0.35 g soil (air-dry, <2mm) and 35 mL of pyrophosphate (0.1 M) were shaken end-over-end for 16 h, before centrifuging and filtering prior to analysis. Aluminium in the extracts was determined by inductively coupled plasma-optical emission spectroscopy.

2.2.3 C stabilisation capacity

As discussed above, the C stabilisation capacity of a soil is defined as the maximum amount of C that a soil can store in a stable form. The stabilisation capacity of each soil was determined using a 90th quantile regression model (where $\tau = 0.9$) as described by McNally et al. (2017). Model coefficients for the C stabilisation capacity of the 0–10 cm archived soils were generated using the model:

Log(FFC) = Log(SA) + Log(Al-p) +Allophanic + Log(SA)*Allophanic + Constant

The extra terms for Allophanic soils account for the higher surface area and C concentrations in these soils. For non-Allophanic soil, the model was simplified to:

Log(FFC) = Log(SA) + Log(Al-p) + Constant

Back transformation of a soil's 90th quantile value (i.e. Log(FFC)) was required to calculate its saturation deficit:

FFC_{SC} = exp[Log(FFC)].

2.2.4 Saturation deficit

The amount of additional C that a soil can store in a stable form is known as the soil C saturation deficit (SD). It is estimated as the difference between the C stabilisation capacity (FFC_{SC}, i.e. dependant on site-specific soil properties) and the current C content of the fine fraction:

$SD = FFC_{SC} - FFC_{predicted}$

For the purposes of this calculation we have used the predicted value of FFC ($FFC_{predicted}$) from the ratio derived between the measured FFC and total C for all soils. The predicted FFC value was used to reflect what would likely be done if this approach was used as an indicator for soil quality monitoring.

2.3 Key findings and discussion

The FFC for the soils in the Council dataset (0–10 cm) represented 80 ± 1% of total C (Figure 1) compared with 85% in the soils (0–15 cm) studied by McNally et al. (2017). This difference was expected given that POM (>53 µm) is concentrated near the soil surface so comprises a greater proportion of total C in shallower samples. The fine fraction held a greater proportion of total C in cropped soils (mean = 85 ± 1%) compared to pastoral soils (mean = 77 ± 1.6%). The higher proportion of FFC in cropped soils was also expected given that C loss upon land conversion from pasture to crop occurs disproportionately from the coarse fraction (i.e. POM) (McNally et al. 2018). There was also greater variability in the FFC of pasture soils compared to cropped soils (Figure 1) reflecting the greater variability in the POM under pasture soils.

While an actual measurement of C in the fine fraction is preferred for the calculation of the C saturation deficit, we acknowledge that this is not a routine laboratory analysis and that the value can vary depending on fractionation method. Therefore, based on the results presented, we recommend estimating the FFC using a nominal value of 80% of total C (for 0–10 cm soil). The recommended nominal value will be used to estimate the FFC for the remainder of this report.

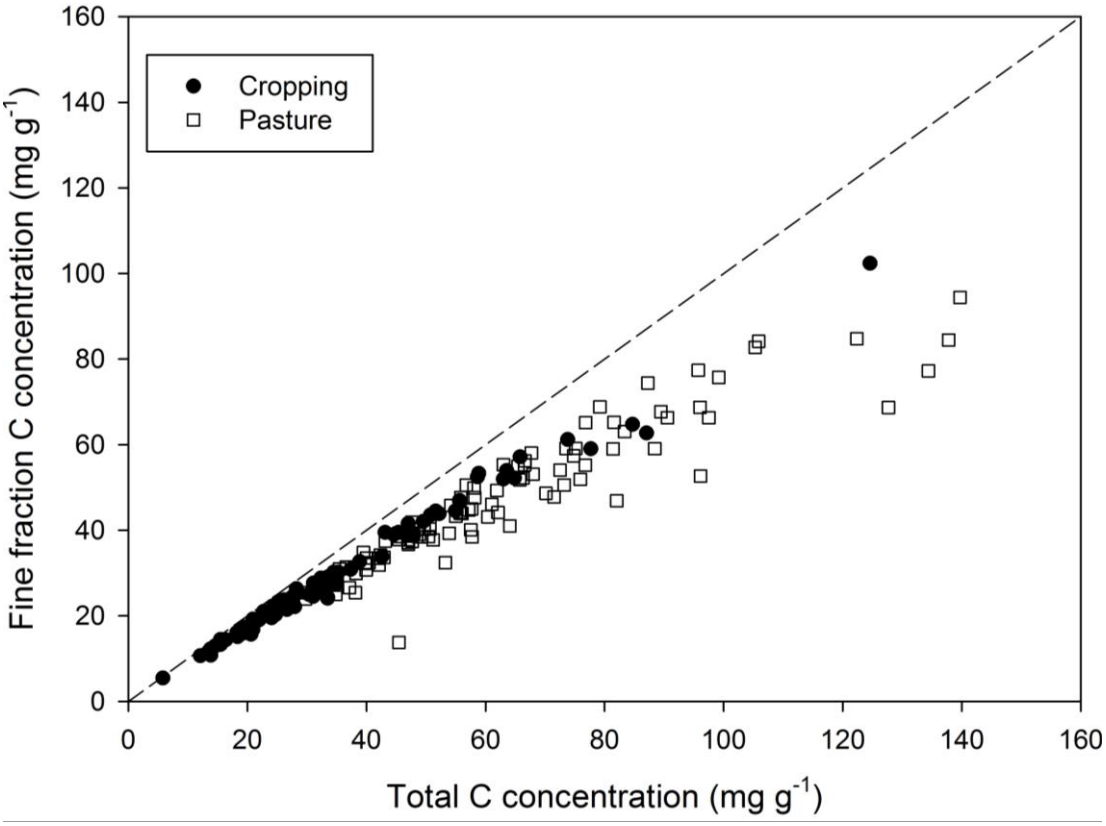

Figure 1. The relationship between total C and fine fraction (<53 µm) C concentration (mg C g^{-1} soil) for soils (0–10 cm) in the Council dataset. The dashed line represents the 1:1 line.

The stabilisation capacity for FFC was calculated for all samples in the Council dataset using the model defined by McNally et al., (2017) (Figure 2, Table 2). The model coefficients for the 0–10 cm depth derived using the Council dataset were similar to the coefficients presented in McNally et al., (2017) for soils sampled to 15 cm (Appendix I, Figure 9). This similarity in the predicted upper limit using either model suggests that the published 0–15 cm coefficients (McNally et al., 2017) would be appropriate for the 0–10 cm depth (ensuring FFC is calculated as 80% of Total C).

We envisioned that the soil C stabilisation capacity and saturation deficit values derived from the calculations described above for individual soils could be used as potential soil quality indicators. However, we acknowledge that extractable aluminium is expensive to measure and this may be an obstacle to implementation of our approach to estimate saturation deficit. Therefore, we ran a simplified 90th quantile regression using only surface area and the term to differentiate between Allophanic and non-Allophanic soils ("Allophanic" term in Table 2). Results from this simplified model demonstrated that, for the Council dataset (0–10 cm depth), the predicted stabilisation capacity was similar to that estimated using the McNally et al., (2017) model (Figure 2). Thus, extractable aluminium contributed very little to the overall fit of the stabilisation capacity model.

To check this result, we applied a forward selection procedure to select the model that best explained the variability in the FFC from the available explanatory variables used by McNally et al. (2017). The simplest model that explained the most variability in the FFC for these soils (Table 2) was:

Log(FFC) = Log(SA) + Allophanic + Log(SA)*Allophanic + Constant

Therefore, we concluded that the stabilisation capacity of all soils could be calculated based on surface area alone, without the need to measure extractable aluminium.

