



Revision of soil quality indicator target ranges

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Jo Cavanagh, John Drewry, Hadee Thompson-Morrison, Robyn Simcock

Manaaki Whenua – Landcare Research

Alec Mackay, Estelle Dominati

AgResearch

Wei Hu, Karin Müller, Mike Beare

Plant & Food Research

Loretta Garrett, Chandra Ghimire, Peter Clinton

Scion

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Reviewed by:

Nathan Odgers
Researcher – Soils and Landscapes
Manaaki Whenua – Landcare Research

Approved for release by:

Sam Carrick
Portfolio Leader – Land Resources and Climate Change
Manaaki Whenua – Landcare Research

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Summary

Project and client

- Soil quality monitoring for regional and national state of the environment (SoE) reporting has been carried out for over 25 years. Provisional soil quality target ranges were developed in the 2000s and first published by Sparling et al. (2008). Although the target ranges have been reviewed and revised (e.g. Mackay et al. 2013), a substantial amount of additional soil monitoring, reporting and research has been undertaken since the provisional target ranges were established.
- The Ministry for the Environment contracted Manaaki Whenua – Landcare Research to lead a collaborative project with AgResearch, Plant & Food Research, and Scion to review and revise the current soil quality target ranges for all seven soil quality indicators, and hot-water-extractable carbon. This revision considered the new research and data that has become available since soil quality provisional target ranges were set, with a focus on the links to environmental outcomes.

Objective

- Develop updated target ranges for seven soil quality indicators used in SoE reporting:
 - pH
 - total carbon
 - total nitrogen
 - phosphorus (Olsen P)
 - anaerobically mineralisable nitrogen (AMN)
 - macroporosity
 - bulk density
- plus hot-water-extractable carbon (HWEC), which has been proposed to replace AMN.

Methods

- The following approach was used to review and revise soil quality indicator target ranges:
 - a targeted literature review and stocktake of available data to inform revision
 - collation and exploratory analysis of the data to develop revised numeric criteria
 - project team and stakeholder workshops to share the initial findings, discuss the purpose and use of soil quality target ranges, explore approaches for revising numeric criteria, and provide feedback on the revised numeric criteria
 - refinement of the revised numeric criteria (which we call 'reference ranges')
 - identification of areas for future focus.
- In this report we use the term 'target ranges' to explicitly refer to the existing soil quality indicator target ranges presented in Sparling et al. 2008 and LMF 2009, with updates included in Mackay et al. 2013. We use the term 'numeric criteria' to refer generally to numeric ranges used for soil quality monitoring. The term 'reference ranges' is introduced to refer to the revised numeric criteria developed through this project.

Results and conclusions

- This project has revised existing soil quality target ranges used for SoE reporting. We have proposed a change in terminology from 'target ranges' to 'reference ranges' to better

reflect the fact that these numeric ranges largely provide context for measured results (i.e. are referred to, as opposed to representing values to aim for, or targets).

- The approaches used to develop reference ranges were based on what was identified as being the most relevant within the constraints of the available data, and they varied with the individual indicators. Ultimately, the reference ranges were based on similar approaches used for the original target ranges, but utilising more extensive and/or recent data. In summary, these approaches were:
 - for pH and Olsen phosphorus: a fixed range based on agronomic recommendations for agricultural land uses, and distribution-based 'typical values' for non-agricultural land uses
 - for carbon, nitrogen, AMN, and HWEC – distribution-based 'typical values' for different land uses and soil order groupings, with a function-based (crop yield) minimum value of 2%C for non-allophanic mineral soils under cropping
 - for macroporosity and bulk density: reference distributions based on a currently small data set of soils from unimpacted controls for pastoral and forestry sites.
- Distribution-based 'typical values' were derived from a baseline monitoring data set (comprising several extensive data sets) to provide the most representative data across New Zealand as was feasible within the project. These typical values reflect the distribution of measured values obtained from previous monitoring programmes for different soil order groups across a range of management practices within a given land-use category. Further sampling is required to extend the undisturbed macroporosity and bulk density data set to enable more robust reference ranges to be developed for the different soil orders.
- Reference ranges were developed for the land-use categories specified in the National Environmental Monitoring Standard for Soil Quality and Trace Element Monitoring (NEMS-SQ): cropping, horticulture, dairy, drystock, indigenous vegetation, and urban open space). Where possible, reference ranges were also developed for intensive vegetable cropping soils, because of markedly different land management practices and for vineyards due to the markedly different soils used for growing grapes compared to other perennial horticulture or cropping.
- For each indicator, an interpretation section is provided to indicate the significance of being inside or outside the reference range. A traffic-light evaluation is provided to assist with interpretation to indicate the type of management response that may be appropriate.
- We were not able to develop reference ranges with existing information that explicitly links the indicators to environmental outcomes such as water quality and greenhouse gas emissions due to a lack of data. This is largely because (i) there are multiple factors influencing environmental outcomes beyond soil-based reference values and (ii) there is a limit to the extent to which individual soil quality indicators influence some environmental outcomes. For example, in the context of SoE monitoring, total nitrogen, AMN and HWEC as indicators of soil N availability are limited in their use for addressing nitrogen-related water quality or greenhouse gas emission, which are most dominated by nitrogen inputs. Further, the processes involved (e.g. plant-uptake of nitrogen, microbial nitrogen-cycling, drainage of water) affect the supply of mineral N and its loss from the soil environment. In contrast, for Olsen P it is conceivable that modelling approaches, assuming generalised transport pathways, could be used to provide a quantitative basis for setting reference values that provide protection for water quality. However, targeted research is required to develop the appropriate modelling approach and provide additional underpinning data, if needed.

- There are surprisingly few studies that attempt to quantitatively link or track the benefits of increased organic matter, such as increased water-holding capacity, improved structure, and nutrient cycling. It is generally recognised that increasing organic matter will increase biological activity, although defining a minimum or optimal level of activity remains largely subjective.
- While there is an enhanced understanding of the processes influencing the effects arising from reduced macroporosity, few studies provide a quantitative assessment of impact on outcomes including pasture production, greenhouse gas emissions, drainage, and nitrate leaching.
- With few publicly available studies on soil quality in perennial horticulture, confidence in distribution-based criteria is lower. Critical gaps in our quantitative understanding of the relationship between measured soil quality indicators and soil functions remain across soil orders and land uses in New Zealand.
- There are tangible alternatives requiring further evaluation for developing target ranges for some indicators. They include the potential use of soil mineral surface area-based carbon saturation deficits or carbon loading for total carbon, and the use of indigenous vegetation sites as reference sites for most indicators excluding pH and Olsen P. However, it is likely that the number of suitable reference sites providing the relevant combination of vegetation type, climate, and soil is limited.
- The key soil quality issues today are the same as those identified in the early 2000s: low soil carbon in cropping soils, elevated Olsen P in some agricultural soils, and soil compaction, particularly in pastoral and cropping systems. This suggests that the objective of the SoE monitoring programme being an early warning system – as currently stated in the NEMS-SQ – should be revisited. It also raises a question about what the relative investment in research should be to develop and link soil quality targets more robustly linked to environmental outcomes, versus investment to achieve improvement in soil quality based on a more qualitative understanding of relationships. The latter includes investment both to demonstrate the extent to which land management practices can achieve that improvement, and to encourage adoption of those practices on-farm or on-site (i.e. extension activities).

Recommendations

There are various recommendations arising are made as a result of the work undertaken in this project. At the highest level it is recommended that clearer national direction on the management of soils be developed. This will provide the opportunity for SoE monitoring to be used more effectively to achieve improvements in soil quality that result in positive environmental outcomes. Such direction should include the following:

- The SoE soil quality programme should be reviewed at a national level to identify gaps in geospatial, soil type and land use representation and to assess whether the current indicators are fit-for-purpose.
- Central and local government agencies should work more closely with primary sector industry groups to provide greater connection between the objectives of SoE soil quality monitoring and the sustainable land management goals of the sectors. This work should include:

- completing a stocktake and evaluate the efficacy of management practices that (i) maintain or improve soil C and (ii) 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 to provide specific case studies for the evaluation of soil properties under best-practice management, and to help develop models to connect soil properties at a farm-scale with broader production and environmental outcomes
- identifying alternative soil quality indicators that may be more linked to production or the environment
- 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.
- Specific recommendations in relation to the proposed reference ranges, are that:
 - the potential for saturation deficit or C loading based on soil mineral surface area to provide a basis for developing target values for soil C is evaluated, alongside further evaluation of the suitability of the low-end 2% for soil C under cropping, particularly for Granular soils
 - the reference macroporosity and bulk density data set is extended through targeted sampling as part of future SoE monitoring programmes to provide more robust reference ranges for these indicators – this could include sampling from less or not compacted areas such as under-fence lines for pastoral and cropping sites, and forestry sites at the end of rotation or after 20-plus years that show no visible past erosion
 - a stocktake and quality assessment of existing indigenous vegetation and urban monitoring sites is undertaken and the purpose of monitoring (e.g. to assess state or as reference sites) confirmed alongside an evaluation of the feasibility of using indigenous vegetation sites as reference sites for other land uses (e.g. as currently suggested in the NEMS-SQ)
 - the benefits and trade-offs associated with the ongoing use of gravimetric basis for reporting on Olsen P reference ranges for SoE reporting be evaluated, given the current reporting of Olsen P results on a volumetric rather than gravimetric basis by many NZ laboratories – this could be undertaken through the development of a background discussion paper and stakeholder workshops
 - the requirements for developing modelling approaches (including any additional underpinning data) for Olsen P criteria based on water quality impacts are scoped.

1 Introduction

Soil quality indicators have been used in state of the environment (SOE) reporting for the past 25+ years and cover several soil characteristics important in the assessment of agronomic performance and environmental outcomes (e.g. macroporosity, Olsen P). Provisional target ranges for soil quality indicators were first published by Sparling et al. (2008). Although the target ranges have been reviewed and revised (e.g. Mackay et al. 2013), a substantial amount of additional soil monitoring, reporting, and research has been undertaken since these provisional target ranges were set. This provides an opportunity for any gains in knowledge and understanding of the factors affecting soils to be incorporated into revised target ranges.

During a previous review of the development of the current target ranges it became clear that there was no definitive source for the current (including revised) target ranges, and that sometimes the reason for changes in specific target values was unclear (Cavanagh et al. 2023). Therefore, providing clarity on the basis on which revised soil quality indicator numeric ranges are derived will provide greater robustness in reporting on the state of New Zealand's soils.

A comprehensive review and revision of soil quality indicator target ranges is a priority for the Land Monitoring Forum (LMF). As a Regional Sector Special Interest Group, the LMF represents professional and technical experts in land and soil science, research, monitoring, and input into policy development from all regional councils and unitary authorities.

The Ministry for the Environment contracted Manaaki Whenua – Landcare Research (MWLR) to lead a collaborative project with AgResearch, Plant & Food Research, and Scion to review and revise the current soil quality target ranges for all seven soil quality indicators, and hot-water-extractable carbon (HWEC). This revision considered the research and data that have become available since soil quality target ranges were established, with a focus on links to environmental outcomes.

2 Objective

The objective is to develop updated 'target ranges' for the seven soil quality indicators used in SoE reporting listed below, and HWEC, which is an indicator of the labile soil carbon pool and has been proposed to replace the anaerobically mineralisable nitrogen (AMN) indicator. The seven soil quality indicators are:

- pH (a measure of acidity)
- Olsen phosphorus (henceforth Olsen P, a measure of fertility)
- total carbon (total C, a measure of organic carbon reserves)
- total nitrogen (total N, a measure of organic nitrogen reserves)
- anaerobically mineralisable nitrogen (AMN, a measure of labile organic nitrogen reserves)
- macroporosity (a measure of physical status)
- bulk density (a measure of physical status)
- plus hot-water extractable carbon (HWEC, a measure of organic reserves).

3 Approach

3.1 Overview

The following approach was used to review and revise soil quality indicator target ranges:

- a targeted literature review and stocktake of available data to inform revision
- collation and exploratory analysis of the data to develop revised numeric criteria
- project team and stakeholder workshops to share initial findings, discuss the purpose and use of soil quality target ranges, explore approaches for revising numeric criteria, and provide feedback on the revised numeric criteria
- refinement of revised numeric criteria (which we will call 'reference ranges')
- identification of areas for future focus.

In this report we use the term 'target ranges' to explicitly refer to the existing soil quality indicator target ranges presented in Sparling et al. 2008 and LMF 2009, with updates included in Mackay et al. 2013. We use the term 'numeric criteria' to refer generally to numeric ranges used for soil quality monitoring. Finally, we use the term 'reference ranges' to refer to the revised numeric criteria developed through this project.

3.2 Targeted literature review and data stocktake

A targeted literature review and stocktake of associated data in New Zealand and international publications was undertaken. This used web-based searching, key-word searches of bibliographic databases (CAB database for cropping references), collation of New Zealand studies and data sources provided in Cavanagh et al. 2023, primary industry guidance, and discussions with colleagues to identify relevant journal publications, grey literature, and unpublished data sets. Specifically, the targeted review drew on the sector-specific expertise of researchers from the individual research organisations to rapidly identify relevant studies and information rather than being a systematic comprehensive literature review.

Specific emphasis was given to identifying studies that related soil quality indicators to environmental outcomes, including soil function, water quality, and greenhouse gas emissions, and that were broadly applicable. Studies linking indicators to primary production (e.g. yield/growth), and those that provided an extensive data set about the state of the environment, were also captured. Soil data sets reporting results for 0–10 cm depth (the depth required for SoE monitoring) that were already published, or were readily accessible, were specifically targeted for inclusion in the review and data stocktake. For forestry, data sets were selected from planted forests that had been established for ≥ 20 years. This was based on the assumption that soil properties are more likely to be representative of the planted forest land use rather than the land use prior to afforestation (allowing for change in soil properties with afforestation). Data sets associated with cross-sectoral monitoring programmes, such as SoE monitoring, and the National Soil Carbon monitoring programme for agricultural soils, were also targeted.

For each sector (pastoral; arable, vegetable and perennial horticulture; forestry) and for a cross-sectoral overview, a matrix was used to summarise the availability of data (number of studies) for each soil quality indicator for several outcomes:

- water quantity
- water quality (N, P, sediment, *E. coli*)
- pest and disease regulation
- greenhouse gas (GHG) emissions (carbon dioxide, nitrous oxide, methane, etc.)
- soil biodiversity
- production (pasture/crop yield)
- an extensive data set (typically a monitoring data set).

Metadata associated with identified extensive data sets were captured in a spreadsheet and used to help select data sets for use in subsequent analysis (see Appendix 5).

3.3 Volumetric and gravimetric Olsen P conversions

In New Zealand, soil Olsen P analysis is undertaken by two methods. Both are based on the original Olsen P test (Olsen et al. 1954), but one method is based on the analysis of a known *mass* of soil (gravimetric method), while the other 'modified' method is based on the analysis of a known *volume* of soil (volumetric method). Questions about the implications of the use of these different methods for SoE reporting have been raised since 2013 (Drewry et al. 2013; Mackay et al. 2013). Section 5 provides an overview of the approaches used to convert between volumetric and gravimetric measures of Olsen P.

3.4 Data exploration for the development of revised numeric criteria

3.4.1 Logic assessment

An overview of current understanding of the key factors that influence environmental and production outcomes associated with each indicator, and how these may vary under different land uses, was captured diagrammatically to provide a 'logic assessment' of the development of numeric criteria. These logic assessments helped capture information collated through literature scan and data identification for discussions during a project team workshop and initial stakeholder workshops to inform revision of the numeric criteria.

Land-use categories considered for individual indicators differed depending on land management activities that may influence those indicators (e.g. fertiliser and lime application for different crop species). The full set of land-use categories is shown in Table 1; land-use categories were merged where land use was not considered to be a key differentiating factor.

Table 1. Land-use categories evaluated to assess their influence on indicator values

Land-use category for logic assessment	Commentary
Pastoral	Dairy and drystock are grouped together under pastoral land use, which includes systems that use forage crop or other crop rotations alongside pasture rotations. Different management intensities occur, particularly across drystock systems, which will influence the measured values of some soil properties. For data analysis and assessment of typical values, dairy and drystock were separated out to evaluate differences associated with these different land-use categories.
Arable and mixed cropping	This group is a continuum, with fully arable (grain) systems at one end and mixed cropping (including pasture and livestock grazing and vegetable rotations) at the other.
Continuous vegetable cropping	This is conceptually separated out from other short-rotation cropping, because it is anticipated to have more frequent cultivation / soil disturbance than arable and mixed cropping systems.
Perennial horticulture	With the exception of vineyards, management practices (fertiliser and pesticide application, irrigation) to optimise yield were considered to be sufficiently broadly similar across different crops (e.g. apples, kiwifruit, stone fruit) to be included within the one group.
Exotic forestry	Land management for forestry is markedly different from other managed land uses. Transition from other land use (e.g. pastoral land use) may occur, and will influence measured soil properties.
Urban greenspace / parks	Land management for urban greenspace and parks is markedly different from other land uses. Consideration of the history (e.g. retained indigenous vegetation vs closed-landfill site) and current use (e.g. botanic gardens vs sports-field) of the site is necessary to assess measured soil properties.
Vineyards	Vineyards are proposed as a separate category from perennial horticulture given they often have markedly different soil types and nutrient requirements from other horticultural crops, and transition from other land use (e.g. pastoral land use) may occur.
Indigenous vegetation	This category is potentially useful for providing baseline reference values. The history of the site (e.g. undisturbed native forest remnant vs restoration planting) along with potential influence from adjacent land uses (e.g. fertiliser drift) should be considered.

Note: Categories were considered individually or grouped for individual indicators depending on how the land management practices could influence their measured value.

3.4.2 Analyses of extensive monitoring data

To provide context for the significance of variation of land-use and New Zealand Soil Classification (NZSC) soil order (Hewitt 2010) on measured values of the indicators, an analysis of existing monitoring data collated from multiple sources was undertaken. Considerations borne in mind in selecting data sets were:

- the results were from soils collected from 0 to 10 cm depth
- they contributed to the representation of regional distribution of land use across New Zealand
- the data set was readily accessible.

The specific data sets that comprise the 'baseline monitoring data set' are:

- the StatsNZ Soil Quality and Land Use environmental indicator for SoE reporting, as reported on in *Our Land 2021* (MfE & StatsNZ 2021) (1059 sites collated from 12

regional/unitary councils, all core parameters excluding HWEC; excludes data for Gisborne District Council and Otago Regional Council)

- Gisborne District council soil quality SoE data (37 sites; all core indicators plus HWEC)
- Otago Regional Council soil quality SoE data (72 sites; all core indicators plus HWEC)
- HWEC data collation (four councils, collated by Waikato Regional Council)
- National Soil Carbon Monitoring data set (440 sites; includes total C, total N, pH, Olsen P, and bulk density, but excludes macroporosity, AMN, and HWEC)
- forestry data set (FR380-data set, 33 sites (Garrett, Watt et al. 2022; total C, total N, Olsen P, pH, macroporosity, and bulk density).

A summary of the number of sites for which data are available for each indicator and land-use combination in the monitoring data set is provided in Table 2, with each indicator and soil order combination shown in Table 3, and the regional distribution shown in Appendix 1. This data set is considered to be as representative of regional distribution of land use across New Zealand as was feasible to collate within the constraints of the project.

The number of results, range, and 10th and 90th percentiles of indicators (pH, total C, C:N, total N, AMN, HWEC, macroporosity, bulk density) were determined for this data set. The choice of the 10th and 90th percentiles was based on the work of Feeney et al. (2023), who used these values to define 'typical' values; this choice was recognised to be arbitrary but similar to other studies (e.g. Drexler et al. 2022; Griffiths et al. 2018). The 10% of values either side were considered to be 'above typical' and 'below typical', respectively.

After the logic assessment and workshop with the project team, some indicators were regrouped to combine soil orders or selected land uses to provide a refined assessment that may be useful for establishing numeric criteria based on typical ranges.

Table 2. Number of sites for which data are available for each indicator and land-use combination in the monitoring data set

Indicator	Cropping	Dairy	Drystock	Exotic forestry	Indigenous vegetation	Lifestyle	Orchard	Urban park / reserve	Vineyard	Total
pH	207	336	508	156	130	17	180	50	46	1,630
Olsen P	209	336	509	156	130	17	180	36	46	1,619
Total C	210	336	510	156	131	17	181	50	46	1,637
Total N	210	336	510	156	131	17	180	50	46	1,636
CN	209	336	510	156	131	17	180	50	46	1,635
AMN	123	214	359	118	126	17	78	36	46	1,117
HWEC	233	145	154	31	39	0	23	0	12	637
Macroporosity	117	191	322	137	116	17	71	36	44	1,051
Bulk density	209	335	506	154	131	17	179	50	45	1,626

Table 3. Number of sites for which data are available for each indicator and soil order combination in the monitoring data set

Indicator	Allophanic	Anthropic	Brown	Gley	Granular	Melanic	Organic	Oxidic	Pallic	Podzol	Pumice	Raw	Recent	Semiarid	Ultic	Total
pH	242	21	396	181	65	12	22	7	206	17	98	4	275	12	72	1,630
Olsen P	240	16	396	183	62	12	22	4	210	17	98	4	275	12	68	1,619
Total C	242	21	392	183	65	12	22	7	211	17	98	6	276	12	73	1,637
Total N	242	21	392	183	65	12	22	7	211	17	98	6	275	12	73	1,636
CN	242	21	392	183	65	12	22	7	211	17	98	6	274	12	73	1,635
AMN	152	14	270	121	43	10	22	3	127	10	80	3	200	7	55	1,117
HWEC	61	0	126	78	17	5	5	0	212	5	37	0	86	1	4	637
Macroporosity	126	14	237	114	43	10	22	3	123	14	82	4	195	7	57	1,051
Bulk density	242	21	387	182	65	12	22	7	209	17	97	6	275	12	72	1,626

3.4.3 Data handling

SoE data set

Vineyards were not specified as a land use in this baseline monitoring data set, so we identified them based on values in the columns labelled 'landuse_generic', 'landuse_specific' and 'landUse_note'. If any of these columns contained any of the words 'vineyard', 'grapes', 'wine', 'viticulture' or 'vine planted', the land use for that site is specified as 'vineyard'. Remaining sites listed as 'orchard/vineyard' that did not contain any of these words were allocated to the 'orchard' land use. The same was attempted for continuous vegetable sites, but there were low numbers of sites that could be identified in this land use so they were left as part of the 'cropping' land use.

National Soil Carbon Monitoring

In the NSCM data set, sites with stony soils were sampled using two pits (Hedley et al. 2012), which had separate measurements. The average value for each site was taken in these cases. Olsen P data were also supplied in volumetric form, so these were converted to gravimetric values using the volume weight supplied by the lab. These steps were done before importing the data into R. The NSCM data import was straightforward. Land uses listed as 'cropping' and 'dairy' were kept as is, while 'hill-country drystock' and 'flat-rolling drystock' were allocated to 'drystock', and 'horticulture' was allocated to the 'orchard' land use.

Hot-water-extractable carbon data

HWEC data from four regional councils (Waikato, Greater Wellington, Marlborough, and Canterbury), collected over 2007–2021, were provided by Waikato Regional Council. These were combined with additional data from Gisborne and Otago and used to indicate the range in HWEC results from the 0–10 cm depth. This data set also included AMN, total C, and some total N measurements, and the relationships between these variables was plotted. The HWEC data from Otago, Waikato, and Gisborne regional councils were combined with the additional data supplied by Waikato Regional Council. Where multiple years of data existed for the same site, the most recent were used. Some of the Marlborough data contained three measurements for a single site; here the average value was taken.

Summary statistics

The data were summarised for each soil order and land-use combination. The number of observations, mean, range, and 10th and 90th percentiles were collated. The means, standard deviations, and coefficients of variation for each indicator were calculated for land uses and soil orders to provide an indication of the variation across the soil order or land-use groups. A high variation can help to inform the groupings (e.g. whether soil order or land use was a significant influence on measured values of the properties).

Soil order differences

Exploratory analysis of soil order differences was undertaken for each indicator in R version 4.3.2 (R Core Team 2023). Significant differences between soil orders were tested for while controlling for

the effect of land use. A linear mixed effects regression (lmer) was run, with soil order specified as a fixed effect and land use as a random effect using the lme4 package (Bates et al. 2015). Response variables (i.e. the indicator values) were log transformed where this yielded a more normal distribution. ANOVA was run on the lmer for each indicator, and in all cases (except HWE) this showed that significant differences were detected between soil orders. Pairwise comparisons between each soil order combination were then run using the emmeans function (Lenth 2023) with a tukey p-adjustment for multiple comparisons. These results are shown in Appendix 2. The resulting p-values for each soil order combination were compiled into a matrix for each indicator (excluding HWE).

This information was used to provide the soil groupings used to present the soil C, total N, and AMN for each land use.

3.4.4 Specific data set analyses

From the data stocktake, analyses were undertaken on selected data sets that were identified as having potential value to inform the development of revised numeric criteria. These data sets were as follows.

- *The fluxmeter data set provided by Ministry for the Environment (MfE).* This data set includes soil properties, along with data on nutrient drainage from the fluxmeter study of Norris et al. (2018, 2023). The fluxmeter study is based on a network of passive-wick tension fluxmeters (at 100 cm depth) that were established on 12 commercial cropping farms (arable and vegetable) in the Canterbury, Manawatū, Hawke's Bay, Waikato, and Auckland regions in July 2014. This network quantified N and P leaching losses in drainage water below the crop root zone. Soil measurements include multiple soil orders and all eight soil quality indicators (except HWE), measured at 20 cm intervals, with data held by MfE. This data set was used to evaluate the potential use of soil properties to indicate nutrient leaching potential under vegetable cropping sites.
- *Under fenceline/untreated data set.* This small data set was compiled mainly from an Auckland Council study reported in Curran-Cournane et al. 2013, which included measurement of macroporosity (at -5 kPa and -10 kPa) and bulk density (plus additional parameters), along with additional data sourced from individual studies (Singleton et al. 2000; Drewry et al. 1999; Drewry & Paton 2000; Mackay et al. 2010). This data set includes measurements of soil samples taken from pasture sites and under adjacent/ungrazed fencelines or untreated sites. The under fenceline/untreated data were used to identify the distribution of macroporosity (-10 kPa) and bulk density results for different soil orders.
- *FR380 trial series data set.* This published data set covers 35 sites in New Zealand, including two pastoral land-use sites (pre-afforestation) (Garrett, Watt et al. 2022), with additional site information provided in Watt et al. 2008. The data set includes samples from undisturbed plots, which were located in areas that had no previous compaction from the recent harvesting operations, and from plots that showed disturbance from harvesting operations. Data from undisturbed forestry treatments were used to determine the distribution of macroporosity (-10 kPa) and bulk density results for different soil orders.

Hot-water-extractable carbon

HWEC has been proposed as a potential indicator of readily biodegradable (mineralisable) soil organic matter and, more specifically, the potential of a soil to supply (i.e. release via mineralisation) N for crop uptake (henceforth potentially mineralisable N, PMN). We investigated the potential to use HWEC as an indicator of PMN and its possible application to predicting soil N supply in agricultural production systems. Firstly, statistical analyses were undertaken to calibrate HWEC for predicting PMN, and then to apply that sites data captured in the Land Management Index (LMI) data set held by Plant & Food Research (see section 4.3.2 for a description).

For the calibration of HWEC to predict PMN, data from Curtin et al. 2017 were combined with results from more recent studies, and linear regression analysis carried out to identify the best-fit model. The calibration data set included measurements from approximately 225 sites representing Allophanic, Brown, Gley, Granular, Pallic and Recent soils obtained from arable and vegetable cropping and dairy and drystock pasture paddocks across six agricultural regions of New Zealand (Canterbury, Southland, Auckland, Waikato, Hawke's Bay, and Gisborne). These data included HWEC, determined as described by Curtin et al. (2006) and Ghani et al. (2003), with a cold-water extraction step preceding hot-water extraction and analysis of carbon, and PMN measured as the net N mineralised in a 14-week (98-day) aerobic incubation. This model was then applied to sites in the LMI data set to predict PMN from the HWEC values.

Predictions of in-field N mineralisation were also made to illustrate the influence of field conditions, such as soil temperature and water content, which can vary regionally depending on climate and whether irrigation is applied to the production system. These predictions were made by applying the methods described by Beare et al. (2023). Briefly, bulk density data were used to express PMN in kg N/ha, with the daily N mineralisation potential calculated as the amount of N mineralised during the 14-week (98 days) aerobic incubation, divided by 98 and expressed as kg N/ha/day. Soil temperature and water content scaling factors can then be applied in the following equation to predict in-field N mineralisation:

$$\text{In-field N mineralisation} = \sum_{j=1}^n (\text{Average daily PMN} \times St_j \times Sw_j) \quad (1)$$

where n is the number of days in the growing season, and St and Sw are scaling factors calculated from the daily average soil temperature and water content, respectively (see Beare et al. 2023 for more detail). We used 20-year average climate data obtained from the Southland, Tasman and Waikato regions to provide in-field N mineralisation predictions.

3.5 Development of reference ranges

During our evaluation of potential options for updating the existing target ranges we identified that, based on current understanding and data, different approaches were required for the individual indicators. Further, there was often not a robust, scientific basis on which to provide values to 'aim' for (i.e. targets). Given that these numeric criteria are primarily being *referred to* in order to provide context for individual sampling results, the term 'reference ranges' is introduced to provide a single term for numeric criteria developed for each indicator using different quantitative approaches.

To help revise the target ranges, project team and stakeholder workshops were also held. These included:

- a stakeholder workshop in August 2024
- a project team workshop in October 2024
- Regional Council Land Monitoring Forum meetings in November 2024 and March 2025
- a stakeholder workshop in November 2024.

An initial virtual workshop was held in August 2024 with a wide range of stakeholders, including representatives from the primary sector (Fertiliser Association of New Zealand, DairyNZ, Forest Owners Association, forestry companies) and central and local government (Regional Council Land Monitoring Forum, consent/compliance staff), MfE, Ministry for Primary Industries, and StatsNZ). This workshop provided an introduction to a wider stakeholder group to the project and the initial literature review, and sought stakeholders' initial views on updating the existing soil quality target ranges, including potentially available data.

The workshop also included a survey to answer the following questions:

- What sector or industry do you represent?
- Have you used the SoE soil quality indicator target ranges?
- How have you used one or more of the SoE target ranges?
- Which target ranges might require the greatest revision (from an environmental perspective)?

A summary of the workshop, including the responses to these questions, is provided in Appendix 3.

Following initial data exploration, a project team workshop was held to work through preferred approaches to developing reference ranges. Further data analysis and development of preliminary reference ranges were undertaken, and the results were presented at the Regional Council Land Monitoring Forum in early November 2024 for comment. Further feedback was sought through a second stakeholder workshop (with the same attendees as the August workshop) in mid-November 2024. Following these workshops the concept of using a traffic light system to assist with interpretation of reference ranges was included.

Details of the approaches used to develop the reference ranges for the individual indicators is outlined in section 7.

3.6 Areas of future focus

Following the analyses described in the preceding sections of this report, MfE staff requested that the following aspects be explicitly considered in the context of the future use of SoE soil quality monitoring:

- Clearly and concisely state why you were not able to revise the soil quality target/optimal ranges against environmental considerations, as intended, highlighting the limitations of the existing data and what research/data would be required to enable such a revision in 5–10-plus years from now.

- Clearly state if setting target ranges against environmental outcomes is achievable, and if not, please clearly and concisely state the value of the SoE soil quality monitoring programme, regardless of the lack of reporting against environmental outcomes.
- Provide options for detecting meaningful changes in soil quality at a national level. This could also consider how regional and community catchment efforts to achieve improved soil quality outcomes could be aggregated or translated to gain a national picture.

This discussion focuses on the factors influencing the development of numeric criteria for the indicators covered in this report. It does not include detailed discussion on additional indicators, nor the use or implementation of this information, which is covered in a parallel Envirolink Tools project ('Improving soil health through improved efficacy of implementing soil quality indicators').

4 Literature review

4.1 Purpose of soil quality indicators

The purpose of monitoring using the core soil quality indicators, as specified in the National Environmental Monitoring Standard for Soil Quality and Trace Element Monitoring (NEMS-SQ, 2022) is shown in Table 4; note that HWEC has been proposed as a replacement for AMN (Mackay et al. 2013).

Table 4. Description of soil quality indicators, and the reason for monitoring, as specified in the National Environmental Monitoring Standard for Soil Quality and Trace Element Monitoring

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 help soil store and supply moisture and nutrients, and improve water movement and root growth.
	Total nitrogen	Organic nitrogen status	Nitrogen (N) is an essential nutrient for plants and animals. 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 phosphorus	Plant-available phosphorus	Phosphorus (P) is an essential nutrient for plants and animals. Plants get their P from phosphates in soil. 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.

Soil quality indicators		Information provided by indicator	Why is the measure important?
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 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 and water 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.

* Hot-water-extractable carbon (HWEC) has been proposed as a replacement for AMN; both measures correlate with microbial biomass (Sparling et al. 2003; Curtin et al. 2017).

4.2 Current use of soil quality indicator target ranges

The primary use of the target ranges for the specified soil quality indicators is for national soil quality reporting (e.g. MfE and StatsNZ's *Our Land 2018*, *Our Land 2021*, and *Our Land 2024*) and many regional monitoring programmes (e.g. Chibnall & Curran-Cournane 2015; Norris 2018; Oliver 2023; Taylor, Cox, Littler, Drewry 2017; Thompson-Morrison 2024). For these purposes, the primary discussion focuses on reporting how many sites fall outside the target range (e.g. MfE & StatsNZ 2018, 2022), with some trend analysis also undertaken (e.g. Drewry, Cavanagh et al. 2021; Stevenson & McNeill 2020; Curran-Cournane 2020). A review of the SoE monitoring programme undertaken in 2017 highlighted various inconsistencies in the way councils collect and report soil quality data, including site stratification groupings, soil quality indicators measured, indicator target ranges used for comparison, as well sampling depth and design (Cavanagh et al. 2017).

In addition to regional and national SoE reporting and journal publications, participants in the August 2024 stakeholder workshop indicated that indicators were used for consenting and compliance purposes, some on-farm quality assurance, as well as other soil quality assessments (see Appendix 1 for more detail).

In contrast, for agricultural land managers, numerous handbooks provide guidance on fertiliser and lime application based on plant requirements for optimal agronomic production and in response to measured soil properties (e.g. Roberts & Morton 2023; Morton & Roberts 2024; Morton 2019, 2020; Nicholls et al. 2012; Reid & Morton 2019). Lime or phosphorus fertiliser addition is based on soil pH and Olsen P, respectively, while measures other than soil total N have been used to determine N requirements (e.g. Reid & Morton 2019). AMN has been used to indicate N-fertiliser requirements in some guidance (e.g. Reid & Morton 2019), although rapid measures of PMN are increasingly being used to inform N-fertiliser application (e.g. Beare et al. 2023).

Foliar measurements may be more commonly used in horticultural crops to determine nutrient application, including for trace elements such as copper. The plantation forestry industry uses foliar measurements to identify nutrient deficiencies (see Davis et al. 2015), although the amount of fertiliser applied is small compared to other land uses (Smaill & Clinton 2016). Research is

underway to improve the use of soil properties to better predict tree response to fertiliser application (e.g. Garrett, Lin et al. 2022; Smaill et al. 2023).

Falling outside the range is generally considered to be 'bad' because it may limit production and/or pose a risk of negative impacts on the environment, and therefore be a trigger for action to be taken to improve soil quality to fall within the range. While some councils may provide information to the landowner informing them of poor soil quality and options for improvement, this is not consistent across councils (Cavanagh et al. 2017).

Cavanagh and Gordon (2023) observed that there was no clear statement on what actions (e.g. policy response, land management response) are intended to be taken if soil quality is observed to deteriorate (e.g. falls outside target ranges) within the objectives for soil quality monitoring specified in LMF 2009 or the NEMS-SQ (2022). It is, therefore, perhaps unsurprising that the key issues reported currently, namely organic matter depletion (i.e. low soil C), nutrient excess (Olsen P), and structural decline (as assessed by macroporosity) (MfE & Stats NZ 2022), are the same issues identified at the commencement of soil quality monitoring programmes in the early 2000s; specifically, structural decline and nutrient excess particularly under dairy but also under intensive beef rearing, horticulture, forestry, and deer farming, and organic matter depletion in cropping soils (Sparling et al. 2001b).

4.3 Existing soil quality indicator target ranges

A detailed review of the numeric basis for the existing seven soil quality indicator target ranges is reported by Cavanagh et al. (2023). Briefly, the original soil quality target ranges were established in the early 2000s to assist with interpreting the results of the newly established national and regional soil quality monitoring programmes (Lilburne et al. 2004; Sparling et al. 2003). The original programme, initiated and funded by MfE and commonly referred to as the 500 Soils project, collected soil quality data from approximately 500 sites across New Zealand (Sparling et al. 2000, 2001a,b). This programme built on an earlier Sustainable Management Fund Project 'Trialling soil quality indicators for land' (Sparling et al. 1996, 1997, 1998), which helped to identify the indicators used for further monitoring.

The target ranges were primarily developed through two expert workshops. The first workshop (in February 2000) involved 24 New Zealand soil scientists, and this was followed by a workshop comprising a sub-group of the original panel. An expert opinion approach was used, with individual scientists encouraged to draw response curves using (a) production considerations, and (b) environmental considerations. These response curves were evaluated in the first workshop, and then by the sub-group, who also established the provisional target value ranges for seven key soil properties: soil pH, Olsen P, total C, total N, AMN, macroporosity, and bulk density. There were limited environmental data to inform the development of provisional target ranges.

When developing target ranges, consideration was given to the extent to which soil order and land use may influence them. A summary of soil order and land-use categories, originally used for developing target ranges, is shown in Table 5. An approximation of the area of primary production on different soil orders is presented in Table 66. This was determined using a combination of land-cover information from the Land Cover Database version 5 (LCDB5) and soil order information from S-map; where S-map information does not exist, we used the Fundamental Soil Layers from the Land Resource Inventory System. Summary statistics were then calculated for the area of each

unique combination of soil order and land-cover class, based on the following combination of LCDB cover classes:

- pastoral – high producing exotic grassland
- pastoral – low producing and depleted grassland
- perennial horticulture – orchard, vineyard or other perennial crop
- short-rotation cropping – short-rotation cropland
- forestry – exotic and harvested forestry.

These areas are an approximation only, because land-cover information relates to a varying extent to primary production uses, particularly for pastoral land. Specifically, while high-producing grassland almost certainly represents primary production use, not all low-producing and depleted grassland will be under primary production.

Table 5. Soil order and land-use categories used in the original development of target ranges

Soil property	Soil orders	Land-use categories
Soil pH	All soils except Organic	Pastures Cropping and horticulture Forestry
	Organic	Pastures Cropping and horticulture Forestry on organic soils (excluded)
Organic carbon	Allophanic Semi-arid, Pumice, and Recent All other soil orders Organic (excluded)	All land uses (i.e. specific land uses not stated)
Total nitrogen	Applicable to all soil orders	Pasture Forestry Cropping and horticulture (excluded)
Anaerobically mineralisable nitrogen	Applicable to all soil orders	Pasture Forestry Cropping and horticulture (target ranges are poorly defined)
Olsen P (phosphorus)	Sedimentary, Pumice, Allophanic, Organic	Pasture, cropping and horticulture Forestry (for all soils)
	[Volcanic Sedimentary and Organic soils Raw sands and Podzols with low, medium and above AEC ^a Other soils Hill country All soils] ^b	Pasture, cropping and horticulture Forestry (for all soils)
Bulk density	Semi-arid, Pallic, and Recent soils Allophanic soils Organic soils Pumice and Podzols ^c All soil orders	All land uses (i.e. specific land uses not stated). (Target ranges for cropping and horticulture are poorly defined.)
Macroporosity	All soil orders (i.e. specific soil orders not stated)	Pastures, cropping and horticulture. (Target ranges for cropping and horticulture are poorly defined.) Forestry

Source: Sparling et al. 2008

^a AEC = anion exchange capacity.

^b Summarised from Cavanagh et al. 2023, which includes criteria for AEC (anion exchange capacity) and hill country, in addition to a wider range of soil orders.

^c Bulk density values excluded from LMF 2009 and Cavanagh et al. 2023.

Table 6. Area of land (ha) of each New Zealand Soil Classification soil order under each land-cover class from LCDB5

NZSC soil order	High producing exotic grassland	Low producing & depleted grassland	Short-rotation cropland	Orchard, vineyard or other perennial crop	Exotic & harvested forest	Total area
Allophanic	1,043,763	23,970	10,578	15,218	148,544	1,242,073
Anthropic	5,803	1,120	155	78	1,468	8,624
Brown	2,706,455	913,277	60,583	16,596	744,768	444,1679
Gley	735,156	17,688	54,051	11,939	23,159	841,993
Granular	132,484	2,550	8,763	1,629	23,812	169,238
Melanic	205,404	35,173	6,096	693	18,519	265,885
Organic	122,561	3,520	5,537	1,018	3,997	136,633
Oxidic	30,909	207	286	2,024	2,907	36,333
Pallic	1,552,258	372,980	15,7364	15,280	133,786	2,231,668
Podzol	199,280	33,149	342	298	112,114	345,183
Pumice	513,128	18,804	5,695	6,579	397,745	941,951
Raw	65,453	31,774	2,554	1,208	40,215	141,204
Recent	888,769	348,137	54,274	25,741	27,8455	1,595,376
Semiarid	87,068	91,409	1,907	4,029	1,239	185,652
Ultic	378,212	6,726	308	2,470	10,4974	492,690
Total area	8,666,703	1,900,484	368,493	104,800	2,035,702	13,076,182

The 'provisional' target ranges reported in Sparling et al. 2008, with some subsequent modifications, were incorporated into the Regional Council Land Monitoring Forum guidance for soil quality monitoring (LMF 2009) as the basis for regional SoE reporting. Further evaluation and refinement of the target ranges and consideration of additional indicators were discussed at an LMF meeting in May 2011, with recommended actions agreed at a meeting that September. The details of these meetings, including meeting notes and briefing papers, were incorporated into a report from an Envirolink Tools project, 'Soil quality indicators: the next generation' (Mackay et al. 2013). Cavanagh et al. (2023) noted that there was no definitive source for the 'most-recent' target ranges, so it is not surprising that during a review of SoE soil quality monitoring it was revealed that different sources (and hence values) for target ranges were used by different councils (Cavanagh et al. 2017).

Cavanagh et al. (2023) also noted that the target ranges for many of the indicators were quite broad, most often ranging between the low/very low and high/very high ends of the range specified in Sparling et al. 2008, rather than a more narrowly defined 'optimal' range. Target ranges were predominantly based on production outcomes, with limited data to underpin environmental outcomes.

4.3.1 Current soil quality target ranges

Cavanagh et al. (2023) collated what appear to be the final 'agreed' ranges for the individual target ranges (Tables 7, 9–14). These values are similar, but not identical, to those used for national reporting by MfE and StatsNZ (Table 15). The latter were provided by Stevenson et al. (2020) as part of the collation of regional council data for national SoE reporting for *Our Land 2021*. Specifically, the full set of target ranges (i.e. for the full range of soil orders and land uses that were captured in the collated soil quality data) was contained in an accompanying R-markdown file provided to MfE and StatsNZ. The primary difference compared to the 'agreed' target ranges reported by Cavanagh et al. (2023) is the greater number of soil orders to which target ranges were applied (which relates to the range of soil orders covered in the monitored sites).

During the current project it was also identified that incorrect measurement units have been used for Olsen P target ranges for SoE reporting. Specifically, target ranges that were considered to be based on gravimetric measures of Olsen P (i.e. mg/kg) are actually based on laboratory volumetric measures (i.e. mg/L). This issue was most evident with the proposed change in Olsen P target ranges at the May 2011 workshop of the Land Monitoring Forum, at which it was proposed that the upper values of the target ranges be changed to be similar to agricultural and fertiliser industry values. A record of the workshop discussions (section 3.4 of Mackay et al. 2013) suggests that the values shown in Table 7, below, were the agreed values. In Mackay et al. 2013, these values were stated to be based on providing for 97% of maximum production and more environmental protection (because they are lower) than the limits (expressed as mg/kg) provided in Sparling et al. 2008 and Hill & Sparling 2009. Significantly, the measurement units associated with this table were not included in the original document and have generally been assumed to be gravimetric measures (mg/kg) (e.g. Stevenson et al. 2020), but have now been confirmed through discussion with the original authors to be laboratory-based volumetric measures (mg/L).¹

There has been recognition since 2013 that different units have been used for Olsen P for SoE reporting (Drewry et al. 2013), including in Mackay et al. 2013. However, the implications of this seeming 'interchangeable' use of units in relation to the use of Olsen P target ranges for national SoE reporting has only now been recognised. In part this is because there is greater understanding of the conversion between volumetric and gravimetric measurement, and that this differs for different soils orders (see Drewry et al. 2022 and section 5). It should also be noted that the apparently 'interchangeable' use of mg/kg and mg/L units for Olsen P is also evident in the original development of the target ranges presented in Sparling et al. 2008, with the text describing Olsen P measured as $\mu\text{g P/cm}^3$, while the axes on the graphs present Olsen P in units of $\mu\text{g/g}$.

¹ Pers. comm., Alec Mackay, AgResearch [October 2024], plus several publications around 2011-2013 report volumetric Olsen P in relation to pasture production (e.g. McDowell & Condron 2012; Smith et al. 2012).

Table 7. Suggested Olsen P target ranges from Mackay et al. 2013

Land use	Soil type	Suggested Olsen P targets ^a	
		Minimum	Maximum
Pasture; horticulture and cropping	Volcanic	20	50
Pasture; horticulture and cropping	Sedimentary and Organic soils	20	40
Pasture; horticulture and cropping	Raw sands and Podzols with low AEC ^b	5	5
Pasture; horticulture and cropping	Raw sands and Podzols with medium and above AEC ^b	15	25
Pasture; horticulture and cropping	Other soils	20	45
Pasture; horticulture and cropping	Hill country	15	20
Forestry	All soils	5	30

^a Units not specified but confirmed to be mg/L. Reported as being assumed to be mg/kg in Cavanagh et al. 2023.

^b AEC = anion exchange capacity. No specific criteria for low or medium AEC were provided; low has been defined as 30% and medium as 30–60%² (Hill Labs, undated).

The fertiliser industry uses a different soil classification from the NZSC for lime and fertiliser applications (e.g. Roberts & Morton 2023). Table 8 provides the correlation between the fertiliser industry classifications and NZSC soil orders.

Table 8. Relationship between soil classification used for fertiliser recommendations and soil order

Fertiliser industry soil classification	Corresponding soil order
Sedimentary	Brown, Pallic, Recent, Melanic, Semi-arid
Ash	Allophanic, Granular, some Gleys
Pumice	Pumice, some Gleys
Organic	Organic

Sources: Roberts & Morton 2023; Reid & Morton 2019; Nicholls et al 2012; Hill et al. 2003.

Table 9. Provision soil quality classes for soil pH (bold values indicate target ranges)

Soil type	Very acid	Slightly acid	Optimal	Sub-optimal	Very alkaline	
Pastures on all soils except Organic	4	5	5.5	6.3	6.6	8.5
Pastures on Organic Soils	4	4.5	5	6	7.0	
Cropping & horticulture on all soils except Organic	4	5	5.5	7.2	7.6	8.5
Cropping & horticulture on Organic soils	4	4.5	5	7	7.6	
Forestry on all soils except Organic		3.5	4	7	7.6	
Forestry on Organic soils			excluded			

Source: LMF 2009.

² Hill Labs undated, Technical note: Anion storage capacity (phosphate retention)

Table 10. Provision soil quality classes for total carbon (% w/w) (bold values indicate target ranges)*

Soil type	Very depleted	Depleted	Normal	Ample
Allophanic	0.5	3	4	9
Semi-arid, Pallic, & Recent	0	2	3	5
Organic	Excluded			
All other soil orders	0.5	2.5	3.5	7

Source: LMF 2009

* No upper limits were defined, as carbon was considered to be a 'more is better' indicator (Sparling et al. 2008).

Table 11. Provision soil quality classes for total nitrogen (% w/w) (bold values indicate target ranges)

Land use	Very depleted	Depleted	Normal	Ample	High
Pasture	0	0.25	0.35	0.65	1.0
Forestry	0	0.10	0.20	0.60	1.0
Cropping and horticulture	Excluded				

Source: LMF 2009.

Table 12. Provision soil quality classes for AMN (mg/kg) (bold values indicate target ranges)*

Land use	Very low	Low	Adequate	Ample	High	Excessive
Pasture	25	50	100	200	200	300
Forestry	5	20	40	120	150	200
Cropping and horticulture	5	20	100	150	150	225

Source: adapted from LMF 2009 using information from Mackay et al. 2013.

* No upper limit was set for AMN as it was not considered to be a good indicator of environmental risk (Mackay et al. 2013).

Table 13. Provision soil quality classes for bulk density (t/m³ or Mg/m³) (bold values indicate target ranges)

Soil type	Very loose	Loose	Adequate	Compact	Very compact
Semiarid, Pallic, and Recent soils	0.3	0.4	0.9	1.25	1.6
Allophanic soils		0.3	0.6	0.9	ns
Organic soils		0.2	0.4	0.6	ns
All other soils	0.3	0.7	0.8	1.2	1.6

Source: LMF 2009.

ns – not specified.

The LMF manual (LMF 2009) provides target ranges for macroporosity (measured at – 10 kPa), largely based on Sparling et al. 2008, but attributes a change in the 'low' value for macroporosity for pasture, cropping, and horticultural soils from 8 to 10% to Mackay et al. 2006. It is unclear when or why the lower threshold for macroporosity for pastures, cropping, and horticulture shifted to

10%, but in the May 2011 workshops the focus of discussion was on whether there was sufficient evidence to change this lower threshold to 12% (Taylor & Mackay 2011; Mackay et al. 2013).

Table 14. Provision soil quality classes for macroporosity (% v/v at –10 kPa) (bold values indicate target ranges)

Land use	Very low	Low	Adequate	High	
Pastures, cropping, and horticulture	0	6 ^a	10 ^b	30	40
Forestry	0	8 ^{a, b}	10	30	40

Source: LMF 2009

^a Lower target value, as shown in LMF 2009.

^b Lower target ranges as commonly used by councils and MfE.

Table 15. Soil quality indicator target ranges used by MfE and Stats NZ in *Our Land 2018* and *Our Land 2021*

Indicator	Soil order	Land use	Min	Max	Unit
AMN	All	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	50	NA	µg/g
	All	Cropping, Orchard/vineyard, exotic forestry	20	NA	µg/g
Bulk density	Allophanic	All	0.5	1.3	Mg/m ³
	Brown, Gley, Granular, Melanic, Oxidic, Podzol, Pumice, Raw, Ultic	All	0.6	1.4	Mg/m ³
	Organic	All	0.2	1	Mg/m ³
	Pallic, Recent, Semi-arid	All	0.7	1.4	Mg/m ³
Macroporosity	All	All excl. exotic forestry	10	30	–10 kPa, %vol/vol
	All	Exotic forestry	8	30	–10 kPa, %vol/vol
Olsen P*	Raw	All, excluding exotic forestry	5	25	µg/g
	Podzol	All excl. cropping and orchard/vineyard, forestry	5	25	µg/g
	Podzol	Cropping, orchard/vineyard	20	50	µg/g
	All soils	Exotic forestry	5	30	µg/g
	Allophanic, Pumice	All excl. exotic forestry	20	50	µg/g
	Brown, Gley, Granular, Melanic, Oxidic, Pallic, Recent, Semi-arid, Ultic	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	15	45	µg/g
	Brown, Gley, Granular, Melanic, Oxidic, Pallic, Recent, Semi-arid, Ultic	Cropping, orchard/vineyard	20	45	µg/g
	Organic	All excl. exotic forestry	20	40	µg/g
	Organic	Exotic forestry	5	30	µg/g
pH	Organic	Exotic forestry	3.5	7	–log(cH ⁺ /c0)
	All excluding Organic	Exotic forestry	3.5	7.6	–log(cH ⁺ /c0)

Indicator	Soil order	Land use	Min	Max	Unit
	All excluding Organic	Cropping, orchard/vineyard	5	7.6	-log(cH+/c0)
	All excluding Organic	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	5	6.6	-log(cH+/c0)
Total C	Pallic, Pumice, Raw, Recent, Semi-arid	All	2	NA	%C gravimetric
	Brown, Gley, Granular, Melanic, Oxidic, Podzol, Ultic	All	2.5	NA	%C gravimetric
	Allophanic	All	3	NA	%C gravimetric
	Organic	All	NA	NA	%C gravimetric
Total N	All	Exotic forestry	0.1	0.7	%N gravimetric
	All	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	0.25	0.7	%N gravimetric
	All	Cropping, orchard/vineyard	NA	NA	%N gravimetric

Note: Anthropogenic soils are not mentioned.

* See text above Table 7 for a discussion on units associated with Olsen P target ranges.

NA – not available.

Provisional targets have been proposed for HWEC by Taylor, Cox, Littler, Drewry, Lynch et al. 2017 and Taylor et al. (2022). A provisional target of 1,800 mg/kg (Taylor, Cox, Littler, Drewry, Lynch et al. 2017) represented the value below which soil degradation was observed, from four regions of New Zealand trialling this soil quality indicator. In 2022 two new targets were proposed (Taylor et al. 2022). These consisted of a target of >1,700 mg/kg, termed a 'background low target', derived from the first percentile of 52 indigenous vegetation sites sampled from Waikato and Wellington, intended as a target to protect environmental services. A second target of >2,000 mg/kg, termed a 'visual soil assessment (VSA) best fit target', was derived by plotting HWEC data against VSA scores for the same soils and taking the HWEC value at the point below which soil was deemed by the VSA score to be moderately damaged.

Taylor et al. (2022) concluded that all three potential HWEC targets (>1,700, >1,800, and >2,000 mg/kg) identified degraded soils and were acceptable targets for soil quality monitoring. Taylor et al. (2022) also provide correlations of HWEC measures with AMN, noting that if HWEC replaces AMN as an indicator there is a need to be able to relate historical measurement of AMN to HWEC in order to undertake trend analysis.

4.3.2 Land-use categories

The 'standard' land uses specified in the NEMS-SQ are shown in Table 16. These are used as a starting point for considering land use in relation to revising numeric criteria for soil quality indicators for SoE reporting. As noted in Cavanagh et al. 2017, there is inconsistency in the capture of land-use information in SoE soil quality monitoring, and hence in the classification of sites to relevant land-use categories.

Further work on land-use categorisation for SoE soil quality monitoring was undertaken by Cavanagh and Whitehead (2022, 2023). One focus was to help provide better delineation of varying land-use intensity for the purposes of reporting. This is particularly associated with the 'drystock' land-use category, which could encompass high-intensity cattle farming (which has a similar

intensity to dairying land use) to very low-intensity high-country farming. This categorisation is shown in Table 17.

Synergy between classifications used for SoE soil quality monitoring and land-use classifications at a regional or national level provides the ability to assess the representativeness of SoE monitoring across land uses at a regional or national level and to extrapolate SoE results to an areal basis. A draft national land-use classification scheme has recently been completed (Law et al. 2024); the proposed classification for agricultural production and forestry land use is shown in Table 18, with an overview of the New Zealand Land Use Management classification system (NZLUM) provided in Appendix 4.

Table 16. Description of land-use categories to be assigned to sampling sites under the National Environmental Monitoring Standard for Soil Quality and Trace Element Monitoring

Land-use type	Definition
Horticulture	Permanent-row orchards and vines.
Cropping	Annual crops, usually grown on a rotational system that can include a short-term (c. 1–3 years) pasture rotation. Includes maize, barley, wheat, peas, other grain and seed crops, fodder crops, and commercial vegetables (includes market gardens).
Dairy	Dairy is the main dairy platform, predominantly used for milking. Dairy may include areas of grazed forage crops and maize for silage.
Drystock (other pasture)	All other (non-dairy platform) pasture, including drystock farms for sheep, beef, deer, goats, horses, dairy support (defined by the absence of a dairy platform), and cut and carry.
Exotic forest	Plantations of exotic tree species grown for pulp and timber production, generally radiata pine but can include other exotic species (e.g. redwood, Douglas fir). Usually harvested using clear-felling methods.
Indigenous vegetation	Native forest, tussock, shrubland and scrub dominated by indigenous species. Undisturbed or unfertilised in recent decades.
Urban open space	Open areas of grass in urban areas, including parks, school grounds, and playgrounds.

Table 17. Proposed land-use categories for regional council soil quality monitoring

Category	Sub-groups	Description
Conservation and natural environment (indigenous vegetation)	Forest, scrub and shrubs, grassland	Native forest, tussock, shrubland, and scrub dominated by indigenous species. Undisturbed or unfertilised in recent decades.
Plantation forestry	Exotic forestry	Plantations of exotic tree species grown for pulp and timber production, generally radiata pine, but can include other exotic species (e.g. redwood, Douglas fir, eucalyptus). Usually harvested using clear-felling methods.
Perennial horticulture	Tree crops, vine crops, berry fruit	Permanent tree, vine or berry crops
Short-rotation cropping	Arable	Predominantly grain, seed or fodder crops; over time may include short-term (c. 1–3 years) pasture and livestock rotations and/or vegetable rotations. Pasture and livestock rotations may occur up to 50% of the time. Includes maize, barley, wheat, peas, other grain and seed crops, and fodder crops. May be used for dairy support.
	Vegetable	Predominantly vegetable rotation; may include livestock rotation, but less likely.
Dairy	Bovine/non-bovine	Dairy is the area on which milking cows are grazed during the milking season, which may include rotations of grazed forage crops and maize for silage, and drystock grazing. Where the land is permanently used for drystock grazing it should be classified under drystock land use.
Drystock	Flat-rolling, hill country	All other (non-dairy platform) pasture, including drystock farms for sheep, beef, deer, goats, horses, dairy support (defined by the absence of a dairy platform) and cut and carry; flat-rolling includes slope < 15°, and typically low altitude; hill country includes slopes ≥ 15°.
Production from relatively natural environments (subset of drystock)	High-country farming (where there are minimal anthropogenic inputs)	This captures high-country farming with domestic stock grazing on native vegetation where there has been limited or no deliberate attempt at pasture modification. Some change in species composition may have occurred.
Rural residential	With agriculture Without agriculture	Residential properties with low-intensity (non-commercial) land management practices (e.g. hobby farm, on land in rural or peri-urban areas).
Recreation and culture (urban open space)	Grassland	Open areas of grass in urban areas, including parks, school grounds, and playgrounds

Source: Adapted from Cavanagh & Whitehead 2023.

Note: Italics indicate sub-groups that were discussed for potential future use.

Table 18. Selected proposed land-use categories from the New Zealand Land Use and Management Classification system (NZLUM, Law et al. 2024) that relate to land uses typically assessed through SoE soil quality monitoring (the relevant NEMS-SQ category is provided in brackets)

Category	Sub-groups	Description
Conservation and minimal use of natural environment (indigenous vegetation)	1.1.1–1.1.3 High to moderate degree of biodiversity protection	Nature conservation classes are based on the suggested classification scheme for the Protected Areas Network of New Zealand (PAN-NZ)
	1.3.0 Minimal use from relatively natural environments	This class includes land that is subject to relatively low levels of intervention or that is largely unused in the context of prime use or use for resource protection. May include indigenous or exotic species; only indigenous species will be of relevance here.
2.1.0 Plantation forests	2.1.1 Exotic plantation forestry (Exotic forest)	An area managed for pulpwood or saw-log production (exotic species).
	2.1.5 Permanent carbon forests	An area planted with indigenous or exotic trees for the purpose of gaining carbon credits (carbon farming).
2.4.0 Perennial horticulture	2.4.1 Tree crops (Horticulture)	Includes long-term cultivated plants, typically trees or woody shrubs, grown for their fruits, nuts, or other edible parts. Management practices may include pruning, pest and disease control, irrigation, and harvesting techniques specific to tree crops.
	2.4.2 Vine crops (Horticulture)	Includes fruit-bearing plants that grow on vines or trailing stems, often requiring support structures such as trellises or arbours. These plants produce fruits that typically hang from vines and may include grapes, kiwifruit, and passionfruit. Vine fruit cultivation involves specific management practices such as pruning, training, trellising, and pest and disease control specific to vine plants.
	2.4.3 Other perennial horticulture	Encompasses perennial plants beyond tree crops and vine fruits, such as berries (e.g. strawberries, blueberries), perennial herbs (e.g. lavender, rosemary), and ornamental perennials (e.g. roses, lilies).
2.3.0. Short-rotation and seasonal cropping	2.3.1 Arable	Predominantly grain, seed, or fodder crops; over time it may include vegetable rotations. Includes maize, barley, wheat, peas, other grain and seed crops, and fodder crops. May be used for dairy support.
	2.3.2 Arable and mixed livestock cropping (Cropping)	Predominantly grain, seed, or fodder crops; over time it may include short-term (c. 1–3 years) pasture and livestock rotations, and/or vegetable rotations. Pasture and livestock rotations may occur less than 50% of the time. Includes maize, barley, wheat, peas, other grain and seed crops, and fodder crops. May be used for dairy support
	2.3.3 Short-rotation horticulture (Cropping)	Crop plants living for less than 2 years that are intensively cultivated, usually involving a relatively high degree of nutrient, weed, and moisture control. Predominantly rotations of vegetable crops or seasonal fruits grown for human consumption; may include livestock rotations, but this is considered less likely.
	2.3.4 Seasonal flowers and bulbs, and turf farming	Agricultural practices focused on the cultivation of seasonal ornamental flowers, bulbs, and turf grass for commercial purposes. This class encompasses activities such as the cultivation of flowers and bulbs for seasonal markets, landscaping, and turf-farming for sports fields, lawns, and recreational areas.

Category	Sub-groups	Description
2.2.0. Grazing modified pasture systems	2.2.1 Dairy (Dairy)	The land on which milking cows (or other stock, such as goats or sheep) are grazed during the milking season. Dairy production systems can include rotations of grazed forage crops and maize for silage, and drystock grazing, but this class should only be used where dairy is the primary purpose of the land. Where the land is permanently used for drystock grazing, it should be classified under drystock land use.
	2.2.2 Intensive drystock (Drystock)	Includes non-milking platform pasture where there is a high level of inputs from fertiliser, water requirements (i.e. may be irrigated), and high stocking rates. This is most likely to occur on flat/rolling terrain. Land used for high-intensity drystock grazing may include rotations for arable or winter forage crops, as well as grazing of non-lactating (dry) dairy cattle, beef cattle, sheep, and cattle breeding. Grazing of other stock, including deer, goats, and horses, should be captured under class '2.2.3 Extensive drystock'
	2.2.3 Extensive drystock (Drystock)	As for class 2.2.2, but for grazing on modified pastures with relatively fewer inputs, lower likelihood of irrigation, and lower stocking rates. This is more likely to take place on hill, hard-hill, or high-country terrain. Grazing livestock other than dairy, sheep or beef should usually be captured in this class (though it does not exclude sheep or beef), and the commodity type appropriately recorded. Where there is a high proportion of indigenous vegetation for grazing land, land use should be classified as grazing native vegetation. Arable or winter forage crops are unlikely to be common rotations in this land-use category
1.3.0 Production from relatively natural environments	1.3.3 Grazing native vegetation* (Drystock)	Land uses based on grazing by domestic stock on native vegetation where there has been limited or no deliberate attempt at pasture modification. This captures high-country farming with domestic stock grazing on native vegetation where there has been limited or no deliberate attempt at pasture modification. Some change in species composition may have occurred.
3.1.5 Rural residential		Residential properties with low-intensity (non-commercial) land management practices (e.g. hobby farm, on land in rural or peri-urban areas). Typically featuring larger parcel sizes amidst agricultural or natural surroundings.
3.2.0 Public recreation and services	3.2.1 Outdoor recreation (Urban open space)	Land areas dedicated to leisure activities conducted in natural or semi-natural settings, such as parks, trails, beaches, sportsgrounds, camping grounds, zoos, botanic gardens, recreational reserves, sports grounds, tourist parks, mountain bike parks, etc., with a primary purpose of recreation and culture and typically with considerable unsealed vegetated areas.

* The adoption of this class has to be verified.

4.4 Available data for developing revised soil quality target ranges

4.4.1 Sector-based studies

A summary of studies found that provided information on soil quality indicators in relation to different environmental outcomes for each sector is shown in Table 19, with more detail provided below and in Appendix 5.

Table 19. Summary of the number of New Zealand sector-based studies that link soil properties to different environmental or production (yield) outcomes, and the availability of extensive data sets or production (yield).

Outcome	pH	Total C	Total N	AMN	Olsen P	HWEC	Macro-porosity (-10 kpa)	Bulk density
Water quantity /infiltration		2	1				9 3 1	7 3 2
Soil function - nutrient cycling	4	4 6	4 5		2 1	2 1 1	1	1 1
Soil biodiversity	1	4 4	4 3	4	2		2	1 2
Pest and disease regulation	1	2 1	1 1		1 1			
GHG emission (CO ₂ , N ₂ , CH ₄ , etc)	2 5	5 5 1	4 4		3 1	3 1	5 1 2	4 3
Water quality (N, P, E. coli, sediment)		1 3 5 1 1 1	2 1	2 1	3 1		11 7 2	7 7 1
Extensive dataset	2	6 2 2	9 2	9 2 2	2	2	2 2	1 2 3
Production	3	5 2 1	7 4 1	7	7	1 1	9 4	1 6 4

Pasture
 Cropping
 Perennial horticulture
 Forestry

Pastoral sector

For the pastoral sector, the relationship between pasture growth and changes in soil pH or Olsen P is based on extensive lime (Edmeades et al. 1985) and P-fertiliser response studies (Edmeades et al. 2006; Gray & Morton 2019) conducted across all major soil types and climatic zones in the country. These form the basis for recommendations by the fertiliser industry to pastoral, forage and vegetable producers (<https://www.fertiliser.org.nz/Site/resources/booklets.aspx>).

In contrast, few studies have investigated the link between pasture growth and changes in soil physical properties (e.g. macroporosity, bulk density) or chemical properties (total C or N, total N, or AMN). Few studies have assessed multiple soil quality indicators simultaneously, or have attempted to connect changes in soil quality indicators to either production or directly to environmental outcomes. Notable exceptions include:

- research on whether decreased pasture growth due to changes in physical soil condition (e.g. macroporosity, bulk density) could be offset by increasing Olsen P (through increased P fertiliser) (Mackay et al. 2011)
- some research investigating the relationship between soil Olsen P levels and dissolved reactive P concentration in surface runoff from Pallic, Brown, and Allophanic soils (McDowell, Monaghan et al. 2003; Morton et al. 2003; McDowell & Condon 2004)
- research exploring the impact of cattle treading on soil properties and runoff (e.g. Gray et al. 2022).

Over 50 peer-reviewed publications were identified in which soil quality indicators were more or less directly linked to environmental outcomes and thus may provide data that could be used to revise soil quality indicator target values. The number of studies is summarised in Table 19, with the details of individual studies presented in Appendix 5.

- *Water quality (including N, P, sediment and E-coli loss) and quantity.* Nine studies link soil physical properties to drainage and infiltration rates, thereby influencing runoff and the risk of P and sediment loss, which includes a further four studies. Six studies have linked Olsen P to P loss, and eight studies have linked total C, total N, HWEC, and soil physical properties to N loss. No studies linked soil quality properties to the risk of *E. coli* contamination of waterways, although this loss is highly dependent on livestock type, the number, timing, and intensity of a grazing events, and proximity to water, more so than for soil type and quality.
- *Greenhouse gas (GHG) emissions.* Fifteen studies were found linking GHG emissions to physical soil properties (pH, total C, total N, and HWEC), with other studies linking AMN and Olsen P directly to GHG emissions. There is also potential to interrogate existing published data, as the nitrous oxide (N₂O) emission factors used in calculating nitrous emissions distinguish between flatland with low slope (<12°) and slopes of >12°, which could be linked to changes in soil fertility (van der Weerden et al. 2020).
- *Soil biodiversity and pest and disease regulation.* Very few studies were found linking the soil quality indicators to soil biodiversity, or to pest and disease regulation. Five studies looked at links between soil biota and total C, total N, and macroporosity. No studies were found that examined the impact a change in AMN has on either primary production or environmental outcomes in pastoral land use.

The following data sets relate to pastoral studies.

- *AgResearch Ballantrae hill country research station.* This includes data from long-term P fertiliser and sheep grazing experiments operating from 1975 to 2024. Data include results for all soil quality indicators from 72 plots (four different P fertiliser and grazing histories × three slopes × three aspects) dating back to 1975, with HWEC also available for a smaller number of samples. Other research includes the effect of N fertiliser inputs on soil biota and organic matter (2007–2014), and studies on the effects of livestock treading on soil physical properties and soil P and sediment losses.
- *AgResearch Winchmore P fertiliser under irrigation:* This includes data sets dating back more than 60 years, which include pasture production and a wide range of soil quality indicators (Kelliher et al. 2012; Anderson et al. 2023).
- *Free-Air Carbon dioxide Enrichment (FACE) facility at Flockhouse.* These data explore the effect of long-term exposure to elevated CO₂ on soil organic C and N in grazed pastures. Includes pH, Olsen P, total C, and total N (Ross et al. 2013; Touhami et al. 2020).

- *Pasture response under non-limiting P fertiliser × N fertiliser × irrigation.* This work involved investigating the upper limit to pasture response when P, N, and water were non-limiting. There were four sites (Waikato, Manawatū, Canterbury, and Southland) across the country. Pasture and soil fertility data were collected for over 4 years (Mackay et al. 2010).
- *Effect of livestock treading on macroporosity.* This was a series of on-farm studies at five locations throughout the North Island (including Northland, Waikato, Manawatū, coastal sand country) examining the effect of livestock treading on macroporosity, covering a range of soil orders (Russel et al. 2001). Data are available for a few other soil properties in published reports only.
- *Effect of compaction on pasture response to P fertilisers.* This work investigated the interaction between Olsen P and bulk density and macroporosity and pasture growth at two sites, one in Manawatū and one in Southland. Field trial design at both sites was a split plot, with four P treatments within each of three compaction levels (Southland) and four compaction levels (Manawatū), with four replicates at each site (Mackay et al. 2011).
- *Effect of grazing on labile organic carbon and pastures.* This work investigated the impact of livestock grazing density and intensity over a grazing cycle on soils and pastures at one site in Hawke's Bay over 1 year. Most soil quality indicators were considered, including pH, Olsen P, soil organic C, total N, bulk density, macroporosity, and HWEC and hot-water extractable nitrogen (Wilson 2024).

Short-rotation cropping and perennial horticulture

For the arable, vegetable, and perennial horticulture sectors, approximately 450 peer-reviewed publications and internal reports focusing on soil quality, environmental outcomes, and yield, primarily in New Zealand, were identified. However, of these only a small number of publications (about 16 in the arable and vegetable sectors and five in perennial horticulture) in New Zealand measured both soil quality indicators and environmental outcomes (Table 19, Appendix 5). International publications were included when they provided review-type research publications relevant to these topics, and are included in Appendix 5.

The review showed that many publications cover soil quality measurements or environmental outcomes affected by various crop management practices and pressures, such as tillage, crop rotation, residue return, growing period, fertiliser application, cover crop, ground cover, and compaction. There are very few publications that include AMN measurement. Based on these, information on the relationships between soil quality indicators and environmental outcomes includes soil health, nutrient cycling and infiltration capacity, N₂O emissions, CO₂ related to soil respiration, and nitrate leaching. These measurements are usually available only at the treatment level, with a limited number of data points. Environmental outcomes such as N leaching, sediment, and P runoff have been measured for some perennial horticultural crops at multiple sites over several years, with concurrent measurements for some soil quality indicators. This is mostly industry-funded research that is not in the public domain. A number of guides and calculators have been developed to help land managers minimise environmental impacts.³

³ For example, <https://agrilink.co.nz/case-studies/>.

In addition to published studies, several data sets from previous projects could provide insights into setting target ranges for soil quality indicators. Examples include the Rootzone Reality Drainage Fluxmeter (a Sustainable Farming Fund project, Norris et al. 2018, 2023), Sustainable Vegetable System (Searle et al. 2024), Land Management Index (LMI, Beare et al. 2007), Millennium Tillage Trial (Curtin et al. 2020; Fraser et al. 2013), and the Land Use Change & Intensification research programme conducted from 2003 to 2008.

While these projects focused on measuring soil quality indicators, some also included data on production, nitrate leaching, and N₂O emissions. However, analysing the relationships between soil quality indicators and environmental outcomes, such as nitrate leaching, is challenging due to the influence of factors such as fertiliser application, residue management, and climate conditions, as well as the limited accessibility of fertiliser input information, which is often protected as farmer intellectual property.

Forestry

Twenty-four New Zealand planted-forest publications were identified as being relevant to the revision of the soil quality indicator target ranges (Table 19, detail in Appendix 5). Very few studies have measured the soil quality indicators and related them to environmental outcomes; the closest is measurement of soil C stocks, which can connect to national greenhouse gas inventory reporting. Overall, the focus of planted-forest research that has measured soil quality indicators has been on understanding the relationship between soils and forest productivity. The following summarises the top priority forestry research findings linked to environmental outcomes that report on soil 0–10cm depth for one or more of the soil quality indicators.

- *Water quality.* There are a limited number of studies that have linked soil properties to water quality outcomes (Table 19). The FR380 trial series does offer an opportunity for further investigation, with N leaching measured on 10 sites (Davis et al. 2012) and soil properties measured on the same site for forest productivity outcomes (Watt et al. 2008). The soil data, published by Garrett, Watt et al. (2022), includes pH, total C, total N, Olsen P, macroporosity, and bulk density. Similarly, the Puruki Experimental Forest work also provides an opportunity to explore the potential link between soil properties and water quality outcomes (Beets et al. 2002; Davis, 2014).
- *Soil carbon stocks.* There are studies that have linked soil C stocks (total C and bulk density) to forest management practices or land use. The studies are: (1) the harvest residue and removal and fertiliser addition trials summarised in Garrett et al. (2021a, b), with raw data from the end of the trial rotation not published; and (2) Puruki Experimental Forest, comparing across pasture, planted forest and native land use (Beets et al. 2002), with raw data not published.
- *Soil biodiversity.* Few studies have linked soil microbial biodiversity to forest management practices, but those that do exist include the work by Addison et al. (2019, 2021). Soil properties measured include pH, total C, and total N. Moreover, there is one study worth noting (0–5 cm sampling depth) that has looked at the impacts of land-cover type (native forest, planted forest with exotic conifers, and pastoral agriculture) on soil microbial communities and their functional potential (Wakelin et al. 2021). Data on five soil quality indicators (pH, total C, total N, Olsen P, and bulk density) are provided, in addition to the soil bacterial community and functional measures.

Following are data sets that are available and could support understanding of the range in soil properties for forestry in relation to productivity outcomes.

- *FR380 trial series (Watt et al. 2008)*. The data set covers over 30 sites in New Zealand, some of which include pastoral land use (pre-afforestation). The data set includes pH, total C, total N, Olsen P, macroporosity, and bulk density. The raw data set is published (Garrett, Watt et al. 2022).
- *Harvest residue and removal and fertiliser addition trials*. Productivity outcomes linked to soil properties are published for five sites, ranging from early rotation (age 5 years), to mid-rotation and end-rotation (summarised in Garrett et al. 2021a, b). The data set includes pH, total C, total N, and bulk density. The raw soil data set is published at the beginning of the experimental trial.
- *Pakuratahi* (Heaphy et al. 2014). This is one site that has measured and reported on site averages for soil pH, total C, total N, and bulk density linked to forest productivity.

Additional data sets that could support an understanding of the range in soil properties are set out below.

- *FR561 trial series data set (Smaill et al. 2023)*. The data set covers six sites in New Zealand, one of which is pre-afforestation. It includes pH, total C, total N, and bulk density. The raw soil data are published.
- *FR531 trial series data set (Paul et al. 2024)*. The data set covers four sites in New Zealand, all of which are pre-afforestation. It includes total C, total N, macroporosity, and bulk density. The raw data are published.
- *Garrett, Sanderman et al. 2022*. This is a large soil chemistry data set used to generate soil spectroscopy predictions. It covers 92 trial sites across multiple Scion forestry experimental trials in New Zealand, and includes pH, total C, and total N. The soil data set is not published.
- *Xue et al. 2013*. This covers two sites, and publishes site average values for pH, total C, total N, and Olsen P.

Further details on the key studies considered to be potentially useful for revising soil quality target ranges have been captured in a spreadsheet (Appendix 5).

4.4.2 Cross-sectoral monitoring programmes and extensive data sets

In addition to the primary-sector-specific information captured in the preceding section, there are a number of different monitoring programmes that provide soil quality data across different land uses, or long-term field trial sites, that include extensive data collected over time. In many cases these data are not linked to any environmental or production outcomes. They include the following.

- *Regional council SoE reporting*. The most recent collation of data for national reporting is described in Cavanagh et al. 2021 and Stevenson et al. 2020. These data include sampling under indigenous vegetation and some sampling in urban parks (mainly Auckland), in addition to the primary sector land uses discussed in the preceding section. Available data from 1995 to 2018 were collated from all 11 councils undertaking SoE monitoring at the time of collation. These data were used for national reporting in *Our Land 2021* and *Our Land 2024*. Since this time, Gisborne District Council and Otago Regional Council have undertaken

some monitoring, and the data collected are useful to include in the existing regional council data collation because they provide information for these regions that are otherwise lacking.

- *Environment Canterbury's Arable and Pastoral Monitoring Programme*. As well as their regional 500 Soils Monitoring Programme, which forms part of regional council SoE reporting (see above), Environment Canterbury (ECan) has a second monitoring programme targeting productive arable and pastoral land. Since 1999 this programme has monitored more than 200 sites and measures the eight soil quality indicators discussed in this report, as well as additional indicators (aggregate stability, aggregate size distribution, total porosity, penetration resistance, cadmium) (Lawrence-Smith et al. 2014). Samples under this programme are collected from 0 to 15 cm depth, with composite samples of three soil cores taken at each site.
- *National Soil Carbon Monitoring (NSCM)*. This programme was established to benchmark and monitor changes in soil C stocks (i.e. reported as t C/ha down to 60 cm depth) across agricultural land uses (Mudge et al. 2022). The programme includes 528 sites grouped into dairy, flat-rolling drystock, hill-country drystock, cropping, and horticulture land uses across multiple soil orders. Samples are collected down to 60 cm in 10 cm increments, and at each site either 10 composited cores, or in the case of stony soils, soil excavated from two approximately 30 × 30 cm pits, are collected. Samples are archived following analysis. The benchmarking round of this programme was recently completed, and the first repeat sampling round is underway. It is intended that each site be repeat sampled every 4 years. As well as C stocks and bulk density, parameters including pH and Olsen P have been analysed in samples from 0 to 10 cm depth at each site by the Fertiliser Association of New Zealand.
- *S-map*. Extensive sampling has been undertaken in many areas across New Zealand to provide data to develop S-map, although soil pH is the only property measured on samples collected for soil survey purposes that is relevant to the current work.
- *Land Use Carbon Analysis System (LUCAS)*. The indigenous forest and shrubland permanent plot network consists of 1,258 plots (established 2002–2007) located on an 8 × 8 km grid throughout the country's indigenous forests and shrublands (one plot every 6,400 ha) to monitor carbon (Holdaway et al. 2017). Soil has been sampled at least once for each LUCAS plot (natural forests and shrublands, public and private lands), with samples analysed for pH, total C, and total P (pers. com., Peter Bellingham, Manaaki Whenua – Landcare Research, November 2024).
- *Tier 1 Biodiversity monitoring programme*. This programme covers all ecosystems on public conservation lands, overlapping with LUCAS plots in forests and shrublands. It collects soil data (mineral soils; 0–10 cm depth), with samples analysed for pH, total C, total N, total P and organic P, in addition to other soil properties (pers. comm., Sarah Richardson, Manaaki Whenua – Landcare Research, August 2024).
- *Land Use Carbon Analysis System (LUCAS) National Planted Forest Inventory (NPMI) plot data set* (MfE 2021). This data set consists of 635 permanent plots (Paul et al. 2024). The NPMI plot network is not monitored for soil. There is a data set that underpins the soil C monitoring model for reporting on soil C stocks administered by MfE that includes data from 90 plots (post-1989 forests). The data set includes soil total C, bulk density, and total N. Permission from MfE will be required to access the soil data set.
- *SLURI (multi-CRI Sustainable Land Use Research Initiative)*. From 2004 to 2008 this initiative (known as SLURI 1) had a key focus on soil quality work to review and establish target ranges for total C, macroporosity, and mineralisable N (Beare et al. 2007). The data set, collected on a national scale, covers multiple land uses and soil orders. Sampling methods and depths

vary based on the study and specific indicators measured, which include total C, total N, AMN, macroporosity, and others (e.g. aggregate stability). Yield data were included in some cases, though environmental outcomes were not directly assessed.

- *LMI (Land Management Index)*. The Land Management Index (LMI) project aimed to determine the state of soils under specific land uses and evaluate whether management within a land use can be used to predict differences in the soil quality state. This project was conducted on a national scale across eight regions. The sampled sites were selected to represent long-term dairy, sheep & beef, arable (intensive and mixed), and vegetable (intensive and mixed), and various soils orders across seven major agricultural regions of New Zealand (Auckland, Waikato, Gisborne, Hawke's Bay, Manawatū, Canterbury, and Southland). Soil orders included Allophanic, Granular, Brown, Gley, Melanic, Pallic, and Recent. All eight soil quality indicators, except macroporosity, were measured at two soil depths: 0–15 cm and 15–30 cm. Bulk density, total C, and total N were measured at both depths, while the other indicators were measured only at the 0–15 cm depth. These measurements were taken once from 711 sites between 2002 and 2007.

Additional data sets have been compiled by MWLR as part of the 'Maximising soil carbon in mineral soils programme (2022–2026)' for MfE and could provide more data.

4.4.3 Selected studies on linking soil quality measures to environmental outcomes

Water quality outcomes

Several studies have assessed the relationship between soil Olsen P and water quality by assessing dissolved reactive phosphorus (DRP) in overland and drainage flow (e.g. (Morton et al. 2003; McDowell & Condron 2004; McDowell, Monaghan et al. 2003; Taylor et al. 2016; McDowell et al. 2020). These are largely underpinned by the data and relationships developed in McDowell & Condron 2004. This study used simulated rainfall experiments to assess the potential for P loss from 44 grassland soils spanning 11 soil orders, using a combination of measured soil chemical properties and concentrations of DRP determined in drainage and overland flow. Relationships between DRP in either flow arising from Olsen P and P-retention were developed.

Taylor et al. (2016) and McDowell et al. (2020) more recently used this information to undertake regional and national-scale assessments of the impact of Olsen P on water quality. Dodd et al. (2012, 2013) provided insight into the reduction in Olsen P after cessation of fertiliser application, which helped inform the estimates in McDowell et al. 2020, who used the equations of McDowell and Condron (2004) to relate measures of water-extractable P (WEP) to Olsen P and anion storage capacity, and a value of 0.02 mg/L for WEP as a target or threshold value. The basis of this value appears to be provided by McDowell et al. (2003), who describe adjustment of a default trigger value for DRP concentration in lowland rivers of 0.01 mg P/L (ANZECC 2000), based on an assessment of the proportion of storm flow in selected catchments. This was estimated to be approximately 53%; hence the limit was determined to be 0.02 mg P/L. Under the National Policy Statement for Freshwater Management (NPS-FM) (MfE 2024b), this concentration falls into category D for freshwater bodies: ecological communities affected by substantial DRP elevation above natural reference conditions (the threshold is 0.018 mg/L).

Relationships have been developed between a range of soil Olsen P values and DRP and total P in surface runoff, and $\text{CaCl}_2\text{-P}$ (an estimator for P in subsurface flow) for a range of soil types in Southland (McDowell, Monaghan et al. 2003), and the potential for P loss in subsurface drainage at Winchmore in Canterbury (McDowell 2012; Macintosh et al. 2019). A caveat is that these studies have used rainfall simulation. However, the studies are still valuable because they suggest that the magnitude of P loss appeared to be influenced by soil order, with lower DRP concentrations measured from Brown soils, than for Recent and Pallic soils (McDowell, Monaghan et al. 2003). High P losses were reported in drained Organic soils, and almost double those of Podzols and a Recent soil, partly attributed to the low bulk density (high infiltration rate) and low P sorption of Organic soils in Southland (Simmonds et al. 2015).

Several plot studies have examined overland flow and water quality (DRP, total P, suspended solids and *E. coli*) on pasture and cattle-grazed winter forage crops in Otago (McDowell, Drewry, Muirhead et al. 2003, 2005). In addition, paddock- and small-catchment-scale studies have examined surface runoff and water quality (and soil properties) under winter forage from grazing in Otago (Monaghan et al. 2017; Ghimire et al. 2024). One study presented macroporosity values versus DRP, total P, and suspended solids for water quality using simulated treading (McDowell, Drewry, Paton et al. 2003a).

Several of these studies also reported macroporosity but were not specifically related to these water quality variables. An exception is McDowell, Drewry, Paton et al. (2003b), who report DRP, total P and suspended solids in relation to macroporosity for grassland and cultivated soil. A caveat is that such studies have focused on the relationship between management practices and water quality impacts rather than developing relationships with specific soil properties. More broadly, factors such as management practices, topography, and extent of area under specific land use can have a greater influence on water quality than site-specific soil properties. This was highlighted in a national study using water quality data from Land, Air, Water Aotearoa and the regional council soil quality data set collated for national SoE reporting, which found that without a large increase in sampling numbers, national soil quality data were not useful at the catchment scale (McDowell et al. 2024).

Norris et al. (2023) provide an assessment of nitrate-N leaching losses in nine commercial cropping farms located in the Canterbury, Manawatū, Hawke's Bay, Waikato and Auckland regions. Leaching losses were measured at 1.2 m below the soil surface using a network of passive-wick drainage fluxmeters, with sites monitored for periods ranging from 51 to 72 months. Physical and hydraulic soil properties were measured, including bulk density and macroporosity (at -10 kPa).

Biological outcomes

There are New Zealand studies that have assessed soil biological indicators and various soil properties. These studies are often more descriptive than causal with regard to the association between soil biological measures and soil properties. For example, a study by Schon et al. (2023) assessed the state of all seven soil quality indicators (excluding HWEC) across a chronosequence of soils under forestry to dairy pasture on Ngāi Tahu properties in Canterbury. A total of 21 samples at 0–7.5 cm depth were collected across three farms and one forestry block with a common soil type (Pallic Firm Brown). Data on soil microbial respiration, earthworm abundance and diversity, and pasture pests and diseases were also collected and discussed in the context of soil health. Schon et al. (2023) discuss the response of soil biology to N and P fertiliser additions in New Zealand studies.

Hermans et al. (2020) demonstrated, from an analysis of 110 sites, a correlation between microbial community composition and soil physicochemical properties. In particular, the authors noted strong correlations between the relative abundances of specific taxa and both soil pH and concentrations of Olsen P in the soil, although the significance of these differences in abundance is unclear.

Stevenson et al. (2016) measured soil organic matter concentration and composition, as well as nutrient ratios and other soil characteristics, on two contrasting soil types (Allophanic and Gley) across three land uses (forest, pasture, maize cropping) to determine their relationships to microbial abundance and specific measures of microbial activity (e.g. qCO_2 , the ratio of respiration rate to microbial biomass and net laboratory N mineralisation). Various chemical properties including total C and N, pH, Olsen P, AMN, and HWEC were measured, in addition to the biological measures. These authors identified that AMN and HWEC (as measures of available C) best explained the variation in microbial biomass and function across sites. AMN generally explained the most variation for microbial biomass and qCO_2 and had the smallest soil or land-use effect. HWEC explained the most variance for net N mineralisation.

Wakelin et al. (2021) assessed the impacts of land-cover type (native forest, planted forest, and pastoral agriculture) on soil bacterial diversity and function. Twelve sites were sampled across an environmental gradient in the South Island. Data on five soil quality indicators (pH, total C, total N, Olsen P, and bulk density) at 0–5 cm depth were collected in addition to the soil bacterial community and functional measures. These authors concluded that land-use intensification, not land cover change *per se*, shifts microbial biodiversity by altering the primary habitat conditions, particularly soil pH.

In addition to soil pH modifying microbial community composition, low soil pH (c. 5.0) has been linked to increases in the proportion of N_2O to N_2 emitted through soil denitrification (van der Weerden et al. 2022). These authors investigated the influence of adjusting soil pH on N_2O emissions in New Zealand pastoral soils, and concluded that adjusting soil pH from c. 6 to c. 7 was not an effective tool for reducing N_2O emissions from urine patches.

4.5 International approaches to developing soil quality target ranges

4.5.1 European indicators and thresholds

Various approaches have been considered to determine thresholds and benchmarks for soil quality indicators in the EU, particularly for soil organic carbon (SOC), N (as C:N ratio), P (as Olsen P or other extractable P), pH, and bulk density (EEA 2023). A wide range of approaches was considered for the derivation of SOC thresholds, as summarised in 20.

Table 20. Approaches considered for setting European thresholds for soil organic carbon, adapted from EEA 2023

Approach	Description/comments
Site-specific reference values – typical SOC values under current management (Arshad & Martin 2002)	Derived from existing monitoring systems for different land uses; 50% of the standard deviation of the mean are 'low'; i.e. deficient
Benchmark values	benchmark sites reflect environmental and management conditions that are representative of a large area (van Lynden et al. 2004), with each site representing a very specific set of local conditions that are distinct from other environments; benchmark sites are particularly important to validate simulation models of indicators, which requires extensive monitoring evaluations and large data sets to sufficiently define site-specific values.
Near-natural forest soils (Arshad & Martin 2002)	Problematic due to differences in humus dynamics between cropland and forest soils.
25 th percentile of values for permanent grassland (Sparling et al. 2003)	The selection of quartile thresholds needs validation.
Modelled SOC steady-state (25 years) for grasslands	80% of steady-state value as target SOC value.
12.5 th and 87.5 th percentiles as upper and lower benchmarks (Drexler et al 2022)	Example done using German inventory of agricultural soils (0-30 cm depth) stratified into 33 strata using land use (cropland, permanent grassland and ley-arable rotation), soil texture and mean annual precipitation, and C:N ratio (<13, 13–15, >15).
Optimal SOC content for soil functioning (Wessolek et al. 2008)	Based on the role of SOC in soil functional pedotransfer function, combined with data from long-term field experiments
SOC:clay ratio – ultimately chosen as the approach to inform threshold values for EEA (2023)	Used to determine a soil vulnerability index. Optimum SOC content is defined as 10% of clay content.
Reciprocal SOC sequestration potential	Optimal SOC content for the CO ₂ mitigation function of soils; target ranges represent SOC equilibrium under long-term sustainable soil management.
Thresholds from long-term field experiments	Minimum SOC levels for sustainable crop production; conceptually comparable to optimal SOC content for soil functioning
Farmers' perspectives on deficient SOC	Degraded SOC levels according to farmers' perceptions

An approach used by Grilli et al. (2021) to determine critical ranges for SOC in Mediterranean topsoils at risk of desertification involved assessing functional relationships between SOC and other soil properties at 38 sites under different land cover and management. Strong relationships were observed between SOC and total N, bulk density, cation exchange capacity, available water capacity, microbial biomass, C fractions associated with particulate organic matter and the mineral soil component, and indirectly with net N mineralisation. A critical threshold was defined based on the value below which steep variation of all the analysed soil indicators was observed (20 g SOC/kg).

Two approaches were considered for the derivation of thresholds for nutrients including N and P:

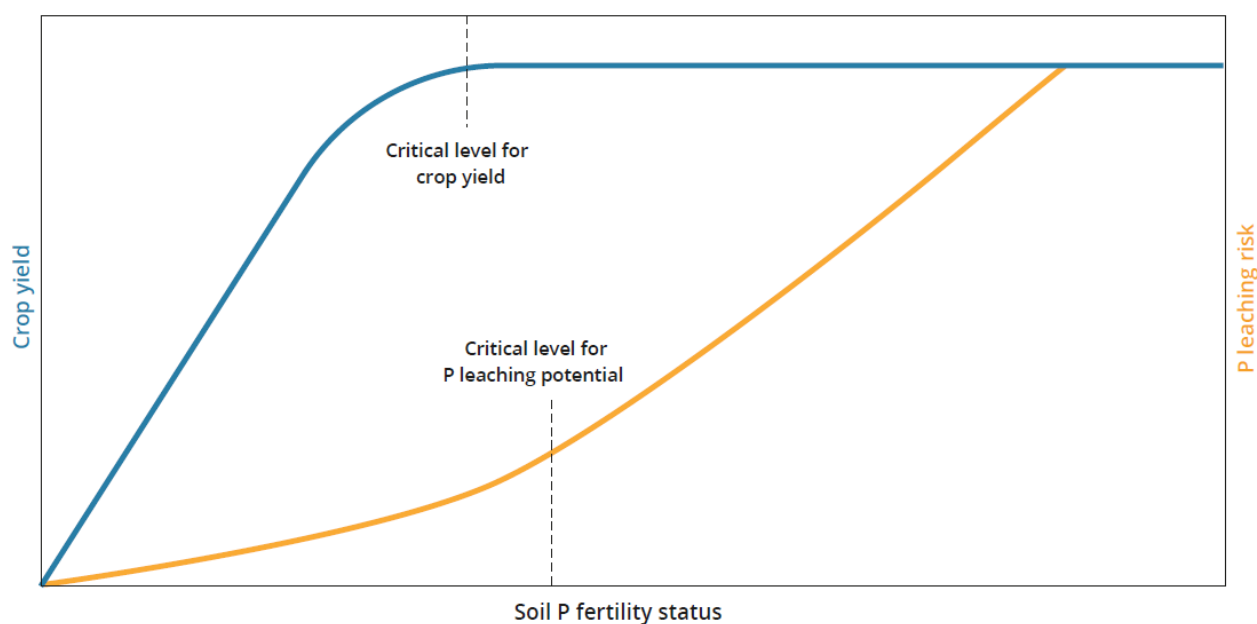
- back-calculation of policy thresholds/targets (e.g. nitrate in groundwater, drinking quality standards) into critical limits in soils (the maximum acceptable concentration at the point of sampling in the soil, so that the threshold in the groundwater or surface water is not exceeded)
- science-based functional limits of soil parameters (e.g. acidification, soil biodiversity) (EEA 2023).

Targets or thresholds were not defined for total N in agricultural soils. Instead, the focus is on N inputs, as

losses of N to air and water, negatively affecting air and water quality, are more related to N inputs and the soil properties affecting denitrification and thus N leaching (especially clay content and groundwater level) and N emissions, rather than the actual soil N status. (EEA 2023)

In this context, mineral N (i.e. nitrate N and ammonium N) is used for fertiliser recommendations, and critical N inputs are calculated as those that result in thresholds for ammonia in air, nitrate in groundwater, and N in surface water being exceeded. In forest soils, threshold C:N (and N:P) ratios for organic layers were defined as a measure for N to prevent N leakage >1 mg N/L.

To determine target ranges for Olsen P in agricultural soils, an approach was discussed that considered both environmental and production outcomes through the use of critical levels for both crop production and water quality. It was noted that target ranges should be both above a limiting concentration for crop yield and below a critical level for P leaching and run-off risk (Figure 1). As with N, an approach focusing on fertiliser input rates rather than total soil concentrations was also discussed. Here it was noted that inputs should be tailored to crop-specific needs and should not exceed crop requirements to minimise the risk of nutrient loss (EEA 2023).



Source: Bai et al. (2013).

Figure 1. Relationships between crop yield (left y-axis), P leaching risk (right y-axis), and soil P fertility status (x-axis), considered in an approach to determine target ranges for Olsen P.
(Source: Bai et al. 2013 as cited in EEA 2023)

Target ranges for bulk density were based on German Rules and Standards (DVWK 1997, 1998 in EEA 2023). However, limitations on the use of this parameter were noted, including high spatial and temporal variability and a lack of quantification of negative effects on pore functions, including direct links to soil strength or compaction from bulk density measurements (EEA 2023). If bulk density is used as an indicator, EEA (2023) recommends that additional (visual) information about, for example, texture or soil structure, is also required to gain a better qualitative judgement of compaction. It was also noted that bulk density measurements can be difficult, and therefore can be misleading, in dry, strongly rooted and stony soils (particularly when using an ‘intact core’ method). Packing density, which is based on bulk density and clay content, has been proposed as a proxy indicator for soil compaction (Panagos et al. 2024).

The chosen thresholds and underpinning approaches for all indicators are detailed in Table 21, although the basis for selecting these particular thresholds is unclear.

Table 21. Recommended thresholds for some soil quality indicators and the underpinning approach or justification

Indicator	Land use	Threshold	Justification
Soil organic carbon*	Cropland	Light soils: <1.2% Medium soils: 1.2–1.9% Heavy soils: >1.9%	Based on SOC:clay ratio (Johannes et al. 2017)
C:N ratio	Forest land	20–25	Forest floor organic layer
Olsen P	Agriculture	25–35 mg/kg	Extractable P concentration less than the optimum (value range refers to Mehlich 3-ICP, available P-Bray P1 and Olsen P)
pH	Agriculture	<4.5–4.7 <5.0–5.5	Critical range – risk of aluminium toxicity Avoid – limited availability of calcium, magnesium, potassium and phosphorus
Bulk density		<1.2 g/cm ³ = very loose 1.2–1.6 g/cm ³ = normal 1.6–1.9 g/cm ³ = dense >1.9 g/cm ³ = very impermeable	Based on German Rules and Standards (DVWK 1997, 1998), although recommended only as a sub-indicator

Source: Adapted from EEA 2023.

* While not mentioned in EEA 2023, a global meta-analysis of the relationship between SOC and crop yields found that yield of maize and wheat increases with SOC but starts to level off at approximately 2% (Oldfield et al. 2019).

4.5.2 UK soil health benchmarks

Feeney et al. (2023) describe an approach to deriving soil health benchmarks for managed and semi-natural environments across Great Britain using nationally representative topsoil (0–15 cm) measurements. The soil properties assessed were soil organic matter (SOM, 4,587 datapoints), pH (3860), bulk density (2908), and earthworm abundance (465). Data were stratified by habitat (nine habitats), soil type (six), and mean annual precipitation (high and low). The minimum sample sizes required for each soil health indicator were determined. For example, the authors found that six high-order soil types were benchmarkable on three habitats (arable and horticulture, modified/improved grassland, and neutral and calcareous grasslands). Benchmarks were defined as the middle 80% of values in each distribution (i.e. between the 10th and 90th percentiles, based on similar benchmarking approaches (e.g. Drexler 2022; Griffiths et al. 2018). This choice was

recognised to be arbitrary, with the middle 80% of observed values of soil health indicators described as 'typical', with the 10% of values either side considered to be 'above typical' and 'below typical'. Medians were also calculated to show the midpoint of each benchmark distribution. The distribution of the measured values of indicators is shown in Figure 2.

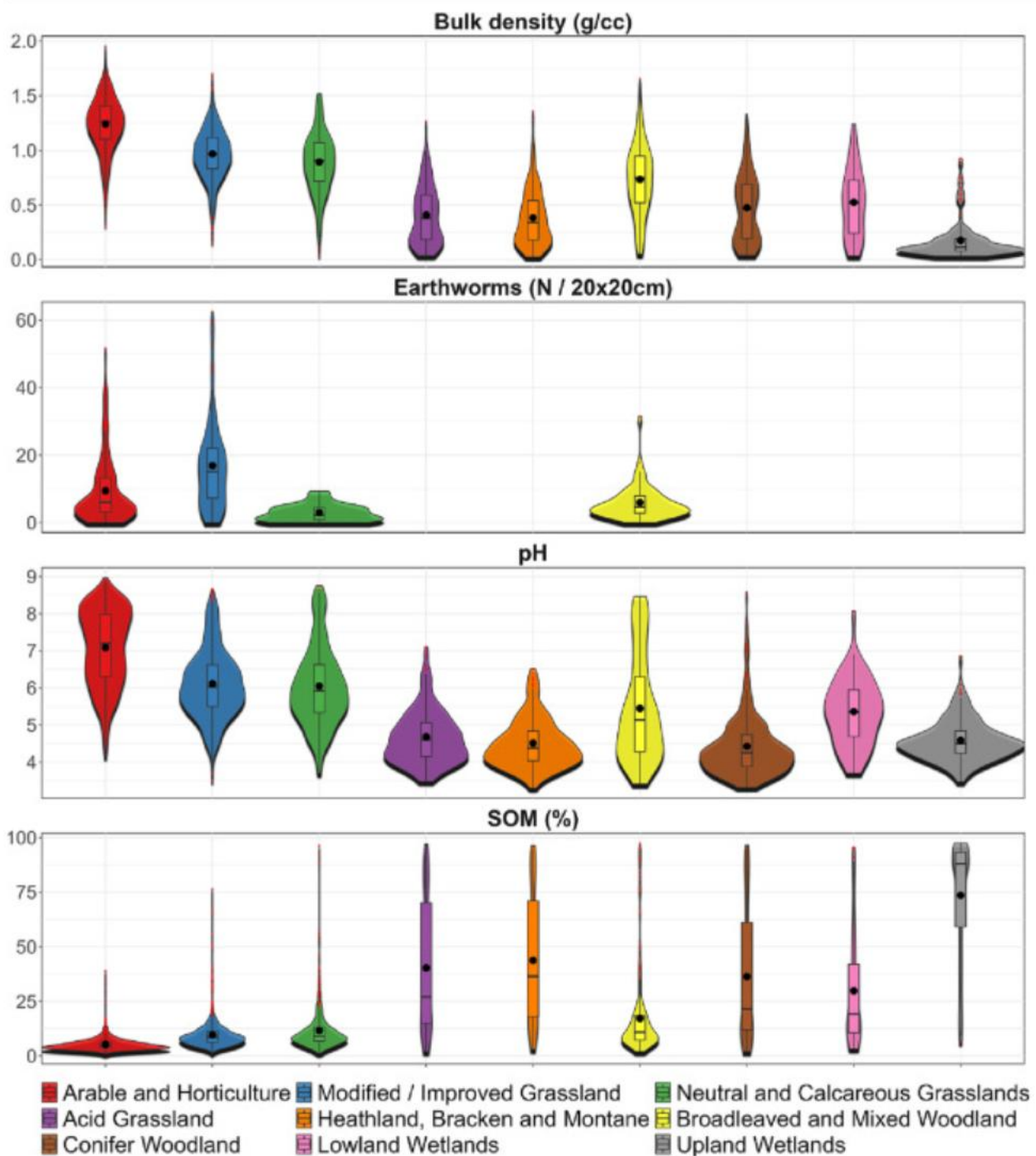


Figure 2. Distributions of soil health indicators within each habitat; units in panel headings.

Note: Earthworm abundance was recorded in all habitat classes, but there were too few data points to display distributions for five of these habitats after deep peats and disturbed industrial soils had been removed. (Source: Feeney et al. 2023).

4.5.3 Cornell Comprehensive Assessment of Soil Health

The Cornell Comprehensive Assessment of Soil Health (CASH) uses scoring functions for each indicator to interpret soil health measurements. Specifically, 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 upon 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 3 provides an overview of the development of the scoring.

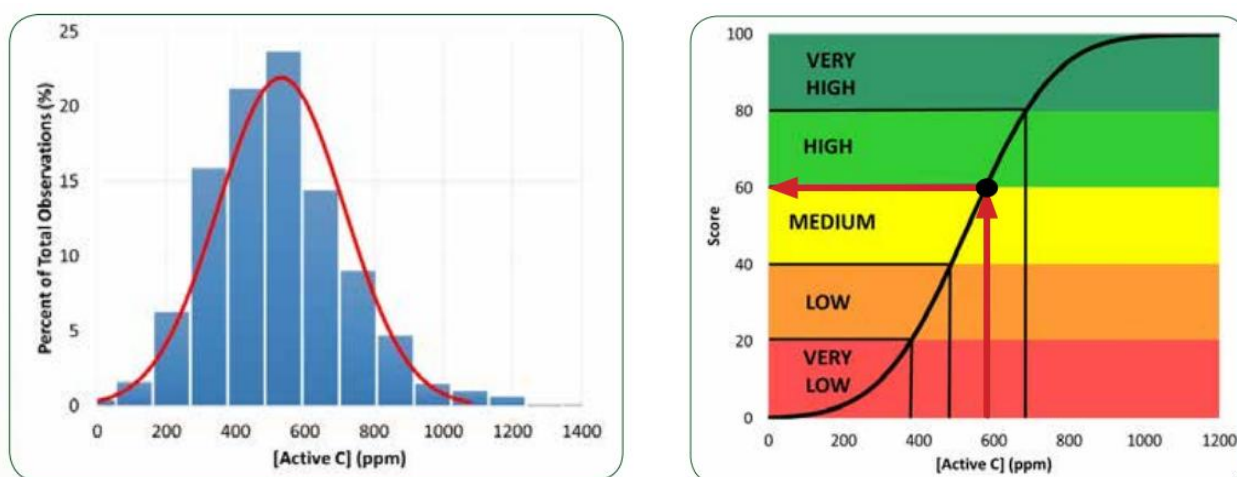


Figure 3. Example of the development and use of scoring indicators for assessing the soil quality results. Left: the mean and standard deviation derived from the normal distribution describing the frequency distribution of active carbon is used to calculate the cumulative normal distribution (CND). The 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)

4.5.4 Soil Health Institute – soil health gap

The use of a 'soil health gap' to determine appropriate benchmarks for soil indicators is an approach used by the Soil Health Institute in the USA. A soil health gap is defined as the 'difference between soil health in an undisturbed native virgin soil and current soil health in a cropland in a given agroecosystem' (Maharjan et al. 2020). This concept is demonstrated in Figure 4.4. The approach was developed for cropland and uses reference sites for particular soils and climatic

regions. Rather than target ranges, indicator values at reference sites are considered to be attainable benchmarks that represent optimal values to be worked towards (B. Stevenson, pers. comm., 11 July 2024). Examples of the use of this approach in Maharjan et al. 2020 focus on soil C measures, with the Soil Health Institute recommending measures of SOC concentrations, C mineralisation potential, and aggregate stability to assess soil health (Bagnall et al. 2023).

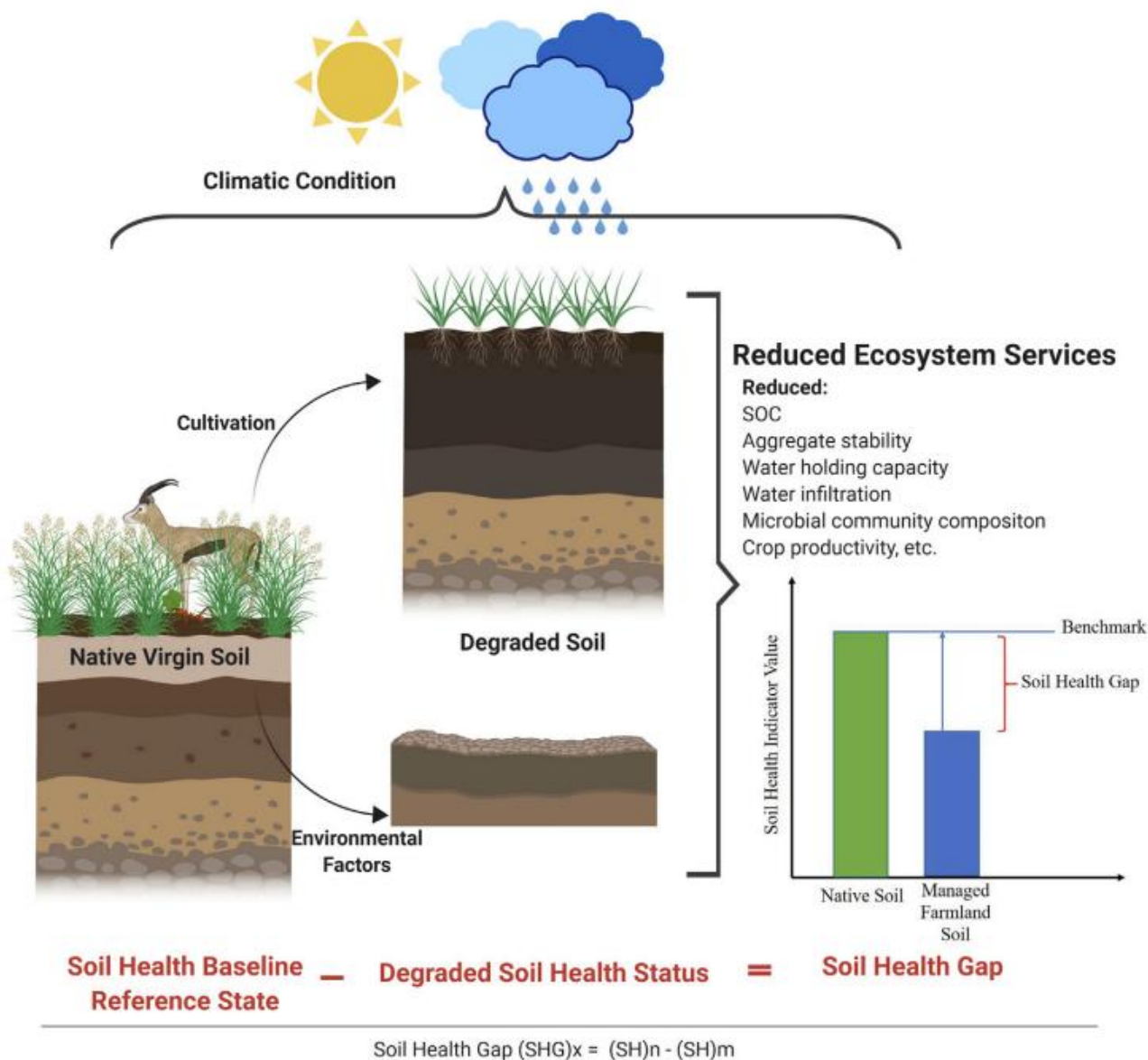


Figure 4. Graphical representation of the soil health gap concept. (Source: Maharjan et al. 2020)

4.5.5 Structural regression

One approach to the development of optimal ranges for soil physical properties that has been widely cited is the structural regression approach of Reynolds et al. (2008). These authors developed relationships between relative water capacity, which expresses the soil's capacity to store water and air relative to the soil's total pore volume, and other soil properties, including organic C, bulk soil air capacity, soil matrix air capacity, macroporosity, matrix porosity, field capacity, plant-available water capacity, saturated hydraulic conductivity, and bulk density. Results were used from soil samples collected at 0–10 cm from a site with 16 treatments, including three

cropping treatments under long-term management (14–16 years), 12 cropping treatments under short-term management (1–4 years), and one 'virgin soil' treatment that had never been cropped or cultivated, to encourage a broad range of indicator values. Management treatments included conventional mouldboard plough tillage, no-tillage, and continuous bluegrass sod.

An optimal relative water capacity of 0.6 to 0.7 is the primary variable against which other parameters are regressed using a 'least squares bisector' method. This optimal range was suggested to be the range that maximises microbial production of nitrate that is usually limiting in field crop production on mineral soils (Reynolds et al. 2008). Optimal ranges for other soil indicators were determined either from their regression relationships with bulk density or directly with relative water capacity. (Soil/site-specific optimal ranges of $3 \leq \text{OC} \leq 4$ wt.%, $1.10 \leq \text{BD} \leq 1.23$ Mg/m³, and $0.09 \leq \text{POR}_p \leq 0.13$ m³/m³, $0.30 \leq \text{FC} \leq 0.35$ m³/m³).⁴

The method is potentially feasible if (1) data for indicators from specific soil–land use–climate combinations are available; (2) there is one indicator with high confidence of, or safely assumed, optimal range; (3) other indicators are correlated with the high-confidence optimal range property, which is analysed by structural regression.

4.5.6 Overview of approaches for deriving target ranges

Stevenson & Drewry (2022) provided a summary of nine approaches used to derive target ranges for soil quality indicators, along with the strengths and weaknesses of each. This summary is provided in Table 22 and was adapted from Taylor 2021. Some of these approaches are mentioned in other sections throughout this report but are tabulated here for clear comparison. Taylor compiled this summary when considering approaches that could be used to set target ranges for New Zealand soil quality monitoring indicators. He concluded that each indicator would probably require a combination of approaches, and that an expert panel would be needed to synthesise and finalise recommended ranges in order to avoid biases in any one approach (Stevenson & Drewry 2022).

⁴ OC = organic carbon; BD = bulk density; POR_p = macroporosity; FC = field capacity.

Table 22. Approaches for deriving target ranges, and the strengths and weaknesses of each approach

Approach	Strengths	Weaknesses
<p>1) Expert panel</p> <p>The panel specialists arrive at conclusions and recommendations through consensus.</p>	<p>Experts have knowledge of the subject. Quick to assemble. Cost effective. Credibility of the conclusions.</p> <p>Adaptability to a variety of situations encountered in evaluation.</p> <p>Can be used to establish standard non-linear scoring functions.</p>	<p>Requires experts with recognised expertise in the area of interest.</p> <p>Requires objectivity, as results can be distorted by lobbyists or a 'dominant' expert who is too influential.</p> <p>Consensus tends to eliminate minority views and tone down conclusions.</p> <p>Experts tend to go beyond their area of expertise.</p>
<p>2) Percentiles</p> <p>A percentile is a value below which a certain proportion of observations fall. Values falling above or below specific percentiles may be considered to be out of range.</p>	<p>Can separate typical behaviour from unusual behaviour.</p> <p>Not strongly influenced by outliers.</p> <p>Can use non-normally distributed data.</p> <p>Informs where a score stands relative to other scores.</p> <p>Allows continuing evolution of the system.</p> <p>Used as a substitute where critical values are absent (Gil-Sotres et al. 2005).</p> <p>Gives a relative assessment.</p>	<p>Oversimplification of underlying physical-chemical processes.</p> <p>Represents rank order only, as it only informs where a score stands relative to other scores – little on the degree of soil quality.</p> <p>Potentially skewed by purpose of observations</p> <p>For example, Dutch soil quality monitoring target ranges are based on median values of the monitoring network.</p>
<p>3) The natural state</p> <p>The outer limit of background variation (Kowalska et al. 2018). This usually takes a percentile as the target.</p>	<p>Distinguishes natural state from unusual, normal from anomalous, usually in relation to contamination.</p>	<p>No information on the quality of soil; does not consider the impact of the parameters measured on soil properties.</p> <p>The reference may not be at an optimum for all parameters.</p> <p>Background soils may not be suitable for productive use, so are of limited comparison value.</p>
<p>4) Reference soils</p> <p>The same type and properties of the studied soil (Bünemann et al. 2018; Kaufmann et al. 2009; Kowalska et al. 2018).</p> <p>Sampled at the same time or once as a baseline.</p> <p>A reference soil is in equilibrium with all the components of the environment; capable of maintaining high productivity and causing the minimum of environmental distortion.</p>	<p>Distinguishes normal from anomalous.</p> <p>Can provide direct comparisons for soil quality parameters.</p>	<p>Needs to be the type and properties of the studied soil, otherwise this introduces uncertainty.</p> <p>Not all monitored soils may have suitable reference sites.</p> <p>Reference properties can change if monitored at the same time as the studied soil (Iturri et al. 2016).</p> <p>Ideal reference will not always match maximum standards of soil quality.</p>

Approach	Strengths	Weaknesses
5) Calibration to risk A risk index or threshold of contamination	Established toxicological critical values for most common contaminants (most commonly applied to trace elements/contaminants).	Complex – depends on test organism and component, so several exposure routes should be considered (Fernández et al. 2006) Emerging and uncommon contaminants may lack toxicological critical values (Cavanagh & Harmsworth 2022).
6) Agronomic optimums	Fertility well established.	Referenced to small plot trials, which adds uncertainty when comparing to soil quality monitoring representative sampling. Values depend on crop and species grown, not soil function or environmental outcome.
7) Comparison with field observations For example, Visual Soil Assessment (VSA)	Field methodology relatively quick and simple. Direct relationship with some soil properties demonstrating unfavourable changes in soil structure (Moncada et al. 2014; Shepherd 2003).	Subject to operator bias (e.g. in comparing results from different operators either temporally or spatially). Mainly applicable to physical measures. Qualitative or semi-quantitative rather than quantitative. Cohesive, sandy, and peaty soils present problems. Lack of research into the influence of soil moisture content on VSA criteria.
8) Demarcation of critical thresholds or triggers for specific soil functions	Would signify a significant change to soil functioning.	While there are some data for critical values for specific plants or organisms (particularly for contaminants), there are few data for many soil functions. Also, many indicators affect different functions in different ways.
9) Biological indicator approach using the behaviour and activities of soil microorganisms (or other soil organisms)	Communities are strongly affected by changes in soil conditions. They are also ubiquitous and can predict soil physico-chemical characteristics.	Response models, thresholds, and critical values have yet to be developed.

Source: Adapted from Stevenson & Drewry 2022

Matson et al. (2024) described four approaches to setting thresholds and target values, and explored stakeholder perception of the approaches, as well as their practical use, using a case study of SOC in three different locations in Europe through two online meetings of the European Joint Programme on Agricultural Soil Management Policy Forum. These meetings included participants from policy, consultancy, industry, and science, with 72 and 263 attendees respectively participating in the online questions to explore the development and approach to setting target and threshold values.

These authors define a target as an indicator value desirable to reach (i.e. a known limit or achievable value), while a critical threshold is the 'minimum criterion,' an indicator value above/below which soils are targeted as needing intervention, without implying that soils that

meet these criteria are in a good state. A range (i.e. defined upper and lower values) was also identified as being able to be used as a broad target, or as a set of critical thresholds. The four approaches to setting thresholds and target ranges are:

- fixed: a static value based on the best available research/knowledge; stratified as required
- reference: a static value, calculated as a percentage of what would be found in a reference situation, where soil processes are occurring in a way that is considered to be desirable; stratified as required.
- distribution: a changeable value, based on the regional state of the soil (i.e. a target/threshold defined as a certain percentile of the current observed range of values); static only until distribution is re-measured, after which the target/threshold may change
- relative change: a changeable value, based on the local state of the soil (i.e. a target defined as an increase or decrease of a certain percentage within a specified number of years); static only for a stated time span, after which the soil is re-measured and the target will change.

Table 23 outlines the strengths and weaknesses of these approaches for developing target and threshold values.

Table 23. Summary of the strengths and weaknesses of different approaches for developing target and threshold values, as outlined in Matson et al. 2024

Approach	Strengths	Weaknesses
Fixed	A quick way to start assessing at a large scale. Can be used at field scale and is simple to understand for practitioners.	Needs stratification: there is a lack of knowledge at the level required to adequately stratify (soil, climate, land use, management, history, etc.).
Reference	Given an appropriate reference, provides an approach to establish a value; a single value is simple to use for practitioners.	Needs stratification: many indicators/ regions will not have an appropriate reference. Criteria to decide percentage are arbitrary and difficult to explain.
Distribution	Provides an approach to establish a region and land-use specific value. Can be useful for practitioners to see how they compare to others in the sense of developing continual improvement.	Needs stratification, dedicated sampling to get an unbiased estimate of the statistical distributions. Distribution will be skewed if area is already degraded. Criteria to decide percentiles are arbitrary and difficult to explain.
Relative change	Provides a quick way to start evaluating trends; highly situation specific (no stratification required); takes starting point into account.	May be problematic for land managers who are already doing well. May not be applicable for mapping if there is high uncertainty with respect to changes. At national level may require the implementation of a robust monitoring network.

These authors highlight the dual requirement for scientific input to assess the targets and thresholds based on a knowledge of soil properties and functions, as well as stakeholder input to clarify the purpose and needs of the assessment. For example, how far a soil is from the threshold can be used as a tool to prioritise the urgency of management changes, depending on the average soil health within the region of interest and/or the level of confidence associated with the

threshold. How far a soil indicator datum is from an 'optimal' target in order for measures to be implemented should be decided by governance authorities and stakeholders, rather than science.

Critically, these authors identify that there is no best approach: the most appropriate approach will depend on the type and quality of available data, and the purpose of soil health assessment (i.e. from stakeholders). They also observe that identifying targets and thresholds, and monitoring soil data against these targets and thresholds over time, is required to identify trends and assess the impacts of land-use changes, management practices, and public policies.

5 Volumetric and gravimetric Olsen P conversions

This chapter is largely drawn from Drewry et al. 2022 and describes the basis for conversions between Olsen P volumetric and gravimetric data.

5.1 Background

In New Zealand, soil Olsen P analysis is undertaken by two methods. Both are based on the original Olsen P test, but one method is based on the analysis of a known mass of soil (gravimetric method), while the other modified method is based on the analysis of a known volume ('scoop') of soil (volumetric method) (Drewry et al. 2022). As discussed in section 4.2.1, during the course of this project we identified that incorrect measurement units have been used for Olsen P target ranges for SoE reporting. Specifically, target ranges that were considered to be based on gravimetric measures of Olsen P (mg/kg) are actually based on laboratory volumetric measures (mg/L).

The gravimetric method is detailed in Blakemore et al. 1987 and is used by MWLR and other New Zealand research institutes (Plant & Food Research, some universities, etc.). It is also the recommended method in the LMF guide for SoE soil quality monitoring (Hill & Sparling 2009) and the National Environmental Monitoring Standards (NEMS 2022). These results are reported as mg/kg.

The 'scoop' or volumetric method was adopted for farm soil fertility–yield assessment during 1992 by the former Department of Scientific and Industrial Research, Ministry of Agriculture and Fisheries, AgResearch, and some commercial laboratories based on research by these agencies that related volumetric measures of Olsen P to plant yield. Consequently, the volumetric method is widely used in New Zealand agriculture and the soil fertility industry for farm nutrient management and Olsen P fertility research trials. As a further result, the modified test is used in much of the soil fertility literature (e.g. Cornforth & Sinclair 1984), and editions of the Fertiliser Association of New Zealand soil fertility booklets for sheep farms (Morton & Roberts 2009) and dairy farms (Roberts & Morton 2023). The units of measurement are milligrams of P per litre of soil (mg/L), but are not always identified in tables of values (e.g. Roberts & Morton 2023).

As a result of this historical evolution, several commercial laboratories (e.g. Hill Laboratories) test soil Olsen P using the 'modified' (volumetric) method on a routine basis. Hill Laboratories can provide a 'volume weight' measure, which is the weight of soil by volume of sieved and air-dried sample, and which allows ready conversion to the gravimetric measure. However, volume weight has seldom been requested by regional councils for regional soil quality reporting (Drewry et al. 2022).

Another confounding issue is that earlier reporting of soil quality SOE results was expressed on a volumetric basis using field bulk density measurements to determine P 'stocks' (e.g. as in Sparling et al. 2004). This is problematic because bulk density can change over time, as discussed in more detail in Drewry et al. 2022.

5.2 Method

A total of 326 soil samples, from 12 New Zealand soil orders, were obtained from five regional authorities' soil quality monitoring programmes, along with bulk density data. Briefly, gravimetric Olsen P was determined on all samples by the MWLR laboratory. Subsamples were prepared and sent to Hill Laboratories, Hamilton, to determine volumetric Olsen P concentration and volume weight.

A series of statistical models was developed to define the relationship between gravimetric and volumetric Olsen P. In short, the best statistical model was a generalised linear mixed-effects model (GLMM) with a log-link (a linear predictor for the log-transformed Olsen P). The GLMM uses the volumetric Olsen P as a fixed effect and the soil order as a random effect. The model can be represented as:

$$\eta = \text{Olsen P} + \text{soil order}_i \quad (2)$$

where η is the linear predictor, and since the log-link is used, $\eta = \log \mu$, where μ is the predicted gravimetric Olsen P. The model to predict volumetric Olsen P from gravimetric Olsen P is developed in the same way.

To assess the relationship between bulk density and volume weight, a linear model between bulk density and volume weight was fitted, as follows:

$$\text{Bulk density (Mg/m}^3\text{)} = \beta_1 \cdot \text{Volume weight (g/mL)} + \epsilon \quad (3)$$

where β_1 is a constant, and the uncertainty is captured by ϵ .

Full details and an explanation of the laboratory analytical and statistical modelling methods are described in in Drewry et al. 2022.

5.3 Key findings

Drewry et al. (2022) confirmed that conversion of volumetric Olsen P concentrations to gravimetric Olsen P concentrations using laboratory volume weight results in no apparent bias of data. The relationship between bulk density (i.e. undisturbed sample, dried at 105°C) and laboratory volume weight (i.e. sample that has been air-dried and sieved) for each soil order was also examined. The results showed that bulk density values are generally greater than the corresponding values of volume weight, which means conversion using bulk density results will lead to errors in converted data.

However, in the event that volume weight is not available (e.g. for historical data), the above equations and the published conversion tables enable gravimetric-to-volumetric and volumetric-

to-gravimetric conversion using laboratory data. The coefficients for the conversion equations for the two GLMM models (volumetric-to-gravimetric and gravimetric-to-volumetric) are presented in Appendix 5. Example values of the conversions are presented in Figure 4 and Figure 5. The full conversion tables for all soil orders analysed are presented as supplementary material in Drewry et al. 2022. Gravimetric values of Olsen P are larger than the corresponding volumetric values, and the difference between them is larger for larger Olsen P (see Table 24).

Table 24. Examples of conversion of Olsen P from volumetric units to gravimetric units for several soil orders

Volumetric Olsen P (mg/L)	Allophanic	Brown	Recent	Gley	Ultic	Granular	Pumice	Pallic
Gravimetric (mg/kg)								
10	13	13	13	13	14	13	19	14
20	27	27	25	27	28	25	38	28
30	40	40	38	40	41	37	57	42
40	53	53	51	53	55	50	76	56
50	67	66	63	66	68	62	94	70
60	80	79	76	79	82	74	113	84
70	93	92	88	92	96	86	132	98
80	106	106	101	106	109	99	150	112
90	119	119	113	119	123	111	169	126
100	132	132	125	132	136	123	188	140

Note: Values have been rounded.

Table 25. Example conversion of Olsen P from gravimetric units to volumetric units

Gravimetric Olsen P (mg/kg)	Allophanic	Brown	Recent	Gley	Ultic	Granular	Pumice	Pallic
Volumetric (mg/L)								
10	8	8	9	9	8	9	6	8
20	16	16	17	16	15	18	12	15
30	23	24	25	24	22	26	18	22
40	30	31	32	31	29	34	23	29
50	37	38	40	39	36	42	29	36
60	44	45	47	46	43	49	34	43
70	51	52	55	53	49	57	39	49
80	58	59	62	60	56	65	45	56
90	65	66	69	67	62	72	50	62
100	72	73	77	74	69	80	55	69

Note: Values have been rounded.

6 Data analysis to inform revised numeric criteria soil quality

6.1 Introduction

Section 4.4 provides an overview of data sets or studies that may help to inform the development of revised numeric criteria. In this section we use both a logic assessment approach and analysis of the baseline monitoring data set (see section 3.4.2) to help 'ground-truth' or assess potential influences of soil orders or land uses on key variables to help identify key factors or approaches. The logic assessment evaluated the first principles on which measured values might be interpreted in the context of environmental or production considerations. This in turn helped to inform additional data analyses that may be useful for developing numeric criteria.

6.2 pH

Soil pH is a measure of soil acidity, and an indication of lime requirement and the likelihood of trace element deficiencies or toxicities. Figure 5 provides an overview of the environmental considerations related to differing pH values and the factors influencing pH on primary production land.

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). Specifically, the influence of pH on N₂O emissions may be the most relevant endpoint to consider from an environmental perspective, particularly for high-intensity livestock grazing systems. However, variable responses of N₂O emissions to pH are reported. For example, van der Weerden et al. (2020) observed an increase in N₂O emissions with pH 6.5–7.4 from a laboratory study, while a global meta-analysis identified that the highest emissions occur over a pH range of 5.6–6.3 (Qui et al. 2024). Other studies identify a positive relationship between soil pH and N₂O emissions: increased rates of nitrification and N₂O production have been observed with increasing pH (Goodroad & Keeney 1984; Li et al. 2015), while van der Weerden et al. (2021) concluded that adjusting soil pH from c. 6 to c. 7 was not an effective tool for reducing N₂O emissions from urine patches in pastoral soils.

From a primary production perspective, there is well-established guidance for the pH range for optimal growth, with results outside the optimal range indicating the potential to limit agronomic production. There are recognised trace element issues arising from soil pH as a result of changes in the bioavailability of these trace elements. This is observed particularly for pastoral systems, and for some specific crops (Figure 5). Specifically, at low pH, plants such as clover that are sensitive to toxicity associated with aluminium may be affected (e.g. Morton & Moir 2018), while at higher pH trace element deficiencies may arise as a result of reduced availability of essential elements. For pastoral land use, the increased availability of molybdenum at higher pH may induce copper deficiency in livestock. Under natural conditions soil pH will vary among soil orders; most often soils will be slightly to moderately acidic (Hewitt et al. 2021).

pH - a measure of soil acidity and an indication of both lime requirement and the likelihood of trace element deficiencies or toxicities

Lime addition as required for target plant species

Lime generally not applied

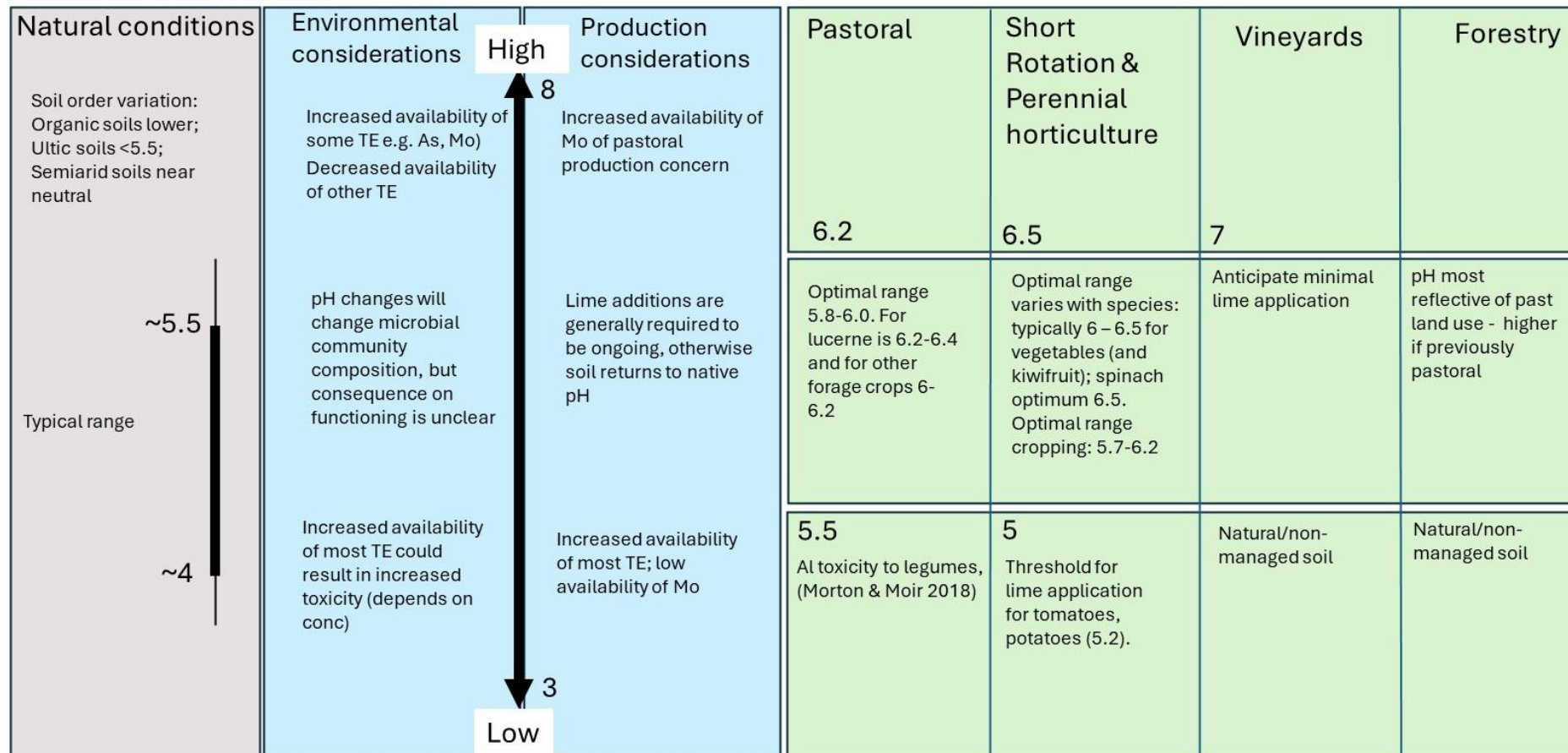


Figure 5. Logic assessment of the potential interpretations of measured values of the pH indicator, and pH requirements associated with different agricultural plant species. (Source: drawn from Reid & Morton 2019 and Morton 2019)

TE = trace element; As -arsenic, Mo- molybdenum.

For comparison with the agronomic recommendations shown in Figure 5, the distribution of pH results from the baseline monitoring data set are shown in Table 26. Cropping and perennial horticulture, including vineyards, have the highest 90th percentile pH measurements.

Table 26. Distribution of pH values in monitoring data set according to specified land use

Soil orders	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile	Agronomic recommendations
All	Cropping & orchards	387	6.2	5.6	6.8	5–6.5 ^a
All	Dairy	336	5.9	5.5	6.3	5.5–6.2 ^b
All	Drystock	508	5.7	5.2	6.2	5.5–6.2 ^b
All	Exotic forestry	156	5.4	4.7	6.0	N/A
All	Indigenous vegetation	130	5.5	4.7	6.2	N/A
All	Lifestyle	17	6.0	5.7	6.2	N/A
All	Urban	50	5.8	5.3	6.3	N/A
All	Vineyard	46	6.4	6.0	7.0	5.5–7

^a Reid & Morton 2019; Nicholls et al. 2012

^b Morton 2019; Morton et al. 2020

6.3 Olsen P

Olsen P is the primary measure of plant-available P. Considerable research on plant response to Olsen P has been undertaken over the last 30 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 information for perennial horticultural crops such as kiwifruit and vineyards, and for forestry. Water quality issues are the environmental outcome of most concern in relation to elevated soil Olsen P, although this is influenced by multiple factors see Figure 8 and surrounding text). Figure 6 provides an overview of the environmental considerations related to increasing Olsen P values, and fertiliser application considerations for primary production land.

Olsen P – measure of plant-available P
(Units in mg/L)

P addition as required for target plant species

P generally not applied

<p>Natural conditions</p> <p>Soil order variation in P-retention/ anion storage capacity (ASC)</p> <p>Generally low (<10)</p>	<p>Environmental considerations</p> <p>Risk to water quality – associated with P-retention/ASC [and other factors]</p> <p>Olsen P changes will change microbial community composition but consequence on functioning is unclear</p> <p>P-addition will reduce mycorrhizal associations, increasing reliance on inorganic P supply but this will occur from low P-addition, and significance depends on plant species</p>	High	<p>Pastoral Intensive</p> <p>45 Pumice, peat</p>	<p>Vegetable Cropping</p> <p>70 Lettuce, potato</p>	<p>Arable & Perennial Horticulture</p> <p>25/30</p>	<p>Vineyards</p>	<p>Forestry</p>
		<p>30 Sedimentary, ash</p>	<p>More often Olsen P of 50–60 is considered the upper limit to no longer apply P</p> <p>Variable depending on crop</p>	<p>20-30</p> <p>Optimal for cropping</p> <p>No clear recommendations for perennial horticultural crops</p>	<p>Anticipate minimal P addition</p>	<p>Minimal P applied; OP most reflective of past land use</p> <p>Higher if pastoral</p> <p>Bray P typically used by forestry industry</p>	
		Low	<p>35 Pumice, peat</p>	<p>45</p>	<p>10-15</p> <p>Arable cropping recommendations of when to apply P</p>	<p>Natural/non-managed soil</p>	<p>Natural/non-managed soil</p>

Figure 6. Logic assessment of the potential interpretations of measured values of the Olsen P indicator, and P requirements (mg/L) associated with different agricultural plant species.

(Sources: drawn from Morton & Roberts 2024; Roberts & Morton 2023; Morton et al. 2020, Reid & Morton 2019; Nicholls et al. 2012; Watt et al. 2008)

Table 27 provides a summary of agronomic recommendations for soil Olsen P across different land uses.

Table 27. Summary of agronomic recommendation ranges for Olsen P for different land-use categories

Soil orders	Land-use group	Agronomic recommendations (mg/L)	Agronomic recommendations (mg/kg)	Sources:
All	Cropping & Orchards	10–30	NA	Reid & Morton 2019; Nicholls et al. 2012
All	Vegetable	10–70		Reid & Morton 2019
All	Vineyard	NA	NA	
Sedimentary, ash	Pastoral	20–30	NA	Morton & Roberts 2024; Roberts & Morton 2023; Morton et al. 2020
Pumice, peat	Pastoral	35–45	NA	
All	Exotic forestry	-	<25*	Watt et al. 2008
All	Indigenous vegetation	NA	NA	-
All	Urban	Depends on intended use	NA	-

NA = not available

* Plateauing of tree growth was observed at Olsen P above 25 mg/kg.

As a point of reference, the distribution of Olsen P concentrations from the monitoring data set are shown in Table 28, although the results are reported in mg/kg so are not directly comparable to the values in Figure 6. Generally, Olsen P concentrations are much lower in exotic forestry and indigenous vegetation sites (based on median values). However, even for these land uses, and other land uses with expected minimal P-fertiliser application (lifestyle, urban, vineyards), some high concentrations are observed, as shown by the maximum value and 90th percentile values. We note that 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). Bray-P is the preferred analytical method to estimate plant-available P in forestry soils, which are typically acidic (Davis et al. 2015).

Table 28. Distribution of Olsen P concentration (mg/kg) across soil orders for different land-use categories, from the monitoring data set

Soil orders	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile
All	Cropping & orchards	389	42	17	109
All	Dairy	336	46	23	101
All	Drystock	509	24	9	57
All	Exotic forestry	156	9	4	32
All	Indigenous vegetation	130	7	3	25
All	Lifestyle	17	29	12	78
All	Urban	36	19	7	54
All	Vineyard	46	28	10	68

A key concern relating to elevated Olsen P concentrations is the potential for negative impacts on water quality. Previous studies using soil boxes and simulated rainfall identified that anion storage capacity or P-retention has a strong influence on dissolved reactive phosphorus (DRP) concentrations in overland runoff (McDowell & Condron 2004; Morton et al. 2003) (Figure 7). The relationship of McDowell & Condron 2004 for predicting surface water runoff was also used by McDowell et al. (2020) to evaluate the potential to reduce legacy soil P in New Zealand.

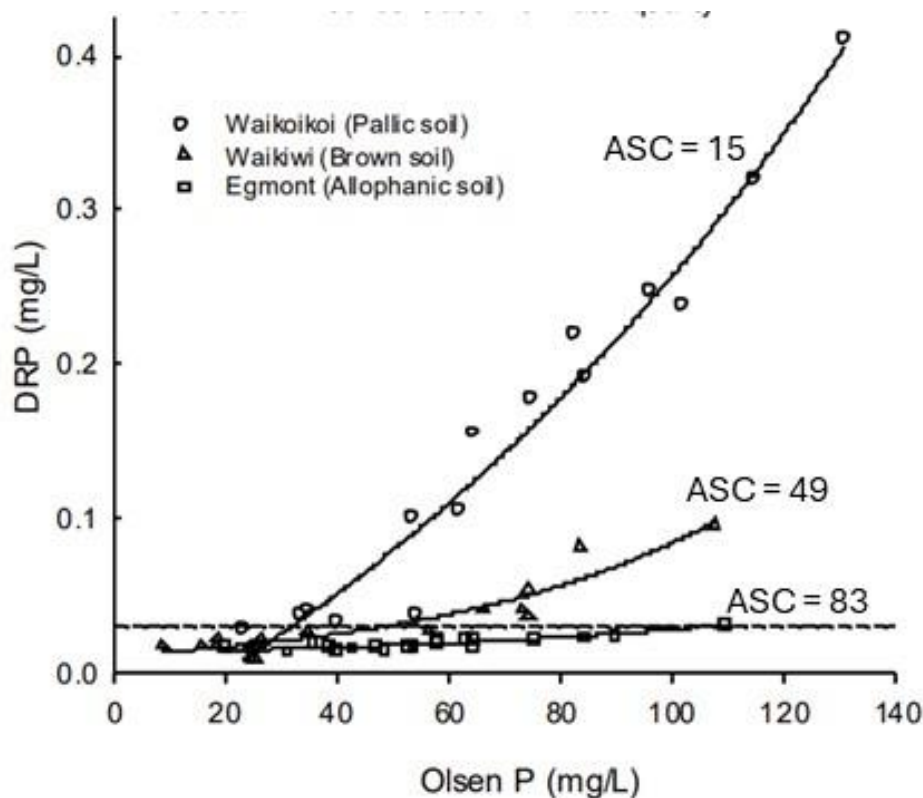


Figure 7. Relationship between dissolved reactive phosphorus (DRP) in overland flow in relation to Olsen P concentrations in three soils with differing anion storage capacity.

(Source: Adapted from Morton et al. 2003.

Note: The dashed horizontal line is a nominal water quality threshold value of 0.03 mg/L.

The relationship for predicting DRP from Olsen P determined by McDowell and Condron (2004) (equation 4), was explored to evaluate its potential to use to set Olsen P values that could be used as numeric criteria for SoE reporting.

$$\text{DRP (mg/L)} = 0.024 \times (\text{Olsen P}^5/\text{P-retention}) + 0.024 \quad (4)$$

Table 29 shows the values of DRP predicted to be present in surface runoff for soils with varying Olsen P and P retention. Comparison with the DRP criteria for different attribute bands specified in the NPS-FM (Table 30) reveals that at *all* Olsen P or P retention levels, the predicted DRP concentrations are *higher* than 0.018 mg/L, the threshold value used to indicate substantial

⁵ We followed McDowell et al. 2020 by using Olsen P values expressed as mg/L in equation 4; this assumes a bulk density of 1 the original equations were based on gravimetric (mg/kg) Olsen P values (McDowell & Condron 2004).

elevation above natural variation (Band D) (Table 30). In fact, the construct of equation 4 means the minimum predicted DRP (i.e. when Olsen P is 0) is 0.024 mg/L and above the Band D median. The bolded values in Table 29 indicate predicted DRP concentrations that are below the 95th percentile limit for Band D of 0.054 mg/L.

Table 29. Estimated dissolved reactive phosphorus concentrations for different values of Olsen P and P retention using equation 4

Olsen P (mg/L)	P retention (%)					
	5	10	20	30	40	45
5	0.048	0.036	0.030	0.028	0.027	0.027
10	0.072	0.048	0.036	0.032	0.030	0.029
15	0.096	0.060	0.042	0.036	0.033	0.032
20	0.120	0.072	0.048	0.040	0.036	0.035
25	0.144	0.084	0.054	0.044	0.039	0.037
35	0.192	0.108	0.066	0.052	0.045	0.043
45	0.240	0.132	0.078	0.060	0.051	0.048
55	0.288	0.156	0.090	0.068	0.057	0.053
65	0.336	0.180	0.102	0.076	0.063	0.059

Notes: Bolded values indicate concentrations <0.054 mg/L, which is the 95th percentile value for Band D in the NPS-FM.

Table 30. Dissolved reactive phosphorus (mg/L) bands specified in the NPS-FM 2020

Attribute band	Numeric criteria – DRP (mg/L (median))	(95th %ile)
Bands A& B – natural reference / sensitive ecosystems	<0.010	<0.030
Band C – moderate DRP elevation above natural reference	>0.010–<0.018	>0.030–<0.054
Band D – substantial elevation above natural elevation	>0.018	>0.054

However, it should be noted that these estimated DRP concentrations are highly conservative, being based on simulated rainfall experiments using pastoral soils in soil boxes at one slope angle (5°) rather than broader field-based assessments. Morton et al. (2003) noted that the experimental set-up is ‘not designed to quantify P losses on the field scale per se’ and was instead designed to mimic the mechanisms controlling the release of P to saturation-excess overland flow. Similarly, McDowell and Condron (2004) indicated that further research was required to more broadly extrapolate the findings from their study.

Multiple factors influence the transport of P to surface water other than soil Olsen P concentrations (Figure 8), noting also that DRP is only one component of total P loss to waterways. Dilution from paddock areas and other transport factors such as sorption of DRP onto sediment also play a role. Therefore, while the relationship above is useful to illustrate the influence of Olsen P (and P retention) on potential P-loss from soils, additional information is required to set numeric criteria for soil Olsen P values that protect waterways for SoE reporting. The spread of P-retention values for different soil orders based on data in the National Soil Data Repository held by MWLR (Figure 9) highlights the generally lower P-retention of Gley, Pallic and Ultic soils, particularly compared to Allophanic soils, while Brown and Granular soils fall in between.

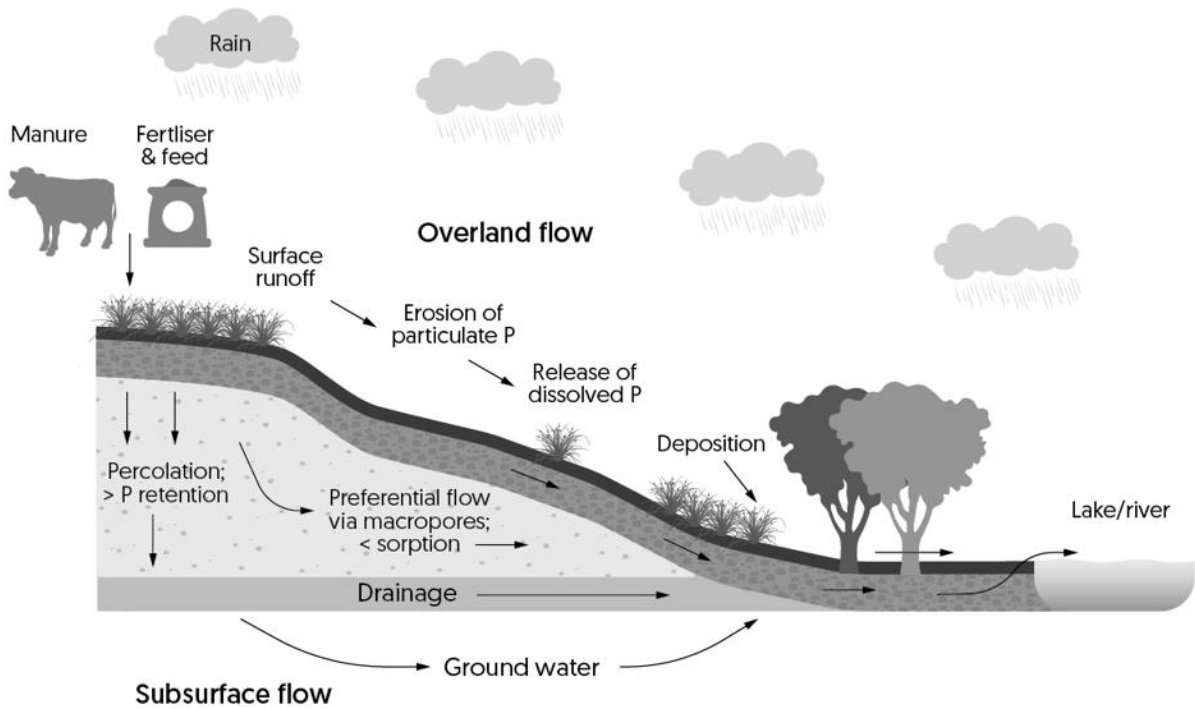


Figure 8. Processes influencing the transport of P to surface water.
 (Source: adapted from McDowell et al. 2004).

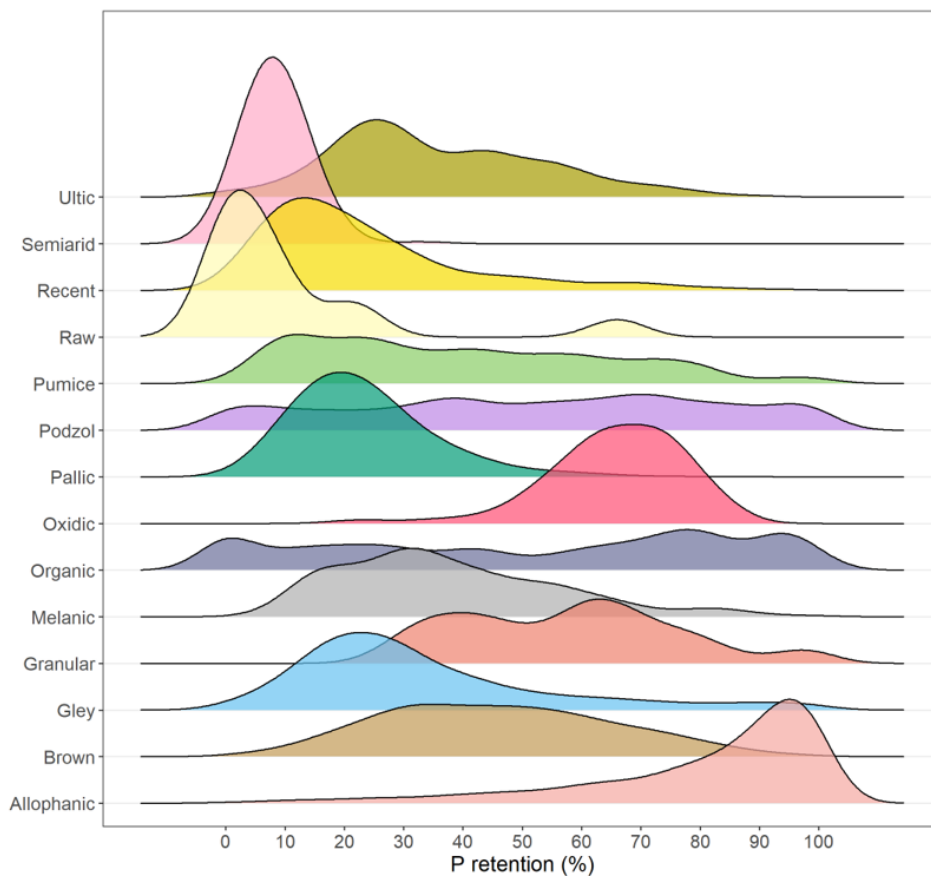


Figure 9. Spread of P-retention (%) in different soil orders from 11,806 samples with P-retention data from the NSD-R.

Note: P-retention is typically considered to be equivalent to anion storage capacity.

6.4 Total C

Total C is an indicator of organic matter content. Although there has been considerable focus on changes in soil C, particularly from a climate change perspective, there has been less focus on relating the significance of those change to changes in soil function, such as water-holding capacity and nutrient cycling (see also Figure 10). 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), although even for the latter, maintaining or increasing soil C/organic matter levels is generally considered more desirable than depletion.

Considerable effort has been put into identifying potential values or specific indicators that give meaning to measured values of C (see section 4.4.1). One of the few studies that provides a comprehensive assessment of soil C in relation to primary production or yield, as a measure of soil function, is that of Oldfield et al. (2019). In a global meta-analysis of cropping soils these authors observed an increase in crop yield of around 2% SOC; thereafter the yield response to SOC flattens out as management factors such as irrigation and fertiliser application become more important. This study does not include New Zealand soils. Other studies discussed in EEA 2023 suggest a yield impact on cropping soils from about 1% SOC. These estimates provide some basis for a lower limit for soil C.

Aside from Oldfield et al. 2019 there are few studies that link production or environmental outcomes to SOC concentration across a broad range of soils and land uses, partly because these outcomes are highly related to specific land management practices applied under specific conditions (Moinet et al. 2022). An example of this is the experimental trials being run by the Foundation for Arable Research to assess the influence of tillage practices on soil properties and crop yield (FAR 2023). No-tillage practices increased C stocks in the top 30 cm, which in turn improved soil structure (measured by aggregate stability), but it was only under dryland conditions that this was observed to increase yield (FAR 2023). This finding 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 than in dryland systems, irrespective of tillage system (and soil carbon present).

Total C – indicator of organic matter

Often considered a ‘more is better’ indicator – ability to achieve more depends in part on saturation potential of soil

<p>Natural conditions</p> <p>Soil order variation: Organic soils ≥18%</p> <p>Allophanic soils 8-12%</p> <p>Carbon sequestration: saturation potential varies between soil orders</p>	<p>Environmental considerations</p> <p>High</p> <p>Increased</p> <ul style="list-style-type: none"> • water-holding capacity • microbial activity • improved soil structure <p>Nutrient cycling = decomposition of organic matter (C-loss) and release of nutrients decrease reliance on inorganic N (AMN/HWEC)</p> <p>‘Tension’ between C-sequestration vs OM decomposition (and potential loss of stock)</p> <p>Decreased</p> <ul style="list-style-type: none"> • water-holding capacity • microbial activity • loss of soil structure <p>Low</p>	Pastoral	Cropping Horticulture	Perennial Horticulture	Vineyards	Forestry
		<p>Typical range for different soil orders Ideally split between differing management intensities</p>	<p>Consideration of typical range for individual soil orders /grouped soil orders</p>	<p>Consideration of typical range for individual soil orders /grouped soil orders</p>	<p>Consideration of typical range for individual soil orders /grouped soil orders</p>	
		<p>Estimates of SOC over which increasing SOC will provide yield benefit = 1-2%</p>				

Figure 10. Logic assessment of the potential interpretations of measured values of the total C indicator, and potential options for setting numeric criteria.

In terms of the ability of soils to sequester C, stabilisation of C is often attributed to the formation of organo-mineral complexes in the fine fraction (silt and clay) (McNally et al. 2017, 2024). For New Zealand soils, mineral surface area (MSA) and extractable aluminium were determined to be a better predictor of the ability of a soil to store carbon compared to the mass proportion of fine particles or clay content for sequestering C (Beare et al. 2014; Curtin et al. 2016; McNally et al. 2017). Building on Beare et al. 2014, McNally et al. (2017) evaluated the maximum C stabilisation capacity and saturation deficit of the fine fraction (stabilisation capacity less the current SOC concentration) of New Zealand soils. This research was based on the relationship between fine-fraction C (FFC)⁶ and the MSA of soil and extractable aluminium; MSA was the dominant variable. Different relationships were identified for Allophanic and non-Allophanic soils. A saturation deficit was determined as the difference between the 90th quantile regression and the 50th percentile or measured FFC. The saturation potential of different soils could be used to provide some basis for the additional sequestration of C that could occur in the fine fraction of individual soils. The soil C loading rate of mineral surfaces (mg C m^{-2}), defined as the FFC divided by the MSA, provides similar information to the saturation deficit but is based on measured properties for a specific soil rather than applying a quantile regression.

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

In terms of the distribution of the soil C results in the baseline monitoring data set (Table 31), statistical analysis revealed that Organic, Allophanic, and Raw soils were clearly distinctly different from each other and from the other soils (see Appendix 2). The higher total C content of Allophanic soils is attributed to the high content of Allophanic clays and hydroxy-aluminium compounds that enable the stabilisation of large amounts of organic C (Percival et al. 2000). For the remaining soil orders there was 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. This suggests that some further differentiation based on soil order may be warranted, however in this study there was no clear statistical basis to further split these soil orders (Appendix 2). We note other NZ studies on soil carbon were also only able to delineate Allophanic and non-allophanic mineral soils (Beare et al. 2014; McNally et al. 2017, 2018).

Organic soils are defined as having > 18% organic C (Hewitt 2010). However, some sites classified as Organic soils have a C content below this threshold (particularly under cropping land use), which suggests that it may be useful to re-examine the classification of soil order at those sites to ascertain whether they are indeed Organic soils.

⁶ McNally et al. (2017) found the relationship between fine fraction C and total C (expressed as mg/g soil) for both Allophanic and non-allophanic soils to be: $\text{fine fraction C} = 2.23 + 0.81 \times \text{Total C}$, r^2 0.991.

Table 31. Distribution of soil carbon (%) in the baseline monitoring data set according to different soil groups and land use

Soil order	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile
Organic	Cropping	5	7.8	6.4	15.9
Organic	Dairy	6	30.4	18.4	49.7
Organic	Drystock	6	16.6	12.7	24.2
Organic	Indigenous vegetation	3	30.8	12.6	46.6
Organic	Orchard	2	14.9	14.5	15.2
Allophanic	Cropping	17	5.2	3.8	8.0
Allophanic	Dairy	74	10.0	6.4	13.5
Allophanic	Drystock	63	9.5	5.5	13.0
Allophanic	Exotic forestry	21	7.9	6.0	18.2
Allophanic	Indigenous vegetation	12	12.3	5.5	18.6
Allophanic	Orchard	39	7.3	5.2	9.7
Allophanic	Urban park/reserve	13	5.3	4.1	10.2
Raw	Cropping	1	0.8	0.8	0.8
Raw	Drystock	1	4.1	4.1	4.1
Raw	Exotic forestry	4	1.6	0.8	2.6
Others	Cropping	187	2.7	1.9	4.5
Others	Dairy	256	5.7	3.5	8.7
Others	Drystock	440	4.8	3.3	8.3
Others	Exotic forestry	131	4.7	3.3	7.9
Others	Indigenous vegetation	116	5.9	3.6	11.3
Others	Orchard	140	3.9	2.5	5.7
Others	Urban park/reserve	37	5.1	2.8	6.8
Others	Vineyard	46	3.5	2.3	4.8

Whether more soil C is better can depend on land use and drainage conditions. For example Clothier et al. (2011) provide an example that increasing soil C from 1% to 1.75% in a vineyard soil, and particularly for soil at depth, was estimated to decrease the terroir value due to enhanced water storage and enhanced mineralisation. Where soil is more poorly drained, increasing soil C, which reflects an increase in soil organic matter, also increases the potential for water-logging and anaerobic conditions. This in turn influences nutrient cycling processes in the soil.

6.5 Total N, C:N ratio, AMN, HWEC

Total N provides an indication of the organic matter N content and is usefully considered in conjunction with the ratio of total C to total N (the soil C:N ratio) and mineralisable N. Mineralisable N may be measured in different ways (see Curtin et al. 2017), including anaerobically mineralisable nitrogen (AMN), and HWEC also shows a strong relationship with potentially mineralisable N (PMN, see below). AMN and HWEC are also correlated with microbial biomass (Ghani et al. 2003; Sparling et al. 2003). 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). Given the strong overlaps in interpretation and use of these four indicators, they are considered together in this section.

The ratio of total C to total N (the soil C:N ratio) gives an indication of the quality of the organic matter to supply N, and is useful, along with total N and mineralisable N, for evaluating the N content of the soil. A widening of the C:N ratio over time reflects declining N fertility, while a narrowing of the ratio may indicate enrichment of N in the soil. Some studies have re-examined the use of total N as an indicator, with Shepherd et al. (2015) finding that total N in the 0–7.5 cm depth was a good surrogate for pasture response. Guinto & Catto (2016), using an extensive data set, found that total N was a reasonable predictor of AMN. However, Curtin et al. (2017), who compared various rapid assays for N-mineralisation, in the context of using that information to inform N-fertiliser recommendations, found that total N was not a good predictor of N-mineralisation. These authors questioned the reliability of AMN for informing N-fertiliser recommendations, and more recent research has focused on using a rapid PMN assay for predicting in-field N mineralisation (Beare et al. 2023).

An overview of the factors influencing Total N and the C:N ratio, and possible interpretations to assist in setting numeric criteria, are shown in Figure 11.

Total N – indicator of organic N content (should be interpreted alongside C:N, and linked to absolute total C/organic matter)

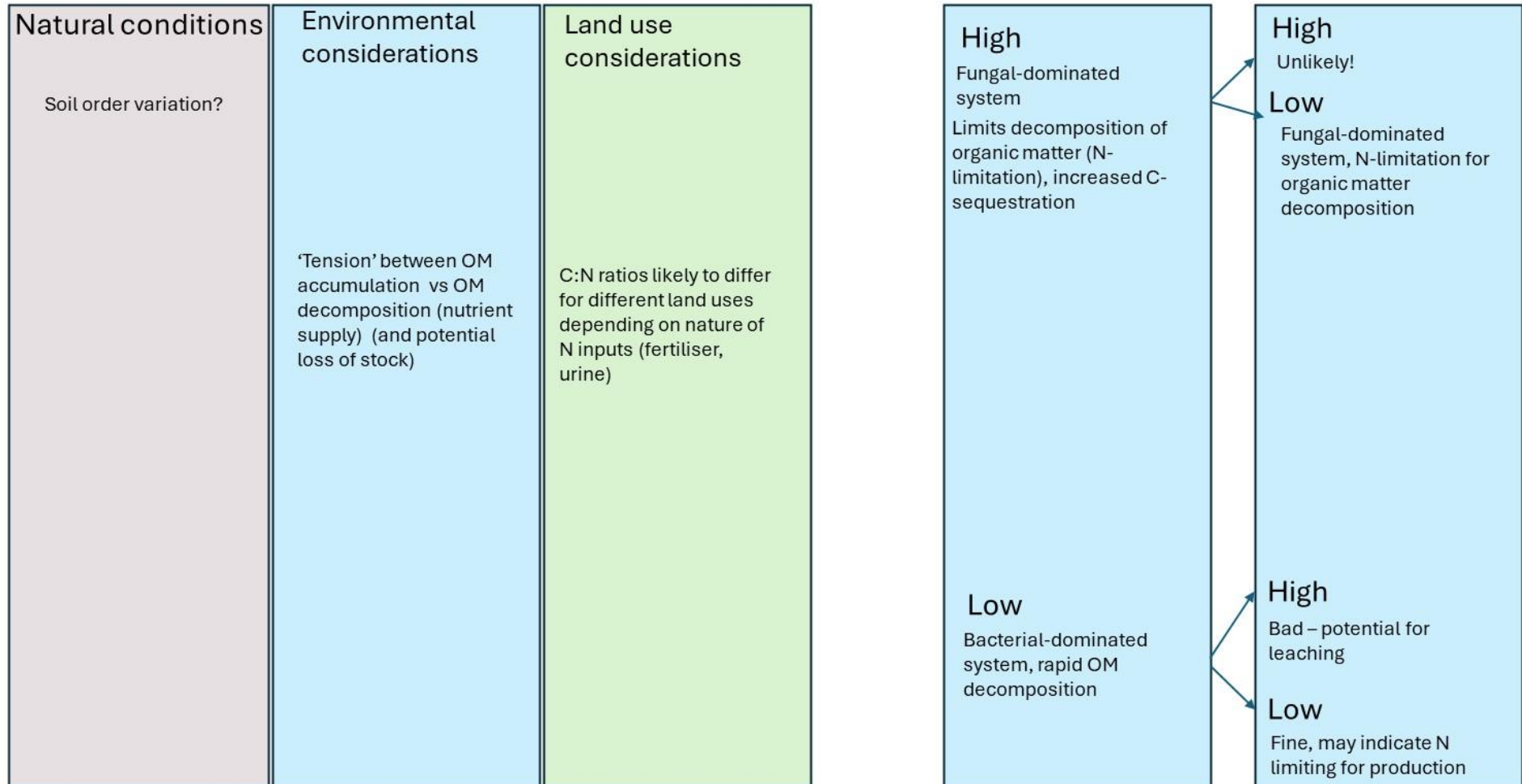
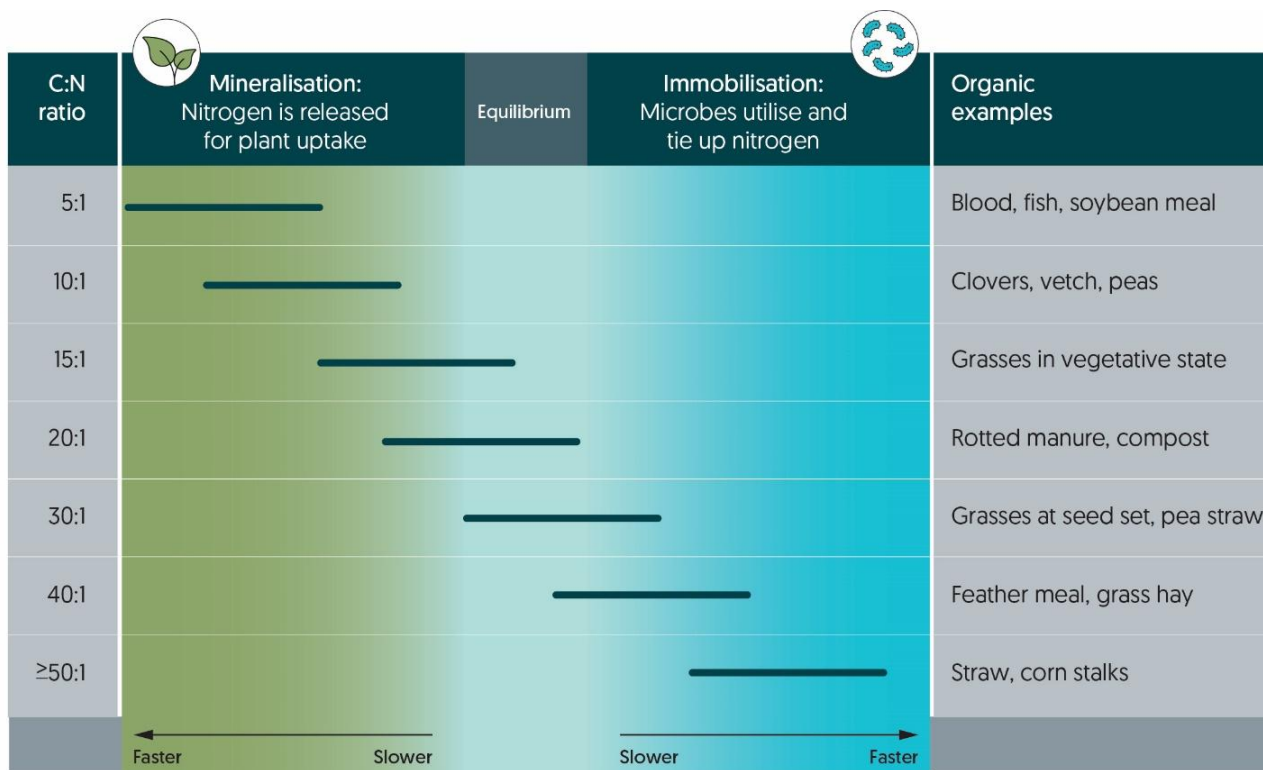


Figure 11. Logic assessment of the potential interpretations of measured values of C:N and total N (%) indicator, and potential options for setting numeric criteria.

An indication of the influence of the C:N ratio on nitrogen release or immobilisation is shown in Figure 12. The lower the C:N ratio, the more rapidly N will be released into the soil for immediate crop use, while a C:N ratio >35 results in microbial immobilisation of N (Brust 2019). A ratio of 20:30 results in an equilibrium state between mineralisation and immobilisation. In New Zealand forestry soils a marked decrease in growth of 4 year-old trees with an increase in C:N was observed (Figure 13; Watt et al. 2008).



The C:N ratios vary over a range for any organic material and these values represent an average of the range.

Figure 12. The C:N ratio of some organic materials and their mineralisation and immobilisation rates.
(Source: Adapted from Brust 2019)

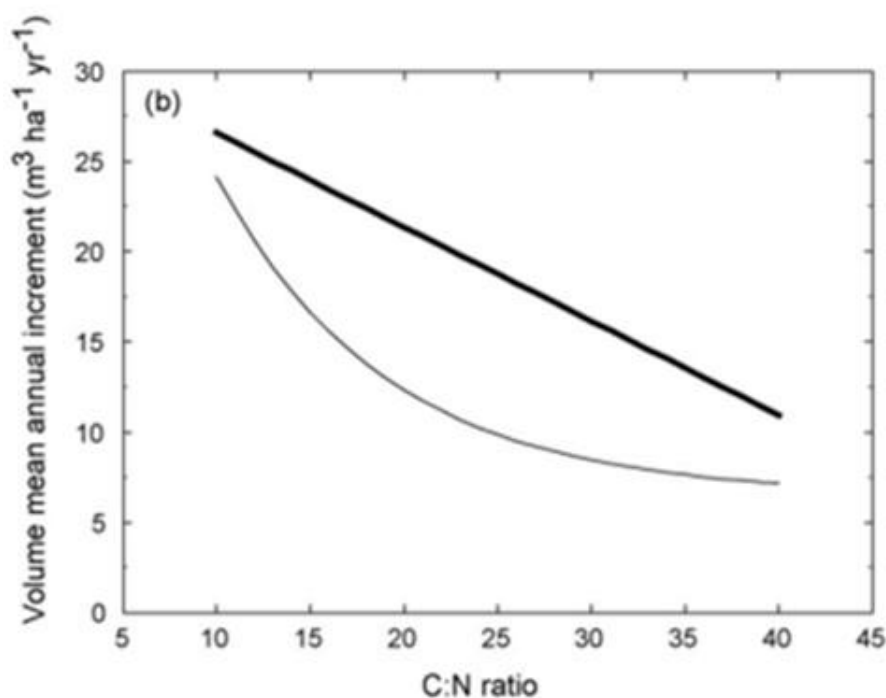


Figure 13. Response of volume mean annual increment (MAI) of 4-year-old *Pinus radiata* (thick line) and *Cupressus lusitanica* (thin line) in relation to C:N ratio; all other variables in the model were held at mean values when each response curve was generated. (Source: Adapted from Watt et al. 2008)

The distribution of C:N ratio in the monitoring data set is shown in Table 32. The median values and 10th to 90th percentile values (the 'typical' range) for C:N ratio are very similar across most land-use categories and have a relatively narrow range. Cropping and vineyards had a marginally lower 10th percentile value of 9, compared to the same percentile for other agricultural and horticultural land use of 10. In contrast, compare these values with forestry and indigenous vegetation, which both had higher median values and a wider typical range. Urban park/reserves had marginally higher median and 'typical value' ranges.

Table 32. Distribution of C:N ratio in the monitoring data set across all soil orders

Soil orders	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile
All	Cropping	209	11	9	12
All	Dairy	336	11	10	13
All	Drystock	510	11	10	14
All	Exotic forestry	156	17	12	26
All	Indigenous vegetation	131	15	12	20
All	Orchard	180	11	10	12
All	Urban park/reserve	50	12	11	14
All	Vineyard	46	11	9	12

The distribution of Total N results in the monitoring data set in relation to different soil groupings and land use is shown in Table 33. Higher values are observed for Organic and Allophanic soils within each land-use category, and lower values for Raw soils. For a given soil order or soil order grouping, total N was generally higher in dairy and drystock soils.

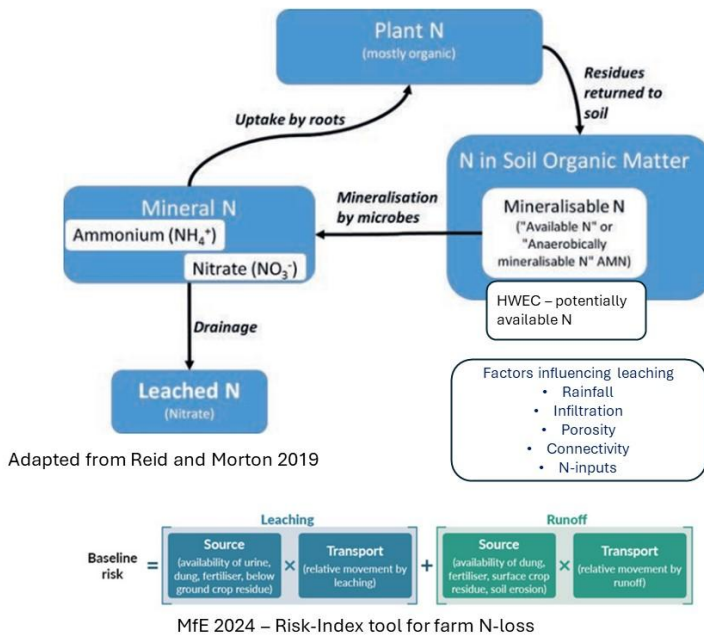
Table 33. Distribution of total N (%) in the monitoring data set, by soil grouping and land use

Soil order	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile
Allophanic	Cropping	17	0.54	0.38	0.78
Allophanic	Dairy	74	0.97	0.59	1.26
Allophanic	Drystock	63	0.89	0.49	1.17
Allophanic	Exotic forestry	21	0.57	0.29	1.04
Allophanic	Indigenous vegetation	12	0.82	0.31	1.33
Allophanic	Orchard	39	0.66	0.45	0.90
Allophanic	Urban park/reserve	13	0.45	0.33	0.77
Organic	Cropping	5	0.69	0.40	1.39
Organic	Dairy	6	1.69	1.22	2.51
Organic	Drystock	6	1.29	0.86	1.71
Organic	Indigenous vegetation	3	1.28	0.64	1.60
Organic	Orchard	2	0.98	0.74	1.23
Raw	Cropping	1	0.06	0.06	0.06
Raw	Drystock	1	0.37	0.37	0.37
Raw	Exotic forestry	4	0.05	0.03	0.11
Others	Cropping	187	0.26	0.18	0.39
Others	Dairy	256	0.53	0.33	0.75
Others	Drystock	440	0.42	0.28	0.72
Others	Exotic forestry	131	0.29	0.17	0.46
Others	Indigenous vegetation	116	0.39	0.21	0.63
Others	Orchard	139	0.36	0.23	0.47
Others	Urban park/reserve	37	0.41	0.20	0.59
Others	Vineyard	46	0.32	0.21	0.44

An overview of the factors influencing AMN and HWEC, and possible interpretations to assist in setting numeric criteria, are shown in Figure 14. Both Total N and AMN were originally proposed as potential indicators of N-leaching risk, but, as shown in Figure 14, many factors influence N-loss, including plant-N demand and drainage volume. The fluxmeter studies of Norris et al. (2023) highlight the variability in drainage volumes at a given site and between sites, while the risk index tool from MfE 2024a,c highlights the importance of different sources of N to leaching and surface runoff losses.

AMN, HWEC (Total N) – measures of N release over time (as determined by [different] standard test measures (& calibration))

Interpretation of the significance (ie 'good', 'bad') of AMN/HWEC value also depends on plant N demand



'Good'	'Bad'
<p>High</p> <p>Lots of N available for plant growth – may offset</p> <p>[Alternative interpretations – higher microbial biomass, higher labile carbon (HWEC)]</p>	<p>High</p> <p>If plant N demand is insufficient, increased potential for leaching</p>
<p>Reduced potential for leaching if low plant demand</p>	<p>Less N available for plant growth, increased reliance on N-fertiliser for supply</p> <p>Low microbial activity (if high OM)</p>
<p>Low</p>	<p>Low</p>

Figure 14. Logic assessment of the potential interpretations of measured values of AMN and the HWEC indicator, and potential options for setting numeric criteria.

HWEC and AMN are broadly correlated with total C and total N, and with each other, across the different land uses (Figure 15). Cropping land use has consistently lower values of AMN and HWEC, which is consistent with the lower total C and N concentrations in this land use. Other than this, the relationship between these variables is variable within and between the land-use categories.

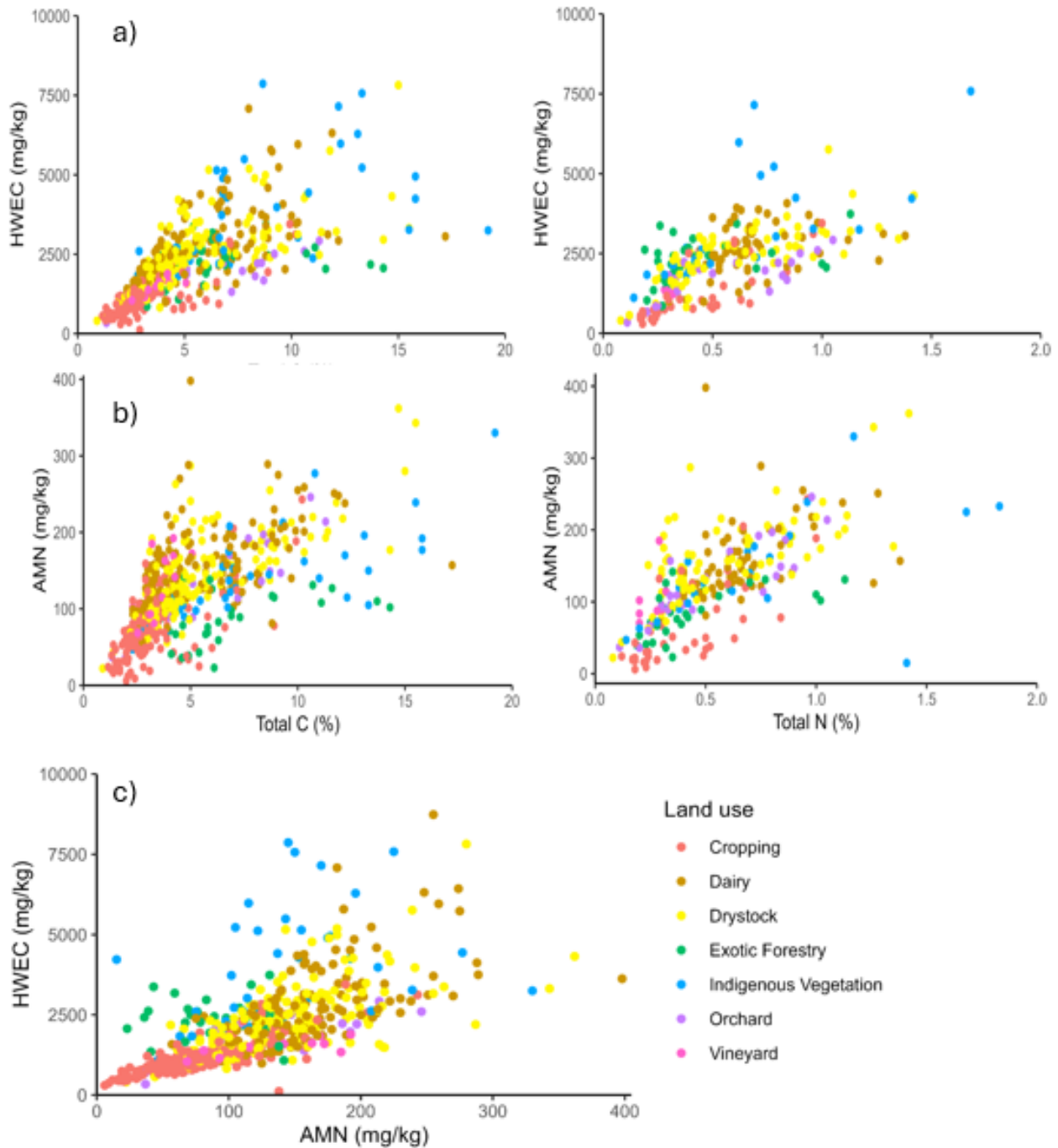


Figure 15. Relationship of a) hot-water extractable C (HWEC) and total C and total N, b) anaerobically mineralisable nitrogen (AMN) and total C and total N, and c) HWEC and AMN, from the HWEC data set.

The distribution of AMN results in the monitoring data set in relation to different soil groupings (Appendix 2) and land uses is shown in Table 34. Observations are similar to that for total N in that higher values are observed for Organic and Allophanic soils within each land-use category, and for a given soil order or soil order grouping. AMN was generally higher in pastoral land uses.

Table 34. Distribution of AMN results (mg/kg) in the monitoring data set according to different soil order groupings and land-use categories

Soil order	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile
Allophanic	Cropping	14	64	31	160
Allophanic	Dairy	40	238	137	341
Allophanic	Drystock	43	215	128	265
Allophanic	Exotic forestry	15	127	77	185
Allophanic	Indigenous vegetation	11	196	75	416
Allophanic	Orchard	15	150	113	201
Allophanic	Urban park/reserve	11	111	75	240
Organic	Cropping	5	118	88	154
Organic	Dairy	6	253	197	297
Organic	Drystock	6	255	189	305
Organic	Indigenous vegetation	3	238	180	257
Organic	Orchard	2	165	165	165
Raw	Exotic forestry	3	10	2	37
Others	Cropping	104	47	21	119
Others	Dairy	168	165	101	255
Others	Drystock	310	137	74	238
Others	Exotic forestry	100	73	39	122
Others	Indigenous vegetation	112	116	53	192
Others	Orchard	61	91	36	147
Others	Urban park/reserve	25	113	64	196
Others	Vineyard	46	85	57	123

There was a more limited data set for HWECC (*n* = 637) compared to other indicators. Cropping soils showed the lowest HWECC, while indigenous vegetation sites showed the highest (Table 35).

Table 35. HWECC concentrations (mg/kg) in monitoring data set

Soil order	Land-use group	<i>n</i>	Median	10 th %ile	90 th %ile
Organic	Dairy	3	6,431	3,113	8,277
Organic	Drystock	1	7,821	7,821	7,821
Organic	Indigenous vegetation	1	18,510	18,510	18,510
Others	Cropping	233	1,073	684	1,488
Others	Dairy	142	2,469	1,439	4,077
Others	Drystock	153	2,204	1,127	3,519
Others	Exotic forestry	31	2,273	1,350	3,176
Others	Indigenous vegetation	38	3,500	2,001	6,547
Others	Orchard	23	1,812	851	2,453
Others	Vineyard	12	1,442	1,159	1,813

For comparison, Hill Laboratories provided the interpretive ranges for HWEC shown in Table 36 (Hill Laboratories, undated) while Taylor et al. (2022) proposed target ranges of 1,700 and 2,000 mg/kg. The basis for the interpretive ranges given by Hill Laboratories is not specified, but is likely to be based on the distribution of available data from all samples analysed. The target value of 1,700 mg/kg of Taylor et al. (2022) was based on the 1st percentile of indigenous vegetation results in the data set used by the author, while the 2,000 mg/kg was based on plotting HWEC results against visual soil assessment scores for the same 223 Waikato sites and using a score indicating moderate soil damage to derive the target value.

Table 36. Interpretive ranges for hot-water-extractable carbon, provided by Hill Laboratories

Level	Hot-water-extractable carbon (mg/kg)
Very low	<350
Low	350–1,000
Medium	1,000–3,500
High	3,500–7,500
Very High	>7,500

The relationship between HWEC and plant-N demand was also explored as a potential option for setting revised numeric criteria (see section 3.4.3 for details of the analysis). A good relationship between HWEC and PMN was identified (Figure 16), and PMN was calculated for the LMI data set (see section 4.3.3 for a description). As with HWEC and AMN, cropping land uses show lower PMN than dairy and sheep & beef land uses (Figure 17).

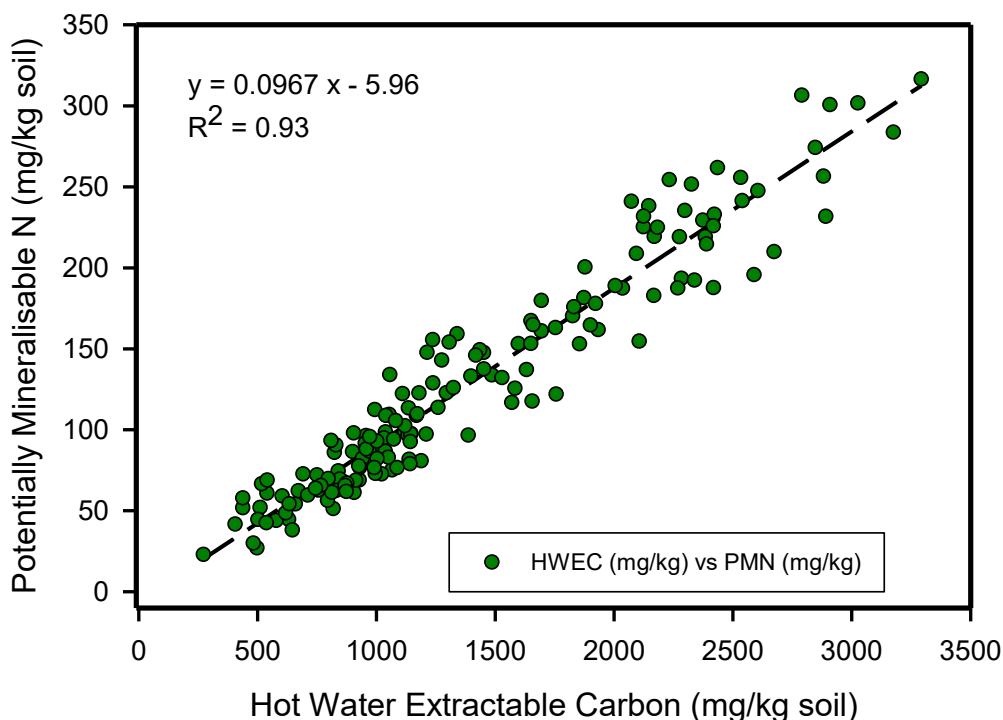


Figure 16. Relationship between HWEC (mg C/kg) and PMN (mg N/kg).

Note: Refer to section 3.4.3 for details.

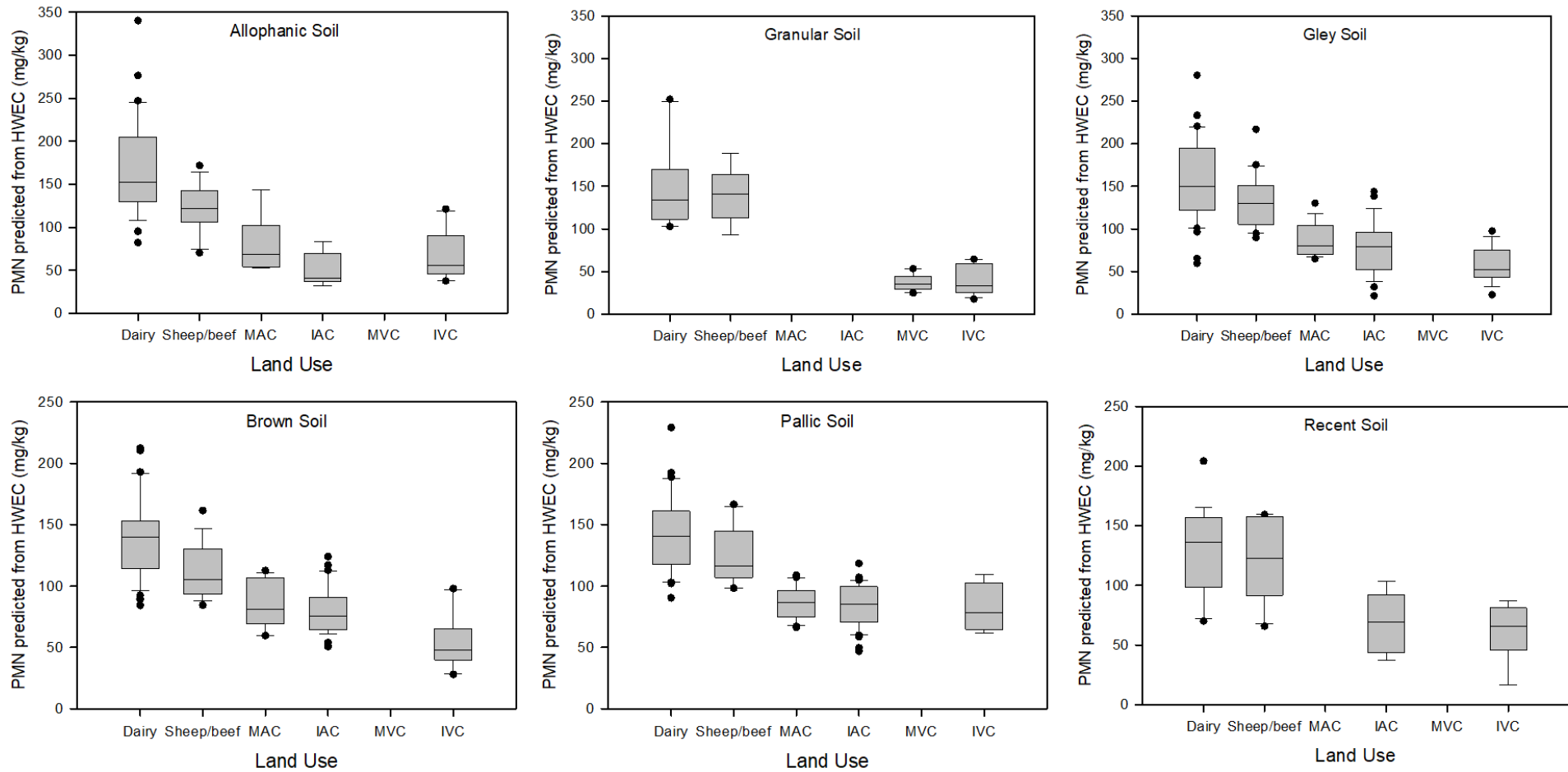


Figure 17. Land-use and soil-order effects on PMN, predicted from HWEC measurements in the LMI data set.

Notes: MAC = mixed arable cropping; IAC = intensive arable cropping; MVC = mixed vegetable cropping; IVC = intensive vegetable cropping.

As an illustration of the influence of field conditions such as soil temperature and water content, which can vary regionally depending on climate and whether irrigation is applied to the production system, estimates of in-field N mineralisation were made for selected land uses (see section 3.4.3 for details). The predicted in-field N mineralisation for a 3-month period (November through January) for the Southland, Tasman, and Waikato regions is shown in Table 37. This illustrates some of the variation in mineralisable-N that can occur due to non-soil factors.

Table 37. Comparison of mean potentially mineralisable N with predicted *in situ* N-mineralisation

Land use	Mean PMN mg/kg	Southland	Tasman	Waikato
		----- kg N/ha -----		
Dairy	140	42	52	71
IAC	80	24	29	40
IVC	54	16	20	27

Nonetheless, considering PMN alongside crop N demand can provide an indicative assessment of potential for N-leaching to occur. Crop N demand can be defined as the total amount of N taken up by a given crop at a designated yield. Some examples are given in Table 38. Crop N demand can be met by the mineral N available at the start of a growing season, the additional N mineralised from soil organic matter over the course of the growing season, and appropriately timed applications of N fertiliser. Comparison between Tables 37 and 38 indicates that *in situ* mineralisable N is markedly lower than the total crop N uptake, which indicates that additional sources of N are required to meet the crop demand.

Table 38. Examples of crop N demand*

Crop type	Harvested product	Target yield	Total crop N uptake
		t/ha	kg N/ha
Wheat	Grain	12	240–280
Barley	Grain	10	180–220
Onion	Marketable bulbs	80	200–230
Potato	Marketable tubers	80	300340

* Sources: Reid & Morton 2019; Beare et al. 2022; Beare et al. 2023

6.5.1 Fluxmeter data set

As a further analysis, we compared the variation in estimated nutrient (N and P) leaching to measured soil properties for the fluxmeter sites assessed by Norris et al. (2018). There were no clear relationships between nitrate-N loss and total N or AMN, with some of the higher values of both having minimal N loss (Figure 18). Similarly, there was no obvious relationship between Olsen P and DRP loss, although it does highlight that some P can be leached from soil with relatively low Olsen P values; there was only one data point with Olsen P > 50 mg/L.

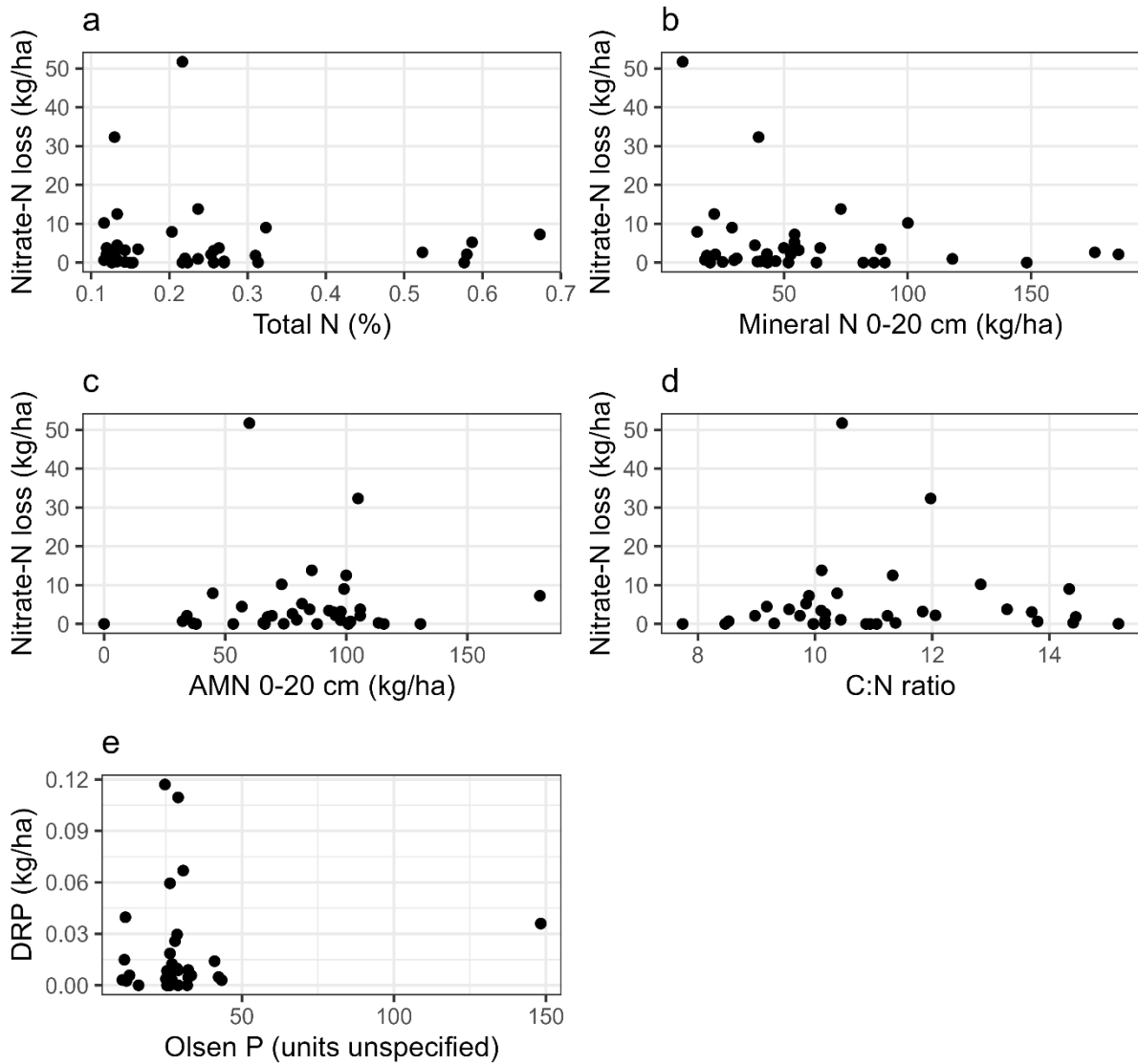


Figure 18. Plot of nitrate-N loss against total N (a), mineral N (b), AMN (c), C:N ratio (d), and DRP (dissolved reactive phosphorus) loss against Olsen P (e).

For each site we also compared the range in N-loss against the range in measured soil properties, which also showed nothing obvious (Table 39). This is likely to be attributable to other factors, such as soil moisture and infiltration capacity, which can influence drainage and nitrate leaching (Yi et al. 2022; Li et al. 2023). Factors such as soil drainage class and management practices can also be important in specific circumstances.

Table 39. Range in nutrient losses in leachate in comparison to measured soil properties at each fluxmeter site in the data set

Site	N*	N loss (kg/ha)	Total N (%)	Mineral N (kg/ha)	AMN (kg/ha)	Total C (%)
1	5	0.36–13.81	—	46.55–118.17	84.89–101.33	1.80–3.52
2	3	0.00–1.07	0.22	30.75–82.04	0.00–88.00	2.16–2.44
3	3	0.00–2.09	0.25–0.27	52.67–148.27	69.33–130.67	2.84–2.94
5	9	0.26–32.32	0.12–0.16	21.66–100.10	73.33–113.33	1.45–1.70
6	4	0.04–9.00	0.27–0.32	18.69–43.13	65.78–99.11	3.89–4.76
7	5	0.00–4.46	0.13–0.15	17.91–63.08	32.44–66.37	1.14–1.27
10	5	0.00–7.25	0.52–0.67	54.15–185.42	77.78–180.00	5.32–6.66
11	1	51.74	0.22	8.87	60	2.27
12	1	7.91	0.20	14.74	44.89	2.11

*Number of drainage events in the dataset for which nutrient losses were determined.

In the context of N-leaching losses, it is also worth highlighting a spatial layer of susceptibility to nutrient loss that has been developed through the Whitiwhiti Ora: Land Use Opportunities programme.⁷ The layer provides a representation of the annual mean susceptibility of N-loss, considering soil and climate factors 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 simulated 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; it focuses solely on inherent soil and regional climatic conditions.

6.6 Macroporosity and bulk density

6.6.1 Macroporosity

Macroporosity fundamentally influences gas, nutrient, and water flows in the soil. As macroporosity declines, the risk of restricting plant growth due to impaired air, water, and nutrient movement to roots increases. Decreased pasture yield associated with a decrease in macroporosity has been identified in several studies (e.g. Drewry et al. 2001; Drewry et al. 2008; Singleton et al. 2000; Mackay et al. 2010), although the threshold at which decreased pasture production occurs is variable.

The environmental impacts of macroporosity are complex and sometimes inconsistent. Reduced macroporosity can increase the risk of sediment and P loss in overland flow (Curran-Cournane et al. 2011; Hu et al. 2021). Reduced macroporosity is often associated with decreased water-holding capacity, but it has also been linked to greater retention of plant-available water due to the disconnection of macropores (Fu et al. 2021). In other situations, and almost counterintuitively, increasing compaction can result in *increased* drainage and nitrate leaching (Yi et al. 2022). These

⁷ <https://landuseopportunities.nz/>.

authors attributed the increased drainage to reduced evaporation (i.e. higher soil moisture content) and a lower capacity to retain water before drainage was triggered, with drainage occurring through larger macropores. Conversely, greater macroporosity has been associated with reduced nitrate leaching, either due to the development of preferential flow pathways that bypass much of the soil matrix (Miranda-Vélez et al. 2022), or to reduced drainage resulting from lower initial soil water.

Compaction from livestock treading has been shown to increase N₂O emissions by between 51 and 814%, which is attributed to an increased abundance of anaerobic microsites (Hu et al. 2021) and decreasing the oxygen supply in soil (Pulido-Moncada et al. 2022; van der Weerden et al. 2017). Although compaction-induced reductions in macroporosity often lead to increased N₂O emissions, further reductions can enhance the completeness of denitrification, potentially lowering N₂O emissions (Hernandez-Ramirez et al. 2021). Finally, increasing compaction can also result in increased surface runoff, with increased bulk density related to increasing sediment loss (Hu et al. 2021).

We were unable to find any studies on the significance of high macroporosity or low bulk density values, which Reynolds et al. (2008) suggest will influence soil–seed contact and water and nutrient uptake by plant roots. High-macroporosity soils may also be loose or relatively unconsolidated, which may increase the risk of erosion.

Factors influencing the interpretation of macroporosity and bulk density are shown in Figure 19.

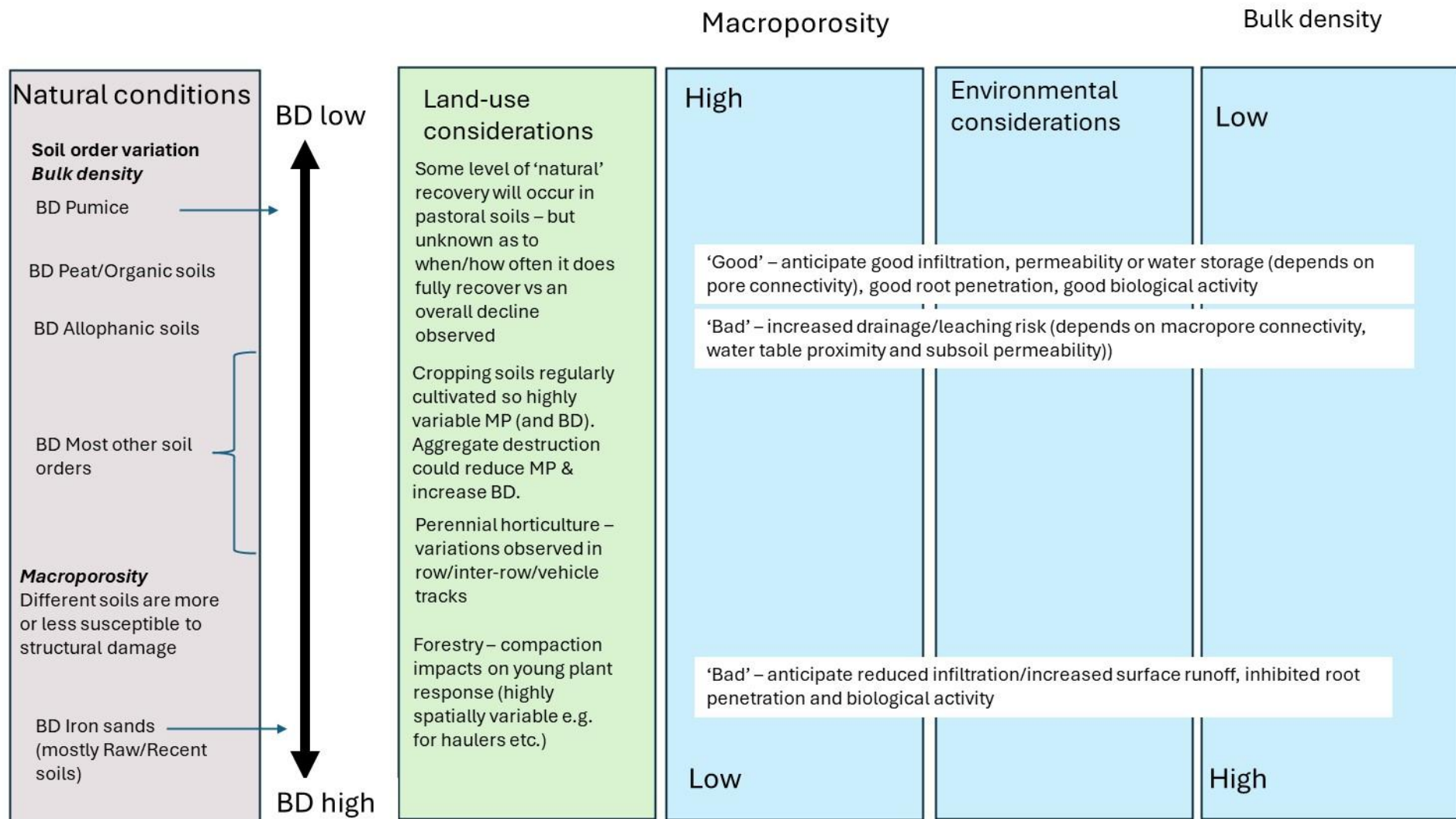


Figure 19. Logic assessment of the potential interpretations of measured values of macroporosity and bulk density.

From a pasture production perspective, the threshold at which markedly decreased pasture production is observed is variable. In a review of the influence on pasture yield of soil compaction from treading and grazing, Drewry et al. (2008) noted that several studies showed that adequate plant growth requires macroporosities ranging from 6% to 17%. Further, macroporosity can vary seasonally, with some recovery occurring between grazing events (Figure 20), and seasons (e.g. Drewry et al. 2004). However, over time there may be a declining trend; i.e. soil does not fully recover before it is grazed again, particularly under grazing with heavier livestock (cattle) (Figure 20).

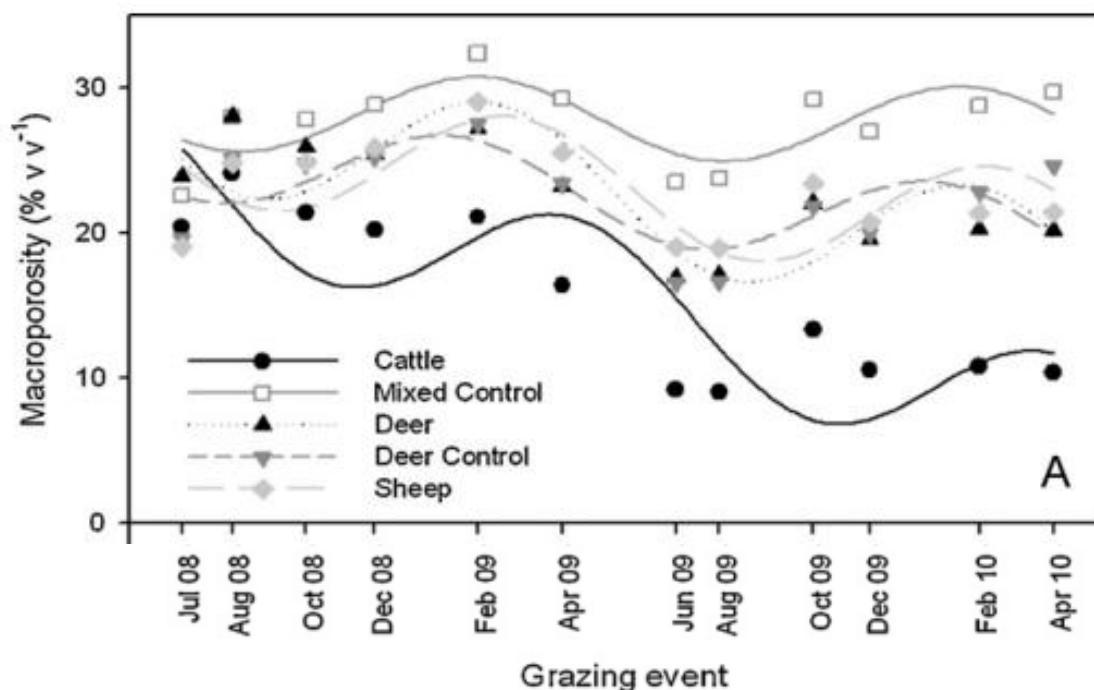


Figure 20. Effect of stock type on mean soil (0–5 cm depth) macroporosity (–10 kPa) in field-grazing trials in Southland on soil intergrade between a Porteous silt loam (Brown soil) and a Warepa silt loam (mottled fragic Pallic soil). (Source: adapted from Curran-Cournane et al. 2011)

Hu et al. (2023) provide a model framework that illustrates the relationships between soil properties, climate/weather, and land management practices and their influence on the vulnerability and risk of soil structural degradation, including reduced macroporosity. Given the confounding influences of these factors on effects associated with macroporosity, we evaluated the use of macroporosity associated with soils that might be considered to be unimpacted (e.g. samples collected from under fencelines of adjacent pastures, or undisturbed forestry sites) as a basis for setting numeric criteria for macroporosity. Only a limited number of published studies providing data for unimpacted sites were found, and these are described in section 3.4.3.

A summary of the distribution of macroporosity in unimpacted soils under pastoral and forestry land use for different soil orders is provided in Table 40. These studies also provided data on macroporosity associated with adjacent 'impacted' sites, and the change in macroporosity between undisturbed and adjacent impacted sites in this data set is shown in Figure 21.

Table 40. Summary of macroporosity (% , -10 kPa) results for undisturbed sites in the under-fenceline/untreated and FR380-forestry data sets

Soil order	Land use	<i>n</i>	Median	10 th %ile	90 th %ile
Allophanic	Pasture	5	14	13	18
Brown	Pasture	3	18	11	21
Gley	Pasture	6	12	11	15
Granular	Pasture	10	17	10	22
Organic	Pasture	4	16	14	17
Pallic	Pasture	4	15	14	19
Podzol	Pasture	1	10	10	10
Recent	Pasture	2	30	28	32
Ultic	Pasture	10	11	9	15
Allophanic	Exotic forestry	5	30	24	34
Brown	Exotic forestry	11	23	16	27
Pallic	Exotic forestry	3	21	17	23
Podzol	Exotic forestry	4	28	14	35
Pumice	Exotic forestry	3	25	24	29
Raw	Exotic forestry	1	28	28	28
Recent	Exotic forestry	3	40	24	50
Ultic	Exotic forestry	3	7	5	13

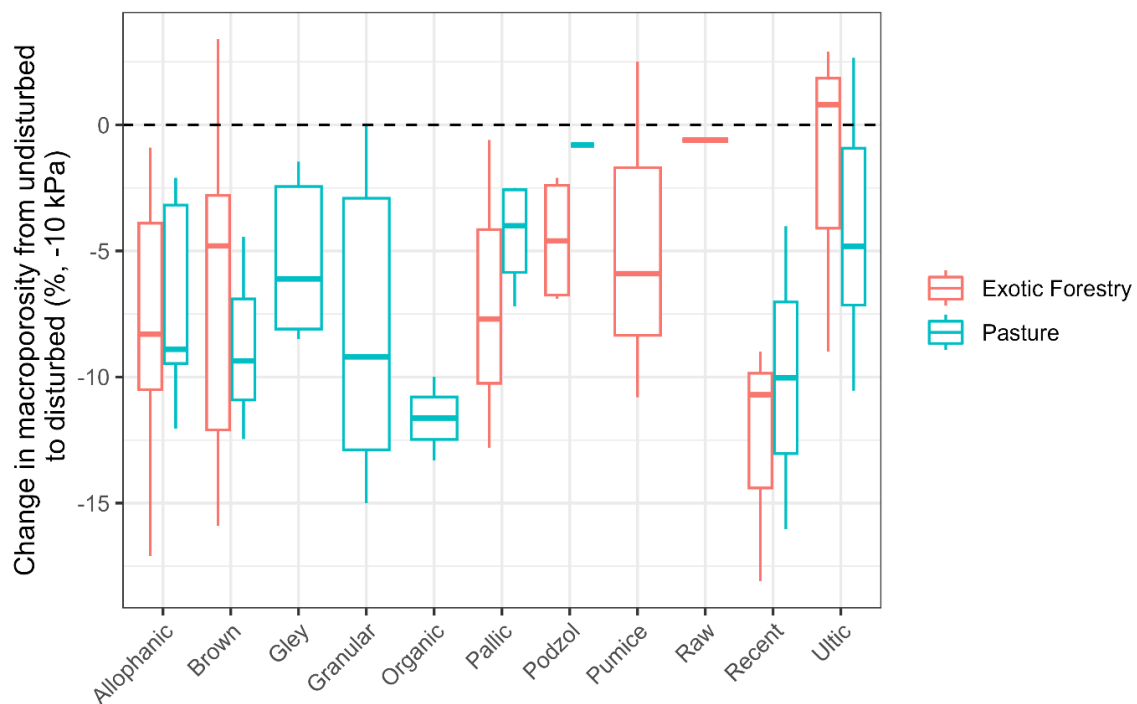


Figure 21. The relative difference in macroporosity (%) between disturbed and undisturbed (either under fenceline or undisturbed forestry).

Note: The 0 line indicates there is no difference between disturbed and undisturbed.

Given the generally low number of data points in Table 40, an alternative option is to group the soils based on their resilience to compaction, according to expert opinion, as follows:

- susceptible soils, which are less likely to naturally recover from compaction: Ultic, Pallic, Gley, Raw, Podzols, poorly-drained Recent soils
- more resilient soils, which are more likely to naturally recover from compaction: Brown, Allophanic, Granular, Organic, Pumice, coarse-textured Recent soils.

The macroporosity distribution of these soil groups is shown in Table 41, with the 10th percentile pastoral values converging on the existing lower-end target value for pastoral and cropping land use of 10% (see section 4.2), while the 90th percentile pastoral values are lower than current target values of 30% for pastoral and forestry land uses. As noted above, there are few studies that have assessed the implications of high values of macroporosity, so collecting additional data from under fencelines would increase the robustness of this data set and derived range. Further, at an individual farm level, comparison between under-fenceline and paddock soils would give a site-specific indication of the extent to which pasture soils have been compacted.

Table 41. Macroporosity (% , -10 kPa) results for undisturbed sites in the under-fenceline/untreated and FR380-forestry data sets, grouped as more resilient or susceptible soils

Soil group	Land use	<i>n</i>	Median	10 th %ile	90 th %ile
More resilient	Pasture	22	16	9.9	22
Susceptible	Pasture	23	12	9.3	24
All	Pasture	45	14	9.6	22
More resilient	Forestry	20	24	15	35
Susceptible	Forestry	13	20	5	50
All	Forestry	35	24	14	35

There is limited information on macroporosity in perennial horticultural crops. One study in apple orchards, where the orchards were managed using either conventional or organic practices, showed that macroporosity of the inter-row soils (range 1–3%) was lower than that of the row soils (range 7–12%) due to wheel traffic (Vogeler et al. 2006). More councils are starting to monitor the soil under different parts of perennial horticultural areas, such as along rows, inter-rows and wheel-tracks, especially in vineyards (e.g. Oliver et al. 2023), but no clear pattern in macroporosity has emerged. This is partly because there is variability in whether the inter-row includes or excludes wheel tracks.

Given the frequency of cultivation and the use of vehicles for short-rotation cropping land uses, care is required in the timing of sampling to ensure it is undertaken when the soil is relatively undisturbed (i.e. just prior to harvesting). Given that the under-fenceline macroporosity data for pastoral systems is considered to represent unimpacted samples, these data are also considered relevant to compare results from perennial and short-rotation horticultural land uses.

For comparison with the macroporosity results from the unimpacted data set, the macroporosity results from the monitoring data set for the different land uses are shown in Table 42. For most land-use categories, the 10th percentile values are lower than 10%, the lower limit of the

undisturbed soils range (Table 40). Given the high percentage of sites with macroporosity less than 10% (Table 43), which it is suggested give rise to negative impacts on pasture growth, we think that the typical range, as derived from the baseline monitoring data set, is not suitable for revising target ranges.

Table 42. Distribution of macroporosity results (%) from the baseline monitoring data set, by land use

Land use	<i>n</i>	Median	10 th %ile	90 th %ile
Cropping	117	16	6	24
Dairy	191	7	3	17
Drystock	322	11	5	21
Exotic forestry	137	25	10	38
Indigenous vegetation	116	16	8	32
Lifestyle	17	9	5	12
Orchard	71	11	5	21
Urban park/reserve	36	10	7	16
Vineyard	44	12	5	23

Table 43. Percentage of sites in the baseline monitoring data set that fall below 10% macroporosity

Land use	<10%
Cropping	26
Dairy	69
Drystock	44
Exotic forestry	9
Indigenous vegetation	20
Lifestyle	65
Orchard	42
Urban park/reserve	53
Vineyard	41

A final observation when plotting macroporosity results from the monitoring data is that many forestry soils have remarkably high macroporosity (Figure 22, Table 44). This is probably attributable to the combined influences of soil parent material for some soils that have a naturally high macroporosity, such as, Pumice, Allophanic, Raw and Recent; dense, near-surface tree roots; biological integration of organic materials (leaves, branches); and the effects of any cultivation or deep ripping at the time of planting that persist throughout the harvest rotation (Ross et al. 2009). On these soils, erosion risk is reduced because the roots preferentially occupy the cultivated space (Ross et al. 2004, 2005). Water-holding capacity is also expected to be lower for high-macroporosity soils. However, beyond these observations there has been no evaluation of the consequences of very high macroporosity. On the other hand, the low macroporosity observed for Ultic soils under forestry (Table 40) highlights the susceptibility of this soil order to compaction.

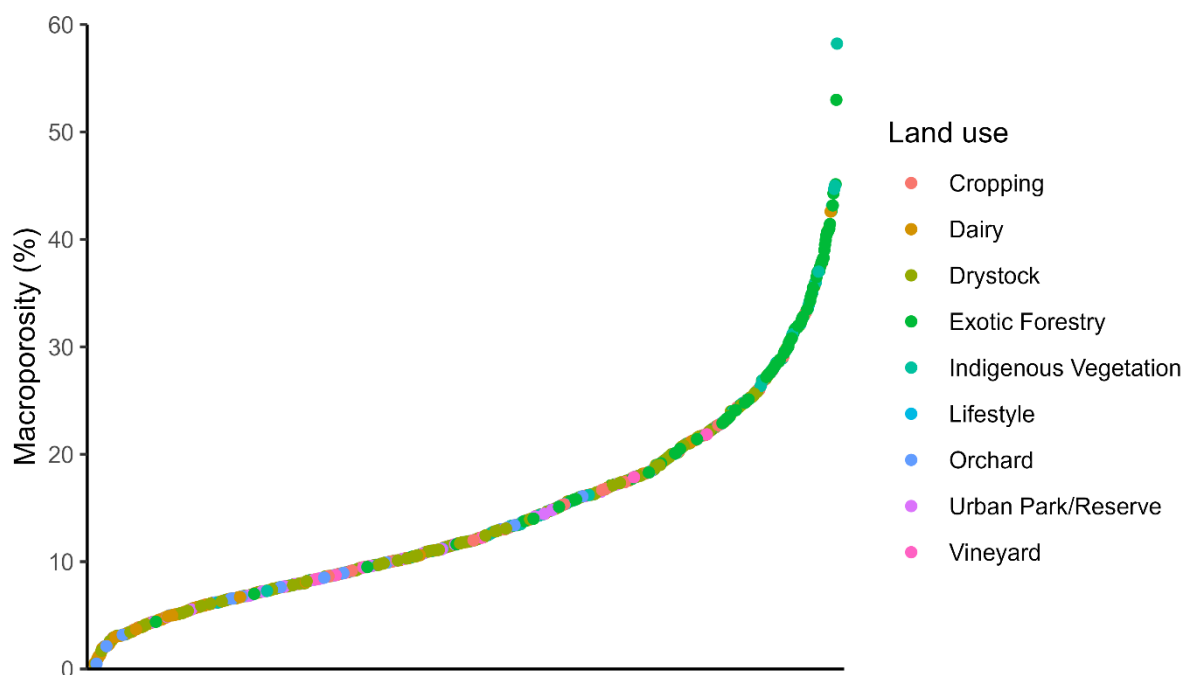


Figure 22. Macroporosity data from the monitoring data set, ordered from low to high values and coloured by land use.

Table 44. Distribution of macroporosity results (%) from the baseline monitoring data set for forestry land, by soil order

Soil order	<i>n</i>	Median	10 th %ile	90 th %ile
Allophanic	18	29	12	36
Brown	43	23	10	34
Gley	1	13	13	13
Melanic	2	24	18	29
Pallic	11	21	16	29
Podzol	6	32	17	36
Pumice	22	31	24	41
Raw	4	38	31	42
Recent	18	32	13	42
Ultic	12	11	6	21

6.6.2 Bulk density

Macroporosity has been identified as a more sensitive indicator of compaction than bulk density (Sparling et al. 2001b). EEA (2023) cites a lack of quantification of negative effects on pore functions, including direct links to soil strength or compaction, from bulk density measurements as a reason for not using bulk density as a primary indicator. However, bulk density measurements are useful because they enable calculations of stock from concentration data, and in the absence of macroporosity data they can provide some indication of compaction.

Reynolds et al. (2008) suggest that, for medium to fine-textured soils, there is an apparent optimal bulk density range for maximal crop yield of between 0.9 and 1.2 Mg/m³. They indicate an initial upper limit of 1.25–1.30 Mg/m³, which is associated with reduced crop yield that arises from inadequate soil aeration. A second upper limit of 1.4–1.6 Mg/m³ is associated with reduced crop yield as a result of excessive mechanical resistance to root elongation (Reynolds et al. 2008). These authors also suggest that bulk density values substantially below 0.9 Mg/m³ in medium- to fine-textured mineral soils lead to inadequate plant anchoring due to low soil strength, reduced plant-available water, and reduced unsaturated flow of water and dissolved nutrients to plant roots. However, bulk density can be affected by texture and so can be specific to soil types or soil orders, making it challenging to define useful generalised threshold values. Thus lower-end values (e.g. 0.9 Mg/m³) do not apply to Pumice or Organic soils, which have a lower bulk density, while Raw soils derived from iron sands have high bulk density.

The range in bulk density for undisturbed sites in the under-fenceline/untreated and FR380-forestry data sets for different soil orders and for grouped soil orders is shown in Table 45. The change in bulk density from undisturbed to disturbed sites in these data sets is shown in Figure 23.

Table 45. Bulk density (Mg/m³) for undisturbed sites in the under-fenceline/untreated and FR380-forestry data sets for different soil orders and for grouped soil orders

Land use	Soil order	<i>n</i>	Median	10 th %ile	90 th %ile
Exotic forestry	Allophanic	5	0.6	0.5	0.8
	Brown	11	1.0	0.9	1.2
	Pallic	3	1.0	1.0	1.3
	Podzol	4	0.8	0.5	1.1
	Pumice	3	0.8	0.7	0.9
	Raw*	1	1.4	1.4	1.4
	Recent	3	0.8	0.6	1.2
	Ultic	3	1.3	1.0	1.4
	All soils (excl. Raw, Allophanic, Pumice)			0.6	1.3
Pasture	Allophanic	5	0.9	0.7	1.0
	Organic	4	0.6	0.5	0.8
	Brown	3	1.0	1.0	1.0
	Gley	6	0.9	0.7	1.0
	Granular	10	0.8	0.7	0.9
	Pallic	2	0.8	0.7	1.0
	Podzol	1	1.1	1.1	1.1
	Recent	2	1.0	1.0	1.1
	Ultic	10	0.8	0.6	1.0
	All soils excl. Allophanic and Organic			0.65	1.0

* This Raw soil was an ironsand, which is expected to have high bulk density

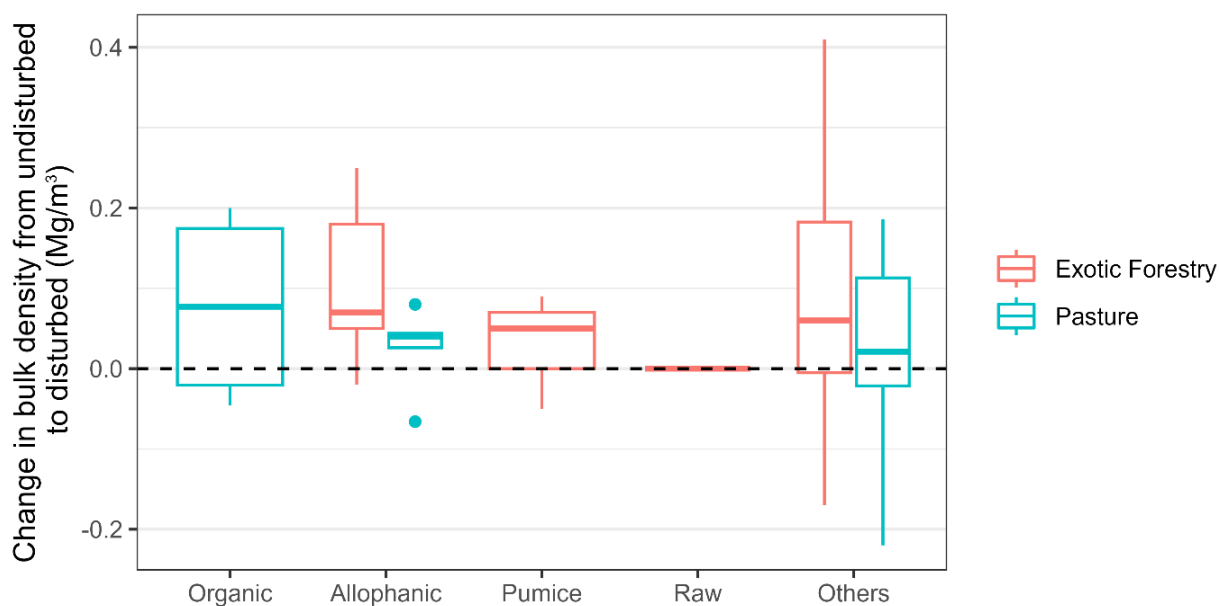


Figure 23. The relative difference in bulk density (Mg/m^3) between disturbed and undisturbed (either under fenceline or undisturbed forestry).

Note: The 0 line indicates there is no difference between disturbed and undisturbed.

The monitoring data set further illustrates bulk density variation associated with soil order. For example, Organic, Allophanic and Pumice soils have lower bulk densities than the other soil orders, whereas Raw soils have the highest bulk densities (Table 46). For the remaining soil orders, the 90th percentile measurements are close to bulk density values anticipated to have an impact on plant growth ($1.3 \text{ Mg}/\text{m}^3$; Reynolds et al. 2008). Notably, these 90th percentile values are also higher than the unimpacted data set, except for some undisturbed forestry sites (Table 45), suggesting that bulk density in the baseline monitoring data set is influenced by compaction.

Table 46. Distribution of bulk density results Mg/m^3 from the baseline monitoring data set, by soil order

Soil order	<i>n</i>	Median	10 th %ile	90 th %ile
Allophanic	242	0.7	0.5	0.9
Anthropic	21	1.0	0.6	1.4
Brown	387	1.0	0.7	1.2
Gley	182	1.0	0.7	1.2
Granular	65	0.9	0.7	1.1
Melanic	12	1.0	0.9	1.1
Organic	22	0.6	0.4	0.8
Oxidic	7	0.7	0.6	0.9
Pallic	209	1.1	0.9	1.3
Podzol	17	0.7	0.5	1.0
Pumice	97	0.7	0.5	0.9
Raw	6	1.3	1.0	1.5
Recent	275	1.1	0.8	1.3
Semiarid	12	1.2	0.9	1.3
Ultic	72	1.0	0.7	1.2

7 Revised soil quality numeric criteria

This section draws on the information given in the preceding sections to propose revised soil quality numeric criteria for use in SoE soil quality monitoring reporting, and clearly outlines the basis for their development. We start by outlining the wider considerations in developing numeric criteria before going on to discuss the revised values.

7.1 Considerations in developing numeric criteria for soil quality indicators

7.1.1 Approach to developing numeric criteria

As highlighted in section 4.4 and discussed in section 6 for the individual indicators, there are a number of approaches to developing numeric criteria for reporting on soil quality indicators. We use the term 'reference range' to provide a single term for the numeric criteria developed for each indicator using the different approaches. This more accurately reflects the fact that numeric criteria are being referred to in order to provide context for individual sampling results. Further, as discussed in section 6, there is often no robust scientific basis on which to provide values ('targets') to 'aim' for.

Following the descriptions of Matson et al. (2024), we use three approaches to develop numeric criteria for the indicators reporting on the state of soil quality in New Zealand.

- **Fixed:** This approach was used for pH and Olsen P in agricultural soils, primarily based on agronomic recommendations, and for total C to set a minimum threshold for cropping soils.
- **Reference:** This approach was used for macroporosity and bulk density, using data from sites that are considered to be desirable (i.e. under fenceline/untreated sites for pastoral land use, undisturbed forestry sites).
- **Distribution:** This approach was used for the remaining indicators (total C, total N, AMN, HWEC) and is based on the baseline monitoring data set described in section 3.4.2, with the 10th to 90th percentiles used to describe the 'typical' range of values associated with land-use and soil-order groupings.

A summary of the approach and the primary data used to inform the development of these reference ranges is given in Table 47.

Table 47. Overview of the approach used for developing reference ranges

Soil quality indicator	Approach used	Basis of value for different land uses
Soil pH	Fixed	Agronomic recommendations, stratified by land use (agriculture and forestry)
	Distribution	Baseline monitoring data set for urban and indigenous
Olsen P	Fixed	Agronomic recommendations, stratified by land use and grouped soil order
	Distribution	Monitoring data set for urban and indigenous
Total C	Fixed	Threshold of 2%C for non-allophanic mineral cropping soils
	Distribution	Baseline monitoring data set, stratified by land use and soil type
Total N (C:N)	Distribution	Monitoring data set, stratified by land use and soil type
AMN	Distribution	Monitoring data set, stratified by land use and soil type
HWEC	Distribution	Baseline monitoring data set, stratified by land use
Macroporosity	Reference	Not-treaded and undisturbed forestry data set
Bulk density	Reference	Not-treaded and undisturbed forestry data set

The significance of falling outside the reference range varies for the different indicators. For some indicators, the upper end (Olsen P, bulk density) or lower end (total C, macroporosity) of this range is of most interest and could be used as critical values to indicate when management action should be taken. In section 7.2 an interpretation section is provided for each indicator to indicate the significance of falling outside the reference range. This includes the use of a 'traffic-light system' to assist in interpreting and communicating results.

The specific approach is adapted from Griffiths et al. (2018) and is illustrated in Table 48. Reference range values in green indicate typical or optimal results. Amber and red categories indicate the need for further review and evaluation to ascertain whether management action is required to improve soil condition, and the red category indicates a greater likelihood that management intervention is required. Currently, this evaluation is based on a qualitative assessment of the potential risk and actions in relation to protecting soil quality.

Table 48. Traffic-light system to communicate reference range values

Traffic light	Comment
Investigate/action	INVESTIGATE and implement land management practices to improve soil quality or mitigate potential negative environmental (or production) outcomes
Review	REVIEW to verify if values are acceptable for the site and/or if management practices can improve soil quality or mitigate potential negative environmental outcomes
Continue monitoring	CONTINUE MONITORING; falls within typical/optimal range for the land use.

7.1.2 Land-use categories for the development of reference ranges

As a starting point, reference ranges were developed for each of the land-use categories specified in the NEMS-SQ (Table 16). We also suggest some additions to these categories to better reflect marked differences in management. Specifically, we recommend that vineyards be separated out from 'horticulture', given the marked differences in management practices that are associated with vineyards (and often different soils) compared to other horticultural crops. Intensive, or continuous, vegetable cropping should also be separated out from arable or mixed arable cropping, given the differences in cultivation frequency and fertiliser inputs in continuous vegetable growing. However, given that these sites were difficult to identify in the monitoring data set, reference ranges were not developed for vegetable cropping for distribution-based criteria (total C, total N, AMN, HWEC).

For some indicators (i.e. Olsen P, pH, macroporosity, and bulk density) there appears to be no case for setting separate numeric criteria for different pastoral systems. However, there is merit, for reporting purposes, in delineating pastoral systems that differ markedly in the level of inputs. This aligns with the NEMS-SQ requirement for more frequent monitoring of soil quality of pastoral systems under more intensive use.

Table 49 summarises the land-use categories for which reference ranges were developed for some or all of the indicators. We have captured some management information in the description of these categories to provide an indication of the range in management practices that may occur within some of the broad categories (e.g. drystock), and that may contribute to variability in measured values. Specifically, the intensity of drystock land use (which includes non-milking, i.e. winter-grazed, dairy cows) is quite diverse, and ranges from intensively managed flat to rolling hill country to low-intensity hill and high-country grazing. For this reason, Cavanagh and Whitehead (2023) and Law et al. (2024) proposed subdividing drystock land use into more intensively managed and less intensively managed categories. It may be appropriate to use these categories in the revision of the existing soil quality target ranges, or at least to consider them in the context of reporting on SoE soil quality monitoring.

Table 49. Land-use and management categories used for developing reference ranges

Land-use and management category	Definition
Horticulture (perennial cropping)	Orchards and vines (excluding wine-grapes).
Vineyards	Wine-grapes
Cropping	Annual crops, often grown on a rotational system that can include a short-term (c. 1–3 years) pasture rotation. Includes maize, barley, wheat, peas, other grain and seed crops, and fodder crops.
Vegetable cropping	Market gardens or continuous vegetable growing
Dairy*	Milking platform, includes areas of grazed forage crops and maize for silage.
Dry stock* (other pasture)	Includes sheep, beef, deer, goats, horses, dairy support, and cut and carry.
Exotic forest	Plantations for pulp and timber production, predominantly radiata pine, but also redwood and Douglas fir. Usually harvested using clear-felling methods.
Indigenous vegetation	Native forest, tussock, shrubland, and scrub dominated by indigenous species.
Urban green-space	Open areas of grass in urban areas, including parks and reserves.

* For some indicators (e.g. pH, Olsen P) these land uses are considered as a single pastoral land-use class.

The NEMS-SQ states that the purpose of monitoring indigenous sites is to obtain information on what soils were like before development for agriculture and forestry; in this context, these sites could potentially be considered reference sites for other land uses. However, it is unclear that this is how these sites are used for SoE reporting (Cavanagh & Whitehead 2023), and they are often not reported in national SoE reporting (e.g. MfE & StatsNZ 2021, 2024). Some of these sites can be of 'poor quality' due to human impacts, such as drift from adjacent agricultural land (Stevenson 2004; Cavanagh & Gordon 2023) and/or browsing and compaction (especially from heavy stock classes). In this regard, the sites are of variable quality (i.e. not necessarily representative of pre-agricultural or forestry land use). Furthermore, these sites are predominantly under trees, which is relevant for comparison with forestry land use, but less so for pastoral or cropping, for which native grassland reference sites would be more appropriate.

Nonetheless, reference ranges have been developed for indigenous vegetation using the existing data set of indigenous vegetation sites. We recommend that the purpose for monitoring indigenous sites be confirmed, and an assessment of existing indigenous sites undertaken to ascertain the level of anthropogenic modification and whether they meet the intended purpose. It may be relevant to increase the number of sites to gain better representation, particularly of native grassland. However, climate and soil order should also be considered for reference sites and may limit the availability of suitable sites. As more data become available, and the purpose is clarified, re-evaluation of the reference ranges may be required.

The purpose of monitoring for urban open space is not identified in the NEMS-SQ. Monitoring of urban spaces was initiated in Auckland in 2012 with the objective of establishing baseline information given the value and wide-ranging soil ecosystem services within urban green-spaces (Curran-Cournane et al. 2015). These authors sampled urban sites in Auckland and developed a pollution index for trace element contaminants, both within urban sites (using urban indigenous vegetation sites), and later across rural and urban sites (using indigenous vegetation sites across the wider regional network) (Curran-Cournane 2020).

Clarification of the purpose of monitoring urban sites in the context of national SoE monitoring is required to help identify representative sites. Specifically, careful consideration of site history is required, because urban parks can be brownfield sites such as historical landfills (see Cavanagh & Whitehead 2023) or involve large-scale cut-and-fill earthworks (e.g. Sullivan et al. 2009), whereas other urban parks may have reasonably unmodified soils. This difference in land-use history contributes significantly to the interpretation of monitoring results (and the development of relevant reference ranges). Currently few councils (mainly Auckland) monitor urban sites. However, the importance of assessing the condition and functioning of urban soils has garnered increasing attention in recent times (e.g. PCE 2023, 2024b).

Given that urban sites targeted for SoE monitoring specified in the NEMS-SQ are predominantly perennial grasses, we use criteria developed for pastoral land use, using lower-end values for fertility (Olsen P). However, as with the sites currently used for monitoring indigenous vegetation, review of existing urban sites is recommended to ascertain whether they meet the intended purpose (when this is confirmed). There is also value in assessing urban sites that are under indigenous forest/shrubland or treed parklands, and not just grass/pasture.

7.2 Reference ranges for individual parameters

7.2.1 pH

Reference ranges for most agricultural land uses, including cropping and orchards, dairy, and drystock, are based on the optimal agronomic range for ensuring near maximum growth (yield). While it is recognised that soil pH can have an influence on the composition of microbial communities and some microbially mediated processes, there is no clear basis for developing numeric criteria for these outcomes. For vineyards, exotic forestry, urban soils and indigenous vegetation, reference ranges are based on the typical range identified from the baseline monitoring data set (Table 50). Calcareous soils appear to be largely unrepresented in the baseline monitoring data set and will have a soil pH that is naturally higher than the pH ranges identified in Table 50.

Table 50. Reference ranges for soil pH

Soil order	Land-use group	Basis of reference range	Reference range
All	Cropping & orchards	Agronomic optima	5–6.5
All	Vineyard	Agronomic optima	6–7
All	Dairy	Agronomic optima	5.5–6.2
All	Drystock	Agronomic optima	5.5–6.2
All	Exotic forestry	Distribution	4.7–6.0
All	Indigenous vegetation	Distribution	4.7–6.2
All	Urban	Distribution	5.3–6.3

Interpretation

For agricultural land uses, the reference range represents the pH range for optimal plant growth, while results outside the reference range indicate the potential to limit agronomic production. Specifically, soil pH outside the optimal range can give rise to recognised trace element issues arising from changes in the bioavailability of these trace elements (see section 6.2 for details). From a land manager's perspective, this would warrant review to ascertain whether negative impacts (e.g. reduced growth) are being observed and mitigation (e.g. lime application to lower pH) is warranted. High pH may be indicative of the presence of calcareous soils, and thus should be considered in the evaluation of high pH soils.

For exotic forestry, indigenous vegetation, and urban land uses, the reference range represents the typical values associated with those land uses based on the baseline monitoring data set. For urban sites where exotic grasses are being grown, low pH may give rise to the same aluminium toxicity issues as for pastoral land use. Outside of this there are no clear negative environmental impacts associated with soil pH falling outside the reference range. Rather, these values may simply reflect the inherent pH at that site, and review of the site could be undertaken to verify this is the case (Tables 51 and 52).

Table 51. Traffic-light evaluation of soil pH reference range

Soil orders	Land-use group	Lower	Reference range	Upper
All	Cropping & orchards	<5.0	5–6.5	>6.5
All	Vineyard	<6.0	6–7	>7.0
All	Dairy	<5.5	5.5–6.2	>6.2
All	Drystock	<5.5	5.5–6.2	>6.2
All	Exotic forestry	<4.7	4.7–6.0	>6.0
All	Indigenous vegetation	<4.7	4.7–6.2	>6.2
All	Urban	<5.3	5.3–6.3	>6.3

Table 52. Description of review and monitoring activities for soil pH

Traffic light	
Review if <lower	REVIEW potential for limited production arising from aluminium and trace element toxicity issues and nutrient availability (agricultural land uses, urban – exotic grasses) REVIEW to verify acceptable value for the site (non-agricultural land uses)
Continue monitoring	CONTINUE MONITORING; falls within agronomic optima, or the typical range for the land use.
Review if >upper	REVIEW potential for limited production arising from trace element deficiency issues (agricultural land uses) REVIEW to verify acceptable value for the site (non-agricultural land uses)

7.2.2 Olsen P

Considerable effort has been put into defining optimal Olsen P ranges for agricultural land uses. Water quality concerns are the primary environmental concern associated with elevated Olsen P values. As discussed in section 0, many factors influence the delivery of soil P to waterways, and no current models adequately capture all these variables to assist in identifying the conditions under which managing soil Olsen P could achieve a significant improvement in water quality. Therefore, the revised Olsen P values remain focused on the production outcomes for different soils and land uses (Table 53).

For forestry sites, Olsen P above the proposed threshold should be interpreted in the same manner as described for agricultural land use; no lower Olsen P thresholds have been identified, although P deficiency is recognised to limit tree growth. Further, it should be noted that the forestry sector typically uses Bray-P to assess plant-available P.

For urban sites, the agronomic recommendation for pasture in sedimentary soils of 20 mg/L is used as an indicative threshold to indicate concentrations above which Olsen P may be present in excess; for sports-fields, turf grass recommendations may be more relevant. For indigenous vegetation sites, a value that indicates potential anthropogenic influence (e.g. less than the lowest agronomic recommendation, 10 mg/L) is used.

Table 53. Summary of agronomic recommendations for Olsen P for different land-use categories

Land-use group	Soil group	Agronomic recommendations (mg/L)	Agronomic recommendations (mg/kg)
Arable cropping & Orchards	All	10–30	–
Vegetable cropping	All	10–50	–
Vineyard	All	NA	–
Pastoral ^a	Sedimentary, ash ^b	20–30	–
Pastoral ^a	Pumice, peat ^b	35–45	–
Exotic forestry	All	NA	<25
Indigenous vegetation	All	Na	Na
Urban	All	<20 ^c	–

¹ Based on 7.5 cm depth.

² Refer to Table 8 for correlation of soil order with fertiliser industry soil classification.

³ Based on lower-end recommendations for pastoral soils.

NA = Not available; Na = not applicable.

Given that reporting of Olsen P values in the NEMS-SQ specifies gravimetric units, we have converted volumetric (mg/L) Olsen P values to gravimetric (mg/kg) values, following Drewry et al. 2022. This was undertaken for individual soil orders (and then grouped where values were the same/within 1 or 2 units), and with depth adjustment for pastoral recommendations (based on 7.5 cm) to the depth of SoE monitoring of 10 cm using equation 5. This relationship was developed through statistical analysis of soil samples taken at 0–10, 0–7.5, and 0–15 cm depths close to each other along a typical soil sampling transect on a range of soil orders and farm systems throughout New Zealand, and bulked by depth (Power et al. 2022). A similar depth adjustment is 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 the same as in 0–15 cm depth. However, an increased use of minimum tillage for cropping may mean that this assumption becomes invalid over time and that depth conversions for 0–15 cm to 0–10 cm may become relevant. In the absence of accessible agronomic recommendations based on soil Olsen P values for perennial horticulture crops, Olsen P values for cropping are considered to be applicable for perennial horticulture crops.

$$OP_{10} = (OP_{7.5} - \beta_0) / \beta_1 \quad (5)$$

where OP_{10} = Olsen P in 10 cm depth, $OP_{7.5}$ = Olsen P in 7.5cm depth, β_0 = 2.06, and β_1 = 1.64.

The gravimetric reference ranges for Olsen P are shown in Table 54. As can be seen, there is variation across soil orders, with Pumice soils having the highest values. However, even the highest value (95 mg/kg for vegetable cropping soils) is below the threshold of 200 mg/L (or 374 mg/kg using the conversions of Drewry et al. [2022]) identified by Lizzaralde et al. (2023) as the limit of P saturation, above which added P is no longer sorbed in Pumice soils, but will be leached.

Volumetric Olsen P reference ranges are also shown in Table 54, with depth adjustment for pastoral recommendations (based on 7.5 cm) to the depth of SOE monitoring of 10 cm, using equation 5.

Table 54. Reference range for Olsen P for different land-use categories and soil orders, developed from the volumetric recommendations shown in Table 53

Land-use category	Reference range Olsen P (mg/L)	Reference range Olsen P ^a (mg/kg)				
		Pumice	Organic, Podzol	Recent, Granular	All others	Raw ^b
Arable cropping & Orchards	10–30	15–55	15–45	10–30	10–35	10–40
Vegetable cropping	10–50	15–95	15–85	10–60	10–70	10–75
Pastoral ^c (sedimentary, ash soils)	17–26	NA	30–45 ^d	20–30	25–35	25–40
Pastoral ^c (pumice, peat)	31–40	60–75	55–70 ^e	NA	NA	NA
Urban ^f	<20	<40	<30	<20	<25	<25
Indigenous ^g	<10	<15	<15	<10	<10	<10
Forestry ^h	Na			<25		

Note: Soil orders with similar gravimetric values have been grouped and rounded to the nearest 5 mg/kg for ease of use. The exact conversions are shown in Appendix 6.

^a Converted to gravimetric values using relationships developed by Drewry et al. (2022) and described in section 5.

^b Conversion of values for Raw soils is based on limited data

^c Depth-adjusted value for conversion of recommendations for pasture based on 7.5 cm depth to 10 cm depth equivalent, based on Power et al. 2023: $OP_{10}=(OP_{7.5} - \beta_0)/\beta_1$, where $\beta_0= 2.06$ and $\beta_1= 1.64$

^d Podzol

^e Organic soil (peat)

^f For urban sites, the agronomic recommendation for pasture in sedimentary soils of 20 mg/L is used as an upper threshold.

^g For indigenous sites, the lower-end agronomic recommendations for pasture in sedimentary soils of 10 mg/L is used as an upper threshold. Naturally high Olsen-P may be observed in some specific ecosystems (e.g. seabird colonies).

^h Watt et al. 2008; Olsen P is recognised to overestimate available P at lower soil pH; Bray P is a more common measure for forestry soils.

Interpretation

For agricultural land uses, P concentrations falling below the reference range indicate a decline in P fertility and hence the productive capacity of the soil for agriculture. For some land uses, such as pastoral farming in hill country, economic drivers limiting P fertiliser inputs result in Olsen P values below the threshold for achieving maximal pasture production. Olsen P concentrations above the upper value of the reference range offer no or minimal agronomic benefit.⁸ Soil Olsen P is a measure of soil P availability and not the impact of P on waterways, the latter of which is influenced by many other factors (see section 0). Generically, it can be stated that risk of P losses to water increases with higher Olsen P. Thus, for SoE reporting, the upper value of the reference range is of most interest. Additional information, such as the P-retention or Anion Storage Capacity (ASC) of the soil, proximity to waterways, and slope, would help to refine the risk of P loss to waterways. This information is collected – or could be collected – as part of a soil quality monitoring programme and could be provided alongside Olsen P values for individual sites as part of reporting. Table

⁸ Although, depending on production and payout, there may be economic incentives to apply fertiliser.

55.55–58 provide the traffic-light evaluation for Olsen P for different land uses, with actions specified in Table 59.

Table 55. Traffic-light evaluation of soil Olsen P reference ranges (mg/kg) for arable cropping and orchards

Soil-order group	<Lower value	Lower value	Upper value	>Upper value
Pumice	<15	15	55	>55
Organic & Podzol	<15	15	45	>45
Recent & Granular	<10	10	30	>30
Raw	<10	10	40	>40
All others	<10	10	35	>35

Table 56. Traffic-light evaluation of soil Olsen P reference ranges (mg/kg) for vegetable cropping

Soil-order group	<Lower value	Lower value	Upper value	>Upper value	Threshold*
Pumice	<15	15	95	>95	115
Organic & Podzol	<15	15	85	>85	100
Recent & Granular	<10	10	60	>30	75
Raw	<10	10	75	>75	85
All others	<10	10	70	>70	85

* Based on gravimetric conversions from 60 mg/L; concentrations between 35 and 70 mg/L are identified by Reid and Morton (2019) as concentrations above which maintenance P application should not be applied for different crops, but rather Olsen P should be allowed to reduce.

Table 57. Traffic-light evaluation of soil Olsen P reference ranges (mg/kg) for pastoral grazing

Soil-order group	<Lower value	Lower value	Upper value	>Upper value
Pumice	<60	60	75	>75
Organic	<55	55	70	>70
Podzol	<30	30	45	>45
Recent & Granular	<20	20	30	>30
Raw	<10	25	40	>75
All others	<10	10	70	>70

Table 58. Traffic-light evaluation of soil Olsen P reference ranges (mg/kg) for urban, indigenous vegetation, and forestry sites

Soil-order group	Urban	Urban upper	Indigenous	Indigenous upper	Forestry	Forestry upper
Pumice	≤40	>40	≤15	>15		
Organic & Podzol	≤30	>55	≤15	>15		
Recent & Granular	≤20	>20	≤10	>10	≤ 25	>25

Raw	≤25	>25	≤10	>10		
All others	≤25	>10	≤10	>10		

Table 59. Description of review and monitoring activities for Olsen P

Traffic light	Actions
Review	REVIEW management practices if P is limiting grass or crop-growth
Continue monitoring	CONTINUE MONITORING; falls within optimum for the land use.
Review	REVIEW potential for movement of soil P into waterways and evaluate practices to reduce soil P levels, and/or management practices to avoid or minimise movement if likely.
Investigate/Action	INVESTIGATE and implement land management practices to reduce soil P and/or management practices to avoid or minimise movement if occurring

7.2.3 Total C

Reference ranges for total C are largely based on the typical ranges identified from the baseline monitoring data set for two soil groups: Allophanic soil, and all other soils (excluding Organic and Raw soils). The 2% C value was identified by Oldfield et al. (2019) as the point at which yield response to soil C plateaus. This function-based endpoint was used as the lower-end reference range value for most non-allophanic mineral soils under cropping because it was higher than the 10th percentile value (1.9%, Table 31). This value of 2% total C equates to the 16th percentile of the data from the monitoring data set. The Raw soils in the database appear (unsurprisingly) to have markedly lower C than other soils, and given the low number of sites, a single range was considered to apply to all land uses. The reference ranges are shown in Table 60.60.

For Granular soils, in particular, there is some concern that the 2% C captures a very depleted state of soils, because it is equivalent to soils that have a long cropping history of around 50 years (Haynes & Tregurtha 1999), and should therefore be viewed with caution as representing an 'acceptable state'. However, no other functional or other quantitative endpoint to provide an alternative basis for setting the lower-end value was identified. The saturation-potential or C-loading of soil (e.g. McNally et al. 2024; McNally et al. 2017; Beare et al. 2014) could give an indication of the 'gap' between measured C levels and potentially achievable C levels, and provide a more functionally oriented basis on which to set soil quality targets (e.g. a saturation deficit of x% is considered unhealthy). However, further evaluation of this approach in the context of SoE monitoring is required. We 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.

Sparling et al. (2008) noted that, by definition, Organic soils have an organic C content >16% (Hewitt 2010 indicates Organic soils contain ≥18% organic C), which means organic C is not a useful measure of their quality. We agree with this philosophy and so are not proposing numeric criteria for Organic soil beyond the diagnostic criterion of 18%⁹. We do note that in the baseline

⁹ We use 18%C as this is specified in the formal soil order classifications of Hewitt 2010.

monitoring data set a number of sites are identified as being on Organic soils even though their C concentrations fall below – well below in the case of cropping soils – the diagnostic criterion for Organic soils of 18% C (Table 31). Therefore, the wider implications of the degradation of these Organic soils needs to be considered.

Table 60. Reference range for soil C% for different land-use categories and soil-order groups

Land-use group	Soil order	Reference range (%) ^a
Cropping	Allophanic	4.0–8.0
	All other soils (excl. Organic, Raw)	2 ^b –4.5
Orchard	Allophanic	5–10
	All other soils (excl. Organic, Raw)	2.5–6
Vineyard	All other soils (excl. Organic, Raw)	2–5
Dairy	Allophanic	6.4–13.5
	All other soils (excl. Organic, Raw)	3.5–8.5
Drystock	Allophanic	5.5–13
	All other soils (excl. Organic, Raw)	3.5 –8.5
Exotic forestry	Allophanic	6–18
	All other soils (excl. Organic, Raw)	3.5–8
Indigenous vegetation	Allophanic	5.5–19
	All other soils (excl. Organic, Raw)	3.5–11
Urban park/reserve	Allophanic	4.0–10
	All other soils (excl. Organic, Raw)	3.0–7.0
All	Raw	1.0–3.0
All	Organic	≥18

^a Values rounded to nearest 0.5%.

^b For Granular soils, in particular, this value represents a very depleted state compared to unmodified soils.

Interpretation

It is generally considered that more soil C, and hence organic matter, is better. The general benefits of increased organic matter include increased water-holding capacity, improved structure, and increased biological activity. The upper end of the reference range provides an estimate of the feasible upper bound for C in soils under different land uses. The lower-end values indicate minimum values that might be expected. For the purposes of SoE reporting, the lower end of the reference range is of most interest, with values below this indicating soils are unduly low relative to that land use, and therefore may represent a degraded state. For all soils the emphasis should be on ensuring that soil C levels are not declining over time and are at least maintained, or if low, are ideally increasing. Tables 61 and 62 provides the traffic-light evaluation for total C for Allophanic and non-allophanic minerals soils, with actions specified in Table 63.

Table 61. Traffic-light evaluation for total C reference range for non-allophanic mineral soils, excluding Raw soils^a

Land use	<10 th %ile	10 th %ile	Median	90 th %ile	>90 th %ile
Cropping	<2.0	2.0 ^b	3.0	4.5	>4.5
Orchard	<2.5	2.5	4.0	6.0	>6.0
Vineyard	<2.5	2.5	3.5	5.0	>5.0
Dairy	<3.5	3.5	6.0	8.5	>8.5
Drystock	<3.5	3.5	5.0	8.5	>8.5
Exotic forestry	<3.5	3.5	5.0	8.0	>8.0
Indigenous vegetation	<3.5	3.5	6.0	11.0	>11.0
Urban park/reserve	<3.0	3.0	5.0	7.0	>7.0

^a Values rounded to nearest 0.5%.

^b Minimum threshold from Oldfield et al. 2019; for Granular soils, in particular, this represents a very depleted state, compared to unmodified soils.

Table 62. Traffic-light evaluation for total C reference range for Allophanic soils*

Land use	<10 th %ile	10 th %ile	Median	90 th %ile	>90 th %ile
Cropping	<4.0	4.0	5.2	8.0	>8.0
Orchard	<5.0	5.0	7.0	10.0	>10.0
Dairy	<6.5	6.5	10.0	13.5	>13.5
Drystock	<5.5	5.5	9.5	13.0	>13.0
Exotic forestry	<6.0	6.0	7.9	18.0	>18.0
Indigenous vegetation	<5.5	5.5	12.3	18.0	>18.0
Urban park/reserve	<4.0	4.0	5.3	10.0	>10.0

* Values rounded to nearest 0.5%.

Table 63. Description of review and monitoring activities for soil C

Traffic light	Action
Investigate/Action	INVESTIGATE and implement land management practice to enhance soil C/organic matter content
Review	REVIEW site and management practices to see if improvements to increase soil C/organic matter content should be made REVIEW to verify an acceptable value for the site (non-agricultural land uses)
Continue monitoring	CONTINUE MONITORING; falls within agronomic optima, or typical range for the land use.

7.2.4 Total N, C:N ratio

Total N is largely dependent on the amount of organic matter, so the N content of the soil is usefully considered in conjunction with the ratio of total C to total N (the soil C:N ratio) and mineralisable N (see section 7.2.5). The C:N ratio provides a relative measure of fertility or plant-available N, while total N content gives an indication of the absolute amount of N present. A widening of the C:N ratio over time reflects declining organic N fertility, while a narrowing of the ratio may indicate enrichment and higher fertility.

C:N ratios between 9 and 11 are typical of well-developed, high-pasture-producing, well-managed dairy farms that have been in permanent pasture for several decades (pers. comm., A. Roberts, Ravensdown, November 2024). In contrast, a very wide range of C:N ratios is found in unmodified soils under indigenous vegetation, from low ratios in Raw soils to >30 in leached, low-fertility soils with elevated C content, such as some Podzols (Bokhorst et al. 2017; Coombes et al. 2013).

The typical ranges of C:N observed in the baseline monitoring data set are proposed as the reference ranges for SoE reporting. Given the similar and relatively narrow range of C:N across the different agricultural and horticultural land uses, and urban grassland (Table 32), these land uses are grouped to provide a single reference range, while exotic forestry and indigenous vegetation retain individual reference ranges (Table 64).

Table 64. Distribution of C:N ratio in the monitoring data set across all soil orders

Land-use group	Soil order	Reference range
Dairy, drystock, cropping orchard, vineyard, urban	All	10–13
Exotic forestry	All	12–26
Indigenous vegetation	All	12–20

Similarly, the typical ranges of total N observed in the baseline monitoring data set for the individual land-use categories for mineral soils are proposed as the reference ranges for use in SoE reporting. Given the similarity in the typical ranges for some land uses for the different mineral soil groupings, and the absence of any identifiable effect associated with any given value of total N, reference ranges are provided for grouped land uses, or separately for Raw soils, given the low number of sites on this soil order, as shown in Table 65.

Table 65. Proposed reference range for total N (%) in mineral soils for aggregated land-use categories and soil orders

Land-use group	Soil order	Reference range
Cropping & orchard & urban	Allophanic	0.4–0.9
Cropping, orchard, vineyard, urban	Others (excl. Organic)	0.2–0.5
Dairy & drystock	Allophanic	0.5–1.2
	Others (excl. Organic)	0.3–0.7
Exotic Forestry, indigenous vegetation	Allophanic	0.3–1.3
	Others (excl. Organic)	0.2–0.6
All	Raw	0.03–0.25
All	Organic	0.7–2.0

Interpretation

As indicated above, the C:N ratio provides a measure for the condition of the organic matter and amount of plant-available N, while total N content gives an indication of the absolute amount of N present. The reference range provides an indication of the range for the land use and soil type in the database, although beyond this only general statements about the significance of the measured values can be made. For example, low total N may limit production. Change over time at a given site is likely to provide the most value for assessing the soil resource, with a widening of the C:N ratio over time reflecting declining organic N fertility, while a narrowing of the ratio indicates enrichment and higher fertility. Changes in total N over time could be used to indicate changes in N stocks. No traffic-light evaluation is provided for C:N and total N because maintaining a watching brief on these indicators is most relevant.

7.2.5 AMN and HWE C

The reference ranges for AMN and HWE C are largely based on the typical value (10th to 90th percentiles) of the baseline monitoring data set and HWE C data set, respectively, excluding the non-allophanic mineral cropping soils. Given the close association of AMN and HWE C with total C, the lower-end reference range has been adjusted up to the 16th percentile for these soils, which is equivalent to the percentile associated with the 2% C lower-end value. These values are shown in Tables 66 and 67.

Table 66. Reference range for AMN (mg/kg) for different land-use categories and soil-order groupings for mineral soils

Land-use group	Soil order	Reference range
Cropping	Allophanic	30–160
	Others	30*–120
Orchard	Allophanic	110–200
	Others	40–150
Vineyard	Others	60–120
Dairy	Allophanic	140–340
	Others	100–260
Drystock	Allophanic	130–265
	Others	80–240
Exotic forestry	Allophanic	80–180
	Others	40–120
Indigenous vegetation	Allophanic	80–420
	Others	50–190
Urban park/reserve	Allophanic	80–240
	Others	60–200

* 16th percentile in non-allophanic mineral cropping soils

Table 67. Distribution of HWEC results (mg/kg) in the monitoring data set for different land-use categories for all mineral soils^a

Land-use group	Reference range
Cropping	800 ^b –1,500
Orchard	850–2,500
Vineyard	1,200–1,800
Dairy	1,400–4,000
Drystock	1,100–3,600
Exotic forestry	1,300–3,100
Indigenous vegetation	2,000–6,500

^a Insufficient Organic soil samples were available to develop reference ranges.

^b 16th percentile in non-allophanic mineral cropping soils.

Interpretation

The reference range provides an indication of the typical range for the land uses and soil type in the baseline data set. Only general statements about HWEC or AMN can be made in relation to measured values (i.e. that higher values indicate a higher amount of N that will be released over time, and that there is probably higher microbial activity). For HWEC, higher values indicate higher levels of readily decomposable C. Low values of AMN/HWEC could indicate N-limitation or low microbial activity, and generally it would be considered that higher AMN or HWEC is better because it indicates higher microbial activity and available N.

However, beyond general management practices that would increase organic matter, little is known about the management practices that would influence AMN or HWEC. A recent study found that neither P fertiliser use, cultivation practices during pastoral renewal, nor sheep and cattle grazing management practices had an influence on HWEC (Wilson 2024). In contrast, each of these practices have large impacts on primary production and the amounts of C and N cycling within the soil (Wilson 2024). The traffic-light evaluations for AMN and HWEC Tables 68–70) and actions (Table 71) are based on those for soil C.

Table 68. Traffic-light evaluation for AMN reference range for mineral soils, excluding Allophanic, Organic, and Raw soils

Land use	<10th %ile	10th %ile	Median	90th %ile	>90th %ile
Cropping*	<30	30	50	120	>120
Orchard	<40	40	90	150	>150
Vineyard	<60	60	90	120	>120
Dairy	<100	100	165	260	>260
Drystock	<70	70	140	240	>240
Exotic forestry	<40	40	70	120	>120
Indigenous vegetation	<50	50	120	190	>190
Urban park/reserve	<60	60	110	200	>200

* 16th percentile value used in place of 10th percentile

Table 69. Traffic-light evaluation for AMN reference range for Allophanic soils

Land use	<10th %ile	10th %ile	Median	90th %ile	>90th %ile
Cropping	<30	30	65	160	>160
Orchard	<110	110	150	200	>200
Dairy	<140	137	240	340	>340
Drystock	<130	128	215	260	>260
Exotic forestry	<80	77	130	190	>190
Indigenous vegetation	<80	80	200	420	>420
Urban park/reserve	<80	80	110	240	>240

Table 70. Traffic-light evaluation for HWECC in all mineral soils

Land-use group	<10 th %ile	10th %ile	Median	90th %ile	>90th %ile
Cropping*	<800	800	1,073	1,500	>1,500
Orchard	<850	850	1,812	2,500	>2,500
Vineyard	<1,160	1,200	1,442	1,800	>1,800
Dairy	<1,440	1,400	2,469	4,100	>4,100
Drystock	<1,140	1,100	2,204	3,500	>3,500
Exotic forestry	<1,350	1,350	2,273	3,200	>3,200
Indigenous vegetation	<2,000	2,000	3,500	6,500	>6,500

* 16th percentile value used in place of 10th percentile

Table 71. Description of review and monitoring activities for soil AMN and HWECC

Traffic light	
Investigate/Action	INVESTIGATE options for enhancing organic matter content
Review	REVIEW management practices to see if improvements can be made
Continue monitoring	CONTINUE MONITORING; falls within or above typical range for the land use

7.2.6 Macroporosity

The reference ranges for macroporosity are based on limited data sets that provide information on 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). This 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 macroporosity range is more relevant for forestry. We have *not* used the typical range for macroporosity from the baseline monitoring data set to provide the reference range, because evaluation of that data, based on comparison with the 'under fenceline' data and wider literature, suggests that there is strong evidence of degradation (affecting productivity) in the baseline monitoring set (see section 6.6).

Given the limited data available for the different soil orders, and the fact that macroporosity values for different soil orders were similar (see section 6.6), a single reference range for all soil orders is used (Table 72). However, the sensitivity of different soils to soil structural degradation (e.g. compaction) and their ability to recover over the length of the forest rotation should be highlighted. A greater effort should be made to avoid compaction of vulnerable soils. This includes fine-textured soils with imperfect to poor drainage such as Ultic, Podzol, and Pallic soils, which have a high structural vulnerability index, and to a lesser extent Gley soils that have a moderate structural vulnerability index (e.g. Hewitt & Shepherd 1997). Similarly, compaction should also be avoided in soils with perched or high water-tables, much of the large-pore volume is filled with water for significant periods of the year, rendering these pore spaces ineffective in air exchange (Mackay et al. 2006).

Soils that are generally more resilient to compaction are Brown, Allophanic, Granular, Organic, Pumice, and coarse-textured Recent soils. However, the response of macroporosity and associated functions such as water retention and transport to compaction in different soils needs to be quantified to better inform soil management practices

Table 72. Reference range for macroporosity (% , -10 kPa) for all soil orders

Land use	Reference range*
All land uses excluding forestry	10–21
Forestry, indigenous vegetation	14–35

* Ultic, Podzol, Gley, and Pallic soils are more susceptible to compaction, so additional care in the management of these soils is required.

Interpretation

Low macroporosity is an indicator of soil compaction. Low macroporosity affects available water capacity, root growth, and movement of air and water through soil. Compaction increases bulk density and reduces crop yields and vegetative cover. By reducing water infiltration into soil, compaction can lead to increased runoff and erosion from sloping land or saturated soils in flatter areas. Increased compaction is linked to increased nutrient losses from drainage, runoff, and gaseous emissions.

However, the environmental impacts of macroporosity are complex and sometimes inconsistent, because they also depend on pore connectivity and continuity, along with other environmental factors (e.g. rainfall). For the purposes of SoE reporting, values below the lower end of the range indicate soil compaction and are the primary focus. High macroporosity may be linked to reduced water-holding capacity or increased erosion risk, but there are insufficient data to evaluate at what point this becomes material. The traffic-light evaluation for macroporosity is shown in Table 73, with a description of review and monitoring activities shown in Table 74.

Table 73. Traffic-light evaluation of macroporosity (% , -10 kPa) for all soil orders*

Land use	<10th %ile	10th %ile*	90th %ile	>90th %ile
All land uses excluding forestry	<10	10	21	>21
Forestry	<14	14	35	>35

* Fine-textured soils with imperfect to poor drainage, such as Ultic, Podzol, Gley and Pallic soils, are more susceptible to compaction and so greater care should be taken to avoid compaction.

Table 74. Description of review and monitoring activities for soil macroporosity

Traffic light	
Investigate/Action	INVESTIGATE management regimes to improve macroporosity
Review	REVIEW management practices to see if improvements can be made and/or to ensure management practices minimise reduced macroporosity
Continue monitoring	CONTINUE MONITORING; falls within the typical range for the land use.
Review	REVIEW and evaluate the potential effect of high macroporosity including reduced water-holding capacity and increased susceptibility to erosion

7.2.7 Bulk density

As for macroporosity, reference ranges for bulk density have been developed using the reference approach, with the pastoral 'under fenceline/untreated' data set and the undisturbed forestry data set used to provide reference ranges. The distribution-based typical values from the baseline monitoring data set were *not* used, because evaluation of that data suggests, based on comparison with the under-fenceline data and wider literature, that there is evidence of compaction of the soils in the baseline monitoring set, and that this could be limiting other soil functions (see section 6.6). This data set was used to provide the reference ranges for all land-use categories except forestry, for which a data set from undisturbed forestry sites (and the baseline monitoring) suggests that a different bulk density range is more relevant for forestry. While the reference ranges presented here are based on soil order (Table 75), soil texture may have a more significant influence on bulk density. Raw and Recent soils derived from iron-rich sands can naturally have bulk density greater than about 1.3 Mg/m³. Given the small data set upon which these reference ranges have been developed, we have also specified an upper limit of 1.4 Mg/m³, which has been associated with reduced crop yield as a result of excessive mechanical resistance to root elongation (Reynolds et al. 2008). This applies most directly to fine to medium-textured soils, and lower limits are likely relevant

Table 75. Reference ranges for bulk density (Mg/m³) for soil-order groups

Land use	Soil order	Reference range	Upper limit
All land uses excluding forestry	Organic	0.5–0.8	NA
	Soils (excl. Raw, Organic, Pumice ^a)	0.7–1.0	1.4
All	Raw soils ^b	1.4	1.4
Exotic forestry	Allophanic	0.5–0.8	NA
	Pumice	0.7–0.9	NA
	Soils (excl. Raw ^b , Allophanic, Pumice, Organic ^a)	0.7–1.3	1.4

^a No information available for this soil order for this land use.

^b Higher bulk density is expected for Raw and Recent soils derived from iron sands.

NA – not available.

Interpretation

High bulk density is an indicator of low soil porosity and soil compaction. High bulk density affects available water capacity, root growth, and movement of air and water through soil. Compaction increases bulk density and reduces crop yields and vegetative cover. By reducing water infiltration into soil, compaction can lead to increased runoff and erosion from sloping land or saturated soils in flatter areas. More generally, the risk of overland flow and runoff, and associated sediment and P load, is higher in compacted soils. Soil texture will influence bulk density, and ideally should be reported alongside bulk density measurements. Further, increased environmental risks are more closely linked to changes in functional properties such as pore size distribution and connectivity, rather than to the state property of bulk density.

For SoE reporting, high bulk density is of most concern, while low bulk density may indicate an increased risk of erosion. The traffic-light evaluation for bulk density is shown in Table 76, with a description of review and monitoring activities shown in Table 77.

Table 76. Traffic light evaluation of bulk density for soil order groups

Land use	Soil order	Lower	10th%ile	90th%ile	Upper	Limit
All land uses excluding forestry	Organic	<0.5	0.5	0.8	>0.8	NA
	All soils (excl. Raw, ^a Pumice, ^b Organic)	<0.7	0.7	1.0	>1.0	≥1.4
Exotic forestry	Allophanic	<0.5	0.5	0.8	>0.8	NA
	Pumice	<0.7	0.7	0.9	>0.9	NA
	All soils (excl. Raw, ^a Allophanic, Pumice, Organic ^b)	<0.7	0.7	1.3	>1.3	≥1.4

^a Higher bulk density is expected for Raw and Recent soils derived from iron sands.

^b No information available for this soil order for this land use.

NA – not available

Table 77. Description of review and monitoring activities for soil bulk density

Traffic light	
Review	REVIEW and evaluate the potential effect of low bulk density such as reduced water-holding capacity and increased susceptibility to erosion.
Continue monitoring	CONTINUE MONITORING; falls within the typical range for the land use.
Review	REVIEW management practices to see if improvements can be made and/or to ensure management practices minimise increased bulk density
Investigate/Action	INVESTIGATE management regimes to improve bulk density

7.3 Interpretation of soil quality reference ranges for SoE reporting in the context of land-use history and change

The reference ranges provided in the preceding section are based solely on consideration of a single land use. Where there is land-use change or a significant extreme event resulting in erosion or deposition of sediments, there will be a lag time in the soil properties responding to changed land management practices. As a result, where a land use changes to a less intensive land use, some indicators 'may fall out of range' for a period of time. Under the NEMS-SQ, more frequent monitoring of these sites (annually to 3-yearly) is recommended to track this change. Such information will be useful to identify the expected timeframe for change and any legacy effects.

A related issue is land-use history (i.e. where the land-use changes have occurred prior to inclusion in monitoring programmes). This is particularly relevant for forestry where some parameters – particularly nutrient values – will be markedly different depending on whether commercial forestry arises from afforestation of pastoral land or has been planted into low-fertility soils or eroded soils. Land-use history is also relevant for urban open space, and for soils that may have been artificially drained to enable agricultural production.

8 Areas for future focus

Following consideration of the analyses undertaken in the preceding sections, Ministry for the Environment staff requested that the following aspects be explicitly considered in the context of the future use of SoE soil quality monitoring.

- 1 Clearly and concisely state why you were not able to revise the soil quality target / optimal ranges against environmental considerations as intended, highlighting the limitations of the existing data and what research/data would be required to enable such a revision in 5 to 10-plus years from now.
- 2 Clearly state if setting target ranges against environmental outcomes is achievable, and if not, please clearly and concisely state the value of the SOE soil quality monitoring programme, regardless of the lack of reporting against environmental outcomes.
- 3 Provide options for detecting meaningful changes in soil quality at a national level. This could also consider how regional and community catchment efforts to achieve improved soil quality outcomes could be aggregated or translated to provide a national picture.

This discussion focuses on the factors influencing the development of numeric criteria for the indicators covered in this report, and does not include detailed discussion of additional indicators. Further discussion on the use of SoE soil quality information is being undertaken through a current Envirolink Tools project ('Improving soil health through improved efficacy of implementing soil quality indicators').

8.1 Challenges in setting soil quality target values against environmental considerations, and future research requirements

There has been a substantial amount of additional soil monitoring, reporting, and research undertaken since the provisional target ranges were set in the early 2000s. However, the anticipation that these data would address some of the gaps in soil quality indicators and the link to environmental outcomes has not materialised. The challenge is two-fold.

- Few studies in New Zealand have been specifically designed to quantitatively relate soil quality indicators to environmental outcomes, or even to soil functions.
- The relationship between individual soil quality indicators and environmental outcomes is complex, and dependent on site-specific conditions in addition to climatic and land management interactions.

Nonetheless, in contrast to the early 2000s we have a considerably better understanding of many soil-related processes, including N processes and processes leading to environmental impacts from land use (e.g. nutrient impacts on waterways). This enhanced understanding suggests that in the context of SOE monitoring, soil N properties (total N, AMN, and HWEC, as an indicator of potentially mineralisable N) 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 (see also Figure 12.).

In contrast to N properties, Olsen P values can provide a general indication of water quality risk, in that higher Olsen P values pose a higher risk to waterways. However, the actual risk depends on the delivery of P to waterways. This movement is influenced by many site-specific and transport factors, including soil P-retention, 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 also Figure 8). Providing a quantitative basis for setting soil Olsen P based on water quality outcomes requires some level of modelling of these processes.

Panagos et al. (2022) provide an example of European-scale modelling that incorporates movement of soil P to waterways, while several New Zealand studies have evaluated off-site movement of soil P (e.g. McDowell et al. 2021). In contrast, the EU soil observatory uses a threshold of 50 mg Olsen P/kg to indicate soils with excess P, with associated possible environmental risk.¹⁰ This threshold is the average of P concentrations used by a number of European countries to define soil phosphorus excess. Conceptually, this is the same approach as has been proposed in this project and as has been previously used to develop target values: Olsen P values above agronomic optima are in excess and pose a possible environmental risk. Greater effort (and level of investment) is required to develop soil Olsen P values that are more explicitly linked to the protection of water quality. This will require modelling approaches, with reference ranges developed using a range of specified scenarios.

¹⁰ <https://esdac.jrc.ec.europa.eu/esdacviewer/euso-dashboard/>

For soil C, the saturation potential or carbon loading of soil based on the MSA 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. Specifically, this could be used to indicate the 'gap' or 'deficit' between measured C levels and potentially achievable C levels of a given soil. Soil quality thresholds could be set whereby x% of the 'deficit' is considered unhealthy/degraded. Agreement on the specific percentage of the deficit is more a stakeholder responsibility, with scientific input, rather than a specific scientific determination. A similar approach is used by the EU soil observatory, whereby an unhealthy soil was considered to be one where the distance that separated it from the maximum soil C is more than 60% of current levels.³ In this case, a modelling approach was used to calculate a maximum soil organic C level that would be achievable if the land were kept under continuous grassland for 40 years (without ploughing) (De Rosa et al. 2024). Further evaluation of the MSA approach in the context of SOE monitoring and setting soil quality targets or thresholds is required.

Alternative approaches for developing soil quality target values for soil C and other indicators that are currently based on the distribution of results (total N, AMN, HWEC) is to use the relative response in relation to suitable reference sites. This could include indigenous vegetation (e.g. the soil health gap approach; see section 4.5.4), or reference sites associated with major land uses and soil orders that demonstrate best practices. Monitoring of these reference sites also provides the opportunity to assess the influence of global-scale changes (e.g. climate) on the soil quality indicators over time.

This approach initially requires an evaluation of the suitability of existing indigenous vegetation sites as reference sites for different land uses. Native grassland sites are likely to be more suitable than indigenous forest sites, although the latter are the dominant indigenous vegetation sites currently monitored. Reference sites should also be located in similar climates and soils, but these requirements potentially limit the 'availability' of suitable reference sites. Finally, such reference sites should also be of good 'quality' (i.e. unimpacted by anthropogenic activities such as fertiliser drift or stock-grazing). It may also be relevant to base the response on a specific percentage of the reference site response. In the absence of robust scientific determination of what constitutes an appropriate percentage of the reference site, this assessment again falls more into the realm of stakeholder agreement with scientific input rather than specific scientific determination. However, while this approach provides a basis for setting target or reference ranges, it has a weaker connection to environmental outcomes.

The biggest gap in our understanding of environmental outcomes is that associated with altered macroporosity. While our understanding of the effects associated with soil compaction and macroporosity has improved since the early 2000s, this has largely highlighted the complexity of outcomes associated with reduced macroporosity (e.g. Fu et al. 2021; Yi et al. 2022; Hu et al. 2021; Hu et al. 2023). In particular, it has emphasised the importance of macropore configuration (e.g. connectivity, tortuosity), rather than simply the amount of macroporosity, in influencing air- and water-transport-related environmental processes, as well as the interactions with other factors such as climate. Beyond this, the handful of studies assessing the impacts of compaction on pasture yield in the early 2000s remain the primary source of data on impacts associated with macroporosity. A current Plant & Food Research-led MBIE Smart Ideas project on redefining soil structural vulnerability may provide greater insight into the development of function-based reference ranges for macroporosity and/or bulk density, although this is not the focus of the study.

As identified by Matson et al. (2024), there is no best approach to setting target values and thresholds. The most appropriate approach will depend on the type and quality of the available data, and the purpose of soil health assessment. Following from this, there is a question of the level of investment that is able to be made towards obtaining 'better' data, versus investment in the use of targets and thresholds to achieve improvements in soil quality.

8.2 Achievability of setting target ranges for environmental outcomes, and the value of the SOE monitoring programme

The achievability of setting target ranges for environmental outcomes depends on the approach adopted and which environmental outcomes are being considered, but, most critically, on the extent to which quantitative links to environmental outcomes are desired. For example, for Olsen P an achievable option would be to focus solely on agronomic productivity and set a target based on best management practice for fertiliser. Alternatively, developing Olsen P values based on quantifiable connection to water quality outcomes requires that modelling be undertaken in order to appropriately capture all the factors that influence the movement of Olsen P into the waterway. This becomes less achievable because of the investment required to appropriately develop and parameterise the model, particularly with site-based management data.

One example for modelling is to use farm-scale, process-based models to help connect on-farm soil quality with wider environmental outcomes. This would require a range of models to link the soil described by soil quality indicators with land use and detailed management (Figure 24).

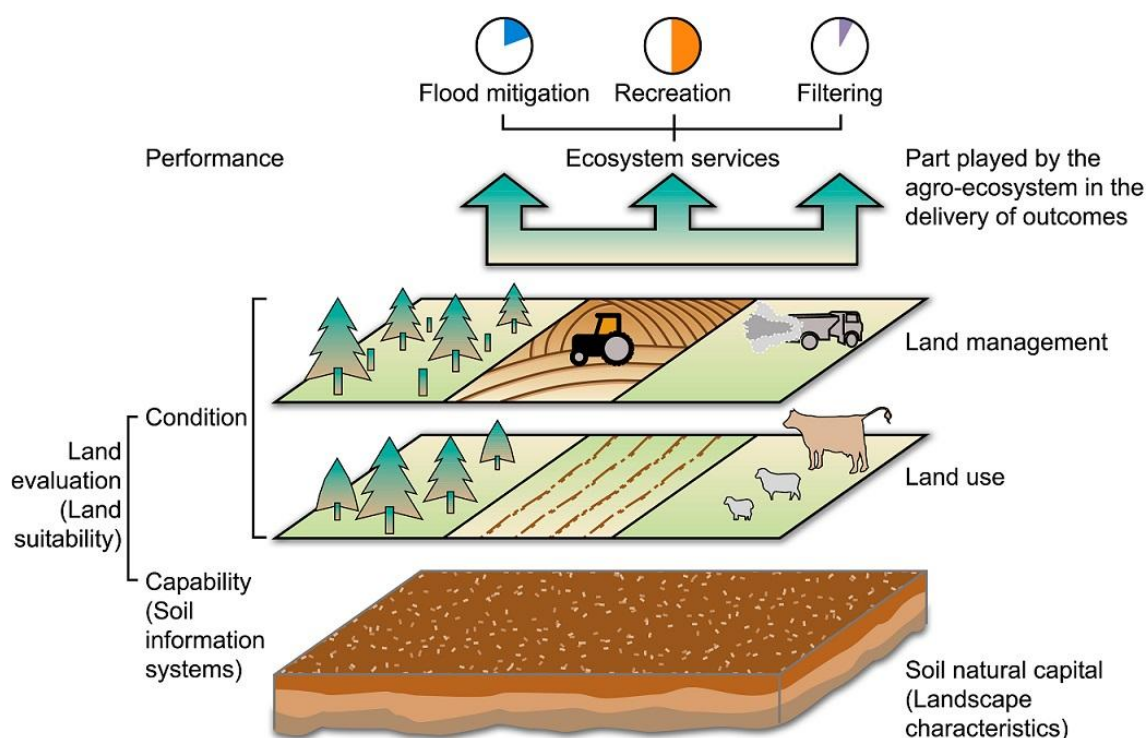


Figure 24. Soil quality indicators provide the underlying information on the condition of the resource that feeds into the analysis of the environmental impact of the enterprise. (Source: Dominati et al. 2016)

For pastoral systems, a suite of models has been used to determine environmental outcomes (nutrients losses and GHG emissions) at farm scale (e.g. Dominati et al. 2019). These are:

- the Agricultural Production Systems Simulator (APSIM) model, a soil–climate process driven model used to generate pasture growth curves based on the underlying soil types and condition (e.g. Olsen P, pH, bulk density, total C and N), and climate and management information such as fertiliser inputs, and defoliation (harvest or grazing) frequency
- FARMAX (a feed budgeting model) to explore uses of the pasture by livestock within the farm system: soil information is not used in FARMAX, so sometimes APSIM is used to generate pasture curves to put into FARMAX if the goal is to link soil management to impacts at farm scale (e.g. Vogeler et al. 2016; Vibart et al. 2015)
- Overseer, to explore the impact of livestock systems on N and P losses and GHG (N₂O, CO₂, and CH₄) emissions numbers: one of key the inputs into OVERSEER is the condition of the soil resource (Olsen P, pH, bulk density, total C and N), along with soil type, slope and climate.

These models provide an example of the current approach required to explore the interactions between the soil, farming enterprise, and climate as it influences environmental outcomes, including water quality and GHG emissions. As the PCE noted for managing freshwater, regardless of the policy framework, robust models and data are needed, although models are just one tool for decision-making (PCE 2024a). Critically, the shortcomings identified by the PCE in the development and use of models for freshwater management should be taken into account for the development of any modelling approaches to linking soil quality to environmental (or production) outcomes.

To help parameterise existing models (e.g. Overseer, the freshwater scenario builder) or develop new process-based models, intensive monitoring (including yield, GHG emissions, leaching, and surface runoff) could be undertaken at identified representative systems. These could include existing long-term research sites such as Ballantrae (Manawatū, Brown and Pallic soils) and Winchmore (Canterbury, Brown soils) pastoral farms, Puruki Experimental Forest (south of Rotorua, Pumice soils), and Pakuratahi experimental catchment (north of Napier, paired pasture and forest catchments, Pallic and Pumice soils), for which existing data are available and could be enhanced. Monitoring of farms identified as using best-management practices would also provide a better understanding of the best achievable measured values of soil quality indicators that occur for a given land use. Critically, any studies undertaken need to be established with the clear purpose of *informing the development of reference ranges*.

Finally, while this report focuses on models, it recognises that models are just one tool in the much broader toolbox of decision-making processes. Models can assist in exploring options and associated consequences, but they cannot make decisions for the decision-makers. Nonetheless, the current soil quality SOE programme is valuable for providing a national set of measures of soil quality that underpin our primary industry-based economy. The extensive data collated to date provide some confidence that we have a reasonably good understanding of the current state of our soils under various land uses in different regions across the country. This includes the identification of issues related to primary land use on soil quality, notably excess Olsen P, soil compaction (measured by macroporosity), and low C in cropping soils. However, these issues were identified at the initiation of soil quality monitoring in the early 2000s and remain the key issues today (Sparling et al. 2001b; MfE & StatsNZ 2021, 2022). Thus, the objective of the SOE monitoring programme – to provide an early warning system to identify the effects of primary land uses on long-term soil quality (physical, chemical, biological) – should be revisited.

8.3 Options for detecting meaningful changes in soil quality at a national level, including aggregation of regional or community catchment efforts

Detecting meaningful changes in soil quality at a national level depends on 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.

The number of sites not meeting target or reference ranges for different soil indicators is one way of reporting changes in soil quality, which has been the traditional reporting approach. Trend analysis is another approach to detecting changes in soil quality that is currently used for national SOE reporting (e.g. Stevenson & McNeill 2020). The identification of a trend will be dependent on the frequency of sampling, the anticipated change in the measured properties, and the inter-annual variation in the soil property. Whether a trend is desirable, and the direction of that trend, depends on the soil property. For example, an increasing trend in soil C would generally be viewed positively, while an increasing trend in Olsen P less so. Trend analysis has been undertaken at national (Stevenson & McNeill 2020) and regional (e.g. Drewry, Cavanagh et al. 2021; Curran-Cournane 2020) levels, and these studies have identified trends for some indicators. For example, a national trend of increasing Olsen P was observed at cropping and drystock sites from 1996 to 2018, while no trend in macroporosity was found in drystock farming or in dairy farming from 1996 to 2018.

The coverage provided by the SOE monitoring programme influences the extent to which monitoring results can be said to be nationally representative of land use across the country. Early soil quality monitoring placed an emphasis on intensive land uses. Assessing this largely comes down to a statistical analysis, including the number and representativeness of monitoring sites in relation to the primary factors (such as land use and soil order) influencing the different soil quality indicators. Stevenson et al. (2012) provided the most recent evaluation of the representativeness of SoE monitoring at a national level and identified gaps in the soil order/land use combinations monitored.

A smaller number of councils were undertaking soil quality monitoring at that time, whereas 14 of the 15 regional councils have since undertaken at least one round of soil quality monitoring for SoE monitoring purposes. It is anticipated that regional council soil quality monitoring data collected to the end of 2024 will be collated in 2025 for national reporting. This will provide an opportunity to evaluate the representativeness of sites currently being monitored and to consider whether additional sites may be useful to provide a better assessment of soil quality, or to inform the development of reference ranges or values.

If this evaluation identifies that additional monitoring sites would be useful, there could be opportunities for extending monitoring through connection with soil C monitoring programmes such as the National Soil Carbon Monitoring programme for agricultural land (NSCM), and the Land Use and Carbon Analysis System (LUCAS) monitoring for national GHG reporting, which includes indigenous vegetation (Holdaway et al. 2017) and planted forest sites (Paul et al. 2024).

The NSCM was designed to directly measure changes in soil C over time using a statistically designed framework to ensure unbiased, representative monitoring across all agricultural land in New Zealand. The sampling is grouped into five broad land-use classes:

- cropland

- horticulture
- dairy pasture
- flat-rolling drystock pasture
- hill-country drystock pasture.

The sampling approach used in the NSCM programme is broadly compatible with those used in the soil quality monitoring programme, with additional soil chemical properties (pH, Olsen P, total N) measured alongside total C and bulk density in soil samples collected during the first round of sampling. It is unclear as whether these additional properties will continue to be measured in subsequent rounds of sampling. Macroporosity, AMN, and HWEC have currently not been measured at these sites.

The LUCAS and NPFI sites offer similar opportunities with regard to extending monitoring of indigenous forest and exotic forestry sites. Further evaluation of sampling approaches is required to ascertain the feasibility of integrating LUCAS and NPFI sites into the soil quality monitoring programme (see DoC 2023). However, collection of samples from the LUCAS and NPFI sites offers the opportunity for other measures (e.g. forest growth) to be linked to soil quality measures.

There are additional opportunities for extending the number of soil quality monitoring sites and/or linking soil quality measures to environmental outcomes such as biodiversity and water quality. Specifically, co-located sampling could occur at regional council biodiversity monitoring sites, which would enable soil quality to be linked to biodiversity outcomes. Alternatively, soil quality monitoring sites could be located to provide better input into catchment modelling and water quality monitoring. This could address issues such as those identified by McDowell et al. (2024), who found that existing SoE point measures of soil quality are weakly linked to water quality, in part because they are unrepresentative of wider catchment land use, and areas of catchments subject to processes such as runoff or leaching (McDowell et al. 2024). As noted earlier, any extension of the soil monitoring programme should be undertaken with a clear purpose in mind as to what is to be achieved by that extension.

9 Conclusions

This project has revised the existing soil quality target values used for SOE reporting, and this report provides a single source for these values and clearly outlines the basis for the reference ranges. We have proposed a change in terminology from 'target ranges' to 'reference ranges' to better reflect the fact that these numeric ranges largely provide context for measured results; in other words, they are referred to as opposed to representing values to aim for (i.e. targets). The approaches used to develop reference ranges were based on what was identified as being the most relevant within the constraints of available data and varied with the individual indicators. Ultimately, the reference ranges were based on similar approaches used for the original target ranges but with more extensive or recent data.

Developing reference ranges that explicitly address environmental outcomes such as water quality and greenhouse gas emissions was not possible using existing information. This is partly because there are multiple factors influencing environmental outcomes that cannot be readily captured as soil-based reference values, and so modelling approaches are more likely to be beneficial in the development of numeric criteria more explicitly linked to environmental outcomes. For Olsen P it is

conceivable that modelling approaches, assuming generalised transport pathways, could be used to provide a quantitative basis for setting reference values to protect water quality. However, targeted research is required to develop the appropriate modelling approach and provide additional underpinning data if needed. A current Plant & Food Research-led Smart Ideas programme on soil structural degradation may provide further insight into the quantitative links between macroporosity and bulk density and environmental outcomes. There are surprisingly few studies that attempt to quantitatively link or track the benefits of increased organic matter such as increased water-holding capacity, improved structure or nutrient cycling. Overall, there remain critical gaps in our quantitative understanding of the relationship between measured values for the soil quality indicators, soil function, and environmental outcomes across soil orders and land uses in New Zealand.

There are alternative options for developing target or reference ranges for some indicators, although these require further evaluation. These include the use of mineral surface area-based saturation deficits or carbon loading for total C, and the use of indigenous vegetation sites as reference sites for total C, total N, AMN, and HWEC. For indigenous vegetation reference sites it is conceivable that the number of suitable reference sites providing the relevant combination of vegetation type, climate, and soil is limited. Alternative reference sites could be 'demonstration' or 'best-practice' sites (those that are consistently using best-management practices), which could provide an evidence base for 'achievable' soil quality target values under known management regimes, as well as potentially providing specific case studies to develop or validate models.

However, the key soil quality issues today are the same as those identified in the early 2000s: low soil C in cropping soils, elevated Olsen P in some agricultural soils, and soil compaction, particularly in pastoral and cropping systems. This suggests that the objective of the SoE monitoring programme being an early warning system – as currently stated in the NEMS-SQ – should be revisited. Rather, an objective of tracking improvements in soil quality may stimulate more deliberate action to achieve positive change. Further, the apparent lack of improvement in soil quality over time raises a question about the relative investment in research to develop soil quality targets and thresholds more robustly linked to environmental outcomes versus investment to achieve improvement in soil quality based on more qualitative understanding of the relationships. The latter includes investment to both demonstrate land management practices that can achieve that improvement, and encourage adoption of those practices on-farm or on-site (i.e. extension activities).

10 Recommendations

There are various recommendations arising from the work undertaken in this project. We start with what we see as the most significant, high-level recommendations, then provide more specific recommendations in relation to further development of target or reference ranges. Which recommendations are acted on depends on the relative priority given to developing soil quality reference ranges or targets and thresholds that are more robustly linked to environmental outcomes, versus undertaking actions to achieve improvements in soil quality based on existing knowledge.

10.1 High-level recommendations

At the highest level it is recommended that clearer national direction on the management of soils be developed. This will provide the opportunity for SoE monitoring to be used more effectively to achieve improvements in soil quality that result in positive environmental outcomes. Such direction should include the following.

- The SoE soil quality programme should be reviewed and evaluated at a national level to identify gaps in geospatial, soil type and land use representativeness and to assess whether the current indicators are fit-for-purpose – this would most effectively be undertaken after the upcoming collation of national SoE soil quality data.
- 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 evaluate the efficacy of management practices that (i) maintain or improve soil C and (ii) 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 to provide specific case studies for the evaluation of soil properties under best-practice management, and to help develop models to connect soil properties at a farm-scale with broader production and environmental outcomes
 - identifying alternative soil quality indicators that may be more linked to production or the environment
 - 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.

10.2 Specific recommendations in relation to reference ranges

Specifically in relation to the proposed reference ranges, it is recommended that:

- the potential for saturation deficit or C loading based on soil mineral surface area to provide a basis for developing target values for soil C is evaluated, alongside further evaluation of the suitability of the low-end 2% for soil C under cropping, particularly for Granular soils
- the reference macroporosity and bulk density data set is extended through targeted sampling as part of future SoE monitoring programmes to provide more robust reference ranges for these indicators – this could include sampling from less or not compacted areas such as under-fence lines for pastoral and cropping sites, and forestry sites at the end of rotation or after 20-plus years that show no visible past erosion
- a stocktake and quality assessment of existing indigenous vegetation and urban monitoring sites is undertaken and the purpose of monitoring (e.g. to assess state or as reference sites) confirmed alongside an evaluation of the feasibility of using indigenous vegetation sites as reference sites for other land uses (e.g. as currently suggested in the NEMS-SQ)
- the benefits and trade-offs associated with the ongoing use of gravimetric basis for reporting on Olsen P reference ranges for SoE reporting be evaluated, given the current

reporting of Olsen P results on a volumetric rather than gravimetric basis by many NZ laboratories – this could be undertaken through the development of a background discussion paper and stakeholder workshops

- the requirements for developing modelling approaches (including any additional underpinning data) for Olsen P criteria based on water quality impacts are scoped.

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Appendix 1 – Regional distribution of baseline monitoring data set

Table A1.1. Regional distribution of sites in the monitoring data set, based on land use and soil order

Region	Soil order	Dairy	Drystock	Indigenous vegetation	Lifestyle	Orchard	Urban park / reserve	Exotic forestry	Vineyard	Cropping	Total
Auckland	Allophanic	5	3	3	3	2	13	—	—	—	29
Auckland	Anthropic	—	—	—	—	—	15	—	—	—	15
Auckland	Brown	1	7	9	—	1	—	3	—	—	21
Auckland	Gley	4	—	—	3	2	1	—	1	—	11
Auckland	Granular	2	3	9	5	4	4	—	—	10	37
Auckland	Organic	1	3	1	—	2	—	—	—	—	7
Auckland	Podzol	1	—	—	—	—	—	—	—	—	1
Auckland	Raw	—	—	—	—	—	—	2	—	—	2
Auckland	Recent	—	2	5	2	1	6	3	—	—	19
Auckland	Ultic	4	8	18	4	2	11	11	2	—	60
Auckland totals		18	26	45	17	14	50	19	3	10	202
Bay of Plenty	Allophanic	7	3	2	—	19	—	4	—	4	39
Bay of Plenty	Anthropic	—	—	—	—	1	—	—	—	—	1
Bay of Plenty	Brown	—	—	—	—	1	—	—	—	—	1
Bay of Plenty	Gley	5	—	—	—	1	—	—	—	2	8
Bay of Plenty	Organic	—	—	—	—	—	—	—	—	2	2
Bay of Plenty	Podzol	—	1	2	—	—	—	1	—	—	4
Bay of Plenty	Pumice	8	9	3	—	3	—	12	—	1	36
Bay of Plenty	Raw	—	—	—	—	—	—	1	—	—	1
Bay of Plenty	Recent	4	2	2	—	2	—	6	—	5	21
Bay of Plenty totals		24	15	9	0	27	0	24	0	14	113
Canterbury	Brown	15	36	15	—	3	—	16	—	20	105
Canterbury	Gley	2	3	—	—	—	—	—	—	7	12
Canterbury	Melanic	—	1	—	—	—	—	—	—	—	1

Region	Soil order	Dairy	Drystock	Indigenous vegetation	Lifestyle	Orchard	Urban park / reserve	Exotic forestry	Vineyard	Cropping	Total
Canterbury	Pallic	4	14	4	—	1	—	2	—	28	53
Canterbury	Raw	—	1	—	—	—	—	1	—	—	2
Canterbury	Recent	4	17	—	—	3	—	—	—	8	32
Canterbury totals		25	72	19	0	7	0	19	0	63	205
Gisborne	Allophanic	—	8	—	—	—	—	—	—	—	8
Gisborne	Brown	—	6	—	—	1	—	4	1	3	15
Gisborne	Gley	—	4	—	—	4	—	—	2	6	16
Gisborne	Granular	—	—	—	—	—	—	—	—	1	1
Gisborne	Pallic	—	3	—	—	—	—	—	—	—	3
Gisborne	Pumice	—	2	2	—	—	—	—	—	2	6
Gisborne	Raw	—	—	—	—	—	—	—	—	1	1
Gisborne	Recent	—	17	4	—	7	—	5	—	6	39
Gisborne totals		0	40	6	0	12	0	9	3	19	89
Hawke's Bay	Allophanic	—	2	—	—	2	—	1	—	—	5
Hawke's Bay	Brown	1	6	2	—	5	—	3	5	3	25
Hawke's Bay	Gley	1	8	—	—	7	—	—	2	9	27
Hawke's Bay	Melanic	—	4	—	—	—	—	—	—	—	4
Hawke's Bay	Organic	—	1	—	—	—	—	—	—	3	4
Hawke's Bay	Pallic	1	14	1	—	3	—	5	—	3	27
Hawke's Bay	Pumice	5	7	2	—	1	—	5	—	—	20
Hawke's Bay	Recent	—	4	—	—	18	—	—	3	6	31
Hawke's Bay totals		8	46	5	0	36	0	14	10	24	143
Manawatū-Wanganui	Allophanic	1	6	—	—	—	—	—	—	—	7
Manawatū-Wanganui	Brown	4	16	1	—	2	—	1	—	5	29
Manawatū-Wanganui	Gley	10	6	1	—	—	—	1	—	3	21
Manawatū-Wanganui	Pallic	2	7	1	—	—	—	—	—	3	13
Manawatū-Wanganui	Recent	4	6	1	—	—	—	—	—	2	13

Region	Soil order	Dairy	Drystock	Indigenous vegetation	Lifestyle	Orchard	Urban park / reserve	Exotic forestry	Vineyard	Cropping	Total
Manawatū-Whanganui	Allophanic	—	—	—	—	—	—	2	—	—	2
Manawatū-Whanganui	Brown	—	—	—	—	—	—	1	—	—	1
Manawatū-Whanganui totals		21	41	4	0	2	0	5	0	13	86
Marlborough	Brown	13	9	2	—	4	—	4	2	—	34
Marlborough	Gley	—	1	—	—	3	—	—	4	—	8
Marlborough	Pallic	—	13	—	—	4	—	3	11	9	40
Marlborough	Recent	6	6	2	—	21	—	—	3	3	41
Marlborough totals		19	29	4	0	32	0	7	20	12	123
Nelson	Brown	—	—	—	—	—	—	1	—	—	1
Northland	Allophanic	1	3	1	—	2	—	1	—	1	9
Northland	Brown	2	3	2	—	—	—	2	—	—	9
Northland	Gley	1	—	—	—	—	—	—	—	2	3
Northland	Granular	4	2	1	—	1	—	1	—	—	9
Northland	Oxidic	2	1	1	—	3	—	—	—	—	7
Northland	Podzol	1	—	—	—	—	—	1	—	—	2
Northland	Recent	—	—	—	—	1	—	—	—	—	1
Northland	Ultic	3	1	—	—	—	—	2	—	—	6
Northland totals		14	10	5	0	7	0	7	0	3	46
Otago	Brown	2	14	—	—	—	—	6	—	1	23
Otago	Gley	2	2	—	—	—	—	—	—	—	4
Otago	Melanic	—	—	—	—	—	—	1	—	1	2
Otago	Pallic	8	16	—	—	1	—	—	—	—	25
Otago	Recent	1	3	—	—	1	—	—	—	—	5
Otago	Semiarid	1	4	—	—	3	—	—	4	—	12
Otago totals		14	39	0	0	5	0	7	4	2	71
Southland	Allophanic	—	1	—	—	—	—	1	—	—	2
Southland	Brown	16	20	3	—	—	—	2	—	—	41

Region	Soil order	Dairy	Drystock	Indigenous vegetation	Lifestyle	Orchard	Urban park / reserve	Exotic forestry	Vineyard	Cropping	Total
Southland	Gley	6	8	—	—	—	—	—	—	—	14
Southland	Melanic	1	2	—	—	—	—	—	—	—	3
Southland	Organic	—	1	—	—	—	—	—	—	—	1
Southland	Pallic	6	7	—	—	—	—	—	—	—	13
Southland	Recent	4	4	—	—	—	—	—	—	—	8
Southland totals		33	43	3	0	0	0	3	0	0	82
Taranaki	Allophanic	37	14	2	—	—	—	4	—	2	59
Taranaki	Brown	3	3	—	—	—	—	1	—	—	7
Taranaki	Gley	1	3	—	—	—	—	—	—	—	4
Taranaki	Recent	—	3	—	—	—	—	1	—	—	4
Taranaki totals		41	23	2	0	0	0	6	0	2	74
Tasman	Anthropic	—	4	—	—	—	—	—	—	—	4
Tasman	Brown	7	7	—	—	2	—	2	—	—	18
Tasman	Gley	—	2	—	—	2	—	—	—	—	4
Tasman	Pallic	—	—	—	—	1	—	—	—	—	1
Tasman	Podzol	2	—	—	—	—	—	—	—	—	2
Tasman	Recent	5	1	—	—	5	—	—	3	3	17
Tasman	Ultic	—	1	—	—	2	—	—	—	—	3
Tasman totals		14	15	0	0	12	0	2	3	3	49
Waikato	Allophanic	23	23	3	—	14	—	8	—	10	81
Waikato	Brown	8	12	2	—	—	—	5	—	2	29
Waikato	Gley	19	4	2	—	—	—	—	—	3	28
Waikato	Granular	3	7	—	—	1	—	—	1	5	17
Waikato	Organic	5	1	2	—	—	—	—	—	—	8
Waikato	Podzol	1	2	1	—	—	—	2	—	—	6
Waikato	Pumice	18	10	1	—	—	—	6	—	1	36
Waikato	Recent	3	2	1	—	—	—	1	—	—	7

Region	Soil order	Dairy	Drystock	Indigenous vegetation	Lifestyle	Orchard	Urban park / reserve	Exotic forestry	Vineyard	Cropping	Total
Waikato	Ultic	2	1	—	—	—	—	1	—	—	4
Waikato totals		82	62	12	0	15	0	23	1	21	216
Wellington	Allophanic	—	—	1	—	—	—	—	—	—	1
Wellington	Brown	3	12	6	—	4	—	5	1	3	34
Wellington	Gley	5	3	1	—	3	—	—	—	7	19
Wellington	Granular	—	—	—	—	—	—	—	—	1	1
Wellington	Melanic	—	1	—	—	—	—	1	—	—	2
Wellington	Pallic	7	16	4	—	3	—	1	1	4	36
Wellington	Recent	4	15	5	—	3	—	2	—	9	38
Wellington totals		19	47	17	0	13	0	9	2	24	131
West Coast	Anthropic	1	—	—	—	—	—	—	—	—	1
West Coast	Brown	—	1	—	—	—	—	1	—	—	2
West Coast	Gley	3	1	—	—	—	—	—	—	—	4
West Coast	Podzol	—	—	—	—	—	—	2	—	—	2
West Coast totals		4	2	0	0	0	0	3	0	0	9
Grand totals		336	510	131	17	182	50	158	46	210	1640

Appendix 2 – Tukey analysis for C, N, AMN, and C:N

To determine soil-order groupings for total C, total N, AMN, and C:N, compact letter displays were generated based on the pairwise comparisons run on the indicator lmers. Based on the results shown below, soil orders have been grouped as follows for total C, total N, and AMN:

- Organic
- Allophanic
- Raw
- all others.

Soil-order groupings for HWEC are: Organic and all others

Results for C:N ratio were not delineated on the basis of soil order.

Table A2.1. Modelled soil order differences in total C when controlling for the effect of land use

Soil order	response	SE	df	Lower CL	Upper CL	group
Raw	1.8	0.4	189.0	1.1	2.6	a
Semiarid	3.5	0.5	71.6	2.6	4.5	abcd
Recent	3.8	0.3	9.2	3.2	4.6	b
Pallic	3.9	0.3	9.8	3.3	4.7	bc
Gley	4.5	0.4	10.0	3.7	5.3	cd
Anthropic	4.5	0.5	42.5	3.5	5.6	bcde
Ultic	4.6	0.4	13.6	3.8	5.5	cde
Brown	4.9	0.4	8.9	4.1	5.8	def
Melanic	5.2	0.7	71.4	4.0	6.7	bcdefg
Granular	5.4	0.5	14.5	4.5	6.5	efg
Podzol	6.1	0.7	46.5	4.9	7.6	efgh
Pumice	6.2	0.5	12.4	5.2	7.4	g
Oxidic	7.7	1.1	149.5	5.7	10.2	fgh
Allophanic	8.2	0.6	9.4	6.9	9.6	h
Organic	17.6	1.6	34.8	14.6	21.3	i

Notes: Response = modelled mean; SE = modelled standard error; df = degrees of freedom; upper and lower CL = confidence limits. Soil orders with the same letter(s) in the group column are not significantly different from each other.

Table A2.2. Modelled soil-order differences in total N when controlling for the effect of land use

Soil order	Response	SE	df	Lower CL	Upper CL	group
Raw	0.17	0.06	240.55	0.06	0.30	a
Semiarid	0.30	0.05	89.15	0.20	0.41	abcde
Recent	0.33	0.03	9.43	0.27	0.40	a c
Pallic	0.34	0.03	10.14	0.28	0.41	abc
Ultic	0.37	0.03	14.83	0.30	0.45	abcd
Anthropic	0.39	0.05	50.94	0.29	0.49	abcdef
Gley	0.39	0.03	10.44	0.32	0.46	b de
Brown	0.41	0.03	9.02	0.34	0.48	de
Podzol	0.45	0.05	56.64	0.35	0.56	bcdef
Melanic	0.46	0.06	89.05	0.35	0.58	bcdef
Granular	0.47	0.04	15.84	0.39	0.55	ef
Pumice	0.49	0.04	13.25	0.42	0.58	f
Oxidic	0.54	0.07	190.29	0.40	0.69	bcdefg
Allophanic	0.73	0.04	9.69	0.64	0.82	g
Organic	1.15	0.07	41.55	1.01	1.29	h

Notes: Response = modelled mean; SE = modelled standard error; df = degrees of freedom; upper and lower CL = confidence limits. Soil orders with the same letter(s) in the group column are not significantly different from each other.

Table A2.3. Modelled soil-order differences in AMN when controlling for the effect of land use

Soil order	Response	SE	df	Lower CL	Upper CL	group
Raw	10.3	3.5	284.4	5.1	20.0	a
Recent	87.2	11.1	9.1	65.4	116.2	b
Ultic	88.7	12.4	13.1	65.7	119.8	bc
Granular	90.4	13.0	14.9	66.5	122.7	bc
Gley	95.3	12.4	10.1	71.2	127.2	bc
Semiarid	99.8	22.7	89.8	63.4	156.8	bcde
Brown	101.3	12.8	8.9	76.1	134.8	bc
Anthropic	102.0	19.3	43.4	69.6	149.4	bcde
Pallic	103.8	13.5	10.1	77.6	138.6	bc
Oxidic	104.3	32.7	278.1	56.1	193.1	bcde
Pumice	116.1	15.6	11.6	86.4	155.8	cd
Melanic	122.6	24.5	55.5	82.0	182.9	bcde
Podzol	124.6	24.9	55.3	83.4	185.9	bcde
Allophanic	144.4	18.5	9.5	108.4	192.4	de
Organic	185.4	30.0	24.3	132.8	258.7	e

Notes: Response = modelled mean; SE = modelled standard error; df = degrees of freedom; upper and lower CL = confidence intervals. Soil orders with the same letter(s) in the group column are not significantly different from each other.

Table A2.4. Modelled soil-order differences in C:N ratio when controlling for the effect of land use

Soil order	Response	SE	df	Lower CL	Upper CL	group
Melanic	11.4	0.8	21.4	9.8	13.2	abcde
Pallic	11.6	0.7	8.6	10.2	13.3	a
Semiarid	11.7	0.9	21.5	10.1	13.6	abcde
Allophanic	11.8	0.7	8.4	10.4	13.5	ab
Recent	11.9	0.7	8.4	10.4	13.5	ab d
Gley	11.9	0.7	8.6	10.4	13.5	ab d
Brown	12.4	0.7	8.3	10.8	14.1	bcd
Granular	12.4	0.7	9.8	10.9	14.2	abcde
Anthropic	12.5	0.8	16.3	10.8	14.4	abcdef
Pumice	12.8	0.8	9.3	11.2	14.6	c e
Ultic	13.4	0.8	9.6	11.7	15.3	ef
Oxidic	14.5	1.2	34.8	12.3	17.1	cdefg
Podzol	14.8	1.0	16.8	12.9	17.1	fg
Organic	16.6	1.1	14.5	14.5	19.1	g
Raw	17.7	1.5	41.4	15.0	21.0	g

Notes: Response = modelled mean; SE = modelled standard error; df = degrees of freedom; upper and lower CL = confidence limits. Soil orders with the same letter(s) in the group column are not significantly different from each other.

Table A2.5. Modelled soil-order differences in HWEC when controlling for the effect of land use

Soil order	emmean	SE	df	Lower CL	Upper CL	group
Ultic	1,847	608	49	626	3,068	abc
Recent	1,885	369	7	1,011	2,758	a
Pallic	2,023	362	6	1,152	2,895	ab
Gley	2,221	371	7	1,346	3,095	ab
Granular	2,284	427	12	1,357	3,212	abc
Semiarid	2,309	1065	293	213	4,405	abc
Brown	2,322	364	7	1,450	3,195	abc
Allophanic	2,488	374	7	1,611	3,364	bc
Pumice	2,889	391	9	2,000	3,778	c
Melanic	2,972	567	38	1,823	4,120	abc
Podzol	3,344	566	38	2,198	4,491	abc
Organic	8,211	568	38	7,062	9,360	d

Notes: Response = modelled mean; SE = modelled standard error; df = degrees of freedom; upper and lower CL = confidence limits. Soil orders with the same letter(s) in the group column are not significantly different from each other.

Appendix 3 – Summary of workshop I

Revision of soil quality target ranges workshop

Virtual workshop held on 8 August 2024.

Attendees: Representatives from MfE, MPI, Regional Council Land Monitoring Forum, regional council compliance, primary sector (agriculture, forestry and fertiliser industry), research organisations.

Background

The Ministry for the Environment has contracted Manaaki Whenua – Landcare Research, AgResearch, Plant & Food Research, and Scion to undertake a revision of the target ranges for the seven soil quality indicators that are used in state of the environment (SoE) reporting, and to propose a target range for hot-water extractable carbon. Provisional target ranges for soil quality indicators were developed in the early 2000s and published in 2008. While there has been review of and some revision to target ranges, a substantial amount of additional soil monitoring, reporting, and research has been undertaken since the provisional target ranges were set.

A summary of the development of the existing target ranges is captured here:

<https://www.envirolink.govt.nz/assets/Envirolink/2333-ORC005-Review-of-methods-and-data-used-to-develop-target-values-for-soil-quality-indicators.pdf>

Workshop purpose

This workshop was held to introduce a wider stakeholder group to the project and the initial literature review undertaken to date, and to seek initial stakeholder feedback on the updating of the existing soil quality target ranges, including potentially available data.

Workshop summary

The following section provides a summary of the mural whiteboard responses to specific questions. We emphasise that the focus for the current project is specifically on the development/update of existing numeric criteria (currently called target ranges), given the availability of extensive new data, rather than an assessment of the efficacy of the use of the existing target ranges to achieve change in the state of the soil. As such, we have identified where comments or responses fall outside the scope of the existing project; these factors will, nonetheless, be valuable in informing future work on the use of numeric criteria. Other comments will be helpful for identifying factors to take into consideration in the next stage of review and revision of the existing numeric criteria.

Mural whiteboard summary

- 1 What are the current and future uses of numeric criteria for these indicators?
 - a Central/local govt
 - Monitoring, SOE reporting, long-term trends
 - Consenting and compliance guidance and monitoring, freshwater farm plans

- Awareness/understanding of land use/human impacts on soil, health of soils relating to water quality
- Setting targets/goals for environmental outcomes

Out of scope of the current project

- Monitoring effectiveness of policies and actions
- Policy development
- Assessing trace element contamination

b Primary industry

- Use by farmers in benchmarking and assessing soil health, integrated production and environmental outcomes.
- Management systems: supporting best practice, sustainable production
- Sustainability monitoring and reporting (ESG)
- Understanding water quality impacts
- Benchmarking climate change impacts on soil and carbon accounting
- To inform gaps that industry and government can fund
- Connect with VSA to validate values and update the VSA framework
- Other comments:
 - land-use change guidance or risk assessments (see other comments under Q7)
 - integrated environmental reporting
 - use of electronic tech like phone apps.

2 What should the basis of numeric criteria be? (Indicator and endpoint, e.g. total N and water quality / how might numeric criteria be used?)

a Environmental considerations

- Suggestions to improve efficacy:
 - use a star rating for strength of the data behind an indicator for soil group, land uses, etc.
 - caution is needed in applying values, e.g. low Olsen P in a critical source area may be more significant environmentally than higher Olsen P with no direct pathway to water.
- Considerations of scale, climate, topography, land use, soil, geology
- Water quality:
 - high N and P
 - anaerobic N and leaching
 - low macroporosity and water quality via runoff
 - infiltration/bypass flow?
 - high carbon resilience to overland flow
- Soil biology:
 - role of N-fixing bacteria
 - soil carbon and biodiversity
- Erosion risk:
 - due to structural damage

- high carbon resilience to overland flow and sheet erosion
 - GHG emission potential
 - Productivity:
- agronomic input
 - Many conflicting