Improving soil health through improved implementation of soil quality indicators

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- Regional council state of the environment (SoE) soil quality monitoring is the primary means by which councils monitor the health of soils in their regions. Monitoring has been conducted since the early 2000s, but there has been no robust review of the performance of the suite of soil quality indicators.
- This project reviews the performance and implementation of existing, and potential new, SOE soil quality indicators in terms of improving environmental outcomes. The project was funded from Envirolink for the Land Monitoring Forum (LMF).
- Together with a recently completed project funded by the Ministry for the Environment, this project aims to support improved interpretation and implementation of the information provided by soil quality indicators to enhance the effectiveness of SoE soil quality monitoring programmes.

Objectives

This project seeks to identify options for improving soil health through improved efficacy of implementing soil quality indicators used for SoE reporting by:

- critically reviewing the performance of existing indicators and identifying any potential new indicators
- developing fact sheets for selected indicators
- assessing options for the web-based delivery of soil quality information.

Methods

- An advisory group comprising members of the LMF, and representatives from the Ministry for the Environment (MfE), the Ministry for Primary Industries (MPI), and Stats NZ, was established to oversee the project and met on a quarterly basis.
- A survey of regional councils was undertaken to provide insight into the current drivers for undertaking SoE soil quality monitoring and subsequent use of the information gathered from the monitoring programmes
- A review of national and international literature was undertaken to assess the performance of existing target values and soil quality indicators. This review draws heavily on the recently completed revision of soil quality indicator target ranges project (Cavanagh, Drewry et al. 2025), funded by MfE, and also on several recent international studies that undertook extensive technical evaluations of different indicators, including those used in SoE soil quality monitoring.
- Our evaluation of the performance of existing indicators and consideration of potential new indicators categorised indicators as:
  - primary indicators – those for which measured limits or thresholds should be used to drive action on improving soil health, or
  - secondary indicators – those that offer additional insight into the response or behaviour of other soil quality indicators.

- For these secondary indicators, a distinction is made between those that provide 'context' and should be measured each time monitoring is undertaken, and those that provide 'characterisation', which involves describing inherent soil properties and can probably be measured once to characterise the site, but is valuable to help explain variations in the primary indicators.
- To identify indicators on which to develop living documents / fact sheets, and to scope options for the web-based delivery of soil quality information (e.g. via the website of Land, Air, Water Aotearoa [LAWA]), a workshop was held on 6 March 2025 with the LMF, which also included council staff and wider stakeholders.
- Four facts sheets ('Overview', 'Organic matter', 'Soil nutrients – Olsen P', and 'Soil physical indicators') were developed. The requirements to upload and display SoE soil quality data on the LAWA website were scoped through discussion with Te Uru Kahika – Regional and Unitary Councils Aotearoa.

Results and conclusions

The regional council survey identified the following.

- Section 35(2) of the Resource Management Act 1991 (RMA) is the primary regulatory driver for 14 out of 15 councils undertaking SoE soil quality monitoring. Only four councils had policies, objectives, methods, and/or rules in policy statements or plans that draw on SoE soil quality monitoring information, or require SoE soil quality monitoring to be undertaken
- For the indicators specified by the Soil Quality and Trace Element Monitoring National Environmental Monitoring Standard (NEMS-SQ), all councils monitor the core soil quality indicators and trace element suite, while fewer have undertaken monitoring of fluorine and aggregate stability. The majority of councils have monitored hot-water-extractable carbon (HWEC) on at least one occasion, with a smaller number of councils also monitoring hot-water-extractable nitrogen (HWEN).
- The majority of councils report the results back to the land manager, but the reporting methods are variable, which is likely to be partly due to the varying frequency with which soil quality monitoring is undertaken (i.e. annually vs every 4–5 years). More broadly, six councils indicated that SoE soil quality data were used only for reporting, with very little other use; in some instances this was due to the young age of the monitoring programme. Other uses of SoE data and/or SoE soil quality target ranges were for resource consent monitoring or by council land management advisors.
- In terms of indicators, the most significant changes from the current state are the recommendation to replace anaerobic mineralisable nitrogen (AMN) with HWEC, and to increase focus on aggregate stability for cropping soils. Analytically, HWEC is cheaper and quicker than AMN and can be interpreted in different ways, including in ways more specific to carbon cycling. HWEC is generally correlated with AMN, with the exception of forestry and indigenous vegetation.
    - Primary indicators are phosphorus (Olsen P), total carbon, air-filled porosity, aggregate stability (cropping systems), HWEC, and trace elements (arsenic, cadmium, chromium, copper, nickel, lead, and zinc).
    - Secondary *context* indicators are pH, total nitrogen, carbon: nitrogen ratio, and bulk density.

    - Secondary *characterisation* indicators are texture, phosphorus-retention, potential rooting depth, topsoil depth, depth of impeding layer, drainage class, and trace elements (fluorine).
    - Additional primary indicators that require further investigation are (a) carbon saturation/loading, based on determination of the mineral surface area of samples; (b) a 24-hour potential carbon mineralisation test to provide a relative measure of biological activity among soils; and (c) biodiversity indicators.
    - We suggest that biological indicators should focus specifically on providing a measure of biodiversity. A higher-level policy objective (regional and/or national) for maintaining/improving soil biodiversity is probably required to provide the mandate to investigate and incorporate this measure as part of SoE monitoring.
- Visual soil assessment is valuable, and is probably the most accessible tool for farmers and communities to use to observe changes in soil quality. It has also attracted interest from Māori groups. Understanding the relationship between observations from visual soil assessment and SoE soil quality monitoring results has the potential to strengthen the connection between changes in land management practices and changes in soil quality in order to effect positive change.

Recommendations for next steps

The following are recommendations for the next steps to take based on the findings of this project.

- Consistently use 'air-filled porosity' (as per the NEMS-SQ) to refer to macroporosity, assessed at –10 kPa, for SoE soil quality monitoring and reporting by all parties.
- Evaluate the benefits and trade-offs associated with the use of volumetric or gravimetric Olsen P for SoE monitoring.
- Use the upcoming collation of SoE soil quality data (funded by MfE) to undertake more detailed analysis of the relationship between AMN and HWEC, and aggregate stability, and provide a stocktake of existing data available for additional parameters for site characterisation.
- Confirm changes to indicators and reference ranges (from Cavanagh, Drewry et al. 2025) and update the NEMS-SQ.
- Confirm if LAWA is the preferred pathway for the display of SoE monitoring data. If so, form a working group and develop a project plan for the development of a LAWA soil quality module to submit to Te Uru Kahika.

Recommendations related to SoE monitoring

In addition to the recommendations related to indicators outlined above, use of SoE monitoring to effect improvements in soil quality and environmental outcomes would be enhanced by:

- investigating the use of visual soil assessment as a way to provide greater connection of land managers and communities with their soil, and with SoE monitoring results
- investigating the environmental and production consequences of the apparently wide-spread compaction issues (as determined from measurement of air-filled porosity) associated with pastoral systems
- promoting SoE soil quality monitoring within councils to inform their resource management policies or plans, and more direct use of the results to assess the effectiveness of relevant provisions
- including soil biodiversity in council policies and plans, to provide greater impetus for the development of soil biodiversity indicators
- reviewing previous, existing or planned local work being carried out by Māori groups (e.g. iwi, hapū, trusts, incorporations) on soils (e.g. to identify the main issues and priorities, monitoring approaches, indicators), and clarifying Māori needs for using soil data to achieve Māori aspirations and inform management decisions
- integrating soil quality monitoring with freshwater and groundwater monitoring to better inform catchment-based and holistic management
- giving greater consideration to scaling up SoE monitoring results to provide a national perspective on the state of soils using geospatial approaches
- using the LMF as principal advocate to the Resource Managers Group and central government (MfE, MPI) to provide national direction, priorities, and clear objectives for managing and improving soil quality and soil health.

1 Introduction

Regional council state of the environment (SoE) soil quality monitoring is the primary means by which councils monitor the health of soils in their region. Monitoring has been conducted since the early 2000s, but there has been no robust review of the performance of the suite of soil quality indicators, and their associated target values and ranges under different types of land use, since these were developed around 25 years ago. Regional council soil quality monitoring and comparison with target values is the basis for national and regional reporting of soil quality (e.g. Drewry, Cavanagh et al. 2021; Curran-Cournane 2020; Taylor et al. 2021; MfE & Stats NZ 2021, 2024, 2025).

Substantial new data, including from an environmental perspective, as well as data on potential new indicators, are now available on which to base a review and update the target values and the development of new indicators. A recently completed Ministry for the Environment (MfE) project 'Revision of soil quality indicator target ranges' (Cavanagh, Drewry et al. 2025) reviewed the available data for the existing seven primary soil quality indicators (carbon, nitrogen, pH, anaerobic mineralisable nitrogen, Olsen P, bulk density, and macroporosity), plus hot-water-extractable carbon, and revised the existing target values.

The current project, funded through the Ministry of Business, Innovation and Employment's Envirolink scheme for the Land Monitoring Forum (LMF), extends that target values review and update to assess the performance of existing SoE soil quality indicators in improving environmental outcomes. It then identifies and evaluates potential new indicators, develops soil quality indicator fact sheets, and scopes the needs for web-based delivery of soil quality information. This project also seeks to consider a te ao Māori / mātauranga Māori perspective for understanding soil health (Harmsworth 2018, 2022a, b).

Cavanagh, Drewry et al. 2025 and the current project will enable improved interpretation and implementation of the information provided by soil quality indicators to enhance the effectiveness of SoE soil quality monitoring programmes and improve soil quality and environmental outcomes.

2 Background

This section provides an overview of the legislative background for the SoE soil quality monitoring programmes, along with an overview of the intended objectives of the programme. This material is largely drawn from Cavanagh et al. 2023 and Cavanagh & Gordon 2023.

2.1 National legislative setting

The Resource Management Act 1991 (RMA) provides the current driver for soil quality monitoring. The purpose of the Act incorporates the requirement to maintain the life-supporting capacity of land and ecosystems. Soils are living ecosystems and support a range of life forms, so the concept of maintaining soil health is embodied in the purpose of the RMA. Section 30 empowers regional councils to control land for the purposes of soil conservation. In this context, soil conservation includes both soil health and soil intactness (erosion). Section 35 also requires local authorities to collect information about the state of the environment. In addition, the Environmental Reporting

Act 2015 requires regular reporting on the land domain, which comprises soil and underlying rock, animals, plants, and structures associated with the land. However, no specific objectives for the purpose of that reporting are given.

Under section 35 of the RMA, councils have the responsibility to collect information about the state of the environment for their region. Each council determines how section 35 is implemented in their region (i.e. what and where is monitored), as there are no specific criteria for what an SoE programme should contain. The national quality planning and regional council environmental monitoring portal Land, Air, Water Aotearoa (LAWA) provides guidance on what SoE monitoring programmes should do[1,2], with SoE monitoring data being used to detect:

- changes in environmental conditions and trends, including their significance
- changes in the state of the environment following the implementation of council plans and strategies.[2]

A representation of the SoE monitoring cycle is shown in Figure 1.

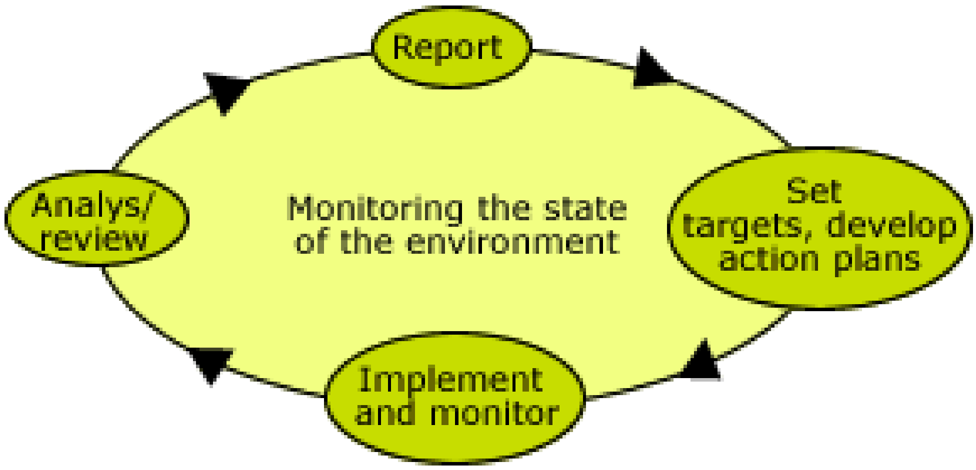

Figure 1. State of the environment monitoring cycle.
(Source: Quality Planning Website, https://www.qualityplanning.org.nz/node/1035)

[1] https://www.qualityplanning.org.nz/node/1034

[2] https://www.lawa.org.nz/learn/glossary/s/state-of-the-environment-soe-monitoring/https://www.lawa.org.nz/learn/glossary/s/state-of-the-environment-soe-monitoring/

In a more general sense, the purpose of SoE monitoring is considered to be:

- to collect information at a regional scale
- to identify and report on the state and trends in the natural environment using the information collected in the regional SoE monitoring programmes to inform the effectiveness of policies and rules contained within the RMA policy framework.[3]

The LAWA website also indicates that communication is the main purpose of SoE reporting, and that SoE reporting 'illustrates whether environmental management is effective or where attention is required'. It is intended to provide early warning of environmental risks (e.g. to air, land and water), and enables councils and communities to understand progress towards desired environmental results.

2.2 Objectives for the soil quality monitoring programme

The statutory requirements under the RMA gave rise to the development of a national soil quality monitoring programme, initially through a Sustainable Management Fund project (#5089), 'Implementing soil quality indicators for land', which began in 1999 and was completed in 2001. This project, commonly referred to as the '500 Soils' project, collected new soil quality data from approximately 500 sites across New Zealand (Sparling et al. 2000, 2001a, b), and built upon an earlier Sustainable Management Fund project (#5001) 'Trialling soil quality indicators for land', (Sparling & Schipper 1997; Sparling et al. 1996, 1998)

A subsequent review by Hill et al. (2003) helped further develop the programme and identified the following objectives for a national soil quality monitoring programme:

- provide an early-warning system to identify the effects of primary land uses on long-term soil quality (physical, chemical, biological)
- track and identify issues relating to the effects of land use on long-term soil quality (may also be district/area-specific)
- utilise the results for SoE reporting and policy development
- where possible, integrate a soil quality monitoring programme with other regional monitoring (e.g. water, especially groundwater).

Subsequently, the LMF developed a guide for soil quality monitoring (LMF 2009) in which the objectives of Hill et al. (2003) were adopted.

[3] Under section 35(2A) local authorities are required to prepare a report at least every 5 years on the results of their monitoring under section 35(2)(b) for policy and plan efficiency and effectiveness. This may be in the form of an integrated policy/plan and SoE report

More recently, regional councils initiated the Soil Quality and Trace Element Monitoring National Environmental Monitoring Standard (NEMS-SQ), which included a similar set of objectives, specified as potential regional programme objectives, including to:

- provide a representative assessment of the quality of the region's soil resource state and trends over time
- assess soil quality across a range of land uses and soils representative of the region's soil resource
- provide an early warning system to identify the effects of primary land uses on long-term soil quality (physical, chemical, biological) and soil trace elements
- assist in the detection of spatial and temporal changes in soil quality and soil trace elements
- integrate with other regional monitoring (e.g. groundwater monitoring)
- collect scientifically robust data
- provide data that can be aggregated for national reporting.

In the early stages of the development of the monitoring programme, soil quality issues identified as being common across all regions were:

- structural decline
- nutrient depletion
- organic matter depletion
- nutrient saturation/excess, biological activity
- soil acidification (Sparling et al. 2001b).

Land-use priorities were structural decline, nutrient saturation, and biological activity, particularly under dairy, intensive beef rearing, horticulture, forestry, and deer farming, while nutrient depletion and acidification were potential concerns under forestry (Sparling et al. 2001b). *It is interesting to note that lacking from both the LMF and NEMS-SQ objectives is a clear statement on what actions (e.g. policy response, land management response) are intended to be taken if soil quality is observed to deteriorate.* It is further noted that organic matter depletion (i.e. low soil carbon), nutrient excess (phosphorus, Olsen P), and structural decline (reduced macroporosity) are key issues still reported on today, with low macroporosity being dominant (StatsNZ & MfE 2021).

3 Objectives

This project seeks to identify options for improving soil health through improved efficacy of implementing soil quality indicators by:

- critically reviewing the performance of existing indicators used for SoE reporting, and identifying any potential new indicators
- developing fact sheets for selected indicators
- assessing options for the web-based delivery of soil quality information.

4 Approach

An advisory group comprising members of the LMF (Haydon Jones and Matthew Taylor, Waikato Regional Council; Erik Button, Otago Regional Council), and representatives from MfE (Nina Koele Tapuwa Marapara), Ministry for Primary Industries (MPI, Kay Brown), and Stats NZ (David Harris), was established to oversee the project, and it met on a quarterly basis.

A survey of regional councils was undertaken to provide insight into both the current drivers for undertaking SoE soil quality monitoring and the subsequent use of the information gathered from the monitoring programmes. This online survey was developed using Qualtrics software and distributed via an email link in December 2024 to council representatives on the LMF. One response per council was sought, with the 15 councils currently undertaking SoE soil quality monitoring all responding. The survey questions are provided in Appendix 1. The survey received approval from the Manaaki Whenua Social Ethics process (application no 2425/18). The results of the survey are summarised and discussed in section 5.

4.1 Indicator review and identification of new indicators

A review of national and international literature was undertaken to assess the performance of existing target values and soil quality indicators. This review draws heavily on the recently completed MfE-funded revision of soil quality indicator target ranges project (Cavanagh, Drewry et al. 2025), and also on several recent international studies that undertook extensive technical evaluations of different indicators, including those used in SoE soil quality monitoring (e.g. Liptzin et al 2022, 2023; Bagnall, Morgan, Bean et al. 2022; Bagnall et al. 2023; Poeplau et al. 2024; Bongiorno et al. 2019; Rieke et al. 2022). This literature review was complemented by reviewing national and international literature to identify potential new indicators, and to assess approaches to the use of soil quality indicators and monitoring data to achieve soil health and positive environmental outcomes.

To assist with assessing the performance of the existing indicator set, a principal component analysis of the baseline monitoring data set collated for Cavanagh, Drewry et al. 2025 was used to compare with analyses run at the commencement of soil quality monitoring in New Zealand, as reported by Sparling et al. (2001b). Variance partitioning was run for all indicators. Indicator data for total carbon (C), total nitrogen (N), phosphorus (Olsen P), and macroporosity were log+1 transformed, while data for anaerobic mineralisable nitrogen (AMN) were square-root transformed to improve normality. The loading values indicate how much each original variable contributes to each principal component. Higher absolute values in a component indicate that a variable is an important source of variation in that direction. If multiple variables have high loadings in the same principal component, they are correlated and contribute to the same source of variation.

Further evaluation of AMN and hot-water-extractable carbon (HWEC) was undertaken using the HWEC/AMN data set compiled in Cavanagh, Drewry et al. 2025. This data set comprised HWEC data from four regional councils (Waikato, Greater Wellington, Marlborough, and Canterbury), collected over 2007–2021, and was provided by Waikato Regional Council. Some of the Marlborough data contained three measurements for a single site; in these cases the average value was taken. These data were combined with additional data from Gisborne and Otago and used to indicate the range in HWEC results from the 0–10 cm depth. The data set also included AMN, total C, and some total N measurements, and the relationships between these variables was plotted. Where multiple years of data existed for the same site, the most recent were used.

4.2 Implementation of soil quality indicators

The original Sustainable Management Fund project (#5089) 'Implementing soil quality indicators for land', began in 1999 and was completed in 2001. This project was commonly referred to as the '500 Soils' project. It involved the collection and interpretation of data on soil quality for SoE reporting – essentially establishing a national soil quality monitoring project. In our consideration of the implementation of soil quality indicators 25 years on, we draw on the review of the indicators undertaken in the preceding section and consider the use, interpretation, and information collected, alongside the stated objectives of the programme and SoE monitoring (section 2.2).

To identify indicators from which to develop living documents / fact sheets, and to scope options for the web-based delivery of soil quality information (e.g. via the LAWA website), a workshop was held on 6 March 2025 with the LMF and included council staff and wider stakeholders (e.g. representatives from central government and the primary sector, and Māori). A summary of this workshop, including identified audiences and content for the fact sheets and web-based delivery, is provided in Appendix 2).

Following the workshop, and working with the advisory group, the following fact sheets were agreed to be developed:

- an overarching fact sheet that covers all indicators and addresses a broader range of indicators
- nutrients – Olsen P
- organic matter – total C (covering both C sequestration and nutrient cycling, and other benefits of organic matter; e.g. the C:N ratio)
- soil structure – macroporosity, bulk density, aggregate stability.

An overarching fact sheet specifically designed for Māori end-users was initially considered but ultimately not developed, because the focus of the fact sheets on SoE soil quality monitoring was difficult to align with the much broader aspirations for achieving soil health under te ao Māori.

It was agreed that the focus for web-based delivery of soil quality information would be an exploration of the requirements to upload and display SoE soil quality data on the LAWA website through discussion with Te Uru Kahika. A second focus was to scope the technical requirements for an interactive filterable display.

5 Regional council survey of the use of SoE soil quality monitoring information

The questions asked during the survey are provided in Appendix 1. A summary of the responses is provided here and includes additional information to provide a better context for some of the responses (e.g. legislative and policy drivers).

5.1.1 Legislative and policy drivers

Section 35(2) of the RMA is the primary regulatory driver for 14 out of 15 councils undertaking SoE soil quality monitoring. Only four councils (Marlborough Council, Greater Wellington Regional Council, Environment Canterbury, Hawke's Bay Regional Council) had policies, objectives, methods, and/or rules in policy statements or plans that drew upon SoE soil quality monitoring information or required SoE soil quality monitoring to be undertaken. Of these, provisions in the Marlborough Environment Plan are the most specific (Chapter 15 Objective 15.4 – Maintain and, where necessary, enhance the quality of Marlborough's soil resource; Policies 15.4.1to 7; and Methods, specifically 15.M.39, 40, 42, 43, and 46), along with specific anticipated environmental results (15.AER.8 and AER.9.

Cavanagh and Gordon (2023) provide a more detailed discussion of the Greater Wellington regional policy and plans in relation to SoE soil quality monitoring, with the following information, including updates, supplied through the survey. Briefly, the main operative policy instruments relevant to the soil quality monitoring programme are the Regional Policy Statement (RPS) (2013) and the Regional Natural Resource Plan (2023). The RPS notes that there are five major management challenges relating to soils and minerals in the region: preventing soil erosion, maintaining soil health, retaining productive soils for agricultural use (urbanisation/fragmentation), preventing unsafe use of contaminated sites, and efficient mineral extraction.

Maintenance of soil health is addressed by objective 30, which states, 'Soils maintain those desirable physical, chemical and biological characteristics that enable them to retain their ecosystem function and range of uses.' Policy 69, 'Preventing long-term soil deterioration – non-regulatory', is most directly relevant to SoE monitoring, and should help to identify whether a soil is deteriorating or improving as a result of policy intervention. The methods underpinning this policy are Method 15, 'Information about sustainable land management practices', and Method 29, 'Take a whole of catchment approach to works, operations and services'.

The RPS also includes anticipated environmental results arising from the policy objectives. These are 10-year targets unless otherwise specified. Objective 30 has three anticipated environmental results, with the first related to soil quality monitoring, specifying that more than 95% of soils sampled for soil health characteristics meet soil health targets.

Section 5.1.2 of the Greater Wellington Regional Council RPS also states that SoE monitoring is a key component of checking whether the RPS policies and methods are effective, and that the achievement of RPS policies and methods will be measured in an SoE report for the region, which is prepared every 6 years using the anticipated environmental results. However, the last integrated SoE report (i.e. where achievement against policies and plans is reported alongside SOE results) for the Wellington region (*Measuring Up*) was published in 2005.

The remaining references to or use of SoE soil quality information across Greater Wellington Regional Council, Environment Canterbury, and Hawke's Bay Regional Council is in higher-level policy statements, although supporting methods and measures are generally lacking. For example, the Greater Wellington Regional Council Natural Resource Plan (2023) has an Objective 33 stating that 'Soils are healthy, and productive to support a range of uses, life supporting capacity is safeguarded and accelerated soil erosion is minimised', although the most relevant underpinning rules primarily relate to managing discharges to soil, or erosion.

Similarly, the Canterbury RPS, Chapter 15, focuses on soil quality, with Objective 15.1 specifically referring to the 'Maintenance and improvement of the quality of Canterbury's soil to safeguard their mauri, their life supporting capacity, their health and their productive capacity'. The most directly relevant policy is 15.3.1: 'Avoid, remedy or mitigate soil degradation'. This specifies, in relation to soil, the requirement (1) to ensure that land uses and land management practices avoid significant long-term adverse effects on soil quality, and to remedy or mitigate significant soil degradation where it has occurred, or is occurring; and (2) to promote land-use practices that maintain and improve soil quality. However, the main focus for the first point is on land-use change and capability, while the second is more focused on managing the accumulation of hazardous substances. The associated anticipated environmental result is non-specific and refers generally to the maintenance or improvement of the quality, life-supporting capacity, and/or mauri of Canterbury's soils, and their health and capability to provide for the social, cultural, environmental, and economic well-being of Canterbury's people and communities.

5.1.2 Monitoring logistics

Five councils monitor all their sites once every 4–5 years, while 10 councils monitor a subset of sites every year. Of the councils that undertake monitoring every year:

- four monitor a mix of land uses
- four monitor a specific land use
- two monitor sites at a specific frequency (e.g. 20 sites every 5 years).

Ten councils use council staff to undertake monitoring, three use a combination of council staff and external consultants, and two only use external consultants.

For the NEMS-SQ-specified indicators, all councils monitor the core soil quality indicators and trace element suite, while fewer have undertaken monitoring of fluorine and aggregate stability (Figure 2). The majority of councils have monitored HWEC on at least one occasion, with a smaller number of councils also monitoring hot-water-extractable nitrogen (HWEN).

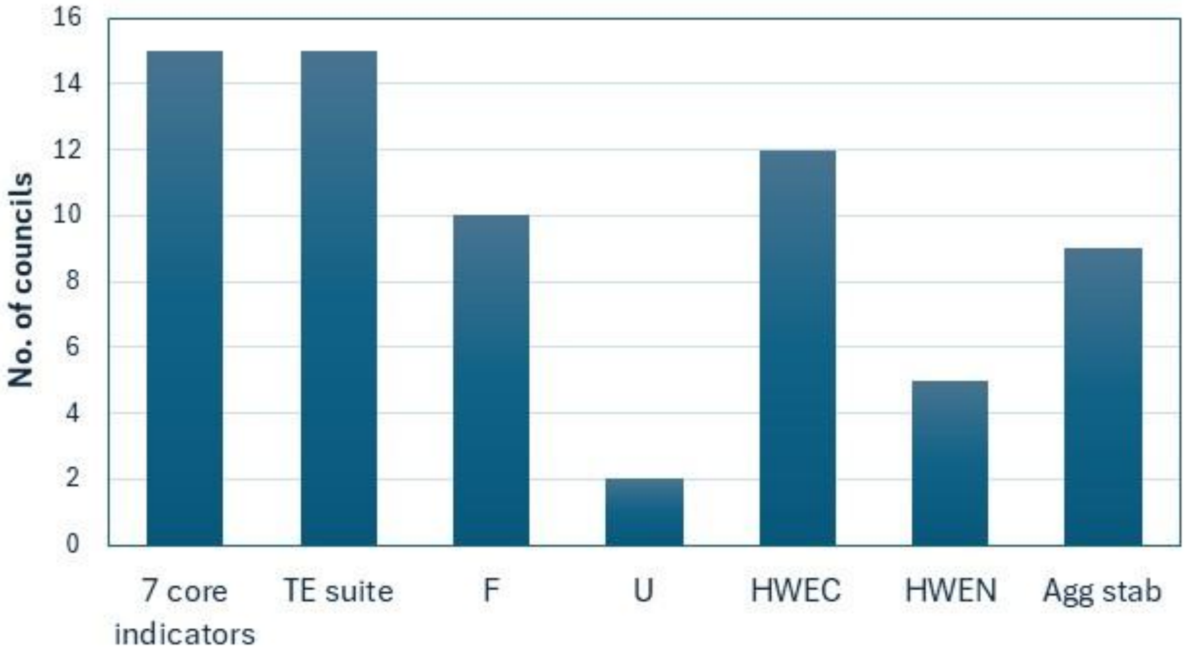

Figure 2. Number of councils monitoring different NEMS-specified soil quality indicators.
Notes: TE = trace element; F = fluorine; U = uranium; HWEC = hot-water-extractable carbon; HWEN = hot-water-extractable nitrogen; Agg stab = aggregate stability.

Additional indicators measured that have been monitored by one or two councils include an extended TE suite, visual soil assessment, soil fauna, eDNA, Readily available water (RAW)/Total available water (TAW), pesticide residues, and P-retention. Additional indicators that are being considered are biological indicators, earthworm eDNA, eDNA, visual soil assessment, deep core (60 cm+) for C stock, and boron in geothermal areas.

Measured values of these indicators are mostly compared to the target values outlined in Hill & Sparling 2009 (12 councils), with a smaller number of councils (three) indicating that Mackay et al. 2013 was used – primarily for Olsen P. Information from Hill Labs and SINDI[4] was also used for the primary soil quality indicators. For trace elements, the NZ Water and Wastes Association (2003) Ecological Soil Guideline Values, or tiered fertiliser management system (for cadmium), was used. Finally, the number of earthworms per spade, as per Schon et al. 2022, was also used by one council.

The indicators most commonly falling outside the specified target or guideline values are shown in Figure 3. Seven councils reported no change over time (in general), but of these councils four had monitored sites only once. Eight councils reported changes in some indicators over time.

[4] SINDI = Soil quality indicators tool developed by Manaaki Whenua Landcare Research, now archived.

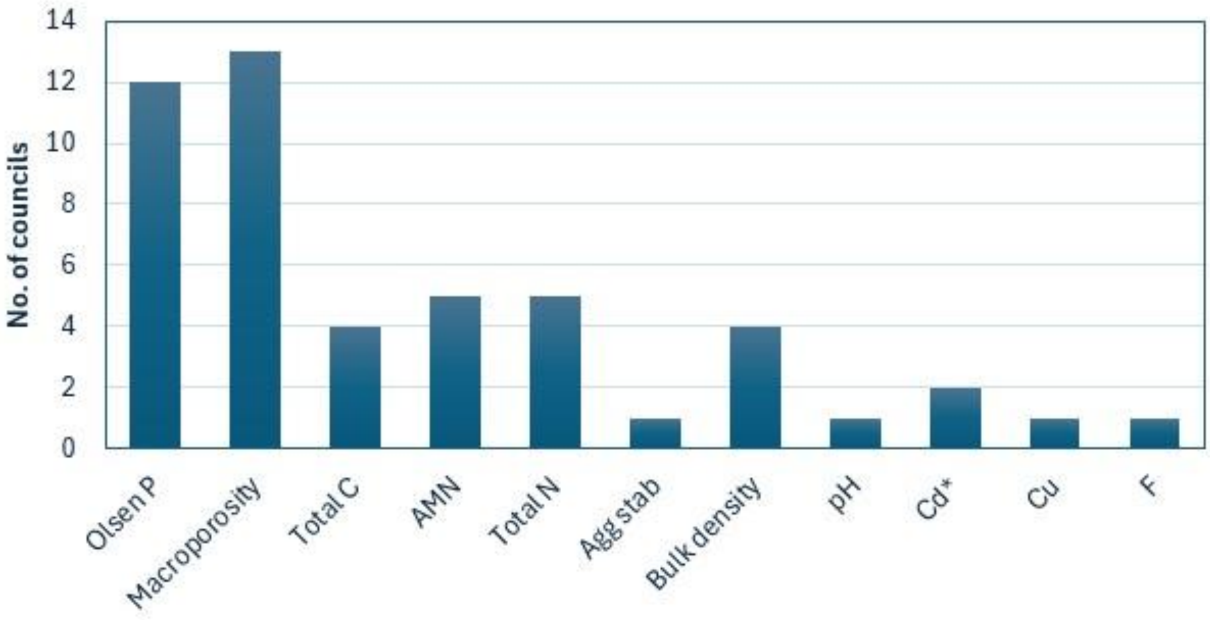

Figure 3. Indicators most commonly identified as falling outside target ranges.
Notes: P = phosphorus; C = carbon; AMN = anaerobic mineralisable nitrogen; N = nitrogen; Agg stab = aggregate stability; Cd = cadmium; Cu = copper; F = fluorine.
* For Cd it is unclear what target/guideline value was being used.

5.1.3 Reporting and use of soil quality information

The majority of councils report results back to the land manager (Figure 4), although one council explicitly doesn't report back to the land manager to avoid influencing management actions and causing results bias. Thereafter, reporting methods are variable, which is likely to be in part due to the frequency at which the soil quality monitoring is undertaken (i.e. annually vs. every 4–5 years).

Actions taken in the event of values falling outside the target range ranged from no action, to discussion with or management suggestions provided to the land manager, or further investigation through additional sampling.

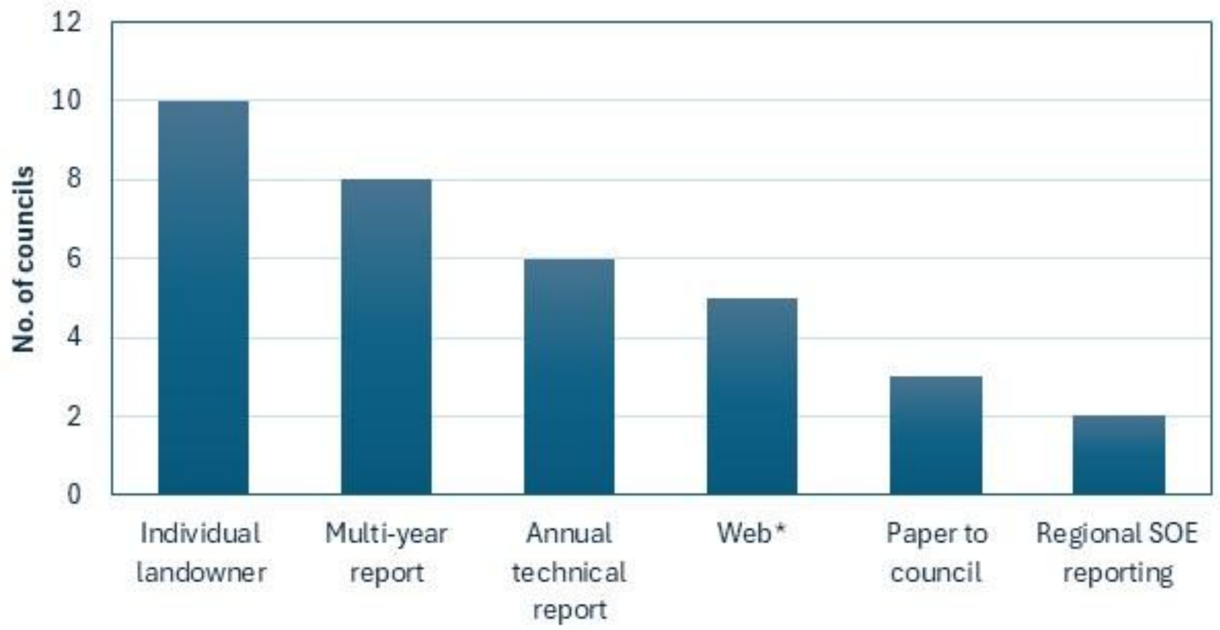

Figure 4. Forms of reporting of SoE soil quality results.
* One council indicated that web-based reporting is currently being investigated.

More broadly, six councils indicated that SoE soil quality data were used only for reporting, with very little other use; in some instances this was due to the young age of the monitoring programme. Three councils indicated that SoE data and/or SoE soil quality target ranges were used for resource consent monitoring (e.g. setting baseline conditions), with two councils also indicating use by the council's land management team. One council indicated that data were used to inform further science-based initiatives.

Most councils indicated there was an interaction between the soil quality team and primary industry, land managers, and catchment advisors or extension staff. Fewer councils indicated that they interacted with policy staff and planners, or consents and compliance staff (Figure 5). Some comments highlighted the potential use in policy or evaluation of policy effectiveness, but it is unclear whether these responses are quantitative or aspirational.

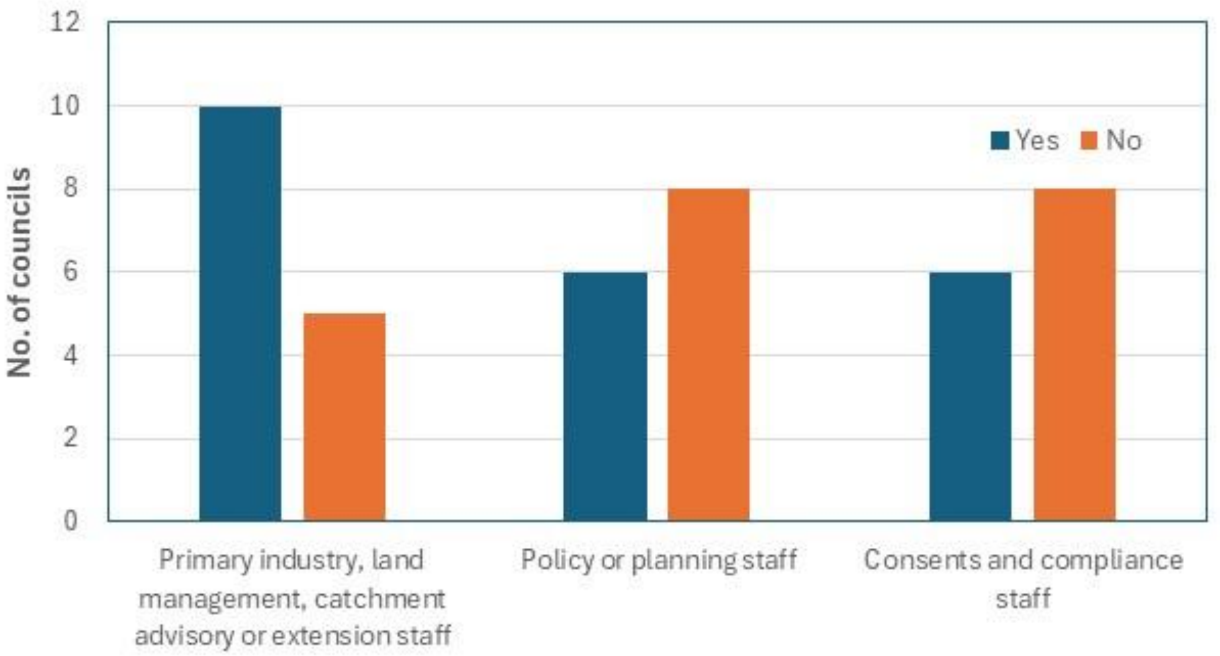

Figure 5. Interaction of council soil quality team with other council staff.

6 Review and evaluation of existing and new indicators

6.1 Evaluating the performance of existing indicators

In this section we provide an overview of the indicators specified in the NEMS-SQ for assessing soil quality (Table1) and an evaluation of their performance. This evaluation is largely qualitative, based on a combination of what meaning can be attached to measured values or changes over time, findings from existing SoE monitoring, as well as multiple recent international studies that have undertaken extensive technical evaluations of the performance of different soil indicators (e.g. Liptzin et al. 2022, 2023; Bagnall, Morgan, Bean et al. 2022; Bagnall et al. 2023; Poeplau et al. 2024; Bongiorno et al. 2022.). The meaning that can be attached to measured values can also be considered in the context of falling inside or outside defined target or reference values, so this evaluation also draws on the recent revision of soil quality indicator target ranges (Cavanagh, Drewry et al. 2025).

Table 1. Description of soil quality indicators, and the reason for monitoring, adapted from the Soil Quality and Trace Element Monitoring NEMS

Soil quality indicators		Information provided by indicator	Why is the measure important?
Chemical	pH	Acidity or alkalinity	Most plants and soil animals have an optimal pH range for growth. Indigenous species are generally tolerant of acid conditions, but introduced pasture and crop species require a more alkaline soil.
	Total carbon	Organic matter status	Organic matter contributes to aggregate building and structure, which helps soil store and supply moisture and nutrients, and improves water movement and root growth.
	Total nitrogen	Organic nitrogen status	Nitrogen (N) is an essential macronutrient for plants and animals, along with phosphorus (P). Most N in soil is within the organic matter fraction. Total N gives a measure of those reserves, although only a small proportion of total N is readily mineralisable and a source of mineral N for plant or microbial uptake.
	Olsen P	Plant-available phosphorus	Phosphorus (P) is an essential macronutrient for plants and animals. Plants get their P from phosphates in soil minerals and organic matter. Many soils in New Zealand have low available P, and P needs to be added for agricultural use. However, excessive levels can increase loss to waterways, contributing to eutrophication.
	Trace elements – arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), fluorine (F)	Contamination status	These trace elements include those essential for plant and animal growth (e.g. Cu, Zn) and also non-essential trace elements (e.g. As, Pb). Low concentrations may result in deficiencies for crops and animals, while anthropogenic activities may result in accumulation of trace elements, potentially to concentrations that have a negative impact on soil biota or human health
Biological	Anaerobic mineralisable nitrogen	Plant-available nitrogen	Not all the organic matter N can be used by plants; soil organisms change the N to forms that plants can use. Anaerobic mineralisable nitrogen gives a measure of how much organic N is readily broken down to release ammonium under anaerobic conditions, and it has been used as an indicator of microbial activity.
Physical	Air-filled porosity (at –10 kPa)	Soil pore function (compaction, root environment, aeration, voids)	Macropores are important for air, water, and root penetration into and through soil and are the first pores to collapse when soil is compacted.
	Dry bulk density (bulk density)	Level of compaction	Compacted soils restrict water and air movement in soil, and restrict root growth.
	Aggregate stability	How resistant soil crumbs are to breakage	A stable, 'crumbly' texture lets water quickly soak into soil, does not dry out too rapidly, and allows roots to spread easily

In selecting soil properties as potential indicators for soil quality monitoring in New Zealand, Sparling and Schipper (1998) originally considered:

- interpretable – indices need to be meaningful so that differences between land uses or soil types can be interpreted
- transferable – soil properties should not be specific to a particular land use or soil type but should apply at all sites
- simple to measure and cost-effective – soil properties need to be relatively simple so that large numbers of samples from a range of sites can be processed (the cost of analysis must be weighed against the information provided)
- acceptable – soil properties must be robust and accepted by national and international communities
- sensitive – soil properties need to be responsive to differences between land uses, soil types and climates.

These are similar to criteria suggested by Doran and Zeiss (2000), whereby indicators must be related to soil functions and should meet the following criteria: be responsive to management, be easy and inexpensive to collect and measure, and be interpretable by land managers. Similarly, Thompson-Morrison and Cavanagh (2023) outlined the following criteria as being those for which there was consensus in the literature:

- accessibility
- sensitivity (although it was noted there may be trade-offs with robustness to seasonal variation)
- relevance – including the ability to be linked with both management and outcomes, and the ability to correlate with ecosystem processes
- interpretability – including the ability to compare between sampling rounds and programmes (e.g. having established baselines)
- reproducibility and reliability
- practicality – including having simple sampling and analytical methods, and non-prohibitive costs.

Specifically in the context of soil health, Bagnall et al. 2023 identified a minimum suite of effective indicators for the North American continent using the criteria that the indicators must:

- primarily reflect soil health rather than inherent soil properties or fertility
- be responsive to agricultural management practices that exemplify soil health principles
- be conducive to measuring soil health at scale, in terms of cost and availability
- not be redundant with regard to linking different soil functions to ecosystem services.

They evaluated 30 measures, and three were ultimately selected.

We also compiled various papers and reports since a previous SoE monitoring programme review (Cavanagh et al. 2017) (see Appendix 1) with a view to using this information to help evaluate the performance of the indicators. We were looking to provide a quantitative assessment of the number of occasions different indicators fell outside target ranges, and to evaluate which indicators showed trends over time.

However, in reviewing these reports, various challenges for comparing results became evident. These challenges included the use of differing target values, different analytical approaches to trend analyses, and confounding of trends because of changes in the number of sites under different land uses over time.

As a result, national reporting (i.e. MfE & StatsNZ 2018, 2021) provided a clearer picture of which indicators predominantly fall out of range, etc., although the trend analysis is still confounded by the differing number of sites under different land uses over time. These national reports support the observation in Figure 4, which shows that Olsen P and macroporosity are the indicators that most commonly fall outside the target ranges.

However, it should also be noted that if there is no target value for an indicator, the indicator cannot fall out of range. For example, no target range was originally developed for total N for cropping and horticultural soils (Sparling et al. 2001b; Hill & Sparling 2009), and so this is not included in evaluations. Similarly, no target values were set for total C of Organic Soils because a diagnostic criterion for Organic Soils is that C content is >16%[5] (Sparling et al. 2008), so no comparison of the total C content of Organic Soils is made. Cavanagh, Drewry et al. (2025) observed that in the baseline monitoring data set some sites identified as being on Organic Soils have C concentrations that fall below (well below in the case of cropping soils) the diagnostic criterion for Organic Soils of 18% C (Hewitt 2010). Therefore, the wider implications of the degradation of these Organic Soils need to be considered.

6.1.1 Organic matter (carbon, total nitrogen, anaerobic mineralisable nitrogen)

Total carbon

Total C is an indicator of organic matter content. Organic matter is widely recognised as a critical component of soil, providing a source of plant nutrients, contributing to soil structure, facilitating the formation of soil aggregates, and enhancing water-holding capacity, as well as providing habitat and food for soil flora and fauna. Given these multiple functions, it is not surprising that soil organic carbon (SOC) or soil organic matter was the most widely measured indicator in an international review of soil indicators (Bünemann et al. 2018) and is essential to measure.

A New Zealand convention considers total C to be equivalent to organic C, since New Zealand soils are generally very low in carbonates, except for calcareous soils (Metson et al. 1979; Sparling & Schipper 1998. Internationally, organic C is generally required to be specifically determined as total C minus inorganic C, or as organic matter determined using loss on ignition (e.g. EEA 2023).

In the most recent national reporting, levels of total C at most sites were within the target range, but soil C was below the target range at 26% of cropping sites (StatsNZ & MfE 2021). This largely reflects the recognised issue of cropping soils being low in C. However, the focus on reporting the

[5] Note that Sparling et al. 2008 state that 16% C is the diagnostic criterion for Organic Soils.

number of sites falling within or above a target doesn't provide an indication of the difference in the range of C values between different land uses, nor does it identify if C in those other land uses is decreasing. Trend analysis showed a decreasing trend in C in cropping soils (StatsNZ & MfE 2021), although, as noted above, the trend analysis is confounded by a changing distribution of sites at different time points, so some caution is advised.

As discussed in Cavanagh, Drewry et al. 2025, there has been a considerable focus on changes in soil C (increasingly as C stocks), particularly from a climate change perspective, with much less focus on relating the significance of those changes to changes in soil function, such as water-holding capacity and nutrient cycling. Further, there is arguably a tension between perceived 'competing' functions of soil C stability (and sequestration) versus decomposition of organic matter (and hence soil C) during nutrient cycling (see also Moinet et al. 2022; Liptzin et al. 2022), although even for the latter, maintaining or increasing the levels of soil C / organic matter is considered more desirable than depletion.

In the absence of quantitative endpoints, Cavanagh, Drewry et al. (2025) based reference ranges for total C on the distribution of C %, stratified by land use and soil order groups, with the 10th to 90th percentile range generally used as the reference range. The exception was the lower end of the non-allophanic mineral cropping soils, which was based on Oldfield et al. 2019. These authors undertook a global meta-analysis of cropping soils and observed an increase in crop yield at around 2% SOC; thereafter the yield response to SOC flattens out as management factors such as irrigation and fertiliser application become more important.

In a New Zealand context, an example is experimental trials being run by the Foundation for Arable Research (FAR) to assess the influence of tillage practices on soil properties and crop yield under continuous cropping (FAR 2023). No-tillage practices increased C stocks in the top 30 cm, which in turn improved soil structure (measured by aggregate stability) relative to other treatments, but it was only under dryland conditions that this increased yield (FAR 2023). The increased yield was attributed to higher SOC stocks providing greater resilience (e.g. greater crop water availability associated with greater organic matter) in systems under pressure. However, overall, irrigation resulted in 30% greater yield compared to dryland systems, irrespective of tillage system (and soil C content).

There has been concern expressed that the approach used for setting reference ranges makes the low C of cropping soils more acceptable. For example, for Granular Soils, the lower end of the cropping soil range of 2% is equivalent to SOC concentrations (having decreased) after 50 years under cropping (Haynes & Tregurtha 1999). However, this approach also gives a realistic perspective on the range in C across different management practices within a given land use and soil order group category, making information more relevant to individual land uses, including indicating what levels of C can be 'achieved' or maintained in that land use.

We want to further emphasise that, for any soil, the focus of land management should be on ensuring soil C does not decline over time, and that for low C soils under intensive land management the focus should be on increasing soil C. This is also supported by a recent study that concluded that it was unrealistic to suggest that SOC in arable soils will reach levels comparable to those under natural vegetation (Powlson et al. 2022). They suggested that, from a global SOC perspective, the priority should be to avoid land clearance in the first place, while ensuring SOC is maintained as high as practically possible in arable soils. In New Zealand we are yet to determine what 'as high as practically possible' might look like in cropping soils, particularly in those soils that have a long history of cropping. Some New Zealand research has been undertaken to determine the potential C saturation deficit associated with different soils (e.g. Beare et al. 2014; McNally et al. 2017; see also section 6.3.2), although this mostly reflects the amount of C lost rather than the amount of C that is likely to be sustained in cropping soils under best C-conservation strategies.

Finally, from the statistical analyses undertaken in Cavanagh, Drewry et al. 2025, Organic, Allophanic, and Raw Soils were clearly distinctly different from each other and from other soil orders. The remaining soils showed a gradient in the modelled mean C %, with Pumice and Oxidic Soils having the highest modelled mean C %, while Semiarid, Recent and Pallic Soils had the lowest. Further, the soil orders with higher soil C (Granular, Pumice, Oxidic Soils) were statistically significantly different from soil orders with lower soil C (Recent, Semi-arid, Pallic, and Gley). This suggests that deeper analysis, pulling in additional information such as site-related climate data, may be warranted to determine whether further stratification based on soil order and/or other factors such as climate can be identified. However, we note that other New Zealand studies on soil C have also only been able to differentiate allophanic and non-allophanic mineral soils (Beare et al. 2014; McNally et al. 2017, 2018).

As highlighted above, total C is an indicator that is essential to measure, although additional indicators of more labile C or biological activity (e.g. AMN, HWEC) will also help interpret measured values.

Total nitrogen

Total N is a measure of the total amount of all forms of nitrogen in soil, including organic N (e.g. N in soil organic matter and crop residues) in addition to inorganic N (e.g. ammonium and nitrate). Organic N makes up the largest fraction of total N, and is often not readily plant-available, whereas inorganic N makes up a small amount of total N but is immediately plant-available.

In New Zealand, total N is typically measured alongside total C to provide an indication of the organic matter N content, and the ratio of total C to total N (the soil C:N ratio). The soil C:N ratio gives an indication of the ability of the organic matter to supply N, with a widening of the C:N ratio over time reflecting declining N fertility, while a narrowing of the ratio may indicate enrichment of N in the soil. This is potentially most relevant in the context of hill-country pastoral farming, where a widening of the C:N over time is anecdotally suggested to be occurring, perhaps indicating 'mining' of the organic matter fertility.

Changes in the C:N ratio also indicate a shift between bacterial (low C:N) and fungal (high C:N) dominance of the microbial community. However, while there are some differences in the C:N ratio between land uses (e.g. primary production land uses typically have lower C:N ratios compared to forestry or indigenous vegetation), whether these differences might be considered 'good' or 'bad' is unclear. Rather, the C:N ratio simply reflects the state of the soil and can be used to infer some attributes (e.g. that nutrient cycling is dominated by bacteria or fungi).

Conceptually, high total N, particularly if combined with a low C:N ratio, could indicate increased potential for N-leaching. Sparling et al. (2008) suggested that very high total N contents under pastures were becoming of concern because of the potential to increase leaching losses and eutrophication of waterways. However, the 2011 review of soil quality indicators noted doubt about the use of total N, in isolation, as an indicator of N loss, and that consideration of the C:N ratio was important for interpreting both total N and AMN results (Mackay et al. 2013).

As discussed in Cavanagh, Drewry et al. 2025, many factors influence N loss, including plant-N demand and drainage volume, with drainage volumes and N inputs (e.g. urine, fertiliser) being significant factors influencing leaching and surface runoff losses (Norris et al. 2023; MfE 2024a,b). Mackay et al. (2013) suggested that it may be useful to examine options for linking the indicators to a model such as Overseer® to assess N leaching and N_2O emission risks. While Overseer currently provides estimates of N leaching (and N_2O) emission), this remains at farm scale rather than regional or national scale.

Anaerobic mineralisable nitrogen

Sparling and Schipper (1998) grouped mineralisable N alongside total C, total N, and C:N as indicators that provide information on the quality of organic matter, which is why we discuss mineralisable N here.

Organic N needs to be mineralised to inorganic forms (ammonium and nitrate) by soil micro-organisms before it can be used by plants. Mineralisable N is broadly considered to be a measure of the capacity of the soil microbial community to convert (mineralise) N tied up in complex organic residues into the plant-available N. More specifically, it is a relative indicator of a soil's ability to mineralise N, and is an indirect estimate of N that could be made available from organic-N throughout the growing season. Mineralisable N can be measured in different ways (see Curtin et al. 2017), including AMN. AMN correlates with microbial biomass and hot-water-extractable C and N (Ghani et al. 2003; Sparling et al. 2003; Curtin et al. 2017).

It is also relevant to note that nationally and internationally there are slight variations in the terminologies used to describe mineralisable N, which can in part also relate to different methods of determining mineralisable N. Internationally, the term 'potentially mineralisable N' (PMN) most commonly refers to mineralisable N determined through 7-day anaerobic incubation of soil (i.e. AMN), with AMN relatively widely used as a soil quality indicator (e.g. Mahal et al 2018; Liptzin et al. 2022) .

In New Zealand, Sparling and Shipper (1998), used the term 'mineralisable nitrogen' when referring to AMN. New Zealand commercial laboratories tend to use the term 'potentially available nitrogen' to refer to mineralisable N determined from anaerobic mineralisation, and provide results expressed as kg/N/ha, with conversions based on laboratory volume weight, and an assumed sampling depth of 0–15cm.[6] More recently a 'potentially mineralisable nitrogen' test based on hot-water-extractable N (HWEN) has been introduced by Hill Labs (see below for further details).

The AMN method uses an incubation temperature of 40°C and anaerobic conditions as pragmatic analytical considerations. The warm temperature accelerates the rate of microbial activity and thus the rate of conversion of organic matter to ammonium-N, while the anaerobic conditions prevent conversion of the ammonium-N to nitrate-N (therefore making analysis of the extract more

[6] 14666v9_services-offered-soil-nitrogen-tests.pdf; https://www.hill-labs.co.nz/media/hgndk3iy/22221v7_technical-note-understanding-soil-nitrogen-tests.pdf;

straightforward). This general method is used by all commercial laboratories, although not all laboratories subtract the free ammonium-N from the mineralisable fraction at Day 0, which can lead to differences.[6] Also, Hill Labs use near infra-red spectroscopy for some soil N and soil C measurements, allowing faster turnaround time,[7] but they suggest that wet chemistry methods be used for more accurate assessments.

AMN was originally considered as a biological measure of soil quality for SoE monitoring because it indicates N reserves that are readily mineralisable by soil organisms (Sparling and Shipper 1998; LMF 2009). It was also suggested that the main risk to the environment from high AMN was the increased chance of nitrate leaching (particularly at times of low plant demand) and eutrophication of receiving waters. However, the value of AMN (and total N) as indicators of N leaching was questioned during the 2011 review of soil quality indicators, and the upper limit for AMN was removed (Mackay et al. 2013).

More generally, for SoE monitoring, soil N properties (total N, AMN) are unlikely to be useful even as a crude indicator of water quality impacts and greenhouse gas emissions. This is partly because the processes involved (e.g. plant uptake of N, microbial N cycling, drainage of water) occur on a much more dynamic basis than can be captured in a single indicator, but also because N inputs will be a dominant influence (Norris et al. 2023; MfE 2024). This is also supported by an analysis of fluxmeter data undertaken by Cavanagh, Drewry et al. (2025), which showed no relationship between AMN and N leaching.

AMN is generally correlated with total C and total N, but not C:N (Figure 6). However, there is still high variability in the relationship, as indicated by the low R^2 values, particularly when separating out individual land uses (Figure 6). AMN was evaluated in a recent study to identify soil health indicators best suited to characterise N cycling at a continental scale (Liptzin et al. 2023). In this study, five N indicators (total soil N, autoclavable citrate-extractable N, water-extractable organic N, potentially mineralisable N [AMN], and N-acetyl-β-D-glucosaminidase activity) were evaluated using data gathered from 124 sites, with long-term experiments using a range of management practices across North America.

Overall, N indicators responded to management in similar ways; i.e. higher values were observed when the quantity of organic inputs increased through a range of management (decreasing tillage, cover cropping, retaining residue, and applying organic sources of nutrients), with most (59–81%) of the variation in N indicators among sites, with indicator values decreasing with temperature and increasing with precipitation and clay content. The final selection of the indicators considered the analytical cost and availability of testing laboratories. Ultimately, because of the strong relationships of the N indicators with C indicators, measuring soil organic C along with 24-hour potential C mineralisation was used as a proxy for N supply instead of measuring potentially mineralisable N or any other N indicator directly.

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[7] 35398v5_technical-note-analysis-of-soils-using-near-infra-red-spectroscopy-nirs.pdf

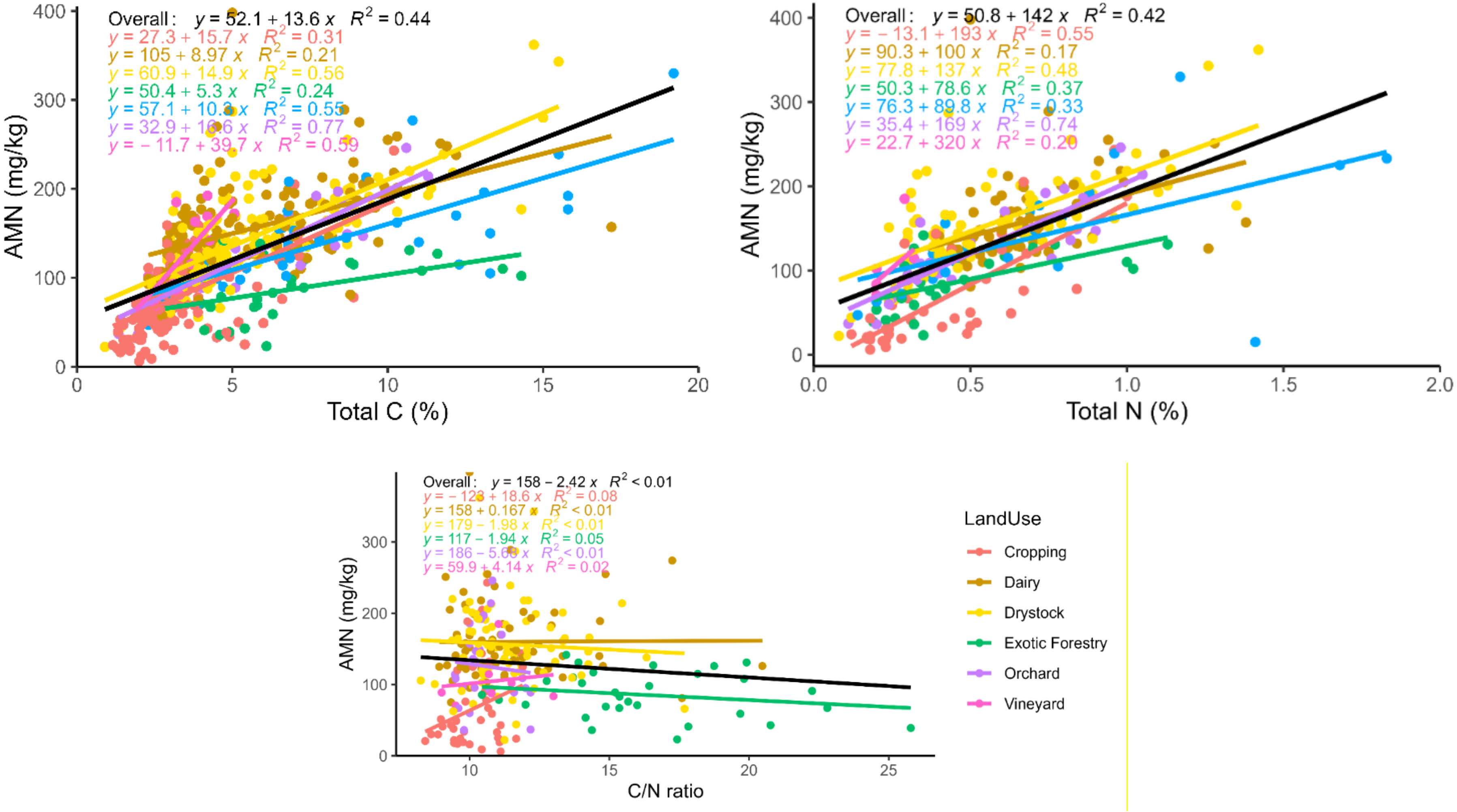

Figure 6. Relationship between AMN and total C, total N and C:N ratio for different landuses.

The 24-hour potential C mineralisation or CO_2-burst method was also evaluated by Curtin et al. 2017, although these authors found HWEN was a better measure of N mineralisation. This HWEN test has been further developed and forms the basis of the current potential mineralisable N (PMN) test offered by commercial laboratories. The test used by Hill Labs uses a field-calibrated factor for cropping soils,[8] although the details of this calibration are unavailable.

Issues have been raised with the repeatability of AMN (Lawrence-Smith et al. 2018), in addition to its relevance to *in situ* mineralisation processes (Norris et al. 2023; Beare et al. 2022). Variability in results is in part due to methodological differences between commercial laboratories across New Zealand in the measurement of AMN – specifically, taking account (or not) of starting ammonium status (Lawrence-Smith et al. 2018) – but is also attributable to the heterogeneity of the microbial community in soils.

A separate concern is that the AMN test has not been extensively field-calibrated, with the actual amounts of N mineralised in the field dependent on factors such as soil temperature and moisture. The significance of this concern depends on the context for using the information. For SoE monitoring, AMN provides a relative measure of the ability of different soils to mineralise organic N, but it is less useful for more accurately predicting how much N is available for plant-uptake over a growing season.

An N mineralisation calculator[9] has been developed by Plant & Food Research, which allows the PMN value to be more accurately interpreted. The N mineralisation calculator uses the PMN value and inputs 'reality' (local climate data and soil order) to provide a farm-specific month-by-month release of mineralisable N. The calculator is available for the main soil orders in the main cropping areas: Canterbury, Tasman/Marlborough, Manawatū-Whanganui, Hawke's Bay, Gisborne, Waikato and Auckland. Outside of the calculator-available areas, Plant & Food Research has also developed general guidelines that allow interpretation of the PMN test.

The PMN test and calculator are valuable tools to inform fertiliser application, but in this context have less relevance for SoE monitoring than AMN. However, while AMN does relate to soil biological functioning, the interpretation of this information is currently reduced to a 'more is better' approach that does not provide any insight into soil microbial community structure or function beyond N mineralisation. There also remains a lack of clarity about what practices may increase AMN, other than general management practices that would increase soil organic matter.

[8] Soil Nitrogen Tests Demystified

[9] New tool to measure soil mineralisable nitrogen; Soil nitrogen testing and predicting nitrogen supply · Plant & Food Research

6.1.2 Soil chemical measures

Olsen P

Olsen P is the primary measure of plant-available phosphorus (P) used in New Zealand. Considerable research on plant response to Olsen P has been undertaken over the last 60 or so years, and this information is captured in several fertiliser industry handbooks and many journal papers, including a national series of trials (Sinclair et al. 1997) and many other studies (e.g. Morton et al. 1995; Smith et al. 2012). The most well-developed information is available for the pastoral industry and vegetable cropping industries, while information is less readily available for perennial horticultural crops such as kiwifruit and vineyards, for forestry, and for indigenous ecosystems. It should also be noted that a different measure of plant-available P, Bray-P, is the preferred analytical method to estimate plant-available P in forestry soils, which are typically acidic (Davis et al. 2015). The Olsen P test can overestimate available P in low pH soils and high P retention soils (Hill Labs Technical note, undated, 'Soil phosphorus tests'; Olsen et al. 1954).

Through both national reporting (MfE & StatsNZ 2021), and more generally across regions (Figure 4), Olsen P is one of the two indicators that are most commonly out of the SoE target range. As highlighted in Cavanagh, Drewry et al. 2025, there has been confusion over the units associated with Olsen P target values, and hence how target values have been applied, particularly in national SoE reporting. Specifically, target ranges that were considered to be based on gravimetric measures of Olsen P (i.e. mg/kg) were actually based on laboratory volumetric measures (i.e. mg/L). Correction reduces the number of sites considered to have excessive Olsen P and increases the number of sites potentially deficient in P.

The reference ranges developed in Cavanagh, Drewry et al. 2025 convert fertiliser recommendations, which are based on laboratory-based volumetric values, to gravimetric (mg/kg) values, following Drewry, Stevenson et al. (2022), with depth adjustment for pastoral recommendations (based on 7.5 cm) to the depth of SoE monitoring of 10 cm. A similar depth adjustment was not made for cropping soils, for which Olsen P agronomic recommendations are based on 15 cm depth, because it is expected that these soils are sufficiently well mixed through cultivation that concentrations in 0–10 cm will be similar to those in the 0–15 cm depth. (However, an increased use of minimum tillage for cropping may mean that this assumption becomes invalid over time.) Given the limited accessibility of recommendations for Olsen P for perennial crops, Olsen P cropping recommendations were considered applicable for perennial horticulture (Cavanagh, Drewry et al. 2025).

Water quality issues are the environmental outcome of most concern in relation to elevated soil Olsen P, although this is influenced by multiple factors. Anion storage capacity or P-retention has been indicated to be a strong influence on dissolved reactive P concentrations in overland runoff (McDowell & Condron 2004; Morton et al. 2003), and this is also highlighted in fertiliser handbooks (e.g. Roberts & Morton 2023). As such, measurement of P-retention in SoE soil quality samples would provide additional insight into the potential for offsite movement of P.

However, while Olsen P values can provide a general indication of water quality risk, in that higher Olsen P values pose a higher risk to waterways, the actual risk depends on the delivery of P to waterways. This movement is influenced by many site-specific and transport factors, in addition to soil P-retention, such as slope and proximity to waterways, land management activities (e.g. grazing regime, cultivation), and climatic factors (e.g. timing of rainfall in relation to grazing or cultivation events) (see Figure 9 in Cavanagh, Drewry et al. 2025). Some of these field factors influencing P transport may be observable during sampling visits and could be recorded at the time of the visit. However, providing a quantitative basis for setting soil Olsen P based on water quality outcomes requires some level of modelling of these processes, using agreed generic scenarios.

Finally, there is an increasing use of volumetric Olsen P analyses because these are offered by larger commercial laboratories, mainly because all calibration of agronomic production commencing in the early 1970s has been undertaken on a volumetric analysis (Drewry, Stevenson et al. 2022; Cavanagh, Drewry et al. 2025). The increasing use of volumetric Olsen P analyses applies also to recent environmentally focused studies of P (e.g. Lizzaralde et al. 2022; McDowell et al. 2020; McDowell et al. 2024) despite early studies on the movement of P in surface water and leaching being undertaken using gravimetric measures of Olsen P (i.e. McDowell & Condron 2004; McDowell et al. 2004). From a wider interpretability perspective, land managers are much more familiar with volumetric measures of Olsen P, so the benefits and trade-offs associated with the ongoing use of a gravimetric basis for reporting on Olsen P results and reference ranges for SoE reporting need to be evaluated.

pH

Soil pH is a measure of soil acidity, and, in the context of agricultural and horticultural land uses, an indication of lime requirement and the likelihood of trace element deficiencies or toxicities in relation to plant growth. Bagnall et al. (2023) considered pH to be an inherent (and critical) soil property because native soil pH is determined by soil-forming factors, such as parent material and weathering. However, in New Zealand, for most agricultural and horticultural land uses lime addition to provide optimal soil pH for plant crops or pasture is common. Outside of these land uses native soil pH is likely to dominate.

As described in more detail in Cavanagh, Drewry et al. 2025, from an environmental perspective there is recognition that pH has a strong influence on the soil microbial community composition (e.g. Wakelin et al. 2021) and important microbial-mediated processes (e.g. nitrification, Cao et al. 2025), as well indicating the likelihood of trace element deficiencies or toxicities for ecological receptors (microbes, plants, and invertebrates. Soil pH is critical for contextualising and interpreting other soil properties and thus remains an important indicator to measure.

6.1.3 Soil physical indicators

Soil physical indicators specified in the NEMS-SQ are macroporosity, bulk density, and aggregate stability. As shown in Figure 3, and from national reporting (MfE & StatsNZ 2021), macroporosity is the soil quality indicator that is most commonly identified as being out of target range. Bulk density is rarely identified as being out of range, while aggregate stability is typically not included in national reporting. This may be because aggregate stability is generally only monitored in cropping land. Further discussion on each of these indicators is provided below.

Macroporosity

The NEMS-SQ notes that, in a general sense, macropores refer to the larger pores that are the main route by which air enters soil, or where initial drainage occurs, and that they are the first pores to be lost when soil is compacted. In the literature, the size range for defining macropores varies between 30 and 3,000 µm.

Cavanagh et al. (2023) outline the historical discrepancy in terminology regarding macroporosity and the pore size, and tension, this is measured at, in the context of soil quality monitoring. Briefly, a –5 kPa tension was initially used to calculate the macroporosity indicator for early (pre-2003) soil quality data, with the New Zealand Soil Bureau defining macroporosity as:

total porosity – volumetric water content at –5 kPa

However, macroporosity was perhaps more widely accepted as being the volumetric percentage of large soil pores >30 µm (measured at –10 kPa matric potential), and this has been adopted as the primary measure for macroporosity in regional and national environmental reporting (e.g. Hill & Sparling 2009) and research studies, including much of the earlier pasture production-based macroporosity research (e.g. Drewry et al. 2004). The NEMS-SQ states that the terminology is from the New Zealand Soil Bureau, which defines macroporosity determined at tension of –10 kPa as *air-filled porosity,* although no reference was cited in the NEMS-SQ. For air-filled porosity, bulk density and particle density are first used to calculate total porosity:

total porosity (%) = (1 – (bulk density / particle density)) x 100

Then air-filled porosity is calculated as follows:

air-filled porosity (%) = total porosity – (volumetric water content at –10 kPa)

Note, however, that MWLR laboratories typically use the term 'air capacity' on samples at –10 kPa (see McQueen 1993), but this is an equivalent term at this matric potential, and the laboratories provide comment on terminology to clients.

For SoE sampling, macroporosity is typically determined on samples at –10 kPa. However, while air-filled porosity is the term specified in the NEMS-SQ, the term 'macroporosity' is still widely used, including in SoE national reporting (e.g. MfE & Stats NZ 2021), and in the recent revision of target values (Cavanagh, Drewry et al. 2025). Thus, a greater effort is required if there is an aspiration for different terminology to be used (which would also probably reduce inadvertent confusion of macroporosity determined using different pressures).

Macroporosity is commonly noted as a sensitive indicator of compaction, particularly in pastoral soils (Singleton & Addison 2000; Sparling et al. 2001b; Drewry et al. 2008; Houlbrooke et al. 2021; Hu et al. 2021, 2022). Although Sparling et al. (2001b) stated that 'macroporosity is not so meaningful for arable soils, because it is greatly influenced and distorted by the tillage regime', it was listed as being relevant for all soils and has typically been measured in all land uses. The NEMS-SQ specifies the collection of samples from cropping sites to occur just before harvest (i.e. when soil has settled, to minimise the effects of cultivation). However, it is unclear how easy it is for soil quality monitoring staff to schedule this in, and whether the samples received may reflect greater disturbance than is desirable. Also, for fields with row and furrows, it is not specified whether the rows or furrows (which may be subject to vehicle trafficking) should be sampled. Similarly for perennial horticulture sites, greater consistency of sampling in rows, inter-rows and wheel-tracks is desirable. In forestry sites, harvesting pattern and site cultivation affect macroporosity, and whereas cultivation is generally predictable, the harvesting pattern can be masked by leaf litter and branches.

Leaving aside sampling issues, a value of 10% macroporosity is a widely used 'rule-of thumb' indicator of detrimental effects. For example, McLaren and Cameron (1996) state that 'it is generally accepted that when air-filled porosity is less than 10% of the total porosity, then plant growth is affected'. They also acknowledge that this is not an absolute value, however, because different plants have different tolerances for low oxygen levels, and that air-filled porosity gives no indication of the continuity of soil pores, and therefore assessment of the possible rate of oxygen exchange.

Regardless, use of 10% as a threshold for negative effects is widespread, including in studies where it provided the basis for determining other metrics such as bulk density and penetration resistance (e.g. Suzuki et al. 2022; Bergamin et al. 2015), or degree of compactness (e.g. Reichert et al. 2009). However, the apparent evidence base for setting this threshold is sparse, particularly for pastoral grazing systems, while a wider range of studies are available for cropping systems internationally, including laboratory and field studies (Table 2. Texture may also influence the 'effects' of macroporosity. For example, Hakansson & Lipiec (2000) found that macroporosity of <10% may be adequate for plant growth in soils with a high clay content, while higher values are needed for sandy soils.

Table 2. Optimum or minimum macroporosity and air-filled porosity for pasture and crop responses determined by experiments or in review studies

Condition	Macroporosity or air-filled porosity or equivalent (%)	Matric potential at which macroporosity was determined (pore diameter microns)	Pasture, crop and comment	Reference
			Field or Lab studies	
Optimum	16–17	–10 kPa (>30)	Perennial ryegrass, field-simulated treading (NZ)	Drewry et al. 2001
Optimum	>14	–6 kPa (>50)	Barley, wheat field study	Carter 1988
Optimum[a]	20–21	–10 kPa (>30)[a]	Lab pore distribution study; yield not measured.	Reynolds et al. 2009
Minimum[b]	7–8	–6 kPa (>50)	Perennial ryegrass seedlings, pot trial (NZ)	Gradwell 1965
Minimum	10–12	–6.7 kPa (>~40)	Corn seedlings, lab study	Grable & Seimer 1968
Minimum	14.5	Varied	Cotton lab study	Hodgson & MacLeod 1989
Minimum	10	Varied	Cotton, but 10% air-filled porosity value from literature	Hodgson & Chan 1982
Minimum (97% of relative yield)	11.5–11.7	–10 kPa (>30)	Perennial ryegrass, clover pasture (dairy field trial) (NZ)	Drewry & Paton 2000
Minimum	10–12	–6 kPa (>50)	Barley, wheat field study	Carter 1990
			International review studies	
Minimum	10+	Varied	Various crops (review)	Grable 1971
Minimum	12	Varied	Various crops (review)	Greenwood 1971
Minimum	8–10	Varied	Sugar beet (Review)	Erikson 1982
Minimum	5–10	Varied	Various crops (Review)	Stepniewski et al. 1994
Minimum	10	Varied	Various crops (Review)	Lipiec & Hatano 2003
Minimum	10	Varied	Various crops (Review)	Hakansson & Lipiec 2000

Source: extended from Drewry et al. 2008.

Note: New Zealand-based experimental studies are denoted by 'NZ'.

[a] Pore distribution study. Air capacity is reported in table above as Reynolds et al. (2009) used –10 kPa.

[b] Minimum macroporosity of 7–8 is conservative, as Gradwell (1965) reported: 'The best overall criterion of adequate soil air-space for seedling grass plants that can be obtained from these trials is at least 7–8 per cent if air-space as measured on cores, but this would be conservative in some cases.'

Partly for this reason, and partly because evaluation of macroporosity in the baseline monitoring data set suggested there was strong evidence of degradation (affecting productivity), Cavanagh, Drewry et al. 2025 based revised reference ranges for macroporosity on limited data sets that provide data for sites for which there is greater confidence if they are unimpacted (e.g. samples collected from under fencelines of pastures, or at undisturbed forestry sites). The pastoral data set was used to provide the reference ranges for all land-use categories except forestry. The forestry data set and the baseline monitoring data set indicate that a different (higher) macroporosity range is more relevant for forestry. Ironically, this approach also yielded a lower-end reference value of 10% for non-forestry land uses (and higher for forestry). As highlighted in Cavanagh, Drewry et al. 2025, additional data from a greater number of undisturbed sites would enable more robust reference ranges to be developed, and perhaps enable soil order difference to be better elucidated. Nonetheless, this approach is based on comparison with an undisturbed state vs. an effects-based value.

Regardless of the approach used to identify a 'threshold' of 10%, this value leads to the identification of widespread compaction, with 70% of dairy sites in the baseline monitoring data set used by Cavanagh, Drewry et al. 2025 falling below 10%; this is an increase from the 50% of (a much smaller number] of dairy sites evaluated in the 500 Soils programme (Sparling & Schipper 2001). This led Houlbrooke et al. (2021) to observe that despite this apparent widespread compaction, the specific consequences of degraded soil quality on pasture production and its financial implications remain unclear at the farm, regional, and national levels.

Similarly, Cavanagh, Drewry et al. 2025 highlighted the need to establish further research on how regional SoE soil quality macroporosity results relate to pasture production and environmental effects (e.g. nutrient leaching, runoff, and greenhouse gas emissions). Perhaps the only broad-scale assessment is that of Hu et al. (2021), who estimated that if the dairy sector improved soil macroporosity values above 10%, then pasture production could increase by 6%. This prediction was based on estimated pasture yield impacts of reduced macroporosity from six New Zealand studies. Anecdotal information suggests that the pasture yield impacts of compaction may be being masked through increased use of fertiliser or other land management practices.

Additional value from measures of air-filled porosity could be gained through its use to calculate available water, which provides a measure of resilience to drought and storage of soil water. This may require a one-off measurement at –1,500 kPa.

Finally, it is worth noting that sub-surface (>20 or 30 cm) compaction, particularly in cropping soils, is a primary concern, rather than surface compaction (see Appendix 4). An air-filled capacity threshold of 5% (measured at –6 kPa), based on German legislation, is proposed for use under the EU Soil Health Monitoring legislation (see also Appendix 4). EEA (2023) identifies soil degradation occurring via both compaction and deformation, which should be addressed through assessment. Compaction was best identified using the following indicators: precompression stress, the ratio of precompression stress to actual stress applied, air capacity (5% at –6 kPa), and saturated hydraulic conductivity (EEA 2023).

Recent New Zealand studies indicate that macroporosity, bulk density, and available water capacity show that soil compaction under dairy farming is occurring to depths of about 30 cm (i.e. the typical depth of topsoil (Drewry, Carrick, Penny et al. 2022; Drewry, Carrick, Mesman et al. 2022). However, the effects of this compaction on yield or environmental outcomes remains unclear.

Bulk density

Bulk density is used widely in many monitoring and research studies, probably because it is easy and inexpensive to measure. Bünemann et al. (2018) reported that in soil monitoring programmes internationally, bulk density was the second most common soil physical indicator, after water storage, while porosity (which included porosity, macroporosity, air capacity) was eighth most common. In an evaluation of indicators for compaction, the EEA (2023) observed that while bulk density was considered sensitive to compaction, it was a non-specific indicator of compaction because it describes changes in volume but not potentially negative impacts on pore functions. Bulk densities between 1.2 g/cm^3 and 1.6 g/cm^3 were considered normal. The EEA (2023) also indicated that visual evaluations (VESS: visual evaluation of soil structure) could be used to determine changes in packing density, which can also be derived from bulk density clay content and is considered to be an indicator of compaction. Panagos, De Rosa et al. (2024) investigated bulk density monitoring across Europe and used 'packing density' to provide a spatial indication of soil compactness. Sparling and Shipper (1998) also mentioned packing density in their original consideration of indicators, although, probably because it required knowledge of percentage clay, this measure was not taken forward in New Zealand.

In New Zealand, a measure of bulk density is required for the determination of macroporosity, and is also useful to provide a cross-check on whether observed differences in concentrations of, for example Olsen P, are influenced by changed bulk density. Bulk density is influenced by soil texture and parent material. For example, Pumice or Organic Soils have a low bulk density of around 0.5–0.8, while Raw or Recent Soils derived from iron sands have a high bulk density of 1.3, or even up to 1.7. Thus, texture and parent material are important contextual information for interpreting bulk density values.

Similar to macroporosity, bulk density results can be influenced by recent soil disturbance, such as cultivation, and samples from cropping and short-rotation horticultural soils should be taken just before harvest, when the soil is relatively undisturbed. As for macroporosity, Cavanagh, Drewry et al. (2025) determined reference ranges from the limited data set of undisturbed pastoral and forestry sites for different soil orders, along with an upper limit of 1.4 Mg/m^3. Reynolds et al. (2008) suggested that this limit was associated with reduced crop yield as a result of excessive mechanical resistance to root elongation for medium- to fine-textured soils.

Aggregate stability

Aggregate stability is generally defined as the fraction of aggregates remaining after exposure to destabilising stressors (often wet sieving) (Rieke et al. 2022). These authors, drawing on multiple references, state that the measure is conceptually linked to soil hydrological function, and empirically linked to reduced erodibility and increased infiltration, as well as to agronomic function (root development, seedling emergence, etc.).

Aggregate stability is required in the NEMS-SQ (2022) framework for regional soil quality monitoring, in addition to the seven indicators specified by the LMF for land uses involving soil disturbance (i.e. soil cropping). However, based on the survey (section 5), only nine councils appear to be currently monitoring this (Figure 2). Laboratories that offer soil aggregate stability are MWLR soil physics (Palmerston North) and Plant & Food Research (Lincoln). We are not aware of other labs that offer this test.

In New Zealand, aggregate stability is typically expressed as a mean weight diameter (MWD) of the aggregates. It is measured by wet sieving several size fractions of soil, following Kemper & Rosenau (1986). Sparling and Schipper (2001) found that aggregate stability is useful to characterise the soil condition of those land uses involving tillage, but of little value in characterising pasture, indigenous vegetation or plantation forestry. In the original establishment of target values (Sparling et al. 2008) for Recent Soils, aggregate stability >2 mm MWD was considered optimal for production and environmental criteria. Lower MWD was considered more detrimental to environmental quality rather than to production, and values of <1.5 mm MWD were noted as being cause for concern.

However, beyond these generic descriptions the basis for these values is unclear. Perhaps the only evaluation of aggregate stability in the context of SoE monitoring is that of Taylor (2011, in Mackay et al. 2013), based on data collected from the Waikato region. Taylor concluded that aggregate stability was not useful for indicating compaction in pastoral soils, but that it seemed useful for indicating loss of soil stability and increased erosion risk, primarily for cropping soils and recent conversions from forestry to pasture on Pumice Soils. One other study that provides context for aggregate stability is that of Beare et al. (2003), who provide a relationship between aggregate stability (as a percentage of total aggregates) and regional average yield in Canterbury.

An alternative measure of aggregate stability, expressed as a percentage of total soil aggregates that are less vulnerable to erosion, based on average aggregate size distribution (e.g. Beare & Tregurtha 2004), was discussed at the 2011 workshop, with the proportion of soil <0.85 mm considered to be a better assessment of erosion risk than aggregate stability in mm MWD (Mackay et al. 2013). The LMF, however, concluded that these were two separate indicators, neither of which would become part of the core soil quality indicator suite, although both are useful 'environmental indicators' that could be developed later for regional council use (Mackey et al 2013). However, no further investigations appear to have occurred.

Table 3. Details of aggregate stability measured by regional councils in New Zealand

Measurement of aggregate stability reported		Target values used	Use of target value	Source of target value as reported in council reports
MWD of stable aggregates (mm)		>1.5	AC, WRC, BPRC, GWRC, ECan, MDC, TDC from 2010	'Scientific opinion' (TDC 2010); Beare et al. 2005; Francis et al. 1991; Sparling et al. 2003
		>2.0	HBRC, TDC until 2009	'Scientific opinion' (TDC 2009); Sparling & Stevenson 2008
Average aggregate size distribution	Potentially erodible aggregates: <0.85 mm (%)	<40	ECan's arable and pastoral soil quality monitoring (Lawrence-Smith et al. 2014)	Wind tunnel studies on Canterbury soils: Eastwood 2001; Leys et al. 1996
	Proportion of aggregates >1 mm (%)	>50	GWRC (Drewry 2017)	'Guidelines obtained from Plant & Food Research' (Drewry 2017)

Source: Cavanagh et al. 2023.

AC = Auckland Council; WRC = Waikato Regional Council; BPRC = Bay of Plenty Regional Council; GWRC = Greater Wellington Regional Council; ECan = Environment Canterbury; MDC = Marlborough District Council; TDC = Tasman District Council; HBRC = Hawke's Bay Regional Council

Internationally, aggregate stability appears to have been given greater weight as a soil health measure. It is one of the three indicators included in the minimum suite of soil health indicators determined through the North American Project to Evaluate Soil Health Measurements (NAPESHM), which assessed over 30 available measurements (Bagnall et al. 2023). There have also been various recent comparisons of methodologies used for determining aggregate stability (e.g. Almajmaie et al 2017; Rieke et al. 2022; Poepalau et al. 2024).

Rieke et al. (2022) evaluated four commonly used measures of aggregate stability recorded on samples collected from long-term research stations across primary agricultural areas in North America. These measures included the Cornell Rainfall Simulator (Moebius-Clune et al. 2016), the wet sieve procedure (Kemper & Rosenau 1986), the SLAKES smart phone app (Fajardo et al. 2016), and the MWD of water-stable aggregates (Franzluebbers et al. 2000). Rieke et al. (2022) found that all four methods analysed in their study were suitable as measures of soil aggregate stability, but that the methods were not inter-operable. Rather, it was most important to consistently use the same method when monitoring changes in soil health over time.

In another study, Poeplau et al. 2024 compared three methods: the MWD method, the proportion of water-stable aggregates, and the SLAKES smartphone app (Fajardo et al. 2016), and found that MWD was the most sensitive and reproducible measure of aggregate stability. However, while the name of the methods used is the same as that used in New Zealand, the detail of the method differs. These authors also found that organic matter composition (as determined from mid-infrared spectra) rather than total amount helped to explain aggregate stability.

While many studies mention using the wet sieve procedure (Kemper & Rosenau 1986), which is the basis for assessing aggregate stability in New Zealand, there are variations in the specific methods used (e.g. drying temperature, starting aggregate size, time of oscillation), so comparison between studies is not readily made. Given the usefulness of aggregate stability for assessing soil structure for cropping soils, this indicator should be retained. However, it would be useful to evaluate the SoE monitoring data captured to date alongside an evaluation of the basis for the existing target values, and also to consider alternative, potentially less expensive, methods for providing this information.

6.1.4 Trace elements

A suite of trace elements – arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), fluorine in the form of fluoride (F), lead (Pb), nickel (Ni), and zinc (Zn) – also need to be monitored under the NEMS-SQ. All elements except F are easily monitored; F is more expensive and difficult to analyse.

At all monitoring locations a baseline assessment of all elements is useful to identify the current state of the site and any potential historical contamination (e.g. sheep-dips). Thereafter Cu and Zn, and potentially Cd, are the elements most relevant to monitoring on an ongoing basis. Cu and Zn have ongoing inputs via Cu fungicides and Zn for facial eczema treatment, while Cd is a contaminant in phosphate fertiliser and is managed under the Tiered Fertiliser Management

System, as well as under a National Cadmium Management Strategy. This includes guidance for the management of Cd to ensure compliance with food standards for different food crops.[10]

The development of soil guideline values (SGVs) to protect ecological receptors (Eco-SGVs) for these trace elements, except Ni, is outlined in Cavanagh & Munir 2019, and a brief description is provided below. No Eco-SGVs for Ni have been derived in a New Zealand context, although Canadian authorities have derived an environmental guideline value for Ni (CCME 2015).

Eco-SGVs for these naturally occurring trace elements have been developed using an 'added-risk' approach. This approach considers that the bioavailability of the background concentration of a contaminant is zero, or sufficiently close that it makes no practical difference, and that the ecological community is adapted to these elevated concentrations such that it is the added anthropogenic amounts that are of primary consideration from a toxicity perspective (e.g. Crommentuijn et al. 1997). Specifically, Eco-SGVs are developed by adding the contaminant limit developed by consideration of the toxicity of the contaminant (referred to as the added contaminant limit) to the background concentration. In this manner, regional variations in background concentrations can be taken into account.

The development of Eco-SGVs is described in Cavanagh & Munir 2019, with updates provided in Cavanagh & Harmsworth 2023. The latter authors outlined the use of Eco-SGVs for the protection of soil quality and the management of contaminated land, with Eco-SGVs based on the protection of 95% of species proposed for use in SoE soil quality monitoring programmes, with an 80% protection level suggested as a concentration at which any ongoing inputs should cease (Table 4).

Table 4. Overview of proposed application of Eco-SGVs for protection of soil quality (Cavanagh & Harmsworth 2023)

Value name (protection level)	Protection of soil quality
Target limit (95%)	Regional council state of the environment monitoring. Discharge consents, including for application of wastes (e.g. biosolids, cleanfill, managed fill) to land, and compost/mulch products. Iwi, hapū, Māori achieve soil health goals, reflecting cultural values.
Cessation limit (80%)	A cessation-of-inputs limit. Where active inputs are still occurring (e.g. use of copper fungicide on primary production land), there is a greater focus on landowners to demonstrate the health of soil to continue inputs.

The Eco-SGVs associated with the different levels of protection for inorganic contaminants are provided in Tables 5 and 6. The values shown in Tables 5 and 6 incorporate the median ambient background concentrations of these trace elements determined by Cavanagh et al. (2023) and shown in Table 7. For most monitoring and assessments, initial comparison should be made with the values in Tables 5 and 6. Depending on the application, and the contaminant, it may also be appropriate to vary the Eco-SGV depending on site background concentrations or other soil properties (e.g. pH). A further update of background concentrations of these trace elements was

[10] https://www.mpi.govt.nz/funding-rural-support/environment-and-natural-resources/land-and-soil-health/cadmium-research/

undertaken by Cavanagh, Thompson-Morrison et al. 2025. Given the closeness of median values determined from the previous model and the current model, the default Eco-SGVs developed in Cavanagh & Harmsworth 2023 (Tables 5 & 6) were retained, although some modifications were made to Eco-SGVs for the upper percentiles (Table 7).

Table 5. Eco-SGVs (mg/kg) developed for selected contaminants, based on the estimated median ambient concentration

% protection	As Eco-SGV (mg/kg)	B Eco-SGV (mg/kg)	B-HWS Eco-SGV (mg/kg)	Cd Eco-SGV (mg/kg)	Cd Eco-SGV_{BM}* (mg/kg)	Cr Eco-SGV (mg/kg)	Pb Eco-SGV (mg/kg)	Pb Eco-SGVBM* (mg/kg)
95	20	14	7	5	1.5	200	290	290
80	60	22	15	17	12	400	1,290	900[1]
60	150	25	17	40	35	660	3,060	2,500[1]

* An extra 5% protection applied to each land use to provide protection against secondary poisoning.

Notes: Eco-SGVs may be adjusted up, based on background concentrations shown in Table 7, as applicable to the location of the site. See Table 1 for an explanation of the element symbols. BM = biomagnification; B-HWS = boron – hot-water soluble.

Table 6. Eco-SGVs (mg/kg) developed for Cu and Zn contamination in the three New Zealand reference soils, based on the estimated median ambient concentration

% protection	Cu Eco-SGV typical soil	Cu Eco-SGV sensitive soil*	Cu Eco-SGV tolerant soil	Zn Eco-SGV typical soil	Zn Eco-SGV sensitive soil*	Zn Eco-SGV tolerant soil
95	110	**95**	135	200	**180**	250
80	245	**190**	350	320	**285**	410
60	430	**330**	640	510	**450**	645

* Suggested default Eco-SGV. See also section Cavanagh and Harmsworth (2023) for adjustment based on soil pH, C, and catin-exchange cation.

Note: Eco-SGVs may be adjusted based on background concentrations shown in Table 7, as applicable to the location of the site.

Some pragmatism is required to determine when it is acceptable to modify the Eco-SGVs based on background concentrations to avoid overly complex application of the Eco-SGVs. This judgement has been made by considering both the percentile range and the proportional contribution of the natural background concentration to the Eco-SGV. Specifically, we recommended that background concentration adjustment only be acceptable for the 95% protection values. Given the lower protection level, and that background concentrations generally comprise a small proportion of the 80% and 60% protection values, adjustment of background soils is not warranted. For the 95% protection values, the general rule used to adjust for background is that the difference between median concentration and the upper percentiles is >10 mg/kg, where background comprised c. >10% of the Eco-SGV.

The full suite of revised background concentrations is shown in Table 7 with bolded values showing the percentile concentrations that are accepted for modification of the 95% protection level Eco-SGVs.

Table 7. A summary of relevant statistics for the range in ambient concentrations (mg/kg) of selected trace elements using an extended data set

Element	Median[a]	Median[b]	90th [b]	95th [b]	99th [b]
As	**4.1**	**3.6**	6.1	7.4	10.5
B	4.6	**4.1**	8.0	**9.7**	**15.3**
Cd	**0.08**	**0.1**	0.2	0.23	0.37
Cr	**16**	**14.5**	25	**34**	**84**
Cu	**16**	**13.6**	21	**24**	**34**
Ni	9	8.7	14	17	47
Pb	**11**	**11.0**	17	19	23
Zn	**48**	**47.3**	**65**	**70**	**80**

[a] From Cavanagh & Harmsworth 2023.

[b] From Cavanagh, Thompson-Morrison et al. 2025.

Cavanagh and Munir (2019) also evaluated the ecotoxicity of F and observed that there are overlapping effects arising from added F depending on what species are being examined. Notably, F addition appears to stimulate microbial processes at lower concentrations, with negative effects at higher concentrations, potentially attributed to pH changes rather than F toxicity. However, the available literature also suggests that negative effects of F on soil rhizobia and plants may also occur at lower concentrations.

Livestock exposure is often the primary concern, and exposure of cattle and sheep to excess F through the diet can result in damage to teeth, jaws, and bones. Cronin et al. (2000) provides one of the most comprehensive discussions of the potential risks to livestock from ingestion of F. Cattle are more sensitive to fluorosis than sheep, with estimated dietary tolerances of 30–50 μg/g dry matter and 60 μg/g dry matter, respectively (Cronin et al. 2000). Tolerances can be higher (>100 μg/g dry matter) if cattle or sheep are exposed to elevated F for short periods. Removal of sheep or cattle from high F input will reduce F that has accumulated over time (Grace et al. 2003, 2005). Soil ingestion is recognised as the primary route of exposure for livestock, given the low concentrations in pasture (Loganathan et al. 2003, 2006; Grace et al. 2011). Using dietary tolerances of 45 μg/g dry matter and 60 μg/g dry matter for cattle and sheep, respectively, and assuming a bioavailability of F in dry matter of 75%, Cronin et al. (2000) estimated threshold F concentrations ranging from 326 to 1,085 mg/kg for cattle, and 372 to 1,460 mg/kg for sheep, based on different soil ingestion rates and soil F bioavailability.

Extractable (water-extractable and $CaCl_2$-extractable) F concentrations appear to be more useful to assess the ecotoxicological risk of F, while total soil F concentrations are more appropriate for determining the risk of fluorosis to livestock, because digestion of ingested soil is likely to release more F than what would be available under environmental conditions. There also remains interest from the National Cadmium Management Group for information on soil F concentrations (M. Taylor, Waikato Regional Council, pers. comm.). There is therefore some value in measuring soil F to provide baseline concentrations for a site.

6.2 Reporting

For regional or national SoE reporting purposes, Sparling and Schipper (2001) originally suggested: (1) monitoring sites through time to obtain trends, (2) noting the number of sites failing to meet a soil quality standard, and (3) determining the area of land that is at risk of not meeting a soil quality standard. The first two approaches have generally been widely adopted at both regional and national reporting (e.g. Drewry, Cavanagh et al. 2021; Taylor et al. 2018; Curran-Cournane 2020; Stats NZ & MfE, 2021, 2024, 2025). However, results have typically not been scaled up to determine the area of land that is at risk of not meeting a soil quality standard.

There are various challenges associated with current reporting. As noted in sections 5.1.2 and 6.1 (and in Cavanagh et al. 2017), there are regional inconsistencies in the target values used to compare SoE monitoring results and in the approaches used for trend analyses, and regional and national trend analysis are confounded by the change in the number of sites under different land uses over time. Further challenges occur with the identification and classification of land use (including the capture of this information by councils) (Cavanagh et al. 2018; Cavanagh & Whitehead 2022, 2023). This can confound trend analysis by 'muddying' identification of when a land-use change has actually occurred, as well as the 'scaling' up of results or determination of the 'representativeness' of a sampling location.

National reporting (e.g. MfE & StatsNZ 2018, 2021) provides a clearer picture of which indicators predominantly fall out of range, etc., although the trend analysis is still confounded by differing numbers of sites under different land uses over time. Ideally, trend analysis should be undertaken by assessing changes over time of individual sites (e.g. Drewry, Cavanagh et al. 2021), but there are also challenges with this approach (e.g. if few sites have remained under the same land use over the sampling period). Nonetheless, changes at the individual site level should be given greater consideration because this is more relevant for the individual indicators: potentially, land use should be considered a secondary factor rather than the primary factor when undertaking trend analysis.

As noted earlier, some indicators may not be identified as falling out of range because no target values exist; for example, total N for cropping and horticultural soils (Sparling et al. 2008; Hill & Sparling 2009). Similarly, for Organic Soils no target values were set for total C because a diagnostic criterion for Organic Soils is that C content be >16% (Sparling & Schipper 1998). Cavanagh, Drewry et al. (2025) observed that in the baseline monitoring data set a number of sites identified as being on Organic Soils have C concentrations that fall below – well below in the case of cropping soils – the diagnostic criterion for Organic Soils of 18% C (Hewitt 2010). Therefore, the wider implications of the degradation of these Organic Soils need to be considered.

Finally, while reporting has typically been based on land-use and soil order groupings, it is also useful to understand how much these factors influence the response observed for the different indicators. In their analysis of indicators for New Zealand soil quality monitoring, Sparling et al (2001b) highlighted the contrasting influence of land use and soil order for Olsen P and total C as an example of the variability in the significance of those factors for individual indicators (Table 2). The main sources of variability were suggested to be land use and management, soil order, spatial (within site and between site), climatic and temporal, and systematic (e.g. analytical and sampling errors), with 40–50% of the variance not explained by land use and soil order (Table 2). Regardless, there was a strong emphasis on the ability to discriminate between land uses (anticipated to be a surrogate for management effects) for indicator selection rather than establishing links to soil function or to help interpret results (e.g. soil texture). Thus, parameters such as particle size distribution were not taken forward for inclusion as part of the soil quality monitoring programme.

Table 8. Sources of variation from Sparling et al. 2001b

Indicator	Land use	Soil order	Interaction*	Unexplained	Total
Olsen P	31	12	(52)	48	100
Total C	21	43	(61)	39	100

* The interaction appears to have been calculated as 100% minus percentage unexplained, and then compared to the sum of percentage explained by land use and soil order.

In a similar analysis, using the baseline monitoring data set of Cavanagh, Drewry et al. 2025, land use and soil order contributed 30–50% of the variation in measured values (Table 3), with soil order most influential for bulk density, total C, and total N. However, 40–60% of the variation remains unexplained, and, as noted above, will be attributable to variability in spatial, climatic, temporal, and systematic (sampling and lab) sources (Table 3).

This suggests that it may be useful to consider additional variables in the analysis of SoE monitoring data to provide a better understanding of the results. For example, Liptzin et al. (2022, 2023) highlighted the importance of soil texture and climate in the interpretation of indicator results, including whether the absolute value of the indicator depends on soil texture or climate; whether the response to management depends on soil texture or climate; whether the methodology is sensitive to soil texture; and, finally, whether it is easy to understand what the analysis is measuring.

These 'site' factors dominated the responses of both C and N cycling indicators in an extensive evaluation across North America. The cropping index number, which refers to the number of consecutive years a paddock had been under arable or pastoral production immediately prior to sampling (Lawrence-Smith et al. 2014), may also be another parameter that could help explain some of the observed values.

Table 9. Source of variation (%) in results for each soil quality indicator from the baseline monitoring data set

Indicator	Land use	Soil order	Interaction	Unexplained	Total
AMN	32.9	9.4	4.8	52.9	100
Olsen P	37.0	3.9	5.2	54.0	100
Bulk density	11.6	29.2	5.2	54.0	100
Macroporosity	26.7	8.9	5.5	58.9	100
pH	31.6	1.9	7.0	59.4	100
Total C	20.8	32.5	4.3	42.4	100
Total N	20.0	33.1	4.2	42.7	100
CN	45.4	7.2	5.5	41.9	100

6.3 Potential new indicators

Internationally, various soil strategies and underpinning programmes (e.g. the EU Soil Strategy,[11] the EU Mission 'A Soil Deal for Europe',[12] BENCHMARKS[13], the North American Project to Evaluate Soil Health Measurements (NAPESHM), and the Australian National Soil Strategy[14]) have led to considerable activity in soil quality monitoring, indicators, and thresholds, (e.g. Faber et al. 2022; Van Leeuwen et al. 2017; Creamer et al. 2022; Liptzin et al. 2022, 2023; Griffiths et al. 2018). A vast number of soil indicators have been evaluated; for example, Zwetsloot et al. (2022) includes a list of 289 measures used to assess soil biology and biological processes in soil, and an earlier European assessment of soil indicators identified 290 potential indicators related to 188 key issues for nine soil threats (Huber et al. 2008). A summary of the indicators used in key recent international programmes is provided in Appendix 4.

In New Zealand, aside from the original studies identifying the soil quality indicators for SoE monitoring, studies that have evaluated or identified potential additional indicators include Mackay et al. 2013 (a review of original soil quality indicators, and additional indicators, including HWEC and earthworms), Hermans et al. 2017 (bacteria via 16S rRNA); Lawrence-Smith et al. 2018 (indicators for C and N), Schon et al. 2021 (indicators potentially useful for regenerative agriculture), Schon et al. 2022 (earthworms), and more recently assessments of biological indicators (Thompson-Morrison & Cavanagh 2023; Biggs et al. 2025). MfE also compiled information on 11 attributes for assessing the ecological integrity of soils (MfE 2025)[15]. We further note that the original development of soil quality indicators specifically excluded erosion (loss of intactness) and ecological integrity/biodiversity. Additional soil properties that were assessed but not ultimately selected for national soil quality monitoring (Sparling & Schipper 1998; Hill et al. 2003) are shown in Table 10.

We are conscious of the cost constraints that councils face, and so have focused our discussion for potential new indicators on those that have come through previous New Zealand evaluations, identified in Cavanagh, Drewry et al. 2025, or on those indicators or soil properties that we think should be further developed or investigated.

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[11] COM_2021_699_1_EN_ACT_part1_VERSION FRIDAY EVENING LUCAS (europa.eu)

[12] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/soil-health-and-food_en

[13] https://soilhealthbenchmarks.eu/

[14] https://www.agriculture.gov.au/sites/default/files/documents/national-soil-strategy.pdf

[15] https://environment.govt.nz/publications/information-stocktakes-of-fifty-five-environmental-attributes/

Table 10. Soil properties that were assessed but not ultimately selected for national soil quality monitoring.

Indicator	Information provided
Cation exchange capacity and base saturation	Buffering capacity and nutrient reserves
Basal respiration (B)	Availability of organic matter reserve, microbial activity
Microbial biomass (B)	Size of microbial population, rapidly cycling organic matter and nutrients
Total porosity	Availability of water and air, retention of water, drainage properties
Unsaturated hydraulic conductivity (K_{40})	Infiltration rate, drainage properties
Available water (total and readily available)	Availability of water to plants
Particle size distribution	Physical environment for roots and soil organisms, potential nutrient holding capacity

Source: Sparling & Schipper 1998

6.3.1 Hot-water-extractable carbon

Hot-water-extractable carbon (HWEC) is a measure of soluble C that has been demonstrated to be highly correlated to soil microbial biomass C, microbial biomass N, AMN, and total carbohydrates, with weaker correlations with cold-water-extractable C and total organic C (Ghani et al. 2003; Sparling et al. 2003; Bongiorno et al. 2019; Curtin et al. 2022). HWEC has also been shown to be correlated with N mineralisation measured in 14-week aerobic incubation at 25^{0}C (Curtin et al 2017; Cavanagh, Drewry et al. 2025). More generally, HWEC provides a measure of labile C, and has been shown to be more responsive to differing land management practices than total C (Curtin et al. 2022).

Labile C has been proposed as an indicator for various soil functions, including: nutrient cycling (measured, for example, by soil nutrient content and C mineralisation), soil aggregate formation (measured, for example, by water-stable aggregates), C sequestration (typically derived from changes in total organic C content), and habitat provision for biodiversity (currently assessed by biological indicators such as microbial biomass and abundance of faunal groups). It is also a starting point for the formation of more stable soil organic matter (Cotrufo et al. 2013).

HWEC was originally proposed as a potential soil quality indicator in May 2011, with the LMF agreeing that further investigation of HWEC would be undertaken (Mackay 2013). Since then, various councils have measured HWEC, and occasionally HWEN, which has provided some data to evaluate the utility of HWEC in the context of New Zealand SoE monitoring. However, there is some variation in the methods used to determine HWEC. For example, the original method (Ghani et al. 2003) and Plant & Food Research (e.g. Lawrence-Smith et al. 2018) typically use a sequential extraction of cold-water extraction followed by hot-water extraction, while commercial laboratories typically use a single hot-water extraction. These differences can give rise to variation in results.

The most extensive evaluation of HWEC results in the context of SoE monitoring has been that undertaken by Taylor et al. (2022), building on earlier evaluations (Taylor et al. 2017; WRC 2016). These evaluations focused on the relationship between HWEC and AMN, and the development of potential target values for HWEC. The data set compiled by Taylor et al. (2022) was extended by

Cavanagh, Drewry et al. (2025) and used to evaluate the relationship between HWEC and total C, total N, and AMN. These analyses were extended to evaluate the relationships for individual landuses and are shown in Figure 7. These graphs illustrate the general correlation between HWEC and total C, total N, and AMN, but also highlight the variability that exists within land-use classes as well as between land uses.

There is a much weaker, or no, relationship between HWEC and AMN for forestry and indigenous vegetation sites, potentially related to the higher C and C:N ratios of these sites. Expression of HWEC as a proportion of total C (Figure 8) also shows variation between land uses, but no obvious trends. Deeper analysis of these data using additional site information and greater evaluation of potential methodological information may help to identify reasons for the observed variation.

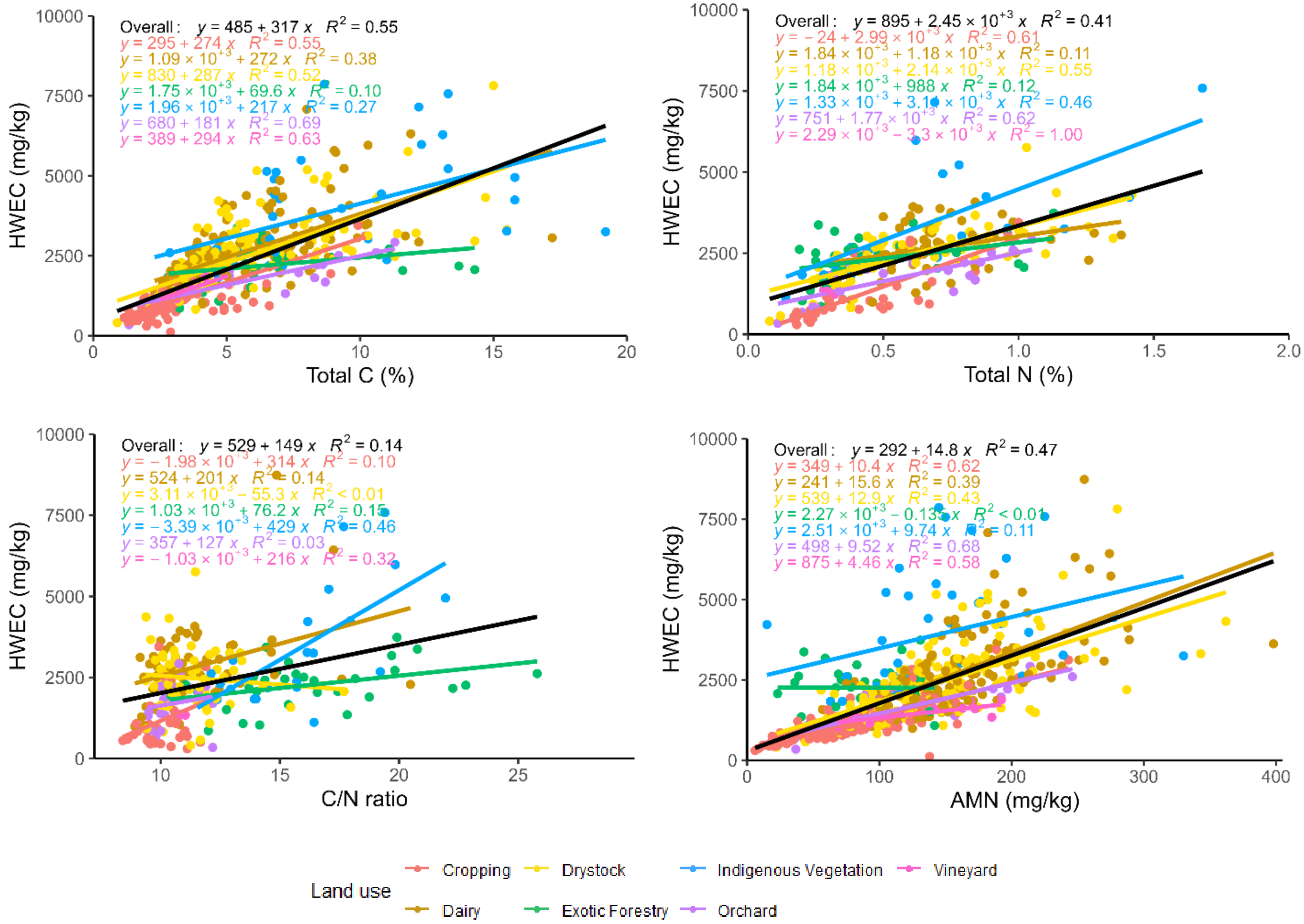

Figure 7. Relationship between hot-water-extractable C (HWEC) and total C, total N, C:N ratio, and AMN, from the HWEC data set.

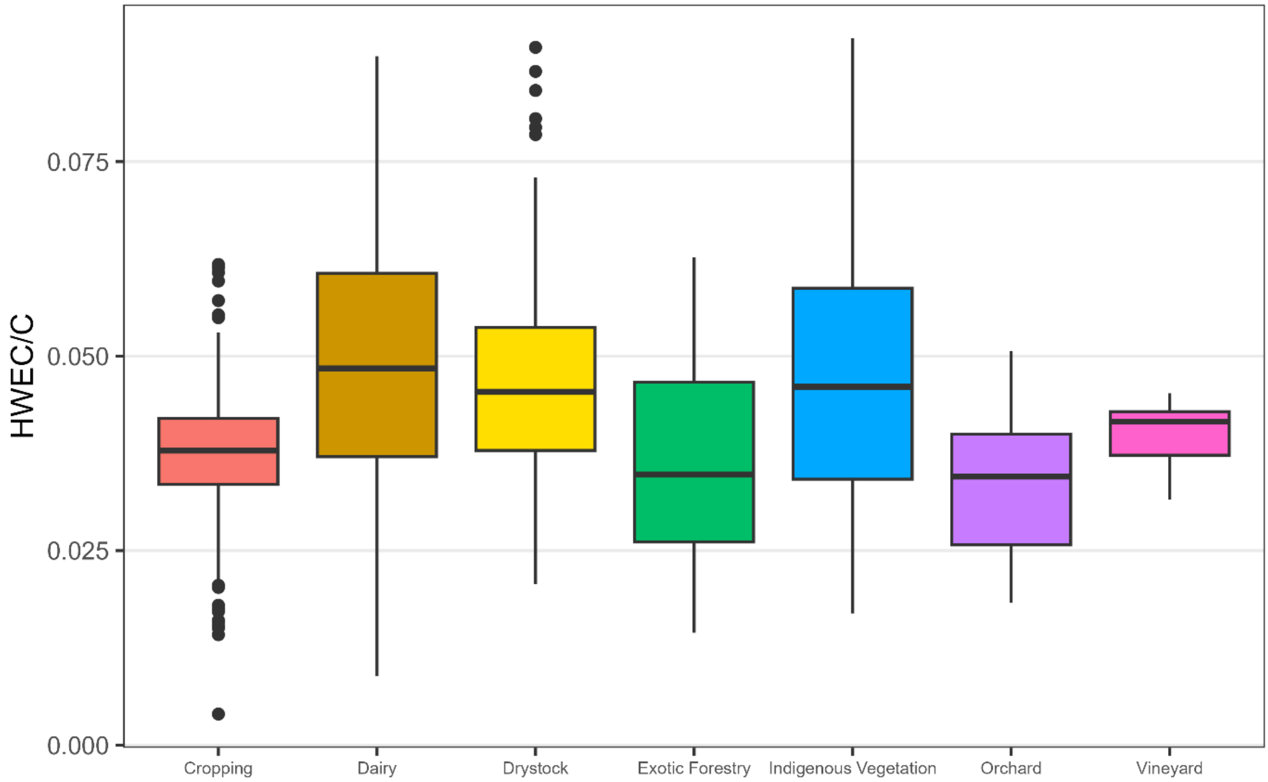

Figure 8. Ratio of HWEC/C for individual land uses, for sites in the HWEC data set. The edge of the boxes represents the 25th and 75th percentile of the data – or the interquartile range (IQR), with the median shown as the solid line within the box. The lower whisker represents the 25th percentile – 1.5 IQR, with the upper whisker being the 75th percentile + 1.5 IQR, with solid circles showing the outliers.

Liptzin et al. (2022) and Bongiorno et al. (2019) also highlight the similarity of responses of different C indicators to management, and with each other, in their extensive evaluations of indicators used in North America and Europe, respectively. Liptzin et al. (2022) evaluated six indicators (potential C mineralisation, permanganate-oxidisable C, water-extractable organic C, and β-glucosidase enzyme activity) across 124 sites in North America, and proposed that, balancing the cost, sensitivity, interpretability, and availability at commercial labs, the 24-hour potential C mineralisation assay could deliver the most benefit to measure in conjunction with SOC.

Bongiorno et al. (2019) assessed HWEC alongside four other measures of labile C fractions – dissolved organic carbon (DOC), hydrophilic DOC (Hy-DOC), permanganate-oxidisable carbon (POXC), and particulate organic matter carbon (POMC) – in 10 European long-term field experiments. They concluded that POXC represents a labile C fraction sensitive to soil management and is the most informative about total soil organic matter, nutrients, soil structure, and microbial pools and activity. Fine et al. (2017) identified POXC as the best overall indicator of soil health from 930 samples in US farms, following the CASH framework. Bongiorno et al. 2019 also support our observations that quantitative relationships between currently used indicators and soil functions are generally under-investigated, and suggest that establishing these relationships is of high priority.

The sensitivity of HWEC to management practices, and thus being an early indicator of total C loss, is often cited as a reason for adopting this measure (e.g. Ghani et al. 2003; Curtin et al. 2022). However, practical application of this observation to SoE reporting remains unclear and requires more specific data analysis. For example, soils under cropping are recognised as having low total C, and also have low HWEC, whereas soil under pastoral land has higher total C and higher HWEC (e.g. Figure 7). McNally et al. 2018 found that while on average 89% more organic C was mineralised from pastoral soils, this amount was small relative to organic C loss inferred from the difference in total organic C between pastoral and cropped soils. Similar to AMN, it is unclear what land management practices can specifically increase HWEC, over and above those practices that generally increase soil organic matter.

Overall, in comparison to AMN, HWEC is quicker and easier to do and is considered to be less analytically variable (Lawrence-Smith et al. 2018). It is also generally correlated with AMN, is commercially available, and there is existing New Zealand research that helps to provide context for the responses of HWEC in different soils and management practices. There are multiple conceptual interpretations that can be applied to HWEC (see above), although, generally speaking, more is better. As with AMN, total C and total N, it is difficult to assign specific values of HWEC that might be considered 'bad' or 'good', and so the typical range approach adopted in Cavanagh, Drewry et al. 2025 probably provides the most logical approach to setting reference or target ranges to assess individual results for SoE monitoring. POX-C and the 24-hour C mineralisation assays potentially provide alternative indicators for C cycling. Curtin et al 2017 found the 24-hour C mineralisation assays showed a strong association with water extractable organic N and C, particularly with HWEON, although POX-C has not been used in New Zealand and neither test is currently commercially available in New Zealand.

6.3.2 Carbon storage/sequestration

Stabilisation of C is often attributed to the formation of organo-mineral complexes in the fine fraction (silt and clay), and in New Zealand soils mineral surface area and extractable aluminium have been determined to be a better predictor of the ability of a soil to store C compared to the mass proportion of fine particles or clay content (Beare et al. 2014; Curtin et al. 2016; McNally et al. 2017). Cavanagh, Drewry et al. 2025 suggested that the saturation potential or C loading of soil based on the mineral surface area of soils (e.g. McNally et al. 2024; McNally et al. 2017; Beare et al. 2014) could provide a more function-oriented basis on which to base soil quality targets or reference ranges. For example, this could be used to indicate the 'gap' or 'deficit' between measured C levels and potentially achievable C levels of a given soil. A similar approach is used by the EU Soil Observatory, whereby an unhealthy soil is considered to be one where the distance that separates it from the maximum soil C is more than 60% of current levels.[16]

The mineral specific surface area (MSA) of soils is determined from the air-dried water content of all soils (as determined by oven drying a subsample at 105°C for 16 hours), following Parfitt et al. 2001:

MSA (m^2/g) = 2 * water content of air dry soil (g water/kg soil).

The fine-fraction carbon (FFC) is considered to be the C fraction associated with soil minerals (also known as mineral-adsorbed organic carbon, MAOC) and is generally determined from the total soil C content less the C in the sand-sized (>53 μm) fraction or particulate organic carbon (POC).

[16] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

McNally et al. (2018) found that FFC varied between 80% and 93% of the total organic C in soils, with the proportion of FFC being larger in the cropping soils, while McNally et al. (2017) found that FFC typically comprises 85% of total organic C. An estimated upper limit or saturation potential for C was determined from the 90th quantile regression of the relationship between FFC and MSA and extractable aluminium by McNally et al. (2017). The saturation deficit can then be calculated by subtracting the measured FFC from the upper limit. The POC:MAOC ratio could be a good indicator for the entire soil.

Initial evaluation of the saturation deficit approach (based on samples collected at 0–15 cm depth) applied to regional council samples (collected at 0–10 cm depth) has been undertaken by Lawrence-Smith et al. (2018). They found that extractable aluminium contributed very little to the overall fit of the stabilisation capacity, and that the published 0–15 cm coefficients (McNally et al. 2017) would be appropriate to predict the upper limits of the saturation potential for the 0–10 cm depth samples. They also found that slight differences in FFC for the soils in the council data set (0–10 cm) represented 80 ± 1% of total C compared with 85% in the soils (0–15 cm) studied by McNally et al. (2017). Finally, Lawrence-Smith et al. (2018) noted that the temperature at which samples are air-dried is critical to determining the surface area and stabilisation capacity, and that air drying at temperatures higher than 25°C resulted in lower surface areas than if they had been dried at 25°C. However, subsequent research determined that the humidity conditions when samples are dried is the more critical factor (S. McNally, MWLR, pers. comm.).

McNally et al. (2024) suggested that the loading of FFC relative to the mineral surface area could provide a simplified way of determining whether the mineral surfaces are at their maximum C loading, suggested to be 1.0 mg C/m^2. In this case, only FFC needs to be measured alongside the mineral surface area.

Further assessment of these measures of soil C fractions and associated metrics are being undertaken by MWLR using an extended data set of samples collected through the National Soil Carbon Monitoring programme (S. McNally, MWLR, pers. comm., July 2025). When this work is completed, further evaluation of this information for use in setting soil quality target ranges can be undertaken. This will focus on both C sequestration and vulnerability to loss of soil C, as opposed to other soil functional properties associated with C and organic matter, such as aggregate stability and water-holding capacity.

6.3.3 Biological indicators

The original identification of New Zealand soil quality indicators explicitly excluded indicators for assessing the ecological integrity or biodiversity (Sparling et al. 2001b). Biological functioning was, however, evaluated by including microbial biomass, basal respiration, and AMN in the initial indicator suite, with AMN retained for the final suite (see section 6.1.1). AMN can be considered a direct measure of biological functioning it is reliant on *in vitro* microbial action for the test.

Both HWEC (see section 6.3.1) and earthworms were initially proposed as potential biological indictors to the LMF in 2011 (Mackay et al. 2013). HWEC measures a fraction of the soil total C that is associated with other measures of biological activity, which means it is an indirect biological indicator. There has been further development of the use of earthworms through both abundance

(Schon et al. 2022) and most recently e-DNA assays.[17] The use of metabarcoding approaches for developing soil biological quality indicators has been investigated since 2013 (e.g. Hermans et al. 2017; Holdaway et al. 2017; Hermans, Buckley et al. 2020a, b; Hermans, Taylor et al. 2020; Lewe et al 2021; Louisson et al. 2023; Hermans et al. 2025), with Biggs et al. (2024) providing a review of metabarcoding and metagenomic approaches to assessing soil biological functioning. Thompson-Morrison & Cavanagh 2023 provide a detailed review of biological indicators for use in SoE monitoring, grouping biological indicators into three categories: chemical proxies (e.g. total C, C:N, HWEC), biological function (e.g. AMN, respiration), and soil biology – essentially measures of abundance and diversity through molecular or visual methods.

In a recent report on resource use and waste generation in New Zealand (PCE 2025), the Parliamentary Commissioner for the Environment highlighted that a key gap in understanding the impact of primary sector activities on soil quality and quantity is the impact of land use on soil microbes and invertebrates and their role in supporting soil productive capacity. This gap extended from basic information regarding the distribution and health of these communities, through to their various functions and contribution to soil quality (see also Drewry et al. 2024).

Internationally, Griffiths et al. (2018) and Zwetsloot et al. (2022) provide an evaluation of, and approaches to, using soil biological indicators. A summary of soil biological indicators used in selected international soil quality monitoring programmes is shown in Table 11. These are a mix of chemical proxies, functional indicators, and biodiversity measures.

[17] technical-note-soil-test-for-earthworm-edna.pdf

Table 11. Soil biological indicators used in selected international soil quality monitoring programmes

Country	Programme	Current use status	Biological indicators
Australia	Soil Quality[a]	Potential *ad hoc* use (data appear to be last updated mid-2010s)	Organic C Labile C (no standard method identified) Soil N supply Microbial biomass Nematode communities Arbuscular mycorrhizal fungi Pathogens, pests, diseases (e.g. fusarium, *Rhizoctonia*, crown-rot, take-all disease)
	National Soil Monitoring Programme[b]	In use	Potentially mineralisable N (measured as anaerobic mineralisable N) eDNA
North America (Canada, US, Mexico)	North American Project to Evaluate Soil Health Measurements (NAPESHM)[c]	In use	Organic C Potentially mineralisable C (measured through the CO_2 burst method)
US	Soil Health Institute[d]	In use	Tier 1 indicators (common, accepted analyses with standardised laboratory methods): • organic C • N • C mineralisation potential (CO_2 burst method). Tier 2 indicators (indicators that show promise but need further development): • enzymes: β glucosidase, N-acetyl-B-D-glycosaminidase, phosphomonoesterase, aryl sulfatase • phospholipid fatty acids • genomics (16S rRNA ITS and shotgun metagenomics) • soil protein index.
	Comprehensive Assessment of Soil Health (CASH) manual[e]	In use	Organic matter Soil protein index Soil respiration (measured as rewetting of dried soil and CO_2 released over 4 days' incubation) Active C (permanganate-oxidisable C) Potentially mineralisable N (add-on test)
EU	Soil Health and Food Mission[f]	Proposed	Organic C stock Soil biodiversity
	BENCHMARKS[g]	In use	Anaerobic mineralisable N Microbial biomass (C & N) Earthworm abundance Microarthropods (morphometric, DNA metabarcoding) Nematodes (extraction, DNA metabarcoding) Microbes (DNA, 16S and ITS PCR) Bacterial abundance (qPCR of 16S marker gene) Fungal abundance (qPCR of 18S marker gene) Nitrifying archea and bacteria (qPCR of ammonia monooxygenease functional gene)

Country	Programme	Current use status	Biological indicators
			Nitrous oxide-reducing bacteria (qPCR nitrous oxide reductase) Proteolytic bacteria Urea-hydrolysing bacteria
	EEA[h]	To be developed	Exceedance of safe minimum standards of ecosystem conservation Exceedance of operating ranges for specific soil animals and microorganisms
	Directive on soil monitoring and resilience [j]	Proposed	*Loss of soil biodiversity* Member states to select at least one of: metabarcoding of bacteria, fungi, protists and animals; phospholipid fatty acid analysis (PFLA); abundance and diversity of nematodes; abundance and diversity of earthworms (in cropland); abundance and diversity of springtails; abundance and diversity of native ants; bacterial diversity based on DNA; soil biological quality based on arthropods (QBS-ar). Optional indicator: *Loss of soil biological function* Member states to select at least descriptors including: soil basal respiration ((mm^3 O_2/g/hr) in dry soil; microbial biomass; soil respiration; enzyme activity
	European Soil Observatory Dashboard[i]	In use	Potential threat to biological function: geospatial layer combines a set of 13 factors (e.g. habitat fragmentation, land-use change, soil pollution or soil sealing) known to be potential threats preventing soil biodiversity from performing its biological functions.

Source: updated from Thompson-Morrison & Cavanagh 2023
[a] https://www.soilquality.org.au/
[b] G. Grealish, CSIRO pers. comm.
[c] Bagnall et al. 2023: aggregate stability via slaking image recognition, and predicted plant-available water-holding capacity based on a development of a pedotransfer functions using soil organic carbon.
[d] https://soilhealthinstitute.org/news-events/national-soil-health-measurements-accelerate-agricultural-transformation//
[e] Moebius-Clune et al. 2016, https://www.css.cornell.edu/extension/soil-health/manual.pdf
[f] EC 2021: the six other indicators are 'Presence of soil pollutants, excess nutrients and salts', 'Soil structure including soil bulk density and absence of soil sealing and erosion', 'Soil nutrients and acidity', 'Vegetation cover', 'Landscape heterogeneity', and 'Forest cover'.
[g] https://soilhealthbenchmarks.eu/soil-sampling-protocols/. These are guidelines developed for undertaking sampling and assessment of agricultural and forest experimental sites and systems, and urban systems. The proposed sampling designs are applied in the different sites for a basic characterisation and to address spatial heterogeneity and variability of soil health indicators across a site.
[h] EEA 2023: indicators to address the threat of soil biodiversity loss.
[i] https://data.consilium.europa.eu/doc/document/ST-11299-2024-INIT/en/pdf. Proposal for a Directive of the European Parliament and of the Council on Soil Monitoring and Resilience (Soil Monitoring Law), 17 June 2024.
[j] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/. Origazzi et al. 2016.

Soils are estimated to hold between 25% and 59% of the world's biodiversity (UNEP & FAO, accessed July 2024; Anthony et al. 2023), and it is only through direct assessment of soil biology that biodiversity in soils can be assessed. Selecting appropriate indicators and interpreting the results remain the biggest barriers to utilising soil biological indicators in New Zealand soil quality monitoring programmes. Thompson-Morrison and Cavanagh (2023) concluded that nationally coordinated efforts are required to develop a greater depth of understanding of the biological functioning and biodiversity of soils. This includes the ongoing evaluation and assessment of the use of molecular data, but also giving greater attention to the use of soil invertebrates. National coordination is required because there are additional costs associated with undertaking the sampling and to ensure consistent data are collected (i.e. it is useful to be specific about which invertebrate groups are assessed).

As noted above, there has been considerable focus on metabarcoding approaches using e-DNA, primarily for bacterial and fungal communities, but also extending to invertebrates (e.g. Dopheide et al 2019; Watts et al. 2019). A recognised limitation of metabarcoding approaches is the limited libraries for the many indigenous species that exist in New Zealand soils, particularly invertebrates. Ongoing investigation of the use of eDNA in soil quality assessment is being undertaken by Waikato Regional Council, working with the commercial laboratory Wilderlab, to develop commercial-scale DNA molecular approaches for potential use in soil quality monitoring.

Otago Regional Council has also recently undertaken an assessment of various biological indicators, including e-DNA (Nilsen & Summerfield 2024), soil invertebrates (extraction, and identification through Massey University), and earthworms.

A key barrier to the use of soil invertebrates in soil assessments is that current methods for monitoring soil invertebrate communities are labour-intensive, costly, and reliant on specialist taxonomic expertise. However, a collaborative, internally funded project between MWLR and AgResearch, working with the University of Waikato, aims to provide a proof of concept pipeline for the rapid identification of invertebrates and biomass estimates using machine-learning-based image analysis. This project draws on international collaborations linking to global soil biodiversity initiatives (SoilBON) (see also Potapov et al. 2020). This project will integrate molecular tools, such as DNA metabarcoding, with machine-learning-based methods to help build a comprehensive, locally relevant DNA reference library of New Zealand soil invertebrates. This project commenced on 1 July 2025, and if successful opens the doorway for significant expanded soil invertebrate biodiversity assessments.

We suggest that the primary focus for a biological indicator should be identifying useful measures for biodiversity that encompass invertebrates as well as microbes and fungi, because this information cannot be otherwise obtained. Some insight into biological function can also come from molecular data (e.g. metagenomic processes) or selected ‘functional biodiversity’ groupings (e.g. nitrifying bacteria) (see also the indicators used by BENCHMARKS in Appendix 4).

Ahead of the availability or evaluation of molecular approaches for assessing biological function, and if a direct indicator for biological function is desired, the 24-hour CO_2 mineralisation test selected as one of three indicators of soil health in North America (Liptzin et al. 2022; Bagnall et al. 2023) is a comparatively simple approach to providing a relative measure of biological activity among soils. Currently this test is not commercially available, but it is a relatively simple modification of basal respiration tests that are available. Evaluation would include comparison of results from HWEC to confirm if this test provides additional value. Direct measures of biological function and/or measures of diversity and abundance are also useful to assess if negative effects arising from soil contamination are occurring; these are otherwise inferred from comparison with guideline values (e.g. ecological soil guideline values) (Cavanagh & Harmsworth 2023), where these are available.

6.3.4 Inherent soil properties

Inherent soil properties are those that change little, if at all, with land use or management practices, and therefore probably only need to be measured once These properties are largely related to soil formation, but can influence the response of other ‘dynamic’ soil properties to land use or management practices. In the context of SoE monitoring, four inherent soil properties that are relevant are soil texture, drainage class, P-retention, and mineral surface area.

Texture (e.g. the amount of sand, silt, and clay) can influence the response of many soil quality indicators (e.g. Liptzin et al. 2022, 2023; Moebius-Clunes et al. 2016) and is widely used internationally, but much less frequently in New Zealand. Particle size was included in the original set of indicators (Sparling & Schipper 1998) but was not carried through because it was not influenced by land use or management. We suggest that particle-size analysis should be undertaken using the pipette methodology, which provides a consistent result. This is a commercially available test. Other options, such as hand-texture (e.g. Richer-de-Forges et al. 2022) or near-infrared spectroscopy (e.g. Blaschek et al. 2022) may be able to be used more routinely for many soil orders if further validated. Information on soil texture at individual monitoring sites would be valuable to ascertain the extent to which soil indicators are being influenced by these parameters to reduce sources of variability. In particular, bulk density and macroporosity are influenced by soil texture.

As noted in section 6.1.2, P-retention influences the extent to which P is retained on the soil particles; measuring this property at SoE monitoring sites provides a greater ability to assess the hazard of movement to waterways associated with elevated Olsen P. However, as also noted in section 6.1.2, many other factors influence the delivery of P to waterways, and hence the impact of soil P on waterways. P-retention is a standard commercially available test (and may be referred to as anion storage capacity), and may have been measured during original site characterisation to determine soil order.

As discussed in section 6.3.2, mineral surface area is a dominant factor influencing the ability of a soil to store carbon, so its measurement would provide an alternative approach. This is a non-standard test and is not currently commercially available.

Finally, potential rooting depth, topsoil depth, and drainage class can also provide information about the response of soils to different impacts; for example, forced shallow-rooting makes pasture plants susceptible to uprooting during grazing (Crush & Thom 2011) and more prone to drought, and increases leaching risk. These are specified in the NEMS-SQ as properties to be collected at the time of site characterisation, in which case they should already be recorded and do not need to be collected. These parameters would only need to be reassessed after major disturbance events (e.g. forest harvest and/or cultivation, deep cultivation/inversion tillage), which should either be visible, or information will have been provided by land managers prior to sampling. This information should be provided alongside results data for analysis.

6.3.5 Soil physical indicators

Plant & Food Research, in collaboration with MWLR, have a Smart Idea project 'Redefining soil structural vulnerability to enhance ecosystem services'. The project commenced in late 2024 and is aiming to redefine soil structural vulnerability by characterising dynamic functional properties (rather than static properties, such as bulk density) to better reflect the effects of soil structure change on soil ecosystem services. Current methods for assessing soil vulnerability rely on traditional, non-functional properties. These provide inadequate predictions from soil physical properties for soil ecosystem services such as plant production and greenhouse gas emission and mitigation.

This project focuses on the dynamic functional properties of soil structure by evaluating how such properties respond to compaction and its impact on crop production and nitrous oxide emissions. This research may allow for the 'calibration' of measured macroporosity to provide more context for the establishment of reference values. Conversely, it may also allow for the identification of alternative parameters that would more usefully inform SoE monitoring. The research will consider a range of soil orders, and therefore drainage and other soil properties.

Available water capacity (AWC) and readily available water capacity (RAWC) are other properties that have been identified internationally as being useful for monitoring soil health, particularly through the use of pedotransfer functions (Bagnall, Morgan, Cope et al. 2022). In New Zealand, various recent studies found that AWC and RAWC can be affected by land use and management (Drewry, Carrick et al. 2021; Fu, Hu, Beare, Thomas et al. 2021; Drewry, Carrick, Penny et al. 2022). Sparling et al. (2001) considered that given the 'shallow' depth of SoE sampling, RAWC is not a valuable indicator, but instead topsoil depth, total rooting depth, and depth to limiting horizon are probably more relevant. However, further exploration would be valuable, particularly of the use of pedotransfer functions for water storage, which have been developed for New Zealand soils (McNeill et al. 2024), and the use of topsoil depth, total rooting depth, and depth to limiting horizon for use in SoE monitoring.

Finally, soil water repellency (or hydrophobicity) is another indicator that has been identified as being of potentially growing importance given the increasing extreme weather events, including drought in New Zealand (Deurer et al. 2011; Müller et al. 2014). Fu, Hu, Beare, Muller et al. (2021) showed that soils with soil organic C >4% tend to be water repellent. However, further evaluation of the use of this indicator in SoE monitoring is required.

6.4 Visual soil assessment

Visual soil assessment (VSA) is probably the most accessible tool for farmers and communities to observe changes in soil quality (Ruf 2025). VSA has also attracted much interest from Māori groups (e.g. Bruce-Iri et al. 2020; Harmsworth G. 2022a) because of its practicality for on-land assessment, monitoring, and soil management. It aligns well with te ao Māori perspectives and Māori conceptual approaches to understanding soil health and developing indicators. For these reasons, developing stronger links between the findings from VSA and SoE monitoring will help to communicate the findings. In the first instance, VSA creates an awareness of the state of the soil, and ideally over time it creates an impetus for change because farmers have a direct connection with (a) comparing soils in areas with different land-use histories (e.g. under fencelines and in ploughed areas) (Figure 9) and (b) changes in their soil arising as a result of changed management practices, particularly if they can also be related to more quantitative laboratory findings.

VSA for New Zealand conditions was developed as a set of four field guides for cropping and pastoral grazing on flat to rolling country, and hill-country land uses (Shepherd 2000, Shepherd & Janssen 2000, Shepherd et al 2000). These guides were developed to provide farmers, land managers, and regulatory authorities with a simple tool that would enable them to assess and monitor the condition of their soil quickly, cheaply, and effectively (Shepherd 2003). Visual observation can show, for example, good or poor soil structure, and identify the presence of mottles, which are an important indicator of drainage in soils.

The New Zealand VSA field guides are provided here: (https://www.landcareresearch.co.nz/publications/vsa-field-guide/). Briefly, VSA involves digging out a 20 cm cube of topsoil with a spade, and comparing samples taken under the fenceline (as a reference site) with three to four sites across the paddock. Analysis takes about 20 minutes at each site. Soil structure is assessed by dropping the soil sample from a specified height onto a rigid surface, then sorting the resulting aggregates so that the coarsest clods are at one end and the finest aggregates at the other end. A visual score (VS) is assigned to each indicator by comparing the soil with the photographs provided in the guides. Earthworms are counted. At cropping sites the source hole is assessed for the presence of a tillage pan, while on pastoral country the surface relief (pugging) is assessed. Each indicator is scored, with different weightings applied to different indicators, and earthworms are weighted more highly in pastoral sites than in cropping sites. These scores are summed to provide an overall rating for each site (Table 12).

Table 12. Indicators and weightings specified for VSA of cropping and pastoral grazing on flat to rolling country along with total scores and their interpretation.

Cropping indicators	Weighting factor	Pastoral flat-rolling hill indicators	Weighting factor
Soil structure and consistency	3	Soil structure and consistency	3
Porosity	3	Porosity	3
Soil colour	2	Soil colour	2
Number and colour of mottles	2	Number and colour of mottles	2
Earthworm count	2	Earthworm count	3
Presence of a tillage pan	2	Surface relief	2
Degree of clod development	1		1
Susceptibility to wind and water erosion	2		2
Total score and interpretation			
Poor	<10		<10
Moderate	10–25		10–20
Good	>25		>20

Source: Shepherd 2000.

In New Zealand, VSA has been used by some regional councils, such as in the Manawatū-Whanganui Region, as a component in reporting results from SoE soil quality monitoring to farmers (M. Todd, Horizons Regional Council, pers. comm.) For example, bulk density and macroporosity laboratory results are shown alongside individual VSA scores for visual structure, visual porosity, visual colour, and visual surface relief (Figure 9). VSA has also been used as part of land management teams' farm plan assessment. For example, Greater Wellington Regional Council land management advisors undertake a brief visual assessment and include a photo of the soil (e.g. spade depth) as information for dairy farmers. VSA has also been used to assess soils on the Southern Dairy Hub dairy farm in Southland after winter forage crop grazing of fodder beat and kale (photos presented in MfE 2023). A field-day handout for farmers from DairyNZ and the Southern Dairy Hub (2022) compared VSA scores before and after winter grazing; the scores averaged 36% lower after winter grazing. There is also increasing use of VSA in farm assurance programmes (e.g. the New Zealand Farm Assurance Programme Plus).

Figure 9. VSA components reported to a farmer of a soil quality site, supplied by Malcolm Todd, Horizons Regional Council.

Most recently, Taylor (2024) found a poor correlation between VSA and soil quality monitoring indicators at 150 sites across the Waikato region. These results contrasted markedly with the results from Shepherd (2003), who found a good correlation between several indicators. The reasons for these marked differences are not clear, although we note that Taylor’s work was based on sites in the Waikato region only, while Shepherd (2003) evaluated VSAs at 91 sites on 40 soil types (representing 11 soil orders) in 10 regions. Given the extensive VSA and soil quality data captured by both Horizons and Waikato Regional Councils, extended analyses may be valuable to help relate SoE data to that derived from VSA.

Internationally, visual assessment approaches appear to be widely used (FAO 2009; Emmet Booth et al. 2016; Bünemann et al. 2018). The Visual Evaluation of Soil Structure (VESS) developed in the UK appears to have increasing uptake (Ball et al. 2017; Emmet-Booth et al. 2020). The criteria used are aggregate size, shape, intra-porosity, rupture resistance, rooting, and redox-morphology, and they all have scores of 1–5 (Emmet Booth et al. 2016); Ball et al. (2017) provide example photos and scoring instructions for VESS. Ball et al. also concluded that VESS is a useful initial test to provide information on the general quality of the soil as a guide for further sampling and measurements.

We recommend that further consideration be given to the linking or integration of visual assessment approaches with SoE soil quality monitoring as a means to provide greater connection between land managers and their soil, and with SoE monitoring results.

7 Implementation of soil quality indicators

7.1 Indicator evaluation

Our evaluation draws on information on the performance of existing indicators and consideration of potential new indicators, provided in sections 6 and 7, respectively. This is summarised in Table 13, which includes:

- the ‘state’ of the indicator – whether it is currently included in the NEMS-SQ and should be retained or removed, or whether the indicator should be added or investigated further
- the ‘purpose’ of the indicator – whether it is an indicator for which measured limits or thresholds should be used to drive action on improving soil health (primary indicator), or whether the soil property offers additional insight into the response or behaviour of other soil quality indicators (secondary indicator).

For these secondary indicators a differentiation is made between those that provide ‘context’ and should be measured each time monitoring is undertaken, and those that provide ‘characterisation’, which refers to inherent soil properties and can probably be measured once to characterise the site, and are valuable to help explain variations in the primary indicators. A qualitative assessment of the cost implications of the proposed changes is also provided in Table 13.

Table 13. Evaluation of existing and potential indicators for state of the environment soil quality monitoring

Indicator	State	Purpose	Comment/rationale	Cost considerations
pH	Retain	Secondary – context	Soil pH is a key soil property that can influence soil biological activity and plant growth, and bioavailability of nutrients and contaminants, and thus is of value to retain to help interpret other soil properties. It is generally managed within the range relevant to the individual land use, and it is rare that pH would need to be modified for environmental reasons.	No change
Olsen P	Retain	Primary	Olsen P is a key indicator for plant-available phosphorus, and has frequently been identified as being outside target ranges. Elevated Olsen P increases risk to waterways, although additional information, including P-retention and proximity to waterways, is needed to better assess this risk. Insufficient Olsen P can reduce pasture or crop yield. To assist with the interpretability of results, evaluation of the challenges and merits of gravimetric and volumetric analyses and measurements units is required (currently some councils are measuring both).	No change (although cost reduction for those councils currently measuring Olsen P both gravimetrically and volumetrically)
Total C	Retain	Primary	Total C is an indicator of organic matter, which is integral to soil structure and functioning. Further data analysis is required to determine whether additional stratification of soil C results will help to further (meaningfully) delineate between non-allophanic mineral soils.	No change
Total N, C:N ratio	Retain	Secondary	Total N is readily measured alongside total C, and the C:N ratio is useful to indicate organic matter fertility, and insight on nutrient cycling processes (i.e. bacterial or fungal dominated).	No change
Anaerobic mineralisable N	Remove	See HWEC	AMN provides a measure of microbial mineralisation of organic nitrogen (mineralisable N), which is also correlated with HWEC in most land uses. The actual amounts of N that will be mineralised in the field will depend on factors such as soil temperature and moisture. Analytically, it is more expensive, takes longer and is more variable than HWEC.	Reduced cost

Indicator	State	Purpose	Comment/rationale	Cost considerations
Air-filled porosity (–10 kPa)	Retain	Primary	Air-filled porosity (AFP) is recognised as a sensitive indicator of soil structural degradation. These measurements are most relevant in land uses with minimal cultivation (pastoral or perennial horticulture systems). AFP could also be used to calculate available water, which provides a measure of resilience to drought and storage of soil water. Measurements are less (or not at all) relevant in recently cultivated sites (cultivated within the last 12 months) because the recent disturbance artificially elevates macroporosity. Samples should be collected just before harvest, when soil is relatively undisturbed. Specific notes on the condition of the site in relation to cultivation or other disturbance activities should be made, and results from samples likely to reflect recent disturbance handled separately from other results. There was agreement from councils that the term 'air-filled porosity', as per the NEMS-SQ, should be used to refer to 'macroporosity' assessed at –10kPa. Concerted effort is required from all parties to ensure this agreed terminology is used consistently for SoE soil quality monitoring. There is an increasing urgency to understand the environmental and production consequences of the apparently widespread compaction issues associated with pastoral systems. Otherwise this indicator is at risk of becoming meaningless for SoE monitoring.	No change
Bulk density	Retain	Secondary – context	Bulk density is a widely used property and can be useful for converting concentrations into stocks. It can also be used as an additional indicator of compaction and can to calculate soil water storage. As noted for air-filled porosity, results can be distorted by the tillage regime, and additional care should be taken when sampling soils under cropping and short rotation horticulture to ensure they are relatively undisturbed. As for air-filled porosity, bulk density is affected by the location of sampling in sites with regular, contrasting conditions, such as orchards, vineyards, and plantation forests. Specific notes on the condition of the site in relation to cultivation or other disturbance activities should be made, and results from samples likely to reflect recent disturbance handled separately from other results.	No change
Aggregate stability	Retain/include	Primary – cropping systems	Aggregate stability provides a more directly relevant measure of the influence of cultivation activities on soil. The value of measuring in uncultivated systems is less clear, so aggregate stability is only recommended for cropping soils Some further review is required to confirm that standardised techniques are being used and the robustness of existing provisional target values.	No change if already doing, otherwise increased cost (c. $110–$200/sample)
Trace elements (As, Cd, Cr, Cu, Ni, Pb, Zn)	Retain	Primary	Analyses of trace elements provide a baseline to establish the concentration of essential and contaminant trace elements, with ongoing monitoring giving the ability to assess potential	No change if already doing, otherwise

Indicator	State	Purpose	Comment/rationale	Cost considerations
			deficiencies, and to track accumulation from ongoing usage. Cu and Zn are the primary trace elements for evaluation.	increased cost (c. $50/sample)
F	Retain	Secondary – characterisation	Fluoride is more expensive and challenging to analyse than the previous trace elements. The primary risks are more likely to be associated with livestock, and are most effectively controlled through the timing of fertiliser applications and grazing events. However, it is valuable to obtain baseline information on F concentrations at individual sites. Thus, the recommendation is to analyse for F once at each site.	Reduced cost if currently measured at all visits, otherwise increased cost (c. $110/sample, plus additional set-up costs)
Hot-water extractable carbon	Retain/include	Primary	Hot-water extractable carbon is a measure of labile carbon, which has multiple interpretations, including being highly correlated with AMN and other measures of mineralisable N. Analytically this property is cheaper and quicker to measure than AMN, and offers wider interpretation value, including information more specific to carbon cycling. Hot-water extractable nitrogen can also be measured, which forms the basis for potentially mineralisable nitrogen, available from commercial laboratories. Commercial laboratories use a single-step hot-water extraction, while some research laboratories may include a cold-water extraction step. Consistency in the methods used would reduce a source of variability in the results obtained.	No change if already doing, otherwise increased cost (c. $25/sample for HWEC, c. $30/sample for HWEN).
Texture	New	Secondary – characterisation	Soil texture is often considered to be a key factor that influences soil function, but it is rarely included as a measured soil property in soil quality analyses. Inclusion of this parameter will assist with interpretation of primary indicators and should be measured quantitatively for the 0–10 cm depth used for soil quality monitoring. Hand-texture information may be acquired during assessment of a soil profile, which will provide information on sub-soil texture and provide additional interpretation of water infiltration through a soil profile.	No cost if this information exists, otherwise c. $200/sample for quantitative determination of particle size using the pipette method
P-retention (anion storage capacity)	New	Secondary – characterisation	Phosphorus (P)-retention is a factor that influences P-loss through leaching and surface waters. It is a largely unchanging soil property so would only need to be measured once at a given site. This information may already be available if collected during site characterisation. P-retention specific to the depth of soil quality monitoring (0–10 cm) is most relevant to assist with interpreting Olsen P results.	No cost if this information exists, otherwise c. $25–$30/sample
Potential rooting depth, topsoil depth, depth of	New	Secondary – characterisation	Identifies any impeding soil layers that prevent root growth. This information is potentially collected already during site characterisation: 'A' horizon (topsoil) thickness (depth), total potential rooting depth, nature of the limiting layer restricting roots, and drainage class are currently all specified in the NEMS-SQ as parameters that should be collected at each site visit.	No cost, other than time to assess parameters by a suitably qualified person

Indicator	State	Purpose	Comment/rationale	Cost considerations
impeding layer, drainage class			These would be simple (and low-cost) to do at the next site visit. Individual crops and cultivation can influence measured depths.	
Carbon loading	Investigate	Primary	The carbon loading of soil based on the mineral surface area of soils could provide a more function-oriented basis on which to base soil quality targets or reference ranges. Further investigation needs to be undertaken to develop standardised protocols and assess the feasibility and cost of this approach for inclusion in SoE monitoring as these analyses are not yet commercially available.	Unknown
Biological function	Investigate	Primary	If a direct indicator for biological function is desired, the 24-hour CO_2 mineralisation test that has been widely used in North America presents a comparatively simple approach to provide a relative measure of biological activity among soils. Further evaluation should include comparison of the results from HWEC to confirm if this test provides additional value, and consideration of variability over time in relation to interpreting long-term trends alongside short-term variability. Currently this test is not commercially available but is a relatively simple modification of basal respiration tests.	Likely to be c. $60/sample based on similar tests
Biodiversity	Investigate	Primary	We suggest that the use of biological indicators should focus on providing a measure of biodiversity. Methods to undertake this cost-effectively are still in development. Molecular and rapid scanning approaches for soil invertebrates are currently being investigated as options. Earthworm abundance and diversity may be useful for pastoral systems. A higher-level policy objective (regional and/or national) for maintaining/improving soil biodiversity is probably required to provide the mandate to investigate and incorporate this measure as part of SoE monitoring.	Unknown
Visual soil assessment	Investigate	Complementary	Visual soil evaluation (VSA) is a valuable and probably the most accessible tool for farmers and communities to observe changes in soil quality, and has also attracted interest from Māori groups. Understanding the relationship between observations from VSA and SoE soil quality monitoring results has the potential to strengthen the connection between changes in land management practices with changes in soil quality, and effect positive change.	30 minutes per site (1 hour if using ‘fenceline’ comparison)

The most significant proposed changes outlined in Table 13 are the replacement of AMN with HWEC, and a greater emphasis on collecting aggregate stability data for cropping soils. These recommendations would benefit from further data analysis, using additional data to support a transition. Further evaluation of the relationship between HWEC and AMN, particularly for forestry and indigenous vegetation (for which HWEC and AMN are poorly correlated), is recommended.

As a reminder, AMN provides a direct measure of biological activity using a standardised method for assessing microbial N mineralisation. HWEC provides an indirect measure of biological activity through identified correlations with microbial biomass, and correlations with N mineralisation in agricultural systems. More directly, HWEC provides information on labile C and is relevant to C cycling. For aggregate stability there has been no review or extensive analysis of aggregate stability results, or the methods used, for SoE monitoring, despite the utility of this measure in assessing soil structure in cultivated soils. Such an analysis would confirm relevant methods and the targets or reference values to use.

Other proposed changes primarily emphasise the capture and use of information that is also specified in the NEMS-SQ to be collected during site visits, and in particular for site characterisation. The remaining indicators require further investigation prior to adoption for SoE monitoring.

Some indicators are closer to potential adoption than others. P-retention, rooting depth, drainage class, and F are relatively straightforward and one-off measures. However, evaluation of the C loading indicator requires more assessment of the logistics and feasibility for SoE monitoring, building on the extensive current and ongoing research being undertaken. The 24-hour CO_2 mineralisation assay largely requires evaluation on New Zealand soils, and against HWEC results. Investigations for a biodiversity indicator remain at a more developmental stage, although there are some strong positive options currently being pursued. VSA soil assessment is a potentially valuable tool to help communicate soil condition and its connection to land management practices, and to empower land managers to take positive steps towards improving soil quality. Further investigation relates mostly to consideration of how this approach could be linked with SoE monitoring to improving soil quality and environmental outcomes.

The cost implications of these recommendations need to be evaluated by individual councils. With the exception of HWEC, many of the additional parameters relate to site characterisation information that may have already been collected during site establishment and are requirements under the NEMS-SQ. If these parameters have not been measured (or haven't been measured for 10 years), this one-off cost should be able to be accommodated through sampling programmes.

As noted in section 6.1.3, we see an opportunity to introduce cheaper methods for assessing aggregate stability, supported by the development of robust reference or target values, which could remove the cost barrier associated with aggregate stability analyses.

Finally, there are different 'levels' (cost, time) of investigation required for the 'to be investigated' indicators, ranging from feasibility assessment for C/loading based on significant current research, to validation of suitability for New Zealand soils (24-hour CO_2 mineralisation), to the identification of suitable indicators (biodiversity).

7.2 Effecting improvements in soil quality

As has previously been observed (Cavanagh et al. 2023; Cavanagh, Drewry et al. 2025), the key issues for soil quality identified during the establishment of the monitoring programme – organic matter depletion (in cropping soils), soil structure decline (as measured by macroporosity), and nutrient excess (primarily excess Olsen P, but also total N) – remain the key issues identified currently. Further, given the extent to which compaction apparently affects pastoral (particularly dairy) land use, there is increasing urgency to quantify the environmental and production consequences of this reduced macroporosity. This is required to provide impetus for changes in management practices to reduce compaction and ensure this indicator retains meaning. Regardless, the continued increase in the proportion of sites that do not meet target values suggests that policy or land management subsequent to SoE monitoring has not been successful in effecting improvements in soil quality.

In the context of SoE monitoring, effecting improvements in soil quality can be considered at two levels:

- analysis and communication of SoE results
- adoption of management practice to effect improvements – this can include the specific adoption of measures in council policy and plans, as well as on-the-ground changes in land management.

7.2.1 Analysis and communication of SoE soil quality results

Analysis of SoE soil quality results

Some challenges to the analysis and reporting of SoE results were discussed in section 6.2. These include regional inconsistencies in the target values used to compare SoE monitoring results and the approaches used for trend analyses, and confounding of regional and national trend analysis arising from changes in site numbers under different land uses at different times. Also, there are further challenges with the identification and classification of land use (including the capture of this information by councils) (Cavanagh et al. 2017; Cavanagh & Whitehead 2022, 2023). Additional discussion on options for detecting meaningful changes in soil quality at a national level are discussed in Cavanagh, Drewry et al. 2025, which included consideration of how results are reported, the extent to which monitored sites can be said to be nationally representative, and statistical considerations such as variability in results and trends over time. Here we emphasise that *closer evaluation of individual site trends would provide more insightful data.*

Cavanagh, Drewry et al. 2025 also highlighted the value of extended analyses of regional council soil quality monitoring data that are likely to be collated in 2025 and early 2026 for national reporting. These extended analyses include an evaluation of the representativeness of sites currently being monitored. The results will inform whether additional sites would provide a better assessment of soil quality, and could inform the development of reference ranges or values.

The increased geographical spread of regional council SoE monitoring since 2018 also provides additional opportunities to 'scale' up and spatially analyse the data. Several good recent international examples of different modelling approaches, largely based on the EU-LUCAS Soil Monitoring Programme, are available that underpin the EU Soil Observatory Dashboard. This includes modelling of 'maximum' soil C (De Rosa et al. 2023), bulk density (and compaction) (Panagos, De Rosa et al. 2024), and P budget (Panagos et al. 2022). Other studies have evaluated the use of pedotransfer functions for national soil health monitoring (e.g. Bagnall, Morgan, Cope et al. 2022).

Expectations that managing soil quality will manage wider environmental issues associated with land management practices are common. However, in many cases it is the wider management practices (e.g. fertiliser application, grazing timing, intensity) or the climatic factors (e.g. rainfall), or the interaction of these two rather than soil properties, that will be the dominant influence on the off-site environmental outcomes. This is particularly true for N and P in waterways.

Thus, alternative approaches to identifying and managing areas of concern are required, along with consideration of a broader range of factors, including inputs. For example, a spatial layer of susceptibility to N loss has been developed through the Whitiwhiti Ora: Land Use Opportunities programme[18] and could be used to identify areas for closer focus, such as more detailed assessment of soil quality and land management practices, including at a catchment scale. The layer provides a representation of the annual mean susceptibility to N loss, considering soil and climate factors, and focusing on the vertical movement of N due to rainfall and soil moisture. The data were derived from the Agricultural Production Systems Simulator (APSIM) model, which simulates N losses from urine patches in a continuous ryegrass/white clover mixed pasture setup.

The analysis does not take into account land use or actual nutrient inputs, but focuses solely on inherent soil and regional climatic conditions. For Olsen P, the spatial distribution of P-retention, along with slope and proximity to surface waterways, could be used to highlight susceptible areas. Similarly, it would be useful to locate soil quality and water quality monitoring sites where they can better inform catchment modelling approaches; this may best be undertaken on selected catchments.

More broadly, evaluating a wider range of factors (e.g. climate, texture), but also management factors or inputs (e.g. irrigation frequency and rates, tillage timing and frequency, surface-run off or drainage) may help better identify the consequences of, for example, reduced carbon or increased compaction in soils.

Communication of SoE results

Communication of SoE soil quality results is currently a hot topic for conversation among councils, with a number investigating different options for the presentation of data. Currently there are varied communication methods used at a regional level (see also section 5.1.3), with national reporting centring on StatsNZ and MfE environmental reporting (e.g. StatsNZ & MfE 2021, 2024, 2025, including web-based reporting.[19]) However, to our knowledge there has been no evaluation of the intended purpose of the communications (other than to present the results) and how effective the communications have been in either meeting that purpose or empowering the receivers to take action in relation to soil quality.

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[18] https://landuseopportunities.nz/.

[19] https://www.stats.govt.nz/information-releases/new-zealands-environmental-reporting-series-our-environment-2025/

Alternative ways to present results may help to communicate findings more meaningfully to a wider audience. For example, visualisation of the distribution of the data would allow a reader to identify where their own results (if they have them) fall relative to their peers in a given land use and soil order grouping (see Figure 10). This would provide better visibility of where an individual farm result might fall, and if at the low end it might prompt questioning of why and how they could bring up their value. Reference or target ranges could be added to give a visual indication of the number of sites falling outside those ranges.

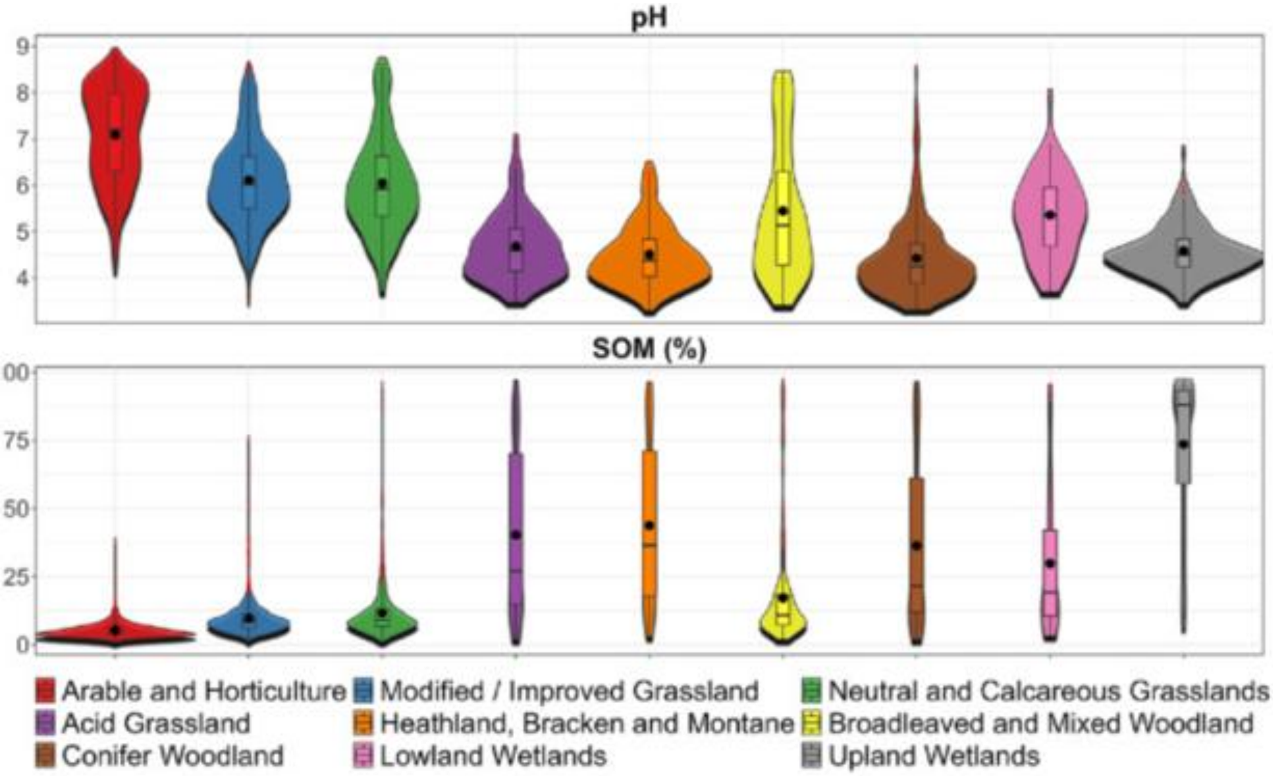

Figure 10. An example of an alternative display of soil monitoring results based on a UK example of monitoring for different habitats.

Notes: This approach provides a visualisation of the distribution of the data for a given grouping, in this case habitat, and would allow a reader to identify where their own results fit (giving better visibility of where an individual farm result might fall). Reference ranges could be added to the graphs to give a visual indication of the number of sites falling outside those ranges. Distributions of soil health indicators are given within each habitat; units are in panel headings.

(Source: Feeney et al. 2023).

Through this project four fact sheets were developed. (These are shown in Appendix 5.) The high-level statement used in the EU documentation on soils strategy mission etc. ('Healthy soils are the foundation for 95% of the food we eat, host more than 25% of the biodiversity in the world and are the largest terrestrial carbon pool on the planet') provides a simple statement that highlights the value of looking after soils and was used in the Overview fact sheet.

The intended audience (identified from workshop and advisory group discussions) is broad, including both within-council use (e.g. consent, policy and planners) and those users external to the council (e.g. farmers, catchment facilitators, farm advisors, consultants, and the general public).

Another important aspect of this project was to investigate the connection between SoE soil quality monitoring and te ao Māori aspirations, knowledge, and perspectives. Māori have a broad holistic understanding of soil health (Harmsworth & Awatere 2013; Harmsworth 2018), of which soil quality is an integral part. Soil quality indicators and monitoring are essential to understanding soil health. Steps toward a universal soil health framework for incorporating te ao Māori and mātauranga Māori have been undertaken (Stronge et al. 2023; Harmsworth 2022a, b; Sevicke-Jones et al. 2021, 25). Localised monitoring of soil and the development of key indicators (i.e. tohu – signposts or guides to soil health) have been considered by some Māori groups (Harmsworth 2018, 2022a, b). The inclusion of traditional knowledge and narratives, such as pūrākau (e.g. traditional knowledge and stories), ngā kupu o taiao (words, terms), and taonga tuku iho (intergenerational soil treasures), along with local contemporary case studies, could be one way to better articulate te ao Māori perspectives as part of wider regional and national monitoring and reporting of soils. These form tangible next steps to explore for connecting SoE monitoring to kaupapa Māori approaches.

Options for web-based reporting of soil quality information - Land, Air, Water Aotearoa

A logical pathway for reporting soil quality information online is to build on the Land, Air, Water Aotearoa (LAWA) platform, which is jointly funded and governed by councils, central government agencies, and industry partners. It provides national visibility for environmental data while allowing regions to retain ownership and control of their information. Using LAWA aligns soil quality reporting with how other environmental indicators are presented, leveraging a framework already familiar to councils, government, and the public.

A draft project plan for land data was developed in 2015 under the Environmental Monitoring and Reporting (EMaR) framework. It aimed to improve access to high-quality environmental data, with provision via LAWA as a key outcome. Many of its aspirations remain relevant, and the current work on soil quality continues that intent.

Initial discussions with Te Uru Kahika – Regional and Unitary Councils Aotearoa indicate that LAWA supports multi-source data integration, as seen with water quality and other indicators. Practices currently vary by contributor, with no standardised integration method, and the approach is often customised depending on council capability and data type. Many councils provide data through manual uploads, such as CSV or XML files, which are processed and published on an annual cycle. Some have exposed APIs for data that are updated more regularly, such as river flows. The LAWA team would prefer to work from a federated data source (i.e. a single data set representing all data collated from individual councils). Any approach must also consider how site-level information is generalised to protect privacy, as this summarisation typically needs to be completed before data are shared or displayed. Aligning this work with national SoE reporting could improve efficiency and maximise the return on investment, as both rely on the same data sets and probably similar, or the same, analyses.

The collation of SoE soil quality data depends in part on the systems and processes used by councils for capturing these data. A short survey of data management undertaken though this project indicated that of the eight council responses, three used an environmental data system, including Hilltop and KiWQM. Three used databases, including a self-designed GDB and an SQL server, while the remaining two used Excel or were transitioning from Excel to a database. Two councils are actively looking to change their data management in the short term, and two are looking to change in the longer term. All councils indicated that their data were well structured.

The development of a new module for LAWA follows a structured process, involving:

- identifying audiences and their information needs
- scoping data
- analysing and validating results
- incorporating stakeholder feedback before go-live.

A project plan template must be completed to initiate new modules, allowing LAWA to assess resourcing for both development and ongoing maintenance. In the near term, defining the target audiences, clarifying what types of information could be presented, and beginning to draft an updated project plan are immediate steps that can be progressed now.

Within LAWA there are several ways in which soil quality data could be presented. The simplest pathway would mirror existing water quality reporting, using regional summaries, fact sheets, and basic indicator displays, although exactly what can be displayed depends on the data provided. Enhanced filtering could allow users to select indicators, land use, soil order, and interpretation models for deeper exploration, but would require additional design and implementation effort.

Based on workshop discussions, the intended audience for web-based information on LAWA is more 'outward' facing, with land managers (and particularly the primary sector) and the general public considered to be the primary audience. In terms of presentation of data, visualisation of the distribution of the data was seen as being of most value. Such graphs could be presented at regional or national level for various combinations of soil orders or soil order groups and land uses. Some examples of visualisations of data distribution are shown in Figure 10 (above) and Figure 11. An alternative presentation is shown in Figure 12, which places a greater focus on the number of sites falling in and out of target or reference ranges.

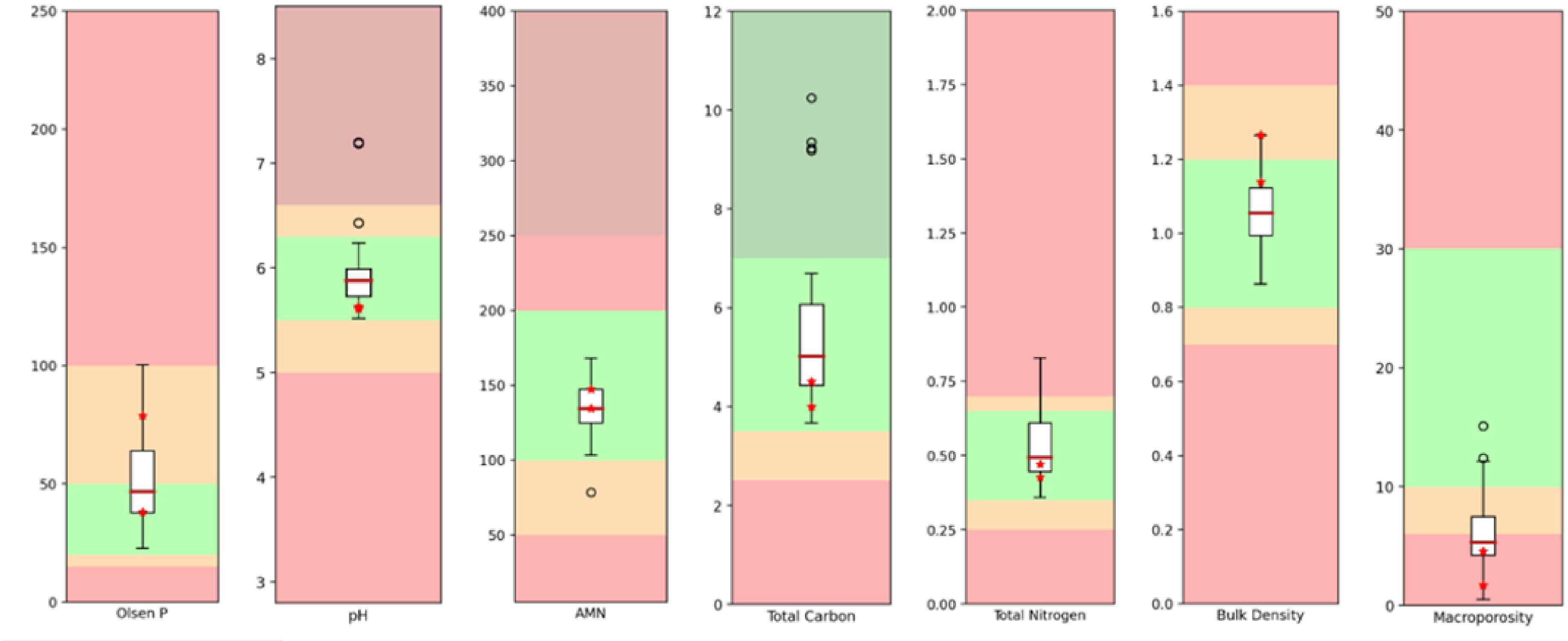

Figure 11. An illustration of an option for presenting SoE soil quality monitoring data.

Notes: In this example, colours indicate existing target ranges (these could also be displayed as horizontal dashed lines) and box plots represent the distribution of data. (Source: Michael Morgan, Horizons Regional Council)

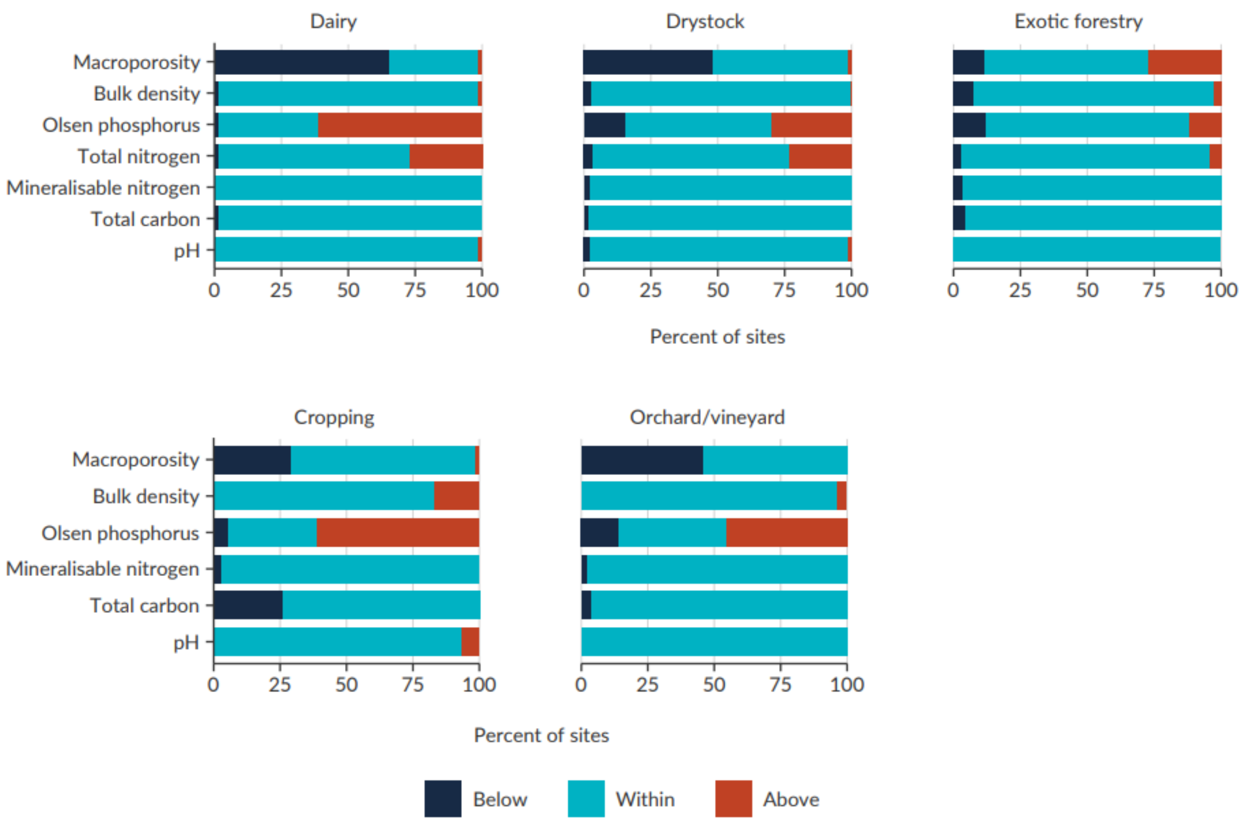

Figure 12. Sites within the target range of soil quality indicators, by land use, 2014–18. (Source Stats NZ & MfE 2021)

Interactive functionality, similar to the earlier SINDI prototype (which enabled users to input their own soil test results and compare them with benchmark ranges), appears unlikely to be readily accommodated within the existing LAWA platform. Supporting this would require a calculation engine to process inputs against reference data sets, a user interface to display outputs, and ongoing maintenance to update benchmarks and host the tool securely. A stand-alone calculator, linked from LAWA, may be a more practical way to offer this functionality, if this was a desired feature. The SINDI tool has also been used by council consent staff to help set consent conditions.

Alternative approaches, such as a collaborative addition to the MWLR Soils Portal[20] or the development of a separate soil quality website, could also deliver exciting functionality. In terms of improving access for Māori groups, soil quality data could be provided through the Māori land visualisation tool[21] to show and interpret soil data on Māori land blocks and within specific tribal areas. These would allow greater flexibility in design and interactivity but would require considerably more resources.

[20] https://soils.landcareresearch.co.nz/

[21] https://whenuaviz.landcareresearch.co.nz/

Whether through LAWA or other means, the next steps include identifying audience needs and clarifying what types of information would be presented. If LAWA is confirmed to be a preferred pathway, drafting an up-to-date project plan is the next step.

7.2.2 Adoption of changed management practices

A multi-pronged and -tiered approach is required to enhance the effectiveness of SoE soil quality monitoring programmes to improve soil quality and environmental outcomes. The most accessible way for members of the LMF to enhance effectiveness is through the interpretation and communication of results obtained through the SoE soil quality monitoring programme and discussed in the preceding section.

However, soil quality improvements also require the adoption of management practices. This can include the specific adoption of measures in council policy and plans, as well as on-the-ground changes in land management. Hill and Sparling (2009) indicated that soil quality monitoring objectives are aimed at policy development, and so potentially provide drivers for intervention to improve soil quality. However, as identified in section 5.1.1, only four councils mention the connection between SoE soil quality monitoring or results and regional policy or plans, highlighting a significant opportunity for change. It should also be noted that SoE soil quality programmes are not integrated with other regional monitoring (e.g. water, especially groundwater), providing challenges in using existing soil SoE monitoring to assess influences on water quality (McDowell et al. 2024). This is arguably a failure of one of the original (Hill & Sparling 2009) and current (NEMS-SQ) objectives of the programme.

Visual soil assessment (VSA) could assist with enabling on-the-ground changes in land management. This approach can help communicate soil condition and its connection to land management practices, and empower land managers and communities to take positive steps to improve soil quality. VSA has also attracted interest from Māori groups because of its practicality for on-the-land assessment, monitoring, and soil management. Further investigation is required to consider how this approach could be linked with SoE monitoring to improve soil quality and environmental outcomes.

Many of the observations made by Cavanagh et al. 2023, drawing on a previous workshop with the LMF, remain relevant to the discussion on the use of SoE soil quality monitoring to bring about improvements in soil quality, particularly the following.

- Councils want greater clarity about the limits or thresholds that could lead to negative environmental impacts, particularly because regional councils are charged with being responsible for the environment. However, this focus can’t be completely divorced from considerations relating to primary production, particularly when it is estimated that approximately 95% of our food comes from soil (FAO 2015). This tension remains apparent in Cavanagh, Drewry et al. 2025, in which pH and Olsen P reference ranges are fundamentally based on agronomic considerations.
- Councils are concerned about ongoing access to soil quality monitoring sites, particularly if punitive actions were to be taken at sites falling outside targets or references. A reframing of SoE soil quality monitoring to highlight the benefit to land owner involvement could help to address this issue.

- Councils prefer 'behaviour-change approaches' to bring about change, but there is a variable appetite among councils to invest in such programmes.

More generally, there are questions about whether improving soil quality should be the role of regional councils, compared to perhaps the primary sector, and whether the SoE monitoring programme should be the primary way to bring about that change. Internationally, various soil strategies and underpinning programmes (e.g. the EU Soil strategy,[22] the EU Mission's 'A Soil Deal for Europe',[23] and the Australian National Soil Strategy[24]) have led to considerable activity on soil quality monitoring, indicators and thresholds (see Appendix 4). These programmes recognise the critical importance of working in partnership with multiple stakeholders to realise improvements in soil health.

In New Zealand more broadly, there have been calls for the development of a national soils strategy (Collins et al. 2015; Sevicke-Jones et al. 2021) or a national policy statement on contaminated land management and soil re-use (Mayhew 2023), with the 2023 Waste Minimisation Strategy including the goal of reducing the volume of soil disposed to landfill[25] (MfE 2023). The current Waste and Resource Efficiency Work Programme 2024–2026 identifies working with industry to identify options to help manage surplus soil generated through construction and infrastructure projects, with the aim of developing cost-effective solutions that recognise the value of soil resources and maximise benefits. The Parliamentary Commissioner for the Environment identified practices undermining the health and extent of soil in new subdivisions and infill (PCE 2024) following an assessment of urban green-space (PCE 2023). Most recently the PCE's report on *Resource Use and Waste Generation in Aotearoa New Zealand: Filling (Some) Gaps* (PCE 2025), included the impact of primary sector activities on soil quality and quantity, with the full details provided in Drewry et al. 2024. It therefore seems clear that a higher-level strategic approach is required to generate the impetus and clear objectives for managing soils so that soils are better protected and valued, and improved soil health is realised.

The development of a national direction on soils, explicitly inclusive of soil health, would provide connection with other aspects of the environment that can be influenced by soils, including climate change, soil carbon trends, the quality or condition of freshwater and ground-water, the functioning and diversity of soil ecosystems, and the maintenance and enhancement of indigenous biodiversity. This directional framework would identify priorities for soil health and management from stakeholders, including communities, industry, local and central government, farmers, land managers, and Māori as a basis for a national soils strategy. Such a coordinated and collaborative approach could provide a wider impetus and momentum for promoting best management practices that improve soil health than potentially disconnected and variable programmes operated by individual councils.

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[22] COM_2021_699_1_EN_ACT_part1_VERSION FRIDAY EVENING LUCAS (europa.eu)

[23] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/soil-health-and-food_en

[24] https://www.agriculture.gov.au/sites/default/files/documents/national-soil-strategy.pdf

[25] https://environment.govt.nz/assets/publications/Te-rautaki-para-Waste-strategy.pdf

8 Discussion and next steps

This project has evaluated the performance of existing indicators and considered potential new indicators to enhance the effectiveness of SoE soil quality monitoring. The most significant changes from the current situation are the recommendation to replace AMN with HWEC and to have a greater focus on aggregate stability for cropping soils. These recommendations would benefit from further data analysis, using additional data, to support a transition. Analytically, HWEC is cheaper, quicker, and less variable than AMN and offers wider interpretation value, including information more specific to C cycling. HWEC is generally correlated with AMN, with the exception of forestry and indigenous vegetation sites. Some further evaluation, including identifying the contribution of any methodological differences, is needed. An analysis of aggregate stability is also needed to confirm relevant methods and target or reference values.

We also considered the 'purpose' of an indicator – whether it is an indicator for which measured limits or thresholds should be used to drive action on improving soil health (primary indicator), or whether the soil property offers additional insight into the response or behaviour of other soil quality indicators (secondary indicator). For these secondary indicators, a differentiation is made between those that provide 'context' and should be measured each time monitoring is undertaken, and 'characterisation' indicators, which are inherent (largely unchanging) soil properties and can probably be measured once to characterise the site, but are valuable to help explain variations in the primary indicators. We grouped the indicators as follows:

- primary indicators – Olsen P, total C, air-filled porosity, aggregate stability (cropping systems), HWEC, trace elements (As, Cd, Cr, Cu, Ni, Pb, Zn)
- secondary context indicators – pH, total N, C:N, bulk density
- secondary characterisation indicators – texture, P-retention, potential rooting depth, topsoil depth, depth of impeding layer, drainage class, trace elements (F).

During this project, councils agreed that 'air-filled porosity' (as per the NEMS-SQ) should be used to refer to macroporosity assessed at –10 kPa. We also observe that there is an increasing urgency to understand the environmental and production consequences of the apparently widespread compaction issues (as determined from measurement of air-filled porosity) associated with pastoral systems. Otherwise, this indicator is at risk of becoming meaningless for SoE monitoring.

We also identified additional primary indicators that require further investigation before potential incorporation into SoE soil quality programmes. These include:

- a C saturation/loading indicator, based on determination of the mineral surface area of soil, which requires assessment of the logistics and feasibility for SoE monitoring, building on the extensive current and ongoing research being undertaken
- a 24-hour potential C mineralisation test that has been widely used in North America to indicate soil health, and provides a comparatively simple measure of relative biological activity.

Further evaluation of this indicator should include comparison with the results from HWEC to confirm if this test provides additional value to HWEC, and also consideration of variability over time in the context of interpreting long-term trends compared to short-term variability.

Finally, we suggest that the use of biological indicators should focus on providing a measure of biodiversity, because this information cannot be gathered in other ways. A higher-level policy objective (regional and/or national) for maintaining/improving soil biodiversity is probably required to provide the mandate to investigate and incorporate this measure as part of SoE monitoring.

Finally, wider use of visual soil evaluation (VSA) is recommended, given that it is valuable and probably the most accessible tool for farmers and communities to observe changes in soil quality, and has also attracted interest from Māori groups. Understanding the relationship between observations from VSA and SoE soil quality monitoring results has the potential to strengthen the connection between changes in land management practices and changes in soil quality, and to effect positive change.

The survey of regional councils was useful to provide insight into the current drivers for undertaking SoE soil quality monitoring and subsequent use of information gathered from the monitoring programmes. This highlighted the general absence of any link between SoE soil quality monitoring and objectives or provisions in regional policies and plans for most councils. A higher-level strategic approach is required to generate the impetus and clear objectives for managing soils so that soils are better protected and valued, and improved soil health is realised.

9 Recommendations

9.1 Recommendations for Next steps

The following are recommendations for the next steps to take based on the findings of this project.

1 Following agreement from councils during this project, ensure consistent use of the term 'air-filled porosity' (as per the NEMS-SQ) to refer to macroporosity assessed at –10 kPa for SoE soil quality monitoring and reporting. Concerted effort is required from all parties to ensure this agreed terminology is used consistently for SoE soil quality monitoring.

2 Evaluate the benefits and trade-offs associated with the specification of gravimetric Olsen P in the NEMS-SQ and ongoing use of the gravimetric basis for reporting on Olsen P reference ranges for SoE reporting, given the current extensive reporting of Olsen P results on a volumetric rather than gravimetric basis by many New Zealand laboratories. This could be undertaken through the development of a background discussion paper and stakeholder workshops.

3 Collate SoE soil quality data gathered since the previous collation undertaken for national reporting in 2021. This collation could also be used to capture existing data on the additional site-specific parameters suggested in Table 13. National data collation has commenced in late 2025, funded by MfE, for the purposes of national reporting, and including comparison of analyses using existing target values with the new reference ranges outlined in Cavanagh, Drewry et al. 2025). This collation would also provide:

- a data set for more detailed analysis of the relationship between AMN and HWEC, and existing aggregate stability data
- a stocktake of existing data available for additional site parameters identified as properties useful to support

- a data set that would allow for a more comprehensive assessment of factors (site, climate) influencing measured results (such an analysis would also determine whether additional stratification of soil C results will help to further [meaningfully] distinguish between non-allophanic mineral soils, and provide a more refined assessment of the water quality risk associated with sites with elevated Olsen P).

4 Confirm changes to indicators and reference ranges, and update the NEMS-SQ. This would best be undertaken when additional analyses of AMN/HWEC results, a review of aggregate stability data and methods, and an evaluation of the use of gravimetric vs volumetric Olsen P analyses and reference values have been undertaken.

5 Confirm if LAWA is the preferred pathway for the display of SoE monitoring data. If so, form a working group and develop a project plan for the development of a LAWA soil quality module to submit to Te Uru Kahika. Confirm if there is value in an interactive tool similar to the previously developed SINDI, and if so, identify pathways for development.

9.2 Recommendations for SoE soil quality monitoring

Following our evaluation of the performance of existing indicators and potential new indicators for SoE soil quality monitoring, we recommend:

- replacing AMN with HWEC, and putting a greater emphasis on the collection of aggregate stability data for cropping soils (these recommendations would benefit from further data analysis, using additional data, to support a transition)
- collecting and using additional site parameters (P-retention, texture, topsoil depth, potential rooting depth, depth / nature of impeding soil layer and drainage class) to enable better interpretation of monitoring results in relation to environmental outcomes
- investigating the feasibility and suitability of a carbon saturation/loading indicator based on soil mineral surface area
- investigating the suitability of a 24-hour potential C mineralisation assay as a biological function indicator, and identifying a suitable biodiversity indicator

To enhance the effectiveness of SoE monitoring to bring about improvements in soil quality and environmental outcomes we recommend:

- investigating the use of visual soil assessment as a means to provide greater connection of land managers and communities with their soil, and with SoE monitoring results
- investigating the environmental and production consequences of the apparently widespread compaction issues (as determined from measurement of air-filled porosity) associated with pastoral systems
- councils promote the use of SoE soil quality monitoring to inform their resource management policies or plans, and more directly use the results to assess the effectiveness of relevant provisions
- councils include soil biodiversity in policy and plans to provide greater impetus for the development of soil biodiversity indicators
- review previous, existing or planned local work being carried out by Māori groups (e.g. iwi/hapū, trusts, incorporations) on soils (e.g. to identify the main issues/priorities,

monitoring approaches, indicators), and clarify Māori needs for using soil data/information to achieve Māori aspirations and inform management decisions
    - councils review opportunities to integrate soil quality monitoring with freshwater and ground-water monitoring to better inform catchment-based and holistic management
    - giving greater consideration to scaling up SoE monitoring results to provide a national perspective on the state of soils using geospatial approaches.

More broadly, we echo many of the recommendations provided in Cavanagh et al. 2023 and Cavanagh, Drewry et al. 2025, including the following.

- The LMF should advocate to the Resource Managers Group and central government (MfE, MPI) to provide national direction, priorities, and clear objectives for managing and improving soil quality and soil health (e.g. a national soils strategy and action plan).
- The key role that all people play in improving soil health through effective soil management actions should be recognised by embracing a wide number of stakeholders and end-users, including industry, communities, farmers, and Māori, to establish priorities and guide implementation of soil monitoring data across multiple land-use areas (from conservation land to urban areas).
- Central and local government agencies should work with primary sector industry groups to provide greater connection between findings from SoE soil quality monitoring and day-to-day land management practices that can achieve improvements in soil quality. This work should include:
    - completing a stocktake and evaluating the efficacy of management practices that maintain or improve soil C, and prevent and remediate soil compaction under different land uses
    - identifying demonstration or 'best-practice' farms that could be incorporated into ongoing monitoring and/or used (i) to provide specific case studies for the evaluation of soil properties under best-practice management, and (ii) to help develop models to connect soil properties at a farm scale with broader production and environmental outcomes
    - developing a targeted research programme that combines empirical and modelling approaches to establish relationships between soil quality indicators with production and/or environmental outcomes, particularly in relation to soil C, Olsen P, and soil structural degradation.

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van Leeuwen JP, Saby NPA, Jones A, Louwagie G, Micheli E, Rutgers M, et al. 2017. Gap assessment in current soil monitoring networks across Europe for measuring soil functions. Environmental Research Letters 12, 124007.

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Zwetsloot MJ, Bongiorno G, Barel JM, di Lonardo P, Creamer RE 2022. A flexible selection tool for the inclusion of soil biology methods in the assessment of soil multi-functionality. Soil Biology and Biochemistry. SBB 108514.

Appendix 1 – Survey questions

[Questions 1–4 were background information questions.]

Q5 Is Section 35(2) of the RMA the primary regulatory driver for your council undertaking SoE soil quality monitoring? Yes/No

Q6 Does your council have any policies, objectives, methods, or rules in policy statements or plans that:

- draw upon SoE soil quality monitoring information (such as target values), or
- require SoE Soil quality monitoring to be undertaken? *If yes, please list.*

Q7 When did SoE SQ monitoring commence at the council?

Q8 Has monitoring been continuous since that time? Yes/No

Q9 How frequently does your council undertake soil quality monitoring?

- Every year (1)
- Every 2 years (2)
- Every 3 years (3)
- Every 4 years (4)
- Every 5 years (5)
- Less often than every 5 years (6)

Q10 For a given monitoring year, on what basis are sites selected? *Tick all that apply.*

- A specific land use (1)
- A subset of sites representing multiple land uses (2)
- Other (please describe) (3)

Q11 Who undertakes soil quality monitoring? *Tick all that apply.*

- Council staff (1)
- External consultants (2)
- Other (please describe) (3)

Q12 What indicators are regularly monitored? *Tick all that apply.*

pH, Olsen P, Total C, Total N, AMN, HWEC, HWEN, Macroporosity, Bulk Density, TE suite (As, Cd, Cr, Cu, Pb, Ni, Zn), F, Aggregate stability, Other (please specify), None of the above

Q13 Did you previously monitor any of those you do not currently regularly monitor?

Q14 Which sources of information do you use to specify the target values of the indicators you regularly monitor?

Q15 In your monitoring, which indicators most commonly fall outside current target values? *Tick all that apply.*

pH, Olsen P, Total C, Total N, AMN, HWEC, HWEN, Macroporosity, Bulk Density, TE suite (As, Cd, Cr, Cu, Pb, Ni, Zn), F, Aggregate stability, Other (please specify), None of the above

Q16 What other soil quality indicators have you considered or are you considering for regular monitoring, if any?

Q17 How are the results of SoE soil quality monitoring currently reported? *Tick all that apply.*

- To the individual land manager/owner (1)
- Annual score-card (e.g. short PDF document on website) (2)
- Web-based reporting (3)
- Annual technical report (4)
- Paper to council (e.g. annual update) (5)
- Multi-year report (e.g. including trend analysis) (6)
- Other (please describe) (7)
- None of the above (8)

Q18 Has a change in soil quality over time been reported through your SoE soil quality monitoring programme? *If yes, please describe.*

Q19 What action is generally taken if individual results are outside soil quality target values?

Q20 How are the results of SoE soil quality monitoring generally used within Council?

Q21 With which other groups/teams within council does the SoE soil quality monitoring team typically interact? For those groups where there is interaction, please explain the purpose.

- primary industry engagement/land management/catchment advisors or extension staff (1)
- policy or planners
- consents and compliance staff.

Q22 Has your council undertaken any work to relate changes in soil quality to changes in environmental or primary production outcomes? *If yes, please describe.*

Q23 Has your council undertaken any work to establish the impact of land use change or the effectiveness of land management practices with respect to soil quality issues? *If yes, please describe.*

Q24 Please describe any future plans your council currently has for SoE soil quality monitoring.

Appendix 2 – Workshop summary

Summary from workshop mural board and discussion

A workshop with the LMF was held on 6 March 2025. This presented an update on the project, and specifically canvassed the items discussed below.

Additional indicators

Need for new indicators

- Three responses, largely relating to the need for a biological indicator that is reliable, with eDNA mentioned as an indicator.
- Four responses in support of more effective use of information from existing indicators.

Criteria for new indicators

- All testing is limited by RC resources.
- Interpretable in relation to soil function, but also responsive to degradation in function and not too expensive.
- Interpretability and response to management.
- To be more responsive to soil states, so reporting on likely changes that will happen as opposed to reporting on what has happened with current soil quality indicators.

Soil quality indicator fact sheets

Audience

- Rural sectors and landowners, but a lot of opportunity to refer to the vast range of existing fact sheets (regionally and nationally developed). More information (disseminated in another way) doesn't necessarily address the problem. We need boots-on-the-ground extension.
- Farmers, public, catchment facilitators, farm advisors, consultants, councillors, Land Management Authorities, RC science.
- Industry groups and the public.
- Landowners.
- General public, farmers, sector bodies, and policy makers.
- General public.
    - [Do we even have a technical reference document that explains the indicators to us?]

Purpose

- For landowners to determine how their soil falls within reference ranges/limits/trigger values.
- For policy-makers to develop suitable policy and/or guidelines, where relevant.
- Planning and resource management: planners are an important audience.
- To give context to the indicators for interpretation of results, and ideally linked to management to improve (if evidence is available for this).

- Depends on the audience: to explain what these indicators mean to normal people or farmers, or the community, so that policy, or farmer, or advisor can do something!

What information is most relevant?

- Soil quality facts sheets. The most relevant information could be straightforward results on soil quality and the soil order. To reach as wide an audience as possible, the presentation can start as graph/map summaries and step down to the technical side, with methodology and data made available.
- What the indicator represents, what reference ranges are, how it can be improved if needed.
- Different audiences seem to make sense. Make the findings as widely accessible and understandable as possible.
- Where to seek further information.
- Why this indicator is measured, what it means, what a result at either end of the scale means, what influences/how the values could be changed.
- Who it matters to, as well as how it can be improved and whose job it is.

Where should they be housed?

- No clear consensus – all options given (i.e. LAWA, Crown Research Institute website, MfE)

Web-based soil quality information

Audience

- Industry groups and central govt.
- Sector and industry groups.
- Landowner/managers and the general public, to engage with and understand the national soil state and relate to local area.
- Landowners.
- Researchers (e.g. for data downloads).

Purpose

- Federating data to inform public.
- Further analyses (e.g. in relation to other [non-soil) indicators].
- For council, our purpose is to provide an independent view on soil quality, from someone who is not selling a product.
- Getting trust from Ag industry sectors.
- Inform policy development / advice to ministers.
- Same purpose as the fact sheets: to get people to do something to improve soil quality.
- For landowners to determine how their soil falls within reference ranges/limits/trigger values.

What information is most relevant?

- Where/how the data are collected.
- Reference ranges, targets, triggers.
- Ultimately it would be good to also highlight how/where the information is being used.
- Would be nice to have data distributions rather than just generalised info. We collect so much specific information that is lost when everything is aggregated.
- Change over time (trends) are very important as these form the basis for the narrative around what is happening out there.
- Trends over time.
- Information on state and trend for the key indicators.
- Eventually, information on the effectiveness of policy responses.
- Explanation of what it all means.

Where should it be housed?

- Everywhere? Or primarily on MWLR/CRI /research organisation website (e.g. https://soils.landcareresearch.co.nz/ , but shared with industry & sector groups, councils, catchment groups, etc.
- LAWA
- Council websites and eventually LAWA.

Appendix 3 – List of papers and reports on SoE soil quality monitoring results since about 2016

This list of papers and reports on SoE soil quality monitoring does not include documents older than about 2016 because a comprehensive list was provided by Cavanagh et al. (2017) in their review of soil quality and trace element SoE monitoring programmes: 'Appendix 2 – Soil quality, trace elements, and nutrient use publication'.

Reports on trend analyses of SoE soil quality monitoring results since about 2016

Note: these reports are additional to those included in the Reference list.

Curran-Cournane F 2015. Soil quality state and trends in New Zealand's largest city after 15 years. International Journal of Environmental, Ecological, Geological and Geophysical Engineering 9: 227–234.

Drewry JJ, Cavanagh JE, McNeill SJ, Stevenson BA, Gordon DA, Taylor MD 2021. Long-term monitoring of soil quality and trace elements to evaluate land use effects and temporal change in the Wellington region, New Zealand. Geoderma Regional 25: e00383. https://doi.org/10.1016/j.geodrs.2021.e00383

Drewry J, Van de Laar A, McNeill S 2023. Soil quality in the Taranaki Region 2022: current status, comparison with 2017, and temporal analysis. Manaaki Whenua – Landcare Research report LC4297.

Stevenson BA, McNeill S 2020. Soil quality and trace element dataset trend analysis (revised version). Manaaki Whenua – Landcare Research Contract Report LC3887, prepared for Ministry for the Environment.

Taylor MD, Cox N, Littler R, Drewry JJ 2017. Trends in soil quality monitoring data in the Waikato region 1995-2015. Waikato Regional Council Technical Report No. 2017/26.

Council reports on SoE soil quality monitoring results since about 2016

Note: these reports are additional to those included in the Reference list or above.

Northland Regional Council

Ballinger J, Macdonald A 2020. Soil quality in Northland. State of the Environment monitoring programme, 2001-2016. Northland Regional Council. https://www.nrc.govt.nz/media/qyrlupey/nrc-soil-monitoring-report-2016-17.pdf

Auckland Council

Guinto DF 2022. Changes in soil quality under different land uses in the Manukau Harbour catchment area, 1995–2017. In: Christensen CL, Horne DJ, Singh R eds. Adaptive strategies for future farming. Palmerston North, Farmed Landscapes Research Centre, Massey University. https://flrc.massey.ac.nz/workshops/22/paperlist22.html

Hawke's Bay Regional Council

Norris T 2017. Soil quality in the Hawke's Bay 2016. Extensive pasture. Hawke's Bay Regional Council Report No. RM17-08 4930. Hawke's Bay Regional Council.

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Norris T 2018. Soil quality in the Hawke's Bay 2018. Cropping. Hawke's Bay Regional Council Report No. RM18–15. Hawke's Bay Regional Council.

Taranaki Regional Council

Drewry J, Van de Laar A, McNeill S 2023. Soil quality in the Taranaki Region 2022: current status, comparison with 2017, and temporal analysis. Manaaki Whenua – Landcare Research report LC4297.

Stevenson B, Laubscher N 2018. Soil quality in the Taranaki region 2017. Manaaki Whenua – Landcare Research Contract Report LC3175.

Greater Wellington Regional Council

Drewry J 2016. Soil quality state of the environment monitoring programme. Annual data report, 2015/16. Publication GW/ESCI-T-16/85. Greater Wellington Regional Council.

Drewry J 2017. Soil quality state of the environment monitoring programme. Annual data report, 2016/17. Publication GW/ESCI-T-17/101. Greater Wellington Regional Council

Gordon D 2019. Soil quality state of the environment monitoring programme. Annual data report, 2017/18. GW/ESCI-T-18/146. Greater Wellington Regional Council.

GWRC 2019. Soil quality monitoring – dairying, dry stock & horticulture. Greater Wellington Regional Council.

GWRC 2020. 2020 Soil quality monitoring – cropping & market garden. Greater Wellington Regional Council.

GWRC 2021. 2021 Soil quality monitoring – drystock. Greater Wellington Regional Council.

GWRC 2022. 2022 Soil quality monitoring – native vegetation. Greater Wellington Regional Council. https://www.gw.govt.nz/assets/Documents/2023/05/2022-soil-quality-monitoring.pdf

GWRC 2024. 2023 Soil quality monitoring – dairying. Greater Wellington Regional Council. https://www.gw.govt.nz/assets/Documents/2024/04/soil-quality-monitoring-2023.pdf

Thompson-Morrison H, Cavanagh J 2024. Analysis of pesticide residues in soils from the Greater Wellington region. Manaaki Whenua – Landcare Research Contract Report LC4516 for Greater Wellington Regional Council.

Marlborough District Council

Oliver M 2022. Soil quality in the Marlborough Region 2021. Marlborough District Council Technical Report No: 22-001.

Oliver M, McMillan J 2020. Soil quality in the Marlborough Region 2019. Marlborough District Council Technical Report No: 20-003.

McMillan J, Oliver M (2023) Soil quality in the Marlborough Region 2022. Marlborough District Council, Number Marlborough District Council Technical Report No: 23-006, Blenheim, New Zealand.

Environment Canterbury

Thompson-Morrison H. 2024. Preliminary analysis of the 500 Soils monitoring data Environment Canterbury Science Summary: R24/15. Environment Canterbury Regional Council. Christchurch. 38 p.

Appendix 4 – Indicators used internationally

EU Soil Observatory

The EU Soil Observatory (EUSO) was launched by the European Commission in December 2019 and is part of the European Soil Data Centre (ESDAC).[26] The EUSO was developed by the Joint Research Centre of the EC and published in a virtual dedicated platform that is publicly accessible.[27] The EUSO aims to be the principal provider of reference data and knowledge at the EU level for all matters related to soil (Panagos Broothaerts et al. 2024).

Underpinning the EUSO are data collected through the Land Use/Cover Area frame Survey soil module (LUCAS Soil) commencing in 2009. Over time, extensive sampling has been undertaken, with the data generated by LUCAS Soil used to establish baselines for several soil indicators across the EU. A key output is the soil degradation dashboard,[21] developed using the LUCAS Soil data, with considerable emphasis placed on spatialisation of the data.

Some of these indicators have been discussed in the main text, and further detail is available from [28]. Some indicators are based on measured soil properties e.g. Olsen P concentrations or arsenic concentrations, while others are based on accumulated information or modelled data. For example, the N surplus layer is based on determining spatial estimates for N input – N output using agricultural data and a European biogeochemical model framework. The biodiversity layer is the most complex and combines a set of 13 factors (e.g. habitat fragmentation, land-use change, soil pollution, and soil sealing) known to be potential threats, preventing soil biodiversity from performing its biological functions (Orgiazzi et al 2016).

Table A3.1. EUSO indicators

Threat to soil degradation	Indicator	Threshold used
Erosion	Water erosion	Erosion rate > 2 t/ha/yr
	Wind erosion	Erosion rate > 2 t/ha/yr
	Tillage erosion	Erosion rate > 2 t/ha/yr
	Harvest erosion	Erosion rate > 2 t/ha/yr
	Recovery after fire	Recovery rate (RCOVER) < 1
Soil pollution	As excess	P(X > 45 mg/kg) > 5%
	Cu excess	Cu concentrations > 100 mg/kg
	Hg excess	Hg concentration > 500 µg/kg
	Zn excess	Zn concentrations > 100 mg/kg
	Cd excess	Cd concentrations > 1 mg/kg
Soil nutrients	N surplus	Agricultural areas where N surplus > 50 kg/ha

[26] https://esdac.jrc.ec.europa.eu/

[27] https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/

[28] https://esdac.jrc.ec.europa.eu/euso/euso-dashboard-sources

Threat to soil degradation	Indicator	Threshold used
Soil nutrients (Cont.)	P deficiency	P deficiency < 20 mg/kg
	P excess	P excess > 50 mg/kg
Loss of soil organic C	Distance to maximum SOC level	Distance from ‘maximum’ SOC > 60%
Loss of soil biodiversity	Potential threat to biological functions	≥ Moderately high level of risk
Soil compaction	Packing density	Packing density > 1.75 g/cm^3
Salinisation	Secondary salinisation	Areas in Mediterranean biogeographical region where >30% is equipped for irrigation
Loss of organic soils	Peatland degradation	Peatlands under hotspots of cropland
Soil consumption	Soil sealing	No threshold applied (all built-up areas)

European Environment Agency (EEA)

The EEA undertook an extensive review of research results on soil indicators in relation to soil functions and soil threats, and their mapping and assessment, which was synthesised in a report (EEA 2023) with the objective of identifying criteria for healthy soils across Europe. The report focuses on eight soil threats and 12 soil quality indicators (Table A3.2), which were selected for their appropriateness to assess soil degradation (unhealthy soils) related to various important soil functions or ecosystem services.

In most cases the indicators selected were considered to be well established, with data availability at the European level at least acceptable, and they were appropriate to describe the key soil degradation types and the impairment of key soil services. Several indicators (e.g. soil organic carbon) have multiple functions and are used to assess several forms of soil degradation related to different soil service.

Table A3.2. Overview of soil threat indicators investigated in EEA 2023

Soil threat	Indicator	Thresholds	Comment
Soil organic carbon loss			
Cropland	Falling below optimal SOC level	Light soils: <1.2% SOC Medium soils: 1.2-1.9% SOC Heavy soils: >1.9% SOC	SOC: clay ratio (Johannes et al., 2017): optimum SOC content as 10% of the clay content/vulnerability limit
Nutrient loss			
Agriculture	Exceedance of critical levels of mineral nitrogen (agricultural land)	NH_3 in air: 1-3mg NH3/m^3 NO_3 in groundwater: 50mg NO_3/l N in surface water: 1.0-2.5mg N/l	Mineral N: sum of available NH_4 and NO_3
Forest land	N limitation based on exceedance of C:N ratio	C:N ratio 20-25 Leakage from forests: 1mg N/l	Forest floor organic layer
Agriculture	Falling below of optimal phosphorus	P concentration: 25-35mg/kg (optimal P fertility class)	Extractable P concentration < optimum (value range refers to Mehlich 3-ICP; also available P-Bray P1 and Olsen P)
Forest land	P limitation based on exceedance of N:P ratio	N:P ratio >18 (coniferous forests) N:P ratio >25 (deciduous forests)	Forest floor organic layer
Acidification			
Agriculture	Exceedance of critical pH levels	1. pH<4.5-4.7 (critical) 2. pH<5.0-5.5 (avoid)	1. Risk of Al toxicity 2. Limited availability of Ca, Mg, K and P
Forest land	Exceedance of critical inorganic Al levels	Base cation (Bc):Al ratio = 1 (0.5-2.0)	Base cations are Ca^{2+}, Mg^{2+} and K^+
Soil pollution			
All land uses	Exceedance of screening values for critical risk from heavy metals and organic pollutants	Updated values for Cd, Cu, Pb and Zn (mg/kg) in this report: By country Database developed (Cd, Cu, Pb, Zn, As, Hg, Ni, Cr) Organic pollutants	Country-specific values vary broadly and are not necessarily comparable Stratification by land use and soil texture
Soil erosion			
Agriculture	Exceedance of actual rate of soil loss by water erosion	2t/ha/year for shallow soils (<70cm depth) 4t/ha/year for deeper soils (≥70cm)[a] (soil loss tolerance)	Soil formation rate: 0.3-1.4 t/ha/year (Verheijen et al., 2009) Preliminary thresholds, derivation of site-adapted tolerable soil loss rates recommended The current indicator description in this report includes only soil erosion by water, whereas the threshold addresses all other erosion types
Soil biodiversity loss			
	Loss of soil biodiversity (sub-indicators)	To be developed: Exceedance of safe minimum standards of ecosystem conservation Exceedance of operating ranges (OR) for specific soil animals and microorganisms	Requires sub-indicators by species and/ or (functional) group

Table A3.2 cont. Overview of soil threat indicators investigated in EEA 2023

Soil compaction			
	Harmful subsoil compaction (sub-indicators)	Priority (sub)-indicators: Saturated hydraulic conductivity (Ks) <10cm/day Air capacity (AC) <5%	Exceedance of 'action values' (Zink et al., 2011) Secondary sub-indicators with available thresholds: bulk density, internal soil strength, air permeability and oxygen diffusion
Soil sealing			
	Sealed area per total land area	National targets to achieve 'no net land take'	

The use of common terminology and approaches (e.g. pedotransfer functions) was considered important to integrate different national and EU-wide soil surveys. Three levels of sampling were identified.

Level I: sites where all general parameters are measured, such as large-scale topsoil surveys, with a central laboratory (LUCAS Soil, Geological Mapping of Forest Soils of Europe), or based on a European network of closely calibrated national/regional laboratories (ICP Forests level I).

Level II: investigations and monitoring of specific parameters and soil threats (e.g. types of erosion, soil biodiversity). Higher sampling densities allow improved identification of systematic errors, and higher sampling depth allows monitoring of subsoil processes.

Level III: related to very specific problems (e.g. radionuclides, military sites, decontamination of specific industrial residues, 'hot spots' of anthropogenic or natural processes). In addition, local sampling and analytical capacity (e.g. analytics for farmers) can be involved and later integrated into larger-scale surveys (involving local laboratories).

Level 1 is most analogous to New Zealand soil quality monitoring programmes.

Table A3.3. Parameters for soil monitoring at different sampling intensity levels from EEA 2023.

Monitoring level	Level I	Level II	Level III
Soil threat		As for level I, and also	As for levels I and II, and also
Soil organic carbon loss	SOC and mineral carbon Total (organic) nitrogen C:N ratio Bulk density (derived with PTF) Texture class, stone content	SOC fractions Bioavailability of nutrients and pollutants GHG emissions Physical parameters (measured)	Refined local SOC monitoring Management types SOC cycling at ecosystem level (input/output)
Soil nutrient loss	Agricultural soils: • Total N, mineral N • Total P, available P: Pox/Al+Feox • Available K Non-agricultural soils: • C:N ratio, base saturation	Agricultural soils: • Cation exchange capacity • Base saturation Non-agricultural soils: • Soil solution concentrations	Agricultural soils: • Minor nutrients Non-agricultural soils: • As for level II
Soil acidification	Agricultural soils: • pH, clay content, SOC Non-agricultural soils: • pH, cation exchange capacity, base saturation	As for soil nutrient loss	As for soil nutrient loss
Soil pollution	Total element concentrations (aqua regia extractable fraction of heavy metals) Natural background (at least at a subset of sampling points) Organic compounds, such as persistent organic pollutants	Specific soil testing, e.g. reactive or available fractions, plastics, antimicrobials Balancing (inputs-outputs, e.g. modelling) to estimate/ validate accumulation	Very specific contamination problems, e.g. radionuclides, military contamination, large chemical facilities Site-specific risk assessment tools to predict actual and future effects (of specific risks such as food quality)
Soil biodiversity loss	Earthworms and Collembola	Parameters targeting functional diversity and DNA-based genetic diversity	Parameters describing complex biological functions (e.g. respiration, N and C mineralisation, microbial biomass)

Soil erosion (see also Table 7.4)	Modelling (using data on land cover/land use, geomorphological data, national soil data, rainfall)	Mapping visible soil erosion features Details on land use (e.g. ground cover)	Monitoring (measurements) of soil erosion (sediment loads): • Plot scale • Catchment scale • Sediment deposition in ponds, lakes or reservoirs
Soil compaction (see also Table 8.3)	Precompression stress (PTF) Soil rigidity ratio (PTF) Penetration resistance (PTF) Morphological features Soil organic matter (measured)	All basic soil parameters for PTFs are measured	Tensiometer, sensors at representative subplots Stress-dependent measurements
	Saturated hydraulic conductivity, air capacity, plant available water capacity (PTF)		As for level II, but with great sampling depth and more subsamples
	Soil texture/coarse fragments/ $CaCO_3$ (estimated) Rooting (estimated)		

Note: GHG, greenhouse gas; PTF, pedotransfer function.

The additional information for soil compaction on monitoring large-scale compaction is shown in Table A3.4. With the additional information on parameter thresholds for subsoil compaction shown in Table A3.5, these provide an interesting comparison to values used in New Zealand.

Table A3.4. The design of large-scale compaction monitoring from EEA 2023.

Compartment	Measurement and estimation parameters		
	Level I	Level II	Level III: wheeling plots and unloaded reference plots
Location of sampling	In the field: hot spots with visible marks of compaction:		Representative sub-plots throughout a given field surrounding the plot centre
	e.g. reduced vegetation cover or growth, puddles	Proportion of affected area, e.g. per field, or per area around a representative observation point	
Direct and indirect monitoring of soil compaction	Morphological features (waterlogging, (platy) soil structure, rooting)		
	Precompression stress (estimated) ([a]) Soil rigidity ratio ([b])		Samples are measured at defined matric potential Contact area pressure of the machines and the actual contact area are determined
	Penetration resistance (PR) ([c]) (estimated with pedotransfer functions, PTFs)		Measurements of depth-dependent PR at a given matric potential
Basic soil physical parameters	Saturated hydraulic conductivity, air capacity, plant available water capacity (estimated with PTFs, e.g. Wösten et al. (1999), Schroeder et al. (2022b))	All basic soil physical parameters for PTF are measured	Tensiometer, sensors, actual soil sampling at defined depths Stress-dependent changes in the parameters are measured under in-field and under lab conditions
	Bulk density (estimated or measured)	Bulk density (measured)	
Basic soil chemical parameters	Soil texture/coarse fragments/$CaCO_3$ (estimated — soil auger)	Soil texture/coarse fragments/$CaCO^3$ (measured — soil profiles)	
	Soil organic matter (measured)		
Biological parameters	Rooting estimated	Root density (measured)	
	Biological activity (bioturbation)	Diversity and community structure of soil microorganisms	
Depth	Soil surface, upper boundary of lower soil horizons (or simply topsoil and subsoil)	Refined depth classes/by genetic horizon	Depths of 40-45cm and 60-100cm
Repetitions	4-8 samples per depth		10-20 samples per parameter and depth
Operations	Field traffic: percentage of the wheeled area, number of wheel-to-wheel passages		Weight, air pressure, wheel type, axle and tyre widths of every vehicle, contact area
Seasonality of monitoring	Spring sampling (soil at field capacity)		Sampling at requested times throughout the year

Notes: ([a]) Precompression stress derived from PTFs for a given texture and aggregation, according to Horn and Fleige (2003): requires pore size distribution, hydraulic conductivity, and soil chemical soil properties. In areas where this approach is not calibrated, horizon-specific stress strain measurements of undisturbed soil samples at a given matric potential and confined shear tests are needed to determine both the internal mechanical strength and the shear strength of a given structured soil.
([b]) Ratio precompression stress/actual stress imposed by field traffic (see also Duttmann et al. 2014, 2022).
([c]) Establish reference sites from undisturbed, uncultivated sites.

Table A3.5. Thresholds for soil physical parameters for detecting harmful *subsoil* compaction, from EEA 2023

Parameter	Explanation and thresholds		Soil sensitivity
	Parameter set I		
Bulk density	<1.2g/cm^3 = very loose 1.2g/cm^3 and 1.6g/cm^3 = normal 1.6g/cm3 and >1.9g/cm^3 = dense >1.9g/cm^3 = very impermeable Based on DVWK 1997, 1998; see also Keller et al. 2019		Soils originating from clay > silt > sand; higher values are due to geological pre-stressing or anthropogenic impacts
Air capacity: air-filled pore volume	A low air capacity impairs root growth, reduces oxygen pressure in soil air and increases the formation of greenhouse gases. Below 5% air capacity at a soil matric potential of -6kPa, aeration or gas diffusion are mostly insufficient. With decreasing particle size, the pore volume increases, and soil aggregation and soil organic matter content increases. Values around 45% total pore volume are at least acceptable while those below 35% are generally defined as very critical irrespective of texture effects).		Soils originating from clay > loam > silt and sandy loam > sandy loess
Visual soil evaluations	Aggregate type and estimated bulk density	The visual assessment of the soil as loose or dense based on aggregate size and strength, pore size and continuity, root density and distribution	Additional assessment for all soils
	Root growth/penetrometer		
	Spade diagnosis		

BENCHMARKS

The EU BENCHMARKS programme commenced in 2022 with the aim of co-developing an integrated soil health monitoring framework that facilitates the quantification of soil health potential and status within a given context,[29] and provides for:

- indicator selection – based on objective, context and practices
- soil health assessment – calculates the soil health index based on indicator measurements
- management optimisation – provides recommendations on which practices can be applied to further optimise soil health for a given context.

This programme has just released a series of sampling protocols, including the specification of soil health indicators to be used in the assessment of agricultural and forestry experimental sites and systems, and urban systems (Table A3.6). Baseline site characterisation soil samples will be collected using BENCHMARKS protocols for bulk soil, bulk density, earthworms, and mesofauna. The intent is for additional samples to be collected using protocols tailored to plastic sampling (i.e. microplastics) or hydraulic property sampling.

[29] https://soilhealthbenchmarks.eu/

Table A3.6. Indicators to be used in BENCHMARKS campaigns

Indicator	Information provided / (methods)
Cation exchange capacity	Buffering capacity and nutrient reserves
Electrical conductivity	
Plant-available P	Plant-available P (Olsen P)
pH	Acidity or alkalinity of soil
Total N	Organic N reserves
Plant-available K	
Trace elements: Cu, Fe, Mn, Mo, Ni, Zn	ICP-OES
Soil organic C	Organic matter reserves, soil structure, ability to retain water
Active C	Availability of organic matter reserve, microbial activity
POM:MAOM (Particulate organic matter: mineral adsorbed organic matter)	Size of microbial population, rapidly cycling organic matter and nutrients
Metals	ICP-MS
Pesticides	As measured following QuEChERS)
POPS	GCMS
Microplastics	FTIR (Foetisch et al. 2024)
Soil texture	
Aggregate stability (wet sieving)	
Bulk density	Soil compaction, physical environment for roots and soil organisms (volumetric conversion)
Soil water retention, unsaturated hydraulic conductivity	Used to calculate porosity and available water
Saturated hydraulic conductivity (lab and field)	
Anaerobic mineralisable N (B)	Availability of N reserve
Microbial biomass: C&N	
Earthworms	
Microarthropods	(Morphometric, DNA metabarcoding)
Nematodes	(Extraction, DNA metabarcoding)
Microbes	(DNA, 16S and ITS PCR)
Bacterial abundance	qPCR of 16S marker gene
Fungal abundance	qPCR of 18S marker gene
Nitrifying archea and bacteria	qPCR of ammonia monooxygenease functional gene
Nitrous oxide-reducing bacteria	qPCR nitrous oxide reductase
Proteolytic bacteria	qPCR of alkaline metallopeptidase and neutral metallopeptidase functional genes
Urea-hydrolysing bacteria	qPCR urease functional gene

EU soil monitoring law

The EU Soil Strategy for 2030 issued by the European Commission (EC) in 2021[30] proposed a soil monitoring law to lay down objectives for the protection, restoration, and sustainable use of soil with the aim of achieving healthy soils in Europe by the year 2050. In April 2025, the European Union Council reached a provisional deal with the European Parliament on a directive establishing a framework for soil monitoring to improve resilience and manage the risks of contaminated sites.[31]

The directive proposes a comprehensive soil monitoring framework to provide comparable data. The assessment of soil health includes the used of common soil descriptors (physical, chemical and biological parameters), and is intended to use target and trigger values to assess classes of soil health:

- non-binding sustainable target values at the EU level to reflect the long-term objectives
- operational trigger values, set at the member state level, for each soil descriptor to prioritise and gradually implement provisions leading to a healthy soil status.

The directive suggests that soil sampling depth should be 30 cm, and proposes the soil 'descriptors' shown in Table A3.7

Table A3.7. Soil descriptors proposed in the soil monitoring directive

Soil Monitoring Law descriptors
Soil texture
Electrical conductivity
Erosion rate
Soil organic C
Soil organic C stock
Bulk density in subsoil
Bulk density in topsoil A-horizon
Extractable phosphorus
Concentration of heavy metals in soil: As, Sb, Cd, Co, Cr (total), Cu, Hg, Pb, Ni, Tl, V, Zn; concentration of a selection of organic contaminants
Soil water-holding capacity, air capacity and saturated hydraulic conductivity
pH
Total N (Kjeldahl or dry combustion)
Base saturation and exchangeable concentrations of Na, K, Ca, and Mg

[30] COM (2021) 699 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0699

[31] https://data.consilium.europa.eu/doc/document/ST-9266-2025-INIT/en/pdf

USA

NAPESHM

The North American Project to Evaluate Soil Health Measurements (NAPESHM) categorised indicators in terms of whether they primarily reflect differences in inherent soil properties, soil health, or soil fertility. An overview of the findings of the project is provided by Bagnall et al. 2023. Briefly, they drew on an analysis of NAPESHM data to assess each measurement's sensitivity to six soil health-promoting management practices as indicators of the C cycle (Liptzin et al. 2022; Rieke Rieke, Cappellazzi, Cope et al. 2022), N cycle (Liptzin et al. 2023), aggregate stability (Rieke, Bagnall, Morgan et al. 2022) and the hydrologic cycle (Bagnall, Morgan, Bean et al. 2022) including development of new pedotransfer functions for plant available water (Bagnall, Morgan, Cope et al. 2022). The price and availability of the indicators at commercial laboratories were also used to determine which indicators were most practical to measure at scale for the North American continent. The subset of indicators was reduced by choosing those with relatively direct links to soil functions when multiple indicators were linked to the same function.

Specifically, the full set of NAPESHM soil measurements were first categorised as (1) inherent soil properties, (2) soil fertility measurements, (3) exploratory measurements, or (4) dynamic soil properties appropriate for a soil health assessment. Six inherent soil properties were identified, including soil texture, soil electrical conductivity, Na adsorption ratio, cation exchange capacity, and pH. Soil pH was considered to be a critical soil property and was included in inherent soil properties, even though pH can be altered by soil management, because native soil pH is determined by soil-forming factors, such as parent material and weathering.

Measurements of inherent soil properties are critical for contextualising and interpreting soil health indicators, because we assess soil health by sampling soil properties that result from a combination of soil management and inherent properties, which depend on soil-forming factors. As an example of how this context was applied in NAPESHM analysis, soil texture and pH were included in regression models to assess the impact of inherent properties of all indicators (Bagnall, Morgan, Bean et al. 2022; Liptzin et al. 2022, 2023; Norris et al. 2023; Rieke, Bagnall, Morgan et al. 2022). Soil fertility measurements include extractable P, K, Ca, Mg, and Na, as well as trace elements such as Fe, Zn, and Cu, with Bagnall et al. 2023 noting that soil fertility management interacts with soil health management to influence soil functioning and soil health expression.

Cornell soil health manual.

The Cornell Comprehensive Assessment of Soil Health (CASH) manual (Moebius-Clunes et al. 2016) provides an overview of the approach used to assess soil health. This includes discussion of the indicators selected, and the approach used to score the indicators to assess soil health. A summary of the soil indicators used is provided in Table A3.8.

Table A3.8. Summary of soil quality indicators used in the Comprehensive Assessment of Soil Health (CASH)

Indicator
Available water capacity
Surface hardness
Subsurface hardness (6–19 inches field penetrometer)
Aggregate stability
Organic matter
Soil protein
Soil respiration
Active C
pH
Extractable P and K
Extractable K
Micronutrient score – Fe, Mg, Mn, Zn

Scoring functions are used for each indicator to interpret soil health measurements. The scoring functions convert a value for a specific indicator to an interpretive rating via a curve that assigns scores between 0 and 100 to the measured values. Most physical and biological indicators are given higher scores for higher measured values, while some are given higher scores for lower measured values (e.g. surface and subsurface hardness, root health rating). Chemical indicators are assigned high scores for measured values that fall within the optimal range for most soils. Outside this range, scores decrease with increasing difference between measured and optimal values.

The scoring functions for some indicators depend strongly on soil textural class, and thus require separate scoring functions for coarse-, medium-, and fine-textured soils. These were developed based on the observed distribution of measured values for the indicators in regional soils of similar texture.

The scoring curves for each indicator have been determined by estimating the cumulative normal distribution function using the mean and standard deviations of samples in the Cornell Soil Health Lab database, a spatially diverse set of samples representing over 60% of the US. Figure A3.1 provides an overview of the development of the scoring.

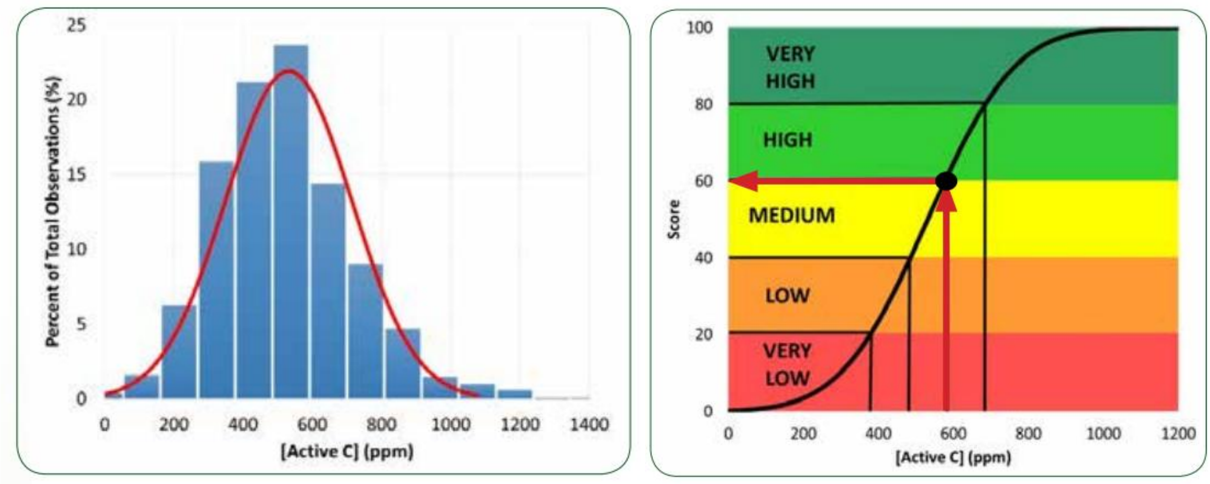


Figure A3.1. Example of the development and use of scoring indicators for assessing the soil quality results. Left: the mean and standard deviation derived from the normal distribution, describing the frequency distribution of active carbon, is used to calculate the cumulative normal distribution (CND). The CND is then used to provide the scoring of the results. Right: in this example, 60% of medium-textured soil samples in the calibration set had an active C content lower than or equal to the sample being scored. (Source: Moebius-Clune et al. 2016)

Australian National Soil Monitoring Program

The National Soil Monitoring Program (NSMP) is a $21.599 million initiative announced as part of the Australian Budget 2023/24, and is a key deliverable of the National Soil Action Plan.[32] The purpose of the NSMP is to monitor agreed physical, chemical, and biological soil properties and to use the data to help understand soil condition and trends in Australia. Sampling protocols and indicators have recently been developed by the CSIRO, and sampling has commenced[33] (Grealish, CSIRO, pers. Comm.). Sampling comprises 10 randomly located points in a 25 m × 25 m plot, with 10 cm increments sampled down to 1 m. Samples from the same depth layers are composited, and a composite sample is also collected for biological testing (eDNA); intact cores are collected for bulk density and soil water retention. The indicators selected for testing are shown in Table A3.9.

[32] https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils/national-soil-monitoring-program

[33] https://research.csiro.au/nsmp/

Table A3.9. Indicators assessed in the Australian National Soil Monitoring Program

Soil chemical indicators	Soil physical indicators
pH (H_2O)	Aggregate stability
pH ($CaCl_2$)	Particle size analysis
Cation exchange capacity (Ca, Mg, Na, K)	VisNIR (visible and near-infrared spectroscopy
Exchangeable acidity (if <pH5.5)	MIR (Mid-Infrared spectroscopy)
Electrical conductivity	Chloride
Total C and total organic C	Bulk density
Total N	
Total S	
Available P (Colwell)	
Biological indicators	
potentially mineralisable N (AMN)	eDNA

Appendix 5 – Fact sheets

Bioeconomy Science Institute

Te Uru Kahika

Regional and Unitary Councils Aotearoa

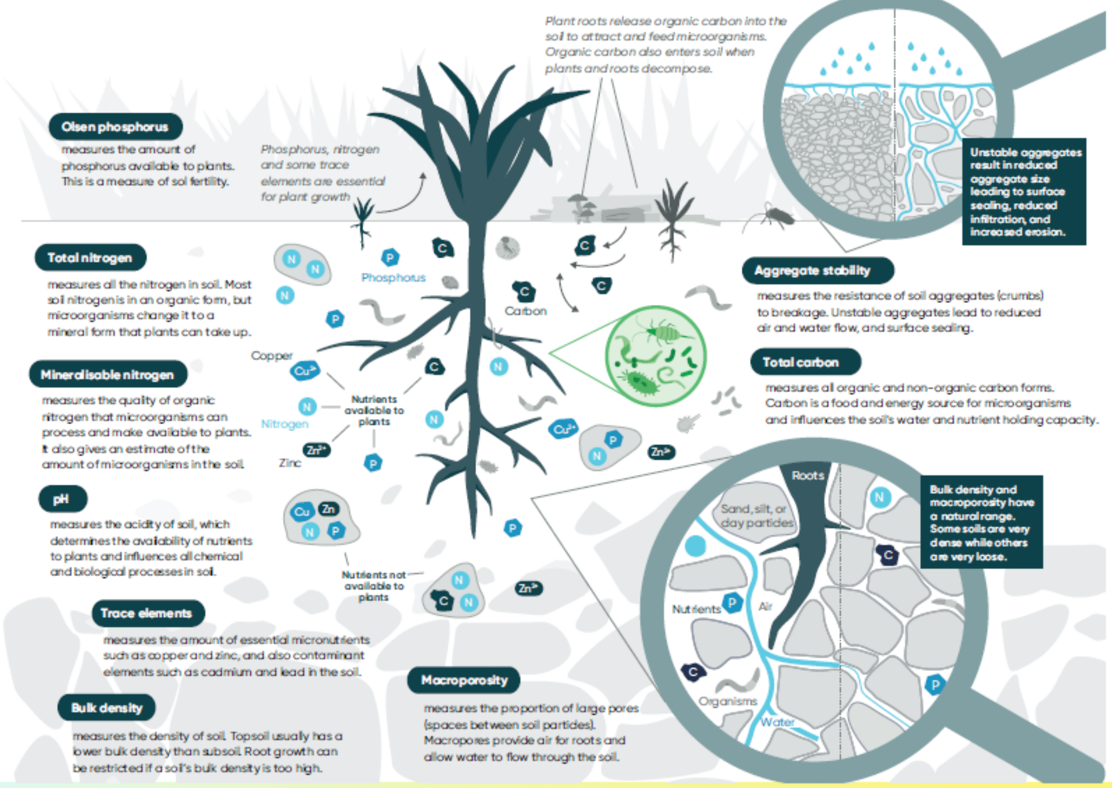
Keeping track of soil health

This factsheet provides an overview of *State of the Environment (SOE) soil quality monitoring and reporting*, for local policy-makers such as councils, land managers, and the general public.

Healthy soils produce 95% of the food we eat, are home to more than 59% of global biodiversity, and represent the largest store of terrestrial carbon on the planet. Healthy soils also deliver other vital ecosystem services, such as nutrient cycling and water filtration. But soil is a limited resource. Soil health is often considered to be broader than soil quality, which is typically associated with measurement of soil physical, chemical and occasionally biological properties.

Regional and unitary councils undertake *State of the Environment (SOE) soil quality monitoring* across a range of land uses and soils representative of a region's soil resources, to provide an assessment of state and trends, and to provide an early warning system to identify the effects of primary land uses on long-term soil quality. Local policy-makers such as councils can use soil monitoring results to inform regional planning and environmental goals.

Monitoring is primarily undertaken on private land. Landowners who are part of the soil monitoring network can access data to understand both productivity potential and environmental capacity of their land. Sites include those under pasture, cropping, perennial horticulture, commercial forestry and urban land uses, as well as sites with indigenous vegetation, typically on the dominant soils of the individual regions. A core set of indicators (see image) are measured at these sites.



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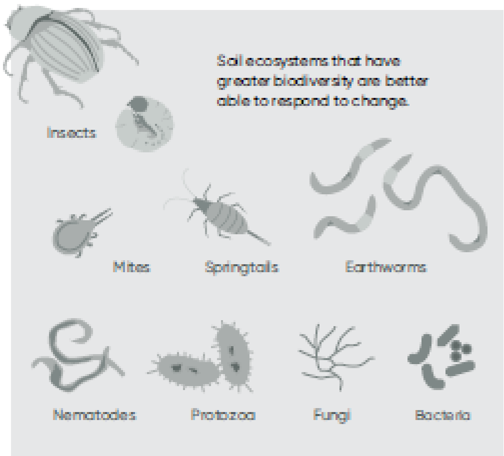
New Zealand Institute for Bioeconomy Science Limited

Reference ranges or target values are used to assess whether soils are within acceptable limits. These may be grouped by land use and soil order, or by grouped soil orders.

Soil biodiversity

Healthy soils support active, diverse, and abundant populations of microorganisms and fauna, such as nematodes, springtails, beetles, fungi and microscopic life. These organisms play critical roles in nutrient cycling, organic matter decomposition, plant pest suppression and more. Soil microorganisms can free up nutrients for plants to grow and can protect them from disease.

The biodiversity of soil is not currently routinely monitored in New Zealand. However, the Hot Water Extractable Carbon (HWEC) test and Anaerobically Mineralisable Nitrogen (AMN) tests used in SOE monitoring provide indirect measures of microbial activity.



Soils in urban environments

The value of soils in urban environments should not be underestimated. These soils underpin our green spaces, and act as a sponge to help mitigate flooding. Urban soils include residential and community gardens, which are also important spaces for food production and environmental stewardship.

Soil monitoring for other purposes, and by farmers and communities

Soil testing for primary production

Soil testing is important for farmers and growers to inform when and how much lime and fertiliser to apply to optimise plant growth and limit environmental impacts. These tests may differ from those used for SOE soil quality monitoring, because the test results are generally interpreted against target ranges based on agronomic considerations.

The Fertiliser Association of New Zealand (FANZ) provides resources for pastoral, arable, and vegetable farming on soil testing and managing soil fertiliser/lime requirements based on soil test results.

Soil testing is not as routine or common in plantation forestry, except when establishing a new plantation, or occasionally for diagnosing a nutrient deficiency (foliar testing is more common).

Soil monitoring by farmers and communities, including kaupapa Māori approaches

More broadly, soil monitoring will help inform what testing may be relevant to undertake and if additional testing available through commercial laboratories is relevant. Kaupapa Māori approaches for assessing soil health are generally broad and holistic, typically based on a value-knowledge perspective, not just a range of indicators. For national, regional, and local monitoring and reporting we are likely to see science-based indicators working alongside kaupapa Māori indicators and narratives to explain the characteristics, values, and changes in soils, as a part of a wider statement of soil and whenua health.

Visual soil assessment (VSA) is a valuable, accessible tool for farmers and communities to observe changes in soil quality. VSA has also attracted much interest from Māori groups because of its practicality for on-land assessment, monitoring and soil management. It aligns well with te ao Māori perspectives and Māori conceptual approaches for understanding soil health and developing indicators. VSA creates an awareness of the state of the soil, and can be inclusive of assessing soil biology. It can enable a direct connection between changes in management practices with changes in soil state.

Free guides and resources are available to help with undertaking VSA.

This factsheet is part of a series produced by the Bioeconomy Science Institute, for the Regional Council Land Monitoring Forum in 2025.

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Te Uru Kahika

Regional and Unitary Councils Aotearoa

Soil organic matter

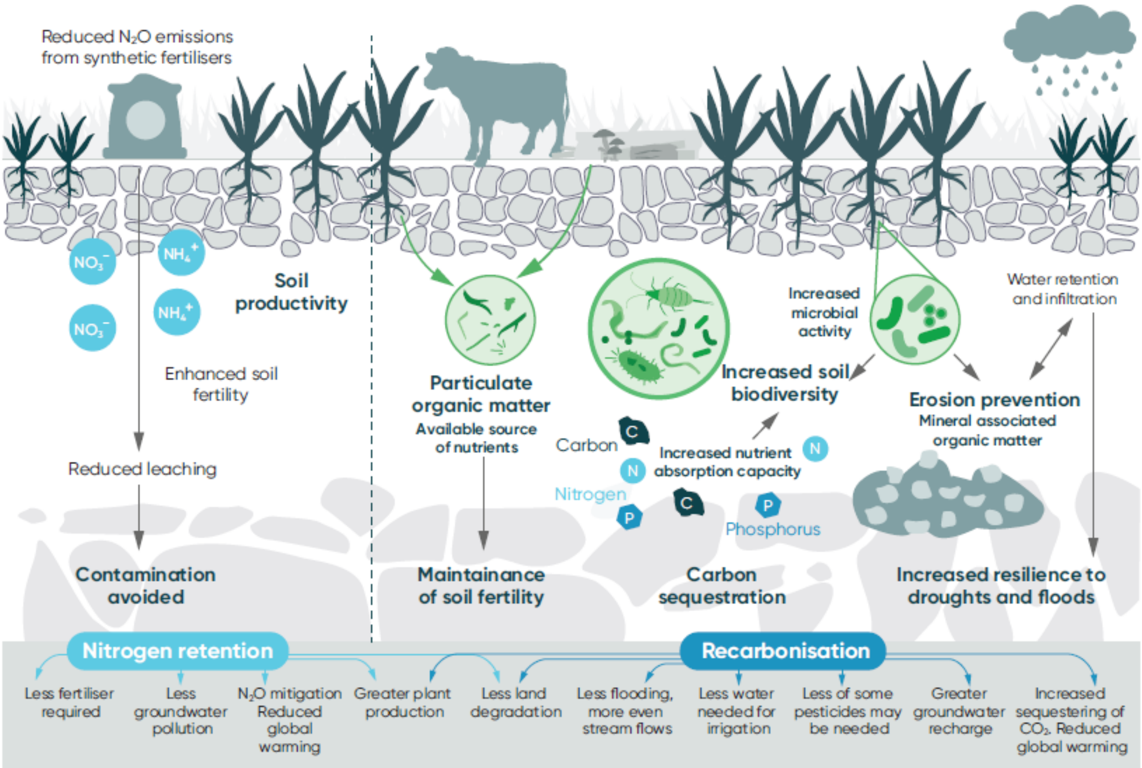
This factsheet contains information on indicators related to organic matter used for *State of the Environment (SOE) soil quality monitoring and reporting*, for local policy-makers such as councils, land managers, and the general public.

Soil organic matter is made from living or once-living material, in various stages of decomposition. Compost, plant and animal residues, roots, and microorganisms all make up organic matter.

Organic matter is the 'engine room' of the soil. It provides a source of plant nutrients, it contributes to soil structure, the formation of soil aggregates and the water-holding capacity of soil, and it provides habitat and food for soil flora and fauna.

Soil organic matter can store significant amounts of carbon, so it plays a critical role in climate regulation.

Most soil organic matter is found in the **topsoil** - a vital limited resource. Within the organic matter, some is used up within months to years (the 'active pool'), some within decades (the 'slow pool'), and the remainder can be present for hundreds to thousands of years (the 'recalcitrant pool'). Organic matter fractions may also be described as particulate organic matter - formed from pieces of decaying plants and animals, and is more active – or mineral-associated organic matter (MAOM). MAOM is primarily adsorbed (adhering to their surface) to clay minerals and undergoes much slower cycling.



The benefits of increasing soil organic matter.

New Zealand soils are naturally high in organic matter, although this varies across soil types and land uses. Management practices can determine whether organic matter accumulates, is maintained, or is used up.

For SOE soil quality monitoring, total carbon and total nitrogen are used to assess the amount and quality of organic matter. Hot-water extractable carbon provides a measure of active carbon. Anaerobically mineralisable nitrogen is a measure of the capacity of the soil microbial community to convert (mineralise) nitrogen tied up in organic matter into plant-available nitrogen.

Total carbon

Total carbon is a test that includes all organic and inorganic carbon (although most New Zealand soils contain very little inorganic carbon), expressed as a percentage of soil weight. Organic matter is assumed to be 58% carbon. Total carbon is converted to organic matter using a factor of 1.72 (i.e. total C x 1.72 = estimated organic matter).

Reference ranges used for SOE reporting vary depending on land use and soil type. In general, more carbon (hence more organic matter) is considered better. Mineral soils under cropping tend to have the lowest carbon contents, whereas pastoral soils tend to have more. Organic Soils (commonly referred to as peat) have the highest carbon contents, whereas Allophanic Soils have the highest carbon content of mineral soils.

Total N

Total N (TN) is a measure of the total amount of all forms of nitrogen in soil, including organic N (e.g. N in soil organic matter and crop residues) in addition to inorganic N (e.g. ammonium and nitrate). Organic N makes up the largest fraction of TN, and often is not readily plant-available, whereas inorganic N makes up a small amount of TN but is immediately plant-available.

Total N is typically measured alongside total C to provide an indication of the organic matter N content, and the ratio of total C to total N (the soil C:N ratio).

C:N ratio

The soil C:N ratio gives an indication of the quality of the organic matter to supply N. A widening of the C:N ratio over time reflects declining N fertility, whereas a narrowing of the ratio may indicate enrichment of N in the soil.

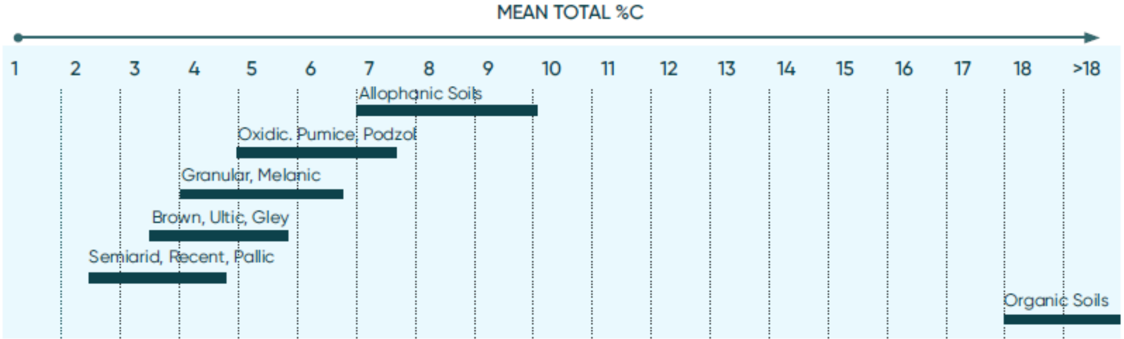
Managing organic matter levels

Soil organic matter tends to be depleted over time, particularly with intensive cropping. It can be difficult to increase organic matter in soil, so the **first priority for management should be to avoid losing organic matter**.

In general, organic matter levels can be improved by:

1. Adding more organic inputs (i.e. cover crops, retaining crop residues, and including legumes in pasture), and/or
2. Reducing the losses of organic matter from soil (such as reducing the depth and extent of cultivation).

However, organic matter takes years to replace naturally. Most organic inputs decompose rapidly, so it can take large and frequent applications to increase soil carbon over the long term.



Approximate soil order differences in mean total C determined from statistical modelling, controlling for the effect of land use.

This factsheet is part of a series produced in 2025 by the Bioeconomy Science Institute, for the Regional Council Land Monitoring Forum.

Soil nutrients – Olsen P

This factsheet contains information on the Olsen P soil indicator used for *State of the Environment (SOE) monitoring and reporting*, for local policy-makers such as councils, land managers, and the general public.

All plants require phosphorus (P) for growth. Many New Zealand soils have naturally low levels of plant-available P, and indigenous plants are adapted to this. Phosphorus 'availability' differs between soils due to differences in soil minerals, organic matter, and chemistry, with P-retention (also called Anion Storage Capacity) being a key factor influencing the loss of soluble P to waterways.

On farms, P primarily comes from fertiliser and organic materials including livestock manure, with loss of P to waterways a major environmental concern.

Regular soil testing helps ensure that P is applied only where needed – supporting plant growth, reducing unnecessary fertiliser costs, and minimising environmental impacts.

Testing for soil phosphorus

Olsen P is the standard soil test used in New Zealand to estimate **plant-available P**. It helps determine how much P fertiliser is needed for optimal plant growth.

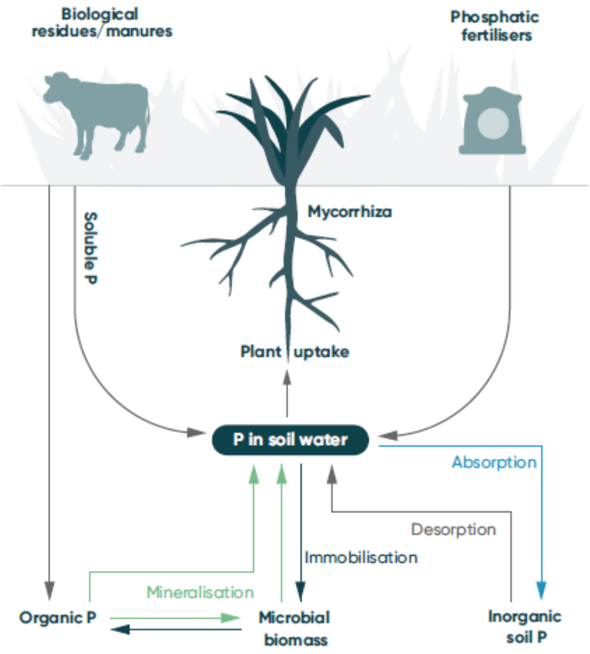
Other soil P tests may be more suitable in specific contexts. For example, the **Bray P** test is often used in **forestry**, because pine forest soils are generally acidic.

Olsen P is measured or reported as follows:

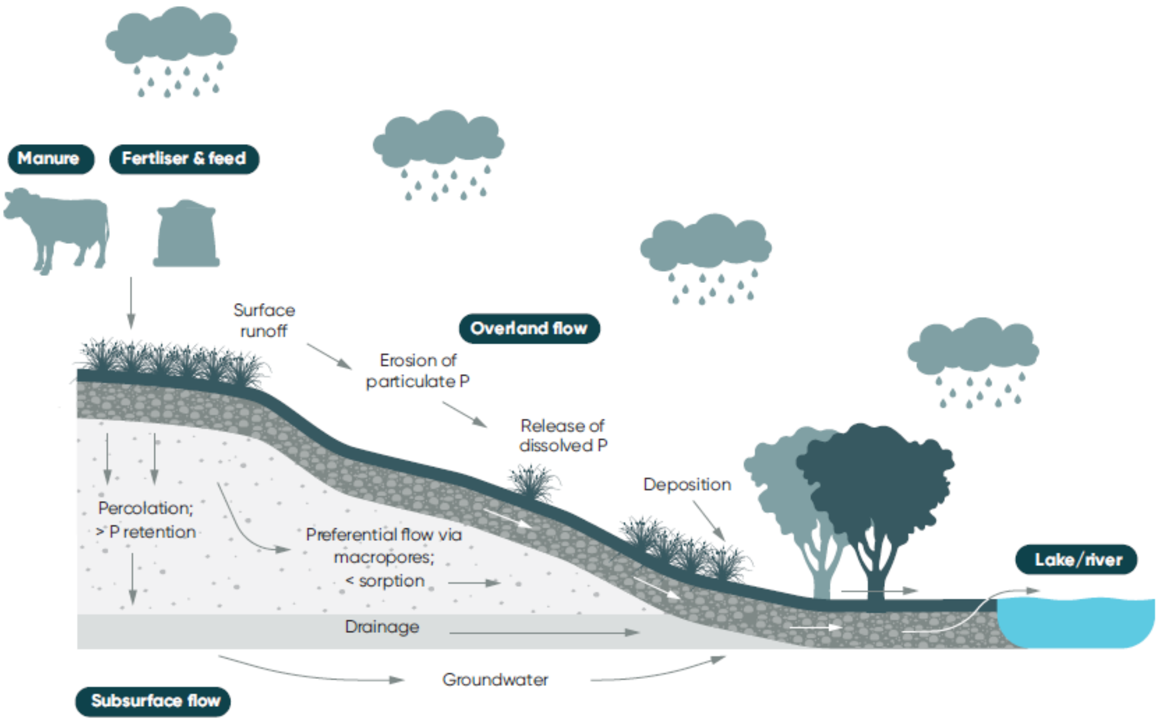
- **Gravimetric** (based on known mass of soil) – often used for SOE monitoring.
- **Volumetric** (based on the laboratory volume-weight of soil) – commonly used in fertiliser recommendations.

For State of the Environment soil quality monitoring, reference ranges for soil Olsen P are largely based on agronomic considerations and have been developed for different land-use categories and soil orders.

Applying more P than recommended offers no real productivity benefit, but increases environmental risk. The loss of P to waterways, mostly by soil erosion, depends on land management practices such as frequency of grazing, stocking rate, and timing of grazing or fertiliser application in relation to rainfall, as well as topography, and proximity to waterways. Higher Olsen P increases the risk that P will end up in waterways.



Soil phosphorus cycle.



Factors influencing the off-site movement of soil phosphorus.

Managing phosphorus levels for farmers and growers

Soil testing of the nutrient status and the chemical/physical status of soil will show farmers and growers which nutrients to apply, how much, and when. If too little is added, crops will not produce as expected. If too much is applied or is applied at the wrong time or in the wrong way, excess nutrients may run off the fields and pollute streams and groundwater.

Phosphorus requirements differ for pastures and individual crop species. The Fertiliser Association of New Zealand (FANZ) and primary sector industry bodies have recommendations for individual crop species. 🌐

Managing cadmium and other contaminants

Phosphate fertilisers are derived from phosphate rock, which contains trace levels of a range of elements. Cadmium is the primary contaminant of concern, and can be detected in varying amounts in root and leafy vegetables. Plant uptake of cadmium can be influenced by many factors.

Factsheets and guides are available for growers and farmers to help manage cadmium in their farming system.

A tiered fertiliser management system is also in place to help minimise cadmium accumulation in soil.

More information on cadmium is available from:

- Monitoing cadmium in NZ soils | NZ Government 🌐
- Managing contaminants | Fertiliser Association of New Zealand Inc. 🌐

This factsheet is part of a series produced in 2025 by the Bioeconomy Science Institute, for the Regional Council Land Monitoring Forum.

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Physical properties of soil

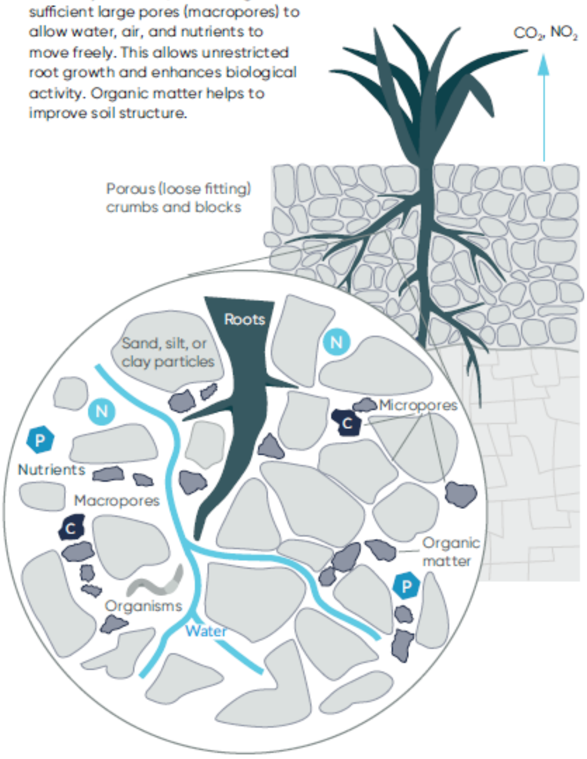
This factsheet contains information on physical soil indicators used for *State of the Environment (SOE) monitoring and reporting*, for local policy-makers such as councils, land managers, and the general public.

Soil structure is important for soil water drainage and storage, root penetration and plant growth, crop and pasture yields, air movement (including oxygen and greenhouse gases), and environmental performance. Organic matter helps to improve soil structure. Good soil structure helps our environment through improved water quality, reduced greenhouse gas emissions and minimising soil erosion.

Soil structural degradation through **compaction** is a key issue, where soils become less friable, have larger, more massive clods, reduced root development, and reduced soil biology such as earthworms. Compacted soils are prone to increased overland surface water flow runoff, which can increase erosion, and reduced water infiltration. This may produce lower crop yields. In New Zealand, pasture production has been estimated to decrease by an average of 2.5% for every 1% reduction in macroporosity.

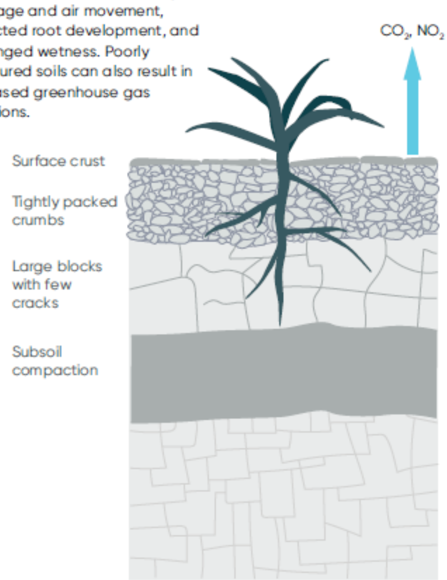
Well-structured soils

are easily crumbed, containing sufficient large pores (macropores) to allow water, air, and nutrients to move freely. This allows unrestricted root growth and enhances biological activity. Organic matter helps to improve soil structure.



Poorly structured soils

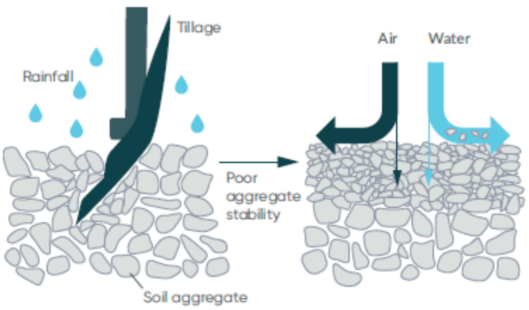
are dense and firm and have poor drainage and air movement, restricted root development, and prolonged wetness. Poorly structured soils can also result in increased greenhouse gas emissions.



Testing for soil physical structure

For State of the Environment (SOE) monitoring, air-filled porosity – sometimes referred to as macroporosity – and bulk density are commonly used indicators of soil physical health; these indicators are also used for soil management research. Aggregate stability may also be measured and is particularly useful to characterise the soil physical health of cropping soils.

- Air-filled porosity is the volume percentage of large soil pores larger than 30 µm (measured at -10 kPa matric potential).
- Bulk density is a measure of the density of soil (i.e. how loose or compacted the soil is).
- Aggregate stability describes the ability of soil aggregates (i.e. soil crumbs) to resist breakage.



In soils with poor aggregate stability rainfall and processes such as tillage reduces soil aggregate size and consequently soil porosity.

Surface sealing arising from reduced aggregate size blocks air and water flow through the soil increasing surface sediment run-off.

Aggregate formation in poorly structured soils.

Degraded soil structure is typically indicated by low air-filled porosity, high bulk density, and low aggregate stability.

Reference ranges used for SOE reporting are used to assess whether soils are within acceptable limits. These values often vary by land use and by soil order or grouped soil orders.

Air-filled porosity

A limited number of studies are available to quantitatively relate air-filled porosity measurements to negative effects for different soil orders. Some soils are more vulnerable to compaction – e.g. Ultic, Podzol, Pallic, and Gley soils – and require more careful management.

Bulk density

Bulk density is not particularly sensitive to changes in soil physical condition or the influence of land management practices. Pumice, Organic, and Allophanic soils typically have low bulk densities. Other than for these soil orders, soil texture may have a greater influence than soil order. High bulk density can be a physical barrier to root growth.

Aggregate stability

In New Zealand, aggregate stability is typically measured by wet sieving and expressed as a mean weight diameter (MWD) of the aggregates. Aggregates larger than 1.5 mm MWD are of minimal concern for soil structure.

Managing soil structure

Best management practices can help restore and maintain good soil structure.

- **Reduce mechanical impacts:** Limit vehicle and machinery traffic, especially in wet conditions. Avoid over-cultivation and deep tillage, especially over the longer term.
- **Manage grazing pressure:** Reduce stocking density in wet paddocks to avoid pugging. Rotational or deferred grazing can help minimise further damage in recovering areas.
- **Encourage plant growth:** Cover crops and growing plants add organic matter to the soil via litter and root inputs. This can increase porosity and stimulate burrowing by soil fauna.

This factsheet is part of a series produced in 2025 by the Bioeconomy Science Institute, for the Regional Council Land Monitoring Forum.