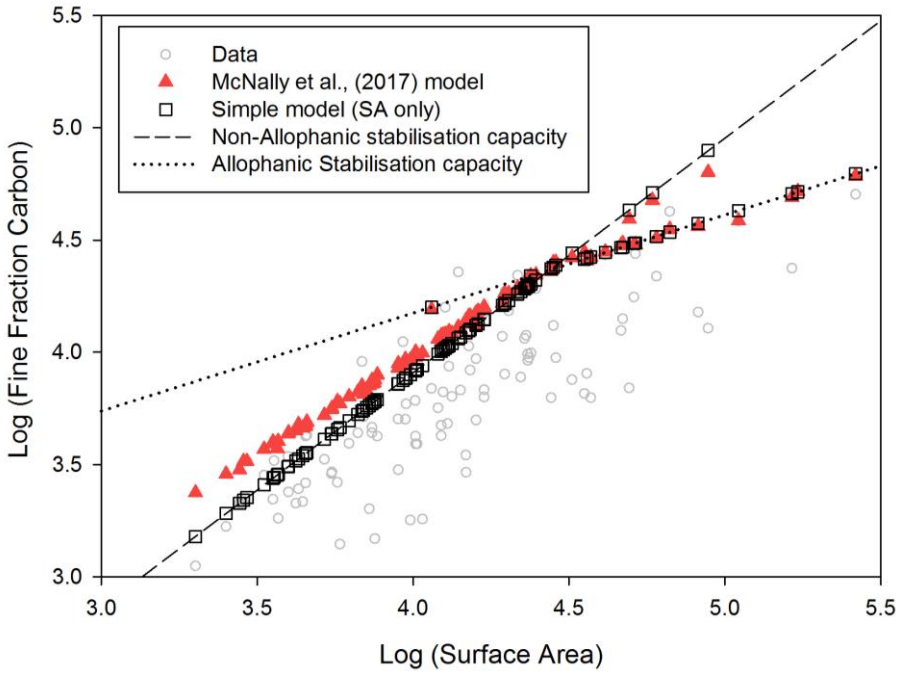

Figure 2. The relationship between the fine fraction C concentration and surface area for the Council dataset calculated using either the McNally et al. (2017) model (red triangles) or the simple model (open squares). The dotted line represents the stabilisation capacity for Allophanic soils using the simple model, and the dashed line represents that of non-Allophanic soils. The open circles are measured data for the Council dataset.

Table 2. Model coefficients of the 90th quantile regression for predicting the stabilisation capacity of fine fraction C (0–10 cm) using the McNally et al., (2017) model or the simple model.

Model	Variables	Estimates	*P*
McNally et al., (2017)	Intercept	0.61 [-0.71, 1.84]	0.366
	LogSA	0.85 [0.58, 1.13]	<0.001
	Log Al-p	0.03 [-0.13, 0.18]	0.687
	Allophanic	1.92 [-1.02, 3.88]	0.161
	LogSA*Allophanic	-0.44 [-0.83, 0.20]	0.136
Simple	Intercept	-0.27 [-0.80, 0.16]	0.257
	LogSA	1.05 [0.95, 1.18]	<0.001
	Allophanic	2.70 [0.17, 4.13]	0.015
	LogSA*Allophanic	-0.61 [-0.93, -0.11]	0.008

Saturation deficit values calculated using the original McNally et al., (2017) model and the simple model are in good agreement (Appendix I, Table 11). The simple model provides a slightly more conservative estimate of the soil C saturation deficits. Use of the simple model would be appropriate if used as an indicator as we outline in section 2.4.

Overall, Allophanic soils had higher mean soil C saturation deficits than the other soil orders despite having the highest concentrations of C (Figure 3). The saturation deficits of pasture soils were lower than those under cropping (Figure 4; Appendix I, Table). In general, the deficit in soils under cropping was 1 to 3 times greater than that of pasture soils, with Allophanic soils showing the greatest difference between these land uses. These results are consistent with those reported by McNally et al. (2017) who demonstrated that cropping soils (0–15 cm) had 1–1.9 times the deficit of pasture soils.

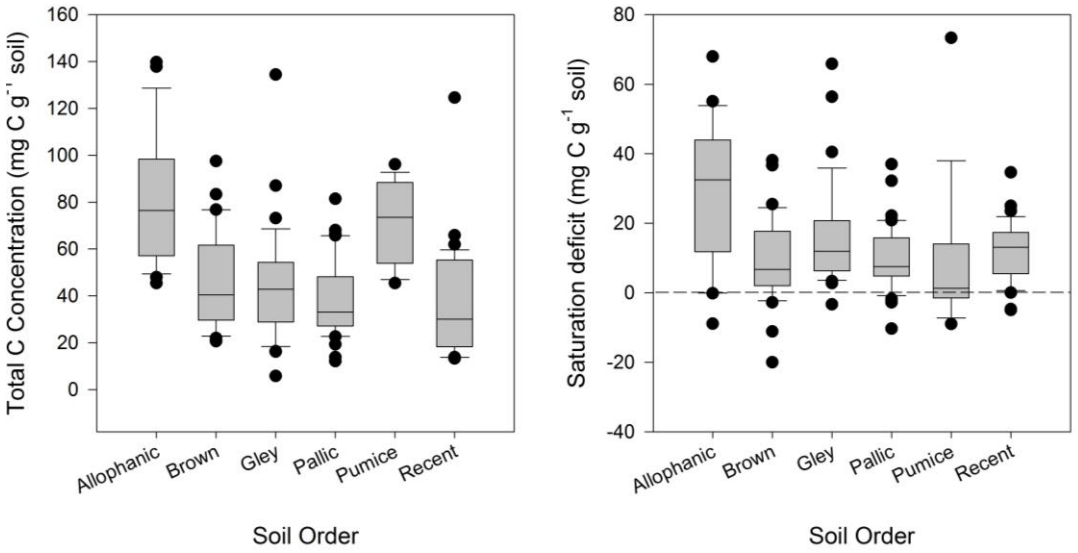

Figure 3. Total C concentration and C saturation deficits of soil samples from the Regional Council soil archive. The saturation deficits are calculated using the surface areas as received from the Councils. The dashed line represents a saturated soil.

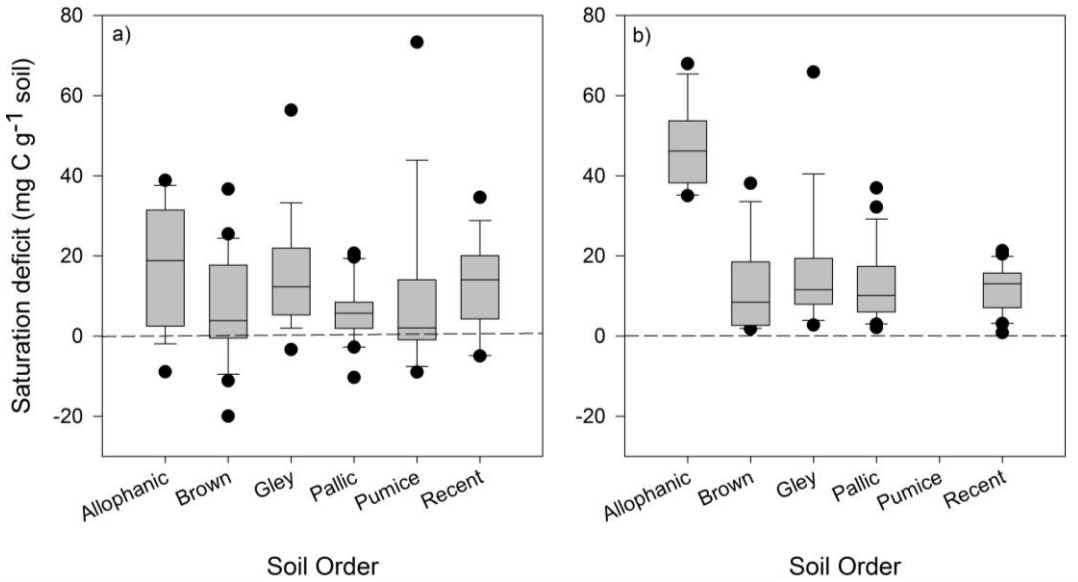

Figure 4. C Saturation deficits for all Soil orders under either a) pasture or b) cropping. The saturation deficits are calculated using the surface areas as received from the Councils. The dashed line represents a saturated soil.

2.4 Target range

The current recommend soil C target ranges for SoE monitoring are given in Table 3. Sites with C concentrations below the "depleted" level would currently be reported as "outside the target range". Applying these targets to the 190 Council-provided soils, 30 (38%) of the cropping soils were outside the target range, while no pasture soils were outside this target range (Table 4). However, we suggest that the current target ranges fail to recognise that soils have very different capacities to stabilise soil C and, therefore, differ in the extent to which they are already near saturation and have no ability to reach "ample" levels. As a consequence these soils would be reported to have lower soil quality (based on soil C) despite having reached their capacity to store C. Conversely, certain soils may have C concentrations greater than the current target range despite having large saturation deficits. For example, all Allophanic soils in the Council dataset would fall into the "normal" to "ample" categories (based on the C contents) and would not be reported as depleted. The results of this study demonstrate that Allophanic soils under cropping have large saturation deficits and are therefore significantly depleted in C.

As a case study to demonstrate how the current target range category of "ample" may not be an achievable target for many sites in the Council dataset, we estimated the Total C for each soil when FFC equalled the stabilisation capacity (section 2.2.3, calculated using the full model which includes Al-p and provides the highest stabilisation capacity estimates, i.e. the best chance of reaching the "ample" category). The estimated Total C, referred to here as TC_{MAX}, was compared to the "ample" category. For approximately 50% of the soils, TC_{MAX} was lower than the "ample" category (Table 5); theoretically these soils wouldn't be able to store enough stable C (i.e. mineral-associated C) to achieve the "ample" category concentrations of total C, even in the absence of production limitations.

Table 3. Current Total Carbon target ranges (% w/w) as reported in Hill and Sparling (2009). Soil quality monitoring. In: Land and Soil Monitoring: A guide for SoE and Regional Council Reporting. Land Monitoring Forum, New Zealand.

	Very depleted	Depleted	Normal	Ample	
Allophanic	0.5	**3**	4	9	12
Semi-arid, Pumice & Recent	0	**2**	3	5	12
Organic			exclusion		
All other soils	0.5	**2.5**	3.5	7	12

Table 4. Numbers of sites from the current study that fall into each category based on the Hill and Sparling (2009) target ranges.

Soil order	n	Very depleted		Depleted		Normal		Ample		Above ample
		Pasture	Crop	Pasture	Crop	Pasture	Crop	Pasture	Crop	
Allophanic	28	0	0	0	0	9	11	4	0	4 Pasture
Semi-arid, Pumice and Recent	51	0	10	1	6	9	2	19	3	1 Crop
Organic					Exclusion (No Data)					
All other soils	111	0	20	7	21	44	11	6	1	1 Pasture
Total	**190**	**0**	**30**	**8**	**27**	**62**	**24**	**29**	**4**	**6**

Table 5. Comparison of TC_{MAX} to the "Ample" category of the Hill and Sparling (2009) target ranges, where TC_{MAX} is the estimated the Total C for each soil if fine fraction C (FFC) equalled the stabilisation capacity.

Soil order	"Ample" category Total C (%w/w) for	Numbers of sites in the Council data set	
		TC_{MAX} > "Ample"	TC_{MAX} < "Ample"
Allophanic	>9	27	1
Brown	>7	10	23
Gley	>7	13	23
Pallic	>7	9	33
Pumice	>5	15	-
Recent	>5	16	20
Total		90	100

In order to apply the saturation deficit concept, Councils would need to identify a new "critical/acceptable" value to continue "by exception" reporting. As an example of how the saturation deficit might be used, we suggest dividing the saturation deficit range into four categories (Table 6); <40% of upper limit ("Very depleted"), 40–60% of upper limit ("Depleted"), 60–80% of upper limit ("Good"), and >80% of the upper limit ("Excellent"). Using this approach, no pastoral soils had C contents below 40% of their upper limit, while 13 (12%) had C contents between 40–60% of their upper limit. For cropping soils, 10 (12%) had C contents <40% of their upper limit, while an additional 33 (38%) had C contents in the 40–60% range.

While it may be unrealistic to expect that soil C could be increased at all sites to achieve saturation (100% of the relevant upper limit), the upper limit does provide a measure of the potential for soils to gain C under a best-case scenario. Challenges in raising soil C towards the upper limit include having insufficient C inputs from plant production (due to climatic factors such as temperature, sunshine hours, inadequate rainfall/irrigation) or a lack of available nutrients (e.g., N, P, K)). We suggest that including the upper limit and saturation deficit in soil quality assessments would be useful for estimating the potential C gain that could be achieved in these soils.

Table 6. Possible application of saturation deficit target range categories to describe fine fraction soil C status as calculated using surface areas derived from the soil samples as received from the Councils.

Soil order	n	<40% of UL "Very Depleted"		40–60% of UL "Depleted"		60–80% of UL "Good"		>80% of UL "Excellent"	
		Pasture	Crop	Pasture	Crop	Pasture	Crop	Pasture	Crop
Allophanic	28	0	2	3	8	6	1	8	0
Semi-arid, Pumice and Recent	51	0	2	6	7	5	8	18	5
Organic					Exclusion (No Data)				
All other soils	111	0	6	4	18	18	15	36	14
Total	**190**	**0**	**10**	**13**	**33**	**29**	**24**	**62**	**19**

UL = upper limit.

2.5 Implementation and further research requirements

The ability to quantify the C status of a soil relative to its C storage potential would improve the scientific rigor and potential application of soil quality assessments (assuming the saturation deficit model is fully validated). We are currently conducting experiments to test some of the key assumptions underpinning the saturation deficit concept. These include a 6-month study in which soils with differing saturation deficits are incubated with differing amounts of isotopically labelled C, to determine if the stabilisation of new C is a function of a soil's saturation deficit.

We have highlighted some examples where we think the saturation deficit approach provides improvements on the existing Total C indicator method (Table 7). However, one limitation of this approach is that the temperature at which samples are air-dried (and subsequent handling performed) is critical to determining the surface area and stabilisation capacity. Evidence from soils within the "incubation subset" lead us to suspect that some soils supplied by the Councils have been previously air-dried at temperatures higher than 25°C, resulting in lower surface areas than if they had been dried at 25°C (Figure 5). The surfaces areas derived after rewetting soils in the incubation subset were approximately 16% greater than the surface areas derived from the samples as received from the Councils (Figure 5).

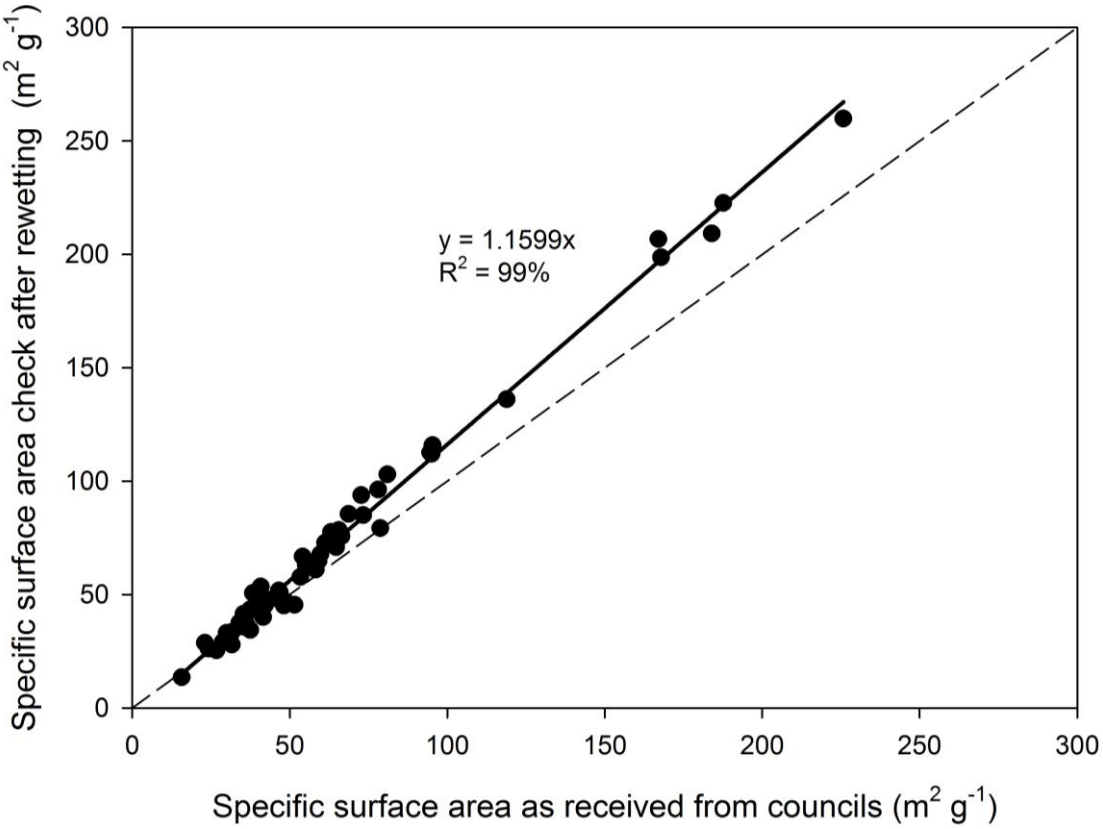

Figure 5. The relationship between the specific surface areas of soils within the incubation subset calculated as received from the Councils compared to calculation after rewetting.

PFR has data on the relationship between air-dried water content across various temperatures and the estimated specific surface area calculated at these temperatures. If a soil is dried at a higher temperature (e.g. 35°C compared to 25°C) the surface area estimation is lower, resulting in an underestimation of the corresponding stabilisation capacity. Consequently, this underestimation would result in some soils being deemed to be closer to their upper limit and hence given a "better" score in the target range approach outlined above. This issue is

highlighted for various soils (e.g. SOE_Soils_Site29; SOE_Soils_Site70; LAND_SITE27) in Table 7, whereby the target range category originally reported was revised downwards as a result of re-estimating the stabilisation capacity (from rewetting data). As shown in Table 8, the revised specific surface area data changed the distribution of sites in each of the target range categories, where the number of sites in each target range, as determined by the specific surface area of the Council-supplied soils, was compared to the rewetted samples from the "incubation subset of 54 soils". Relationships between air-dried water content and air drying temperature may be useful for standardising moisture contents to 25°C after-the-fact.

Table 7. Specific examples of anomalies between the existing State of Environment C monitoring targets and the proposed C saturation method.

Sample ID	Soil order	Land use	Total C (%)	Current target category	Proposed new target category	New target category (Surface area check)[1]
EW 05-02, 93	Allophanic	Cropping	5.1	Normal	Depleted	ND
SOL000093	Allophanic	Pasture	9.6	Normal	Excellent	ND
SOE_Soils_Site29	Pallic	Cropping	2.3	Very depleted	Excellent	Good
SOE_Soils_Site70	Recent	Cropping	2.2	Depleted	Excellent	Good
EW07-22, 122	Recent	Pasture	5.6	Normal/Ample	Depleted	ND
EW08-19, 137	Brown	Pasture	6.0	Normal	Depleted	ND
LAND_SITE76	Brown	Cropping	6.4	Normal	Depleted	Depleted
LAND_SITE27	Gley	Pasture	3.5	Depleted/Normal	Excellent	Good

[1] Result derived from the recalculation of stabilisation capacity using surface areas calculated from the subset of soils that were rewetted. ND = Not determined.

Table 8. Number of sites in each target range category determined from specific surface area at 25°C as received from the Councils or determined after rewetting of samples from the "incubation subset of 54 soils".

	Very Depleted	Depleted	Good	Excellent
Surface area determined from soils as received from Council	25	10	13	6
Surface area calculated following rewetting of soils	10	25	16	3

Based on the results outlined above, we recommend that New Zealand's SoE soil quality monitoring programmes begin implementing a new indicator of soil C status based on the current concentration of soil C expressed as a percentage of the projected soil C stabilisation capacity (upper limit of soil C stabilisation) of individual soils. This indicator of soil C status could be added to the current suite of soil quality indicators with very little additional analytical cost and time, as it would only require measurements of total soil C concentrations (already included in the suite of recommended soil quality indicators) and measurement of the water content of air-dried soils (as a proxy for the soils specific surface area).

The following steps are important to adopting this new indicator of soil C:

1. Develop and apply a consistent methodology for processing all soils and analysing their total C content and air-dried water content. A standardised approach to determining air-dried water content is important to obtaining the correct estimates of the soil C stabilisation capacity. Ideally, this would involve all samples (field moist) being dried using the same methodology (i.e. 25°C) and laboratory. At an absolute minimum, the temperature at which samples were air-dried and the corresponding air-dry water content should be recorded.
2. Review and analyse existing data to establish scientifically defensible and practical target ranges for soil C contents relative to the upper limit of soil C stabilisation for individual soils.

The routine collections of these data going forward would allow further testing and validation of the method to ensure that it is robust and scientifically defensible.

3 ABILITY OF SOIL TO SUPPLY N

3.1 Introduction

Optimal nitrogen (N) management is limited by our inability to predict the amount of N a soil can supply via mineralisation. The best available evidence suggests that the N mineralisation potential of New Zealand soils can range between about 40 kg N/ha/yr and several hundred kg N/ha/yr. There is a pressing need to find reliable and rapid N mineralisation tests in order to improve N fertiliser use efficiency and reduce environmental consequences of N loss via leaching and gaseous emissions. The "gold standard" soil N mineralisation test is a 14-wk aerobic incubation, but this is not suited to routine use in commercial laboratories. This test represents the amount of N that could be mineralised from a soil under optimal conditions of temperature and moisture, which is often referred to as potentially mineralisable N (PMN). For many years NZ has used the anaerobically mineralisable N (AMN) test as an approximation of PMN, although the AMN test has not been calibrated against the gold-standard method or validated for use in N management under field conditions. Recent research by Curtin et al. (2017) using 130 NZ soils (0–15cm depth) found a stronger relationship between hot-water-extractable organic nitrogen (HWN) and the gold standard PMN method than for AMN and PMN. The HWN test recommended from their research and discussed below was based on a single hot water extraction.

Our objective was to evaluate the ability of HWN and AMN to predict N mineralisation as determined by a 14-wk aerobic incubation (the gold standard PMN method) based on 0–10 cm soil samples obtained from the Regional Council sample archives. The results are compared to the findings of Curtin et al. (2017).

3.2 Methods

3.2.1 Calibration soil samples

Practical limitations of running a 14-wk aerobic incubation restricted our analysis to 54 sites. The quantity of soil required meant many sites used in the Saturation deficit study (Section 2) were unsuitable for this N study owing to sample availability. A total of 54 soils were selected to represent a broad range of major agricultural soil orders and land uses across New Zealand (Table 9). Total C concentration ranged from 0.6 to 14 g kg^{-1} and included samples from the following regions: Auckland Regional Council (n=3), Bay of Plenty Regional Council (1), Waikato Regional Council (9), Hawkes Bay Regional Council (11), Greater Wellington Regional Council (12), and Marlborough District Council (18).

Table 9. Soils used to characterise N mineralisation indices, referred to as the Council dataset.

Soil order	Pasture		Crop			Total
	Dairy	Drystock	Horticulture	Vegetable	Arable	
Allophanic	3	2	2	1	1	9
Brown	2	2	1	1	1	7
Gley	2	3	1	2	2	10
Pallic	2	4	3	1	2	12
Pumice	3	1	-	-	1	5
Recent	2	2	2	3	2	11
Total	**14**	**14**	**9**	**8**	**9**	**54**

Previous work of Curtin et al. (2017) included 130 soils from the same soil orders, with the exception of Pumice soils, and a similar number but somewhat different representation of regions (Auckland, Waikato, Hawkes Bay, Gisborne, Canterbury and Southland).

3.2.2 Mineralisation potential

As noted above, the gold standard measure of PMN is a 14-wk aerobic laboratory incubation. Samples of air-dry soil (equivalent to 25 g of oven-dry soil) were weighed into plastic vials (70 mL) and deionized water was added to adjust soil water content to 90% of field capacity (-10 kPa, measured using a tension table). Each vial of soil was placed into a 500-mL air-tight jar (fitted with rubber septa) and incubated at 25°C for 14 wk (98 days).To minimize moisture loss during incubation, the vials were covered with film (holes were punctured into the film to facilitate aeration). Water was added, if required, at fortnightly intervals to compensate for any evaporative losses. Mineral N was extracted (by 2 mol L^{-1} KCl) after 14 wk of incubation and determined using an automated colorimeter (QuickChem 8000 FIA+, Lachat Instruments, Loveland, CO). Mineralized N was calculated by subtracting mineral N (measured on a separate subsample) at the start of the incubation from the amount determined from the incubated sample at the end. Mineral N was determined by 1-h extraction of 5 g soil with 25 mL of 2 mol L^{-1} KCl and subsequent analysis of the filtered extract for NH_4-N and NO_3-N on a Lachat QuikChem 8500 Series 2 Flow Injection Analysis System (Lachat Instruments, Loveland, Colorado, USA) (Keeney and Nelson, 1982).

Carbon mineralisation was also measured by determining the amount of CO_2-C evolved during the 14-wk incubation. At regular intervals, a 20-mL gas sample was collected from the jar head space using a syringe; jars were then opened and flushed with fresh air to return CO_2 concentrations to ambient levels before returning the incubation jars to the incubator. Headspace CO_2 was sampled between 19 and 26 times (depending on CO_2 production rates of individual soils). The CO_2 concentration in the gas samples was determined using an infrared gas analyser (LI-COR, Lincoln, NE).

3.2.3 Anaerobically mineralisable N

AMN was determined as the amount of ammonium-N generated during a 7-day anaerobic incubation (Sparling and Searle (1993), adapted from Keeney and Bremner, (1966)). Ten millilitres of water was added to a 5-g soil subsample to create anaerobic conditions, prior to incubation at 40°C. After 7 days, the incubated soils were extracted with 40 mL 2.5 mol L^{-1} KCl. A second 5-g subsample of each air-dry, sieved soil was extracted using 10 mL water and 40

mL 2.5 mol L^{-1} KCl. Ammonium-N in the extracts was measured on a Lachat QuikChem 8500 Series 2 Flow Injection Analysis System (details above). The AMN value was calculated by subtracting the ammonium N in the soil prior to incubation from the amount measured after incubation.

3.2.4 Hot water extractable N & C

Hot-water-extractable N (and C) was determined by extracting 4 g soil with 40 mL water in a water bath at 80°C for 16 h. The samples were then centrifuged and the supernatant collected after filtration. Total dissolved N was determined by persulfate oxidation, and dissolved organic N was estimated by subtracting mineral N (NH_4^+ and NO_3^- determined using an automated colorimeter) from the total dissolved N. Dissolved organic C in the hot-water extracts was determined using a total organic carbon analyser (Shimadzu TOC-V CSH, Shimadzu Corp, Japan).

3.2.5 Total soil carbon (C) and total nitrogen (N)

Total C and total N were determined by Dumas dry combustion of 0.5 g soil samples on a LECO TruMac CN analyser (LECO Corporation, St. Joseph, Michigan, USA) at 1250°C. Each subsample of soil for total carbon (C) and total nitrogen (N) analysis was mixed thoroughly, sieved <2 mm diameter and oven-dried overnight at 60°C prior to analysis.

3.2.6 Particulate Organic N

Particulate organic nitrogen (POM-N, i.e., organic N in the >50-µm particle size fraction; Cambardella and Elliott, 1992; Gregorich et al., 2006) was separated after dispersion of soil (15 g) by sonication for 45 s with energy equivalent to 64 J s^{-1} (Qiu et al. 2010). Due to difficulty with dispersion, Allophanic soils received two sonication events separated by placing the sample in a cold water bath for 10 min to ensure the sample did not over heat (total of 90 s of sonication). The dispersed soil was washed on a 50-µm sieve until the draining water was clear. Material retained on the sieve was dried at 60°C and weighed, ground using a mortar and pestle, and a subsample analysed for N and C using a LECO C/N analyser.

3.3 Key findings & discussion

Total N mineralised in the 14-wk incubation (i.e. PMN) ranged from 30 to 592 mg kg^{-1} (mean 268 mg kg^{-1}). Land use history had a dominant influence on PMN with pastoral soils mineralising 2.3 times more N than cropped soils (pasture 364 ± 129 vs. crop 157 ± 102 mg kg^{1}), which was consistent with the results of Curtin et al. (2017). The mean ratio of CO_2–C evolved to N mineralised was 10.7 ± 2.1 for the 14-wk incubation. A smaller proportion of total soil N was mineralised in Allophanic than in sedimentary soils (4.8 vs 6.1 % respectively) (Table 10), which was also consistent with the findings of Curtin et al. (2107).

The indicators that were evaluated varied in their ability to predict the gold standard PMN. Total N and POM-N showed the least promise for predicting mineralisable N. The two best indicators were HWN and AMN. Correlation matrix data are provided in Appendix II (Table 12). Our calibration dataset covered a wider range of N mineralisation potentials than Curtin et al. (2017); only one soil in the Curtin et al. (2017) dataset mineralised >325 mg N/kg, compared with 18 soils in the Council dataset (Figure 6). Most of these high HWN (and PMN) values were

from Allophanic soils. When these very high values are excluded, the general distribution of data points over a comparable concentration range was similar.

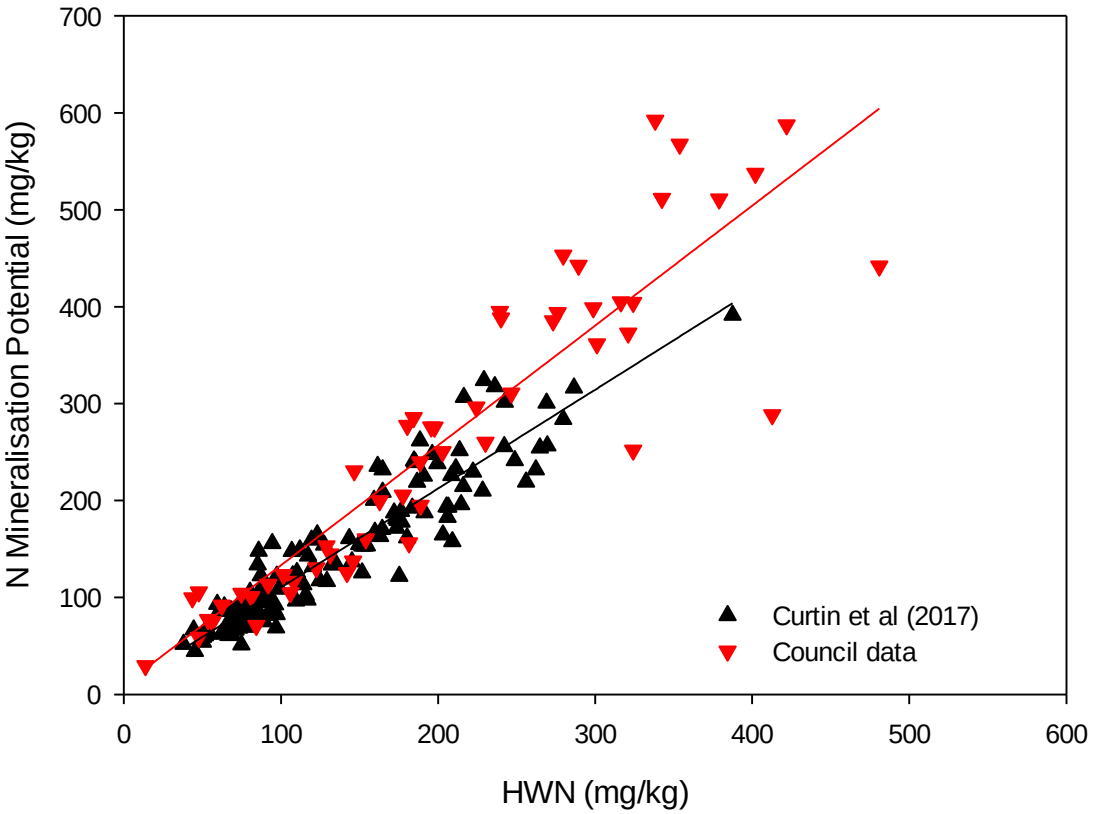

Figure 6. Relationship of hot-water-extractable Nitrogen (HWN) with N mineralisation potential (measured by 14-wk aerobic incubation at 25 deg C). Data from Curtin et al. (2017) are for 130 soils sampled to 15 cm. Council data are for 54 soils sampled to 10 cm.

Overall, correlations between N mineralisation potential and most mineralisation indices were stronger for the Council dataset compared with those reported by Curtin et al. (2017): r=0.96 vs 0.86 for AMN, 0.84 vs 0.69 for total N, and 0.78 vs 0.60 for POM-N. However, the correlation of PMN with HWN was slightly weaker for the Council dataset (r=0.91 vs 0.94).

For the Council dataset, HWN ranged from 14 to 498 mg kg^{-1}; mean of 209 mg kg^{-1}. HWN was strongly influenced by land use (pasture 280 vs. cropping 123 mg kg^{-1}). Regression analysis indicated 82% of the variation in PMN was explained by HWN (Figure 7). A wide range of AMN concentrations were also measured, 12 to 489 mg kg^{-1}; mean 184 mg kg^{-1}. AMN concentration was also strongly influenced by land use (pasture 253 ug/g, cropping 101 mg kg^{-1}). Regression analysis indicated 92% of the variation in PMN was explained by AMN.

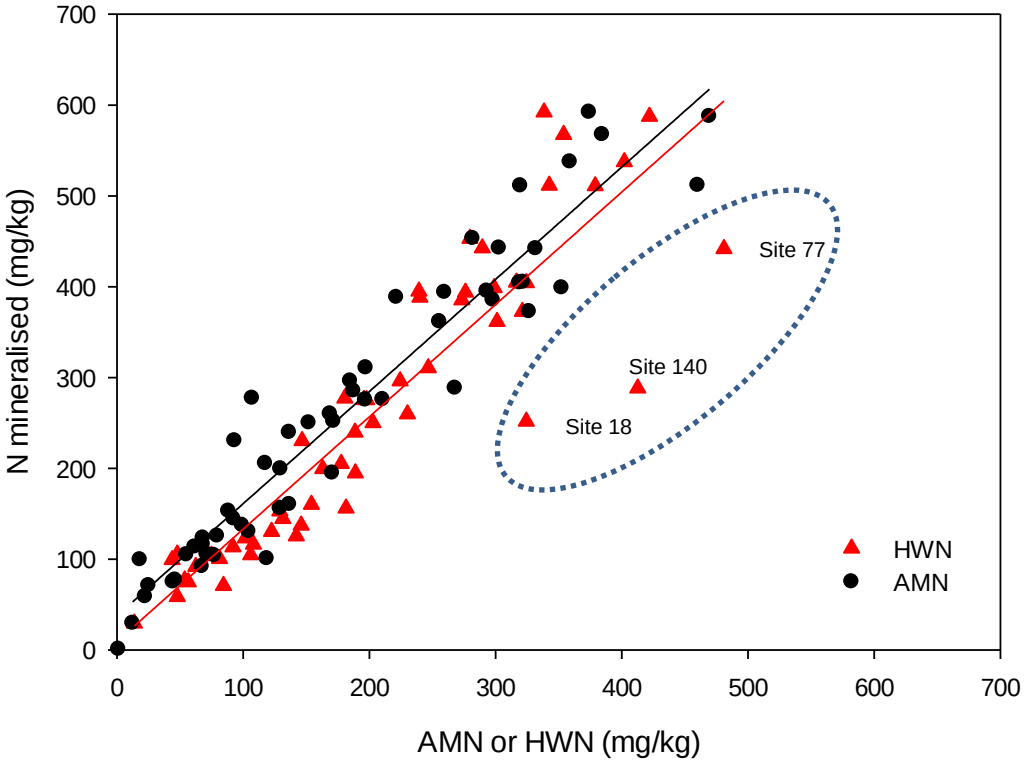

Figure 7. Relationship of hot-water-extractable Nitrogen (HWN) and anaerobically-mineralisable N (AMN) with N mineralisation potential (PMN, 14-wk aerobic incubation at 25 deg C) for the Council dataset.

The slope of best fit lines for HWN and AMN were comparable, while HWN had an intercept closer to zero. An intercept of zero is preferable as a soil with no N mineralised during the incubation would not be expected to release N during the HWN or AMN test.

Results from three sites contributed strongly to the difference in R^2 for HWN and AMN (#18, 77 and 140). We reviewed data for evidence of why these three sites appear as outliers. The sites were from three different regions and soil orders, but were all long-term pasture sites. The amount of N extracted during the hot water extraction was consistent with the amount of C extracted for all three sites (See Appendix II for Figures). The amount of N mineralised during the incubation seems consistent with the amount of C mineralised for sites 18 and 77, but there is some evidence to suggest N mineralisation was low relative to C mineralisation for site 140 (See Appendix II, Figure 10). Unfortunately, it was not practical to repeat the incubation for this soil to determine if the original N mineralisation result was in error. We re-tested KCl-extractable mineral N from a subsample of the incubated soil which suggested the final KCl-extractable mineral N value may have been low, but the soil had been air-dried between the two extractions, therefore the new value could not be directly substituted into the calculations. Another possible explanation for these results is that the 14-wk aerobic incubation underestimated the N mineralised from these high organic matter soils owing to N immobilisation, which would not be reflected in the HWN test result. A possible explanation for all three outliers is that the samples taken from these long-term pasture sites included soil from fresh livestock urine patches. In this case, C and N mineralisation could have been supressed by high concentrations of urea and salts, yet would release high levels of extractable organic N. Further investigation of these outliers is outside of the scope of this project, but it may be worthwhile to investigate further in future. Exclusion of Site 140 from the dataset

increased the percentage of variation in PMN explained by HWN from 82 to 87%, which improved further to 93% with the three 'outliers' removed. Although the three 'outliers' appear different to remaining data, it is difficult to justify the exclusion of all three based on other available information.

PFR's internal laboratory quality control standards show differences in the repeatability of HWN and AMN analysis. Statistical analysis of HWN results obtained from our internal quality control check soil (at least two subsamples of the homogenised check soil were extracted for every 43 samples analysed, samples extracted on the same date were considered a batch) in the later-half of 2017 were: mean 155.6 mg N/kg soil, std dev 8.7, CV 5.6%, where n=16 across 4 batches. Quality control check standards have been consistently measured with all HWC extractions; statistics for samples extracted between 2015 and late 2017: mean 1793.3 mg C/kg^{-1}, std dev 112.9, CV 6.3%, n=48 across 15 batches. In comparison, statistics for AMN (2014–2018) were: mean 77.9 mg kg^{-1}, std dev 8.8, CV 11.3%, n=66 across 21 batches. The variation in HWN concentrations was less than that measured for AMN, thereby suggesting a more repeatable indicator.

The AMN method used in this study and that of Curtin et al (2017) is consistent with the original method published by Keeney and Bremner (1966). However, the AMN methods used by the two largest commercial laboratories in New Zealand both differ from the Keeney and Bremner (1966) method and each other. This can lead to substantial inter-laboratory differences in AMN results depending on the specific methodologies applied (Figure 8). We regressed Council-provided AMN data (sourced from commercial laboratories) with data obtained in this project and found the relationships to be highly variable. The amount of variation in Council AMN data explained by our AMN data varied between 41 and 80% depending on region (data not provided). We highlight this as a significant issue and advise Regional Councils to ensure they use a consistent laboratory and recommend inclusion of quality control samples when forwarding samples for analysis. The high variability in the AMN results obtained from different laboratories has important implications for predicting the N mineralisation potential within reasonable confidence limits. As HWN is not routinely offered by commercial laboratories a comparable dataset is not yet available, however we understand that both laboratories are investigating the HWN test for future commercial application.

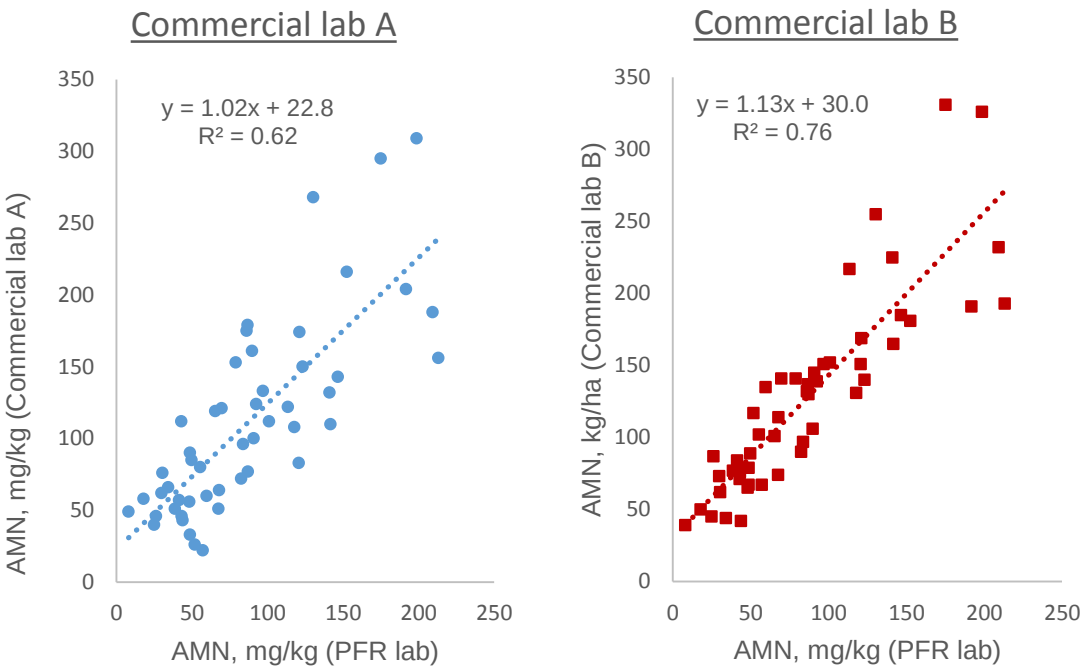

Figure 8. Inter-laboratory comparison of anaerobically-mineralisable N (AMN) data (n=50). PFR data (unpublished).

Table 10. Effect of land use and soil type on potentially-mineralisable N (PMN, aerobic 14-wk incubation), anaerobically-mineralisable N (AMN), hot-water-extractable N (HWN), particulate organic matter N (POM-N) and total N. Data in parentheses are values for the wider dataset of 190 sites.

Land use	No. of soils (n)	AMN	HWN	POM-N	Total N	PMN	PMN	C min/N min ratio*
		----------ug/g----------			g kg^{-1}	mg kg^{-1}	% of total N	
Allophanic								
Dairy	3 (10)	320 (362)	330 (370)	1885 (1898)	7.6 (8.8)	431	5.8	10.6
Drystock	2 (7)	379 (297)	346 (283)	3481 (2138)	11.6 (8.5)	580	5.0	9.4
Horticulture	2 (5)	240 (202)	212 (180)	1076 (904)	6.3 (5.8)	340	5.7	10.1
Vegetable	1 (2)	67 (92)	62 (99)	397 (523)	4.3 (4.8)	92	2.1	13.8
Arable	1 (4)	71 (106)	48 (112)	705 (952)	5.0 (6.5)	106	2.1	8.5
Sedimentary								
Dairy	11 (44)	280 (274)	304 (305)	1158 (1251)	5.4 (5.7)	383	7.4	9.3
Drystock	12 (43)	205 (202)	245 (235)	804 (722)	4.5 (4.4)	295	6.7	11.3
Horticulture	7 (21)	105 (114)	144 (158)	327 (391)	3.0 (3.4)	175	5.5	10.7
Vegetable	7 (22)	68 (64)	86 (76)	238 (222)	2.4 (2.1)	102	4.4	10.9
Arable	8 (32)	101 (100)	127 (124)	299 (322)	3.0 (2.9)	157	5.4	12.1
Total	**54 (190)**							

3.4 Implementation and further research requirements

The Council data provide evidence that HWN is a good indicator of a soil's ability to supply plant-available N from the top 10 cm of New Zealand's pasture and cropping (arable and horticultural) soils. Strong relationships between PMN and HWN (R^2 = 87[1]%), and PMN and AMN (R^2 = 92%) are reported. The criteria for selecting indicators suitable for SoE monitoring include that they should be: (1) useful in predicting a specific quality trait, (2) sensitive to change, (3) repeatable such that changes over time can be discerned, and (4) suitable for routine use. Although the AMN test explained a slightly higher percentage of variation in PMN (measured via a 14-wk incubation) than HWN in this study (but not that of Curtin et al. 2017), we believe the HWN test is preferable to the AMN test, as the best available evidence suggests that it is more repeatable and faster to measure than AMN.

The adoption of HWN for use in routine Regional Council soil quality monitoring programmes, would require identifying suitable target ranges or critical thresholds. These ranges or thresholds could be applied to identify soils that are depleted in PMN, where additional fertiliser N may be required to maintain productivity levels. Alternatively, soils with high PMN values may reflect an increased risk of N losses when disturbed by cultivation or left fallow for extended periods of time. The setting of such target ranges is beyond the scope of this project. Upon consultation with Regional Councils, we propose a follow-up project to set appropriate target ranges for HWN which could be based on a review of published HWN studies and compilation and analysis of relevant research data using similar methodologies. Furthermore, PFR is currently undertaking field validation of the HWN test; preliminary results indicate the HWN test is able to accurately predict the N mineralised under field conditions (when adjusted for field temperature and moisture) during a growing season. Data analyses and further testing are ongoing. We caution against the setting of HWN target ranges from native sites given that native sites typically have no N inputs and wide C:N ratios; as such, PMN may be lower than predicted by HWN owing to greater potential for N immobilisation. This warrants further investigation.

New Zealand's two largest commercial laboratories are investigating the HWN test for future commercial application. If Councils are interested in the HWN test for routine soil quality monitoring PFR would support this uptake and could undertake the HWN analysis for monitoring paddocks until the test is commercially available.

HWC could offer an alternative to HWN for SoE monitoring, as it was strongly correlated with N mineralisation potential (Appendix II, Figure 10). Measurement of HWC is more straight-forward than that of HWN. It can be directly determined using a TOC analyser, whereas measurement of HWN requires determination of both total dissolved N (by persulfate digestion) and mineral N in the hot water extract as well a measurement of mineral N in the soil prior to extraction.

Based on the results outlined above, we recommend that New Zealand's SoE soil quality monitoring programmes begin implementing HWN as a new indicator of the capacity of soils to supply plant-available N (i.e. PMN). Given the high variability in commercial test results for AMN, we recommend that HWN replaces AMN as an indicator of PMN for routine SoE monitoring. However, there would be value in retaining both indicators of PMN in the short-term in order to build a comparative dataset and verify the conclusions drawn from this study. Further

[1] Data for site 140 excluded as we expect the PMN was underestimated; analysis unable to be repeated owing to quantity of sample and time restrictions.

testing of HWC is also recommended wherever HWN is measured in order to establish whether this may serve as a suitable analogue for HWN in the future.

The following steps are important to adopting this new indicator of PMN:

1. Develop and apply a consistent methodology for processing soils and analysing HWN and HWC. PFR has well established protocols and technical expertise in HWN and HWC testing. The commercial laboratories have expressed a strong interest the HWC and HWN tests and we have offered to share our expertise with them. We would be able to offer one or both of these tests for Regional Council SoE monitoring until such time that one or more of the commercial labs is able to offer the tests.
2. Review and analyse existing data to establish scientifically defensible and practical target ranges for HWN relative to values obtained for appropriate benchmark soils.

4 ACKNOWLEDGEMENTS

We thank Peg Gosden, Rebekah Tregurtha, and Weiwen Qui for their technical contributions to completing the laboratory analyses. We also thank each of the Regional Councils involved for their time delving into archives to provide soil samples and supporting information: Auckland Regional Council, Bay of Plenty Regional Council, Environment Canterbury, Greater Wellington Regional Council, Hawkes Bay Regional Council, Marlborough District Council, Taranaki Regional Council and Waikato Regional Council.

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APPENDIX I

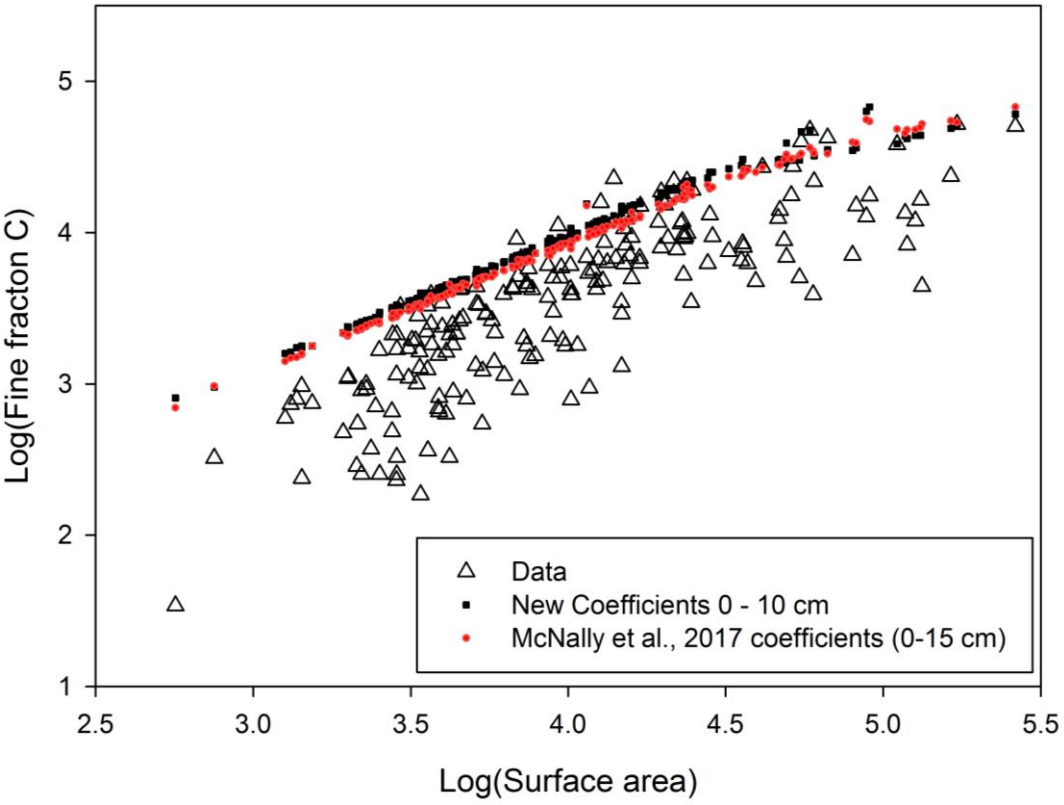

Figure 9. The relationship between the fine fraction C concentration and surface area for the Council dataset calculated using either the published coefficients from McNally et al., (2017) (red circles) or new coefficients for the 0–10 cm depth using the McNally et al., (2017) model (black circles). The open triangles are the measured data for the Council dataset. Please note that there is no differentiation on the figure between Allophanic and non-allophanic soils despite the stabilisation capacity being calculated using this differentiation. Apparent deviations are explained using this differentiation.

Table 11. Mean saturation deficits (mg C $g^{-}1$) for pasture and cropping soils under the various soil orders. Values in parentheses represent 1 SE.

Soil order	Pasture		Cropping	
	McNally et al., 2017 model	Simple model	McNally et al., 2017 model	Simple model
Allophanic	16.6 (3.7)	17.0 (3.6)	45.7 (2.6)	47.0 (2.9)
Brown	11.5 (2.6)	7.7 (2.8)	16.5 (2.9)	11.9 (3.2)
Gley	16.8 (3.1)	14.7 (3.4)	20.3 (2.8)	16.6 (3.6)
Pallic	9.8 (1.4)	5.8 (1.7)	17.8 (2.0)	13.0 (1.9)
Pumice	9.4 (4.4)	7.8 (5.4)	-	-
Recent	16.3 (2.7)	12.7 (2.9)	15.7 (1.3)	11.4 (1.3)

APPENDIX II

Table 12. Correlation coefficients (r) between indices of N mineralisation potential (PMN) (n=54).

Parameter	PMN	HWN	HWC	SUVA	AMN	Total N	POM N	C Resp
PMN	1.00							
HWN	0.91	1.00						
HWC	0.93	0.98	1.00					
SUVA	-0.66	-0.55	-0.57	1.00				
AMN	0.96	0.92	0.92	-0.60	1.00			
Total N	0.84	0.77	0.83	-0.63	0.81	1.00		
POM N	0.78	0.72	0.78	-0.49	0.74	0.93	1.00	
C Resp	0.94	0.90	0.95	-0.59	0.91	0.81	0.78	1.00

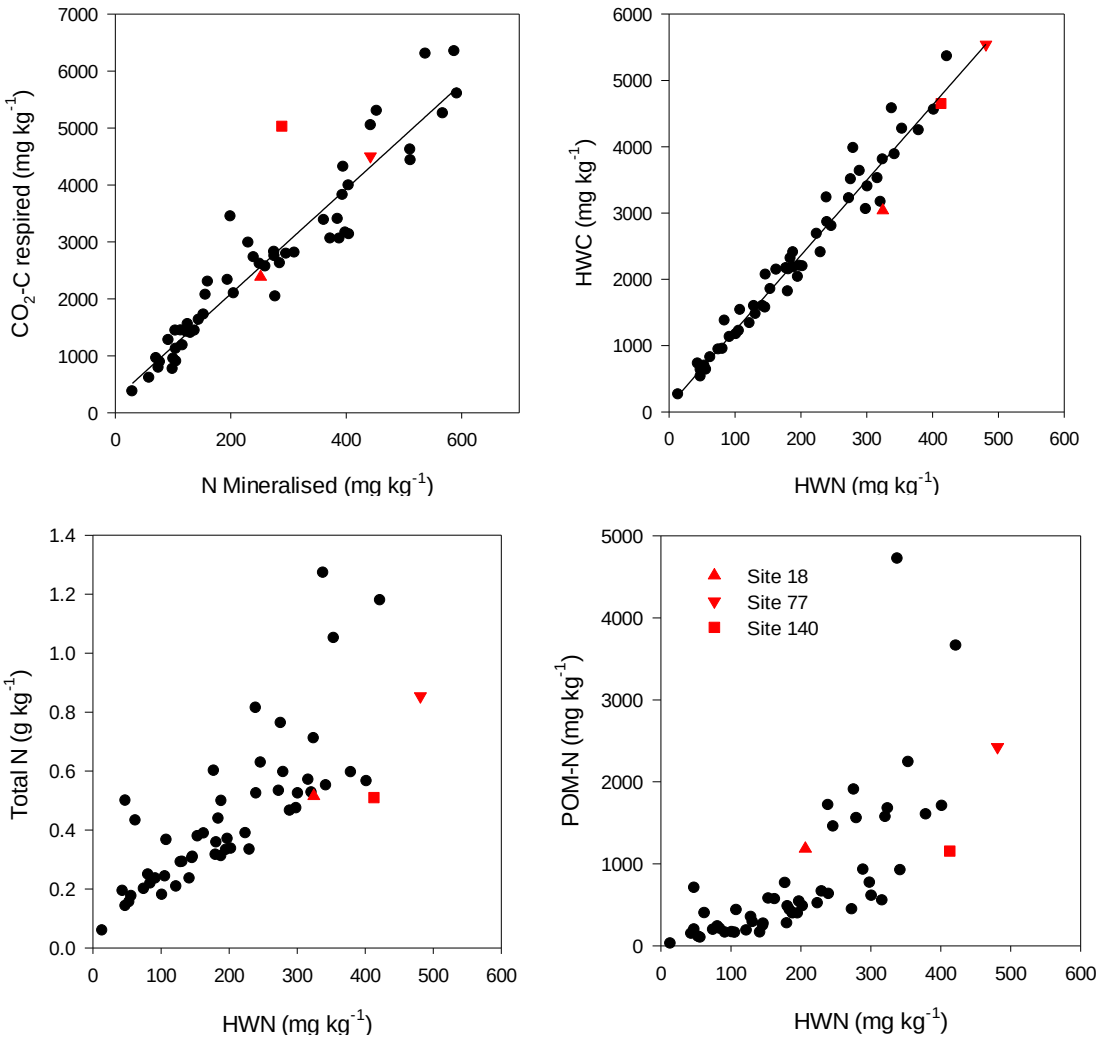

Figure 10. Relationship between C and N mineralisation indices.

DISCOVER. INNOVATE. GROW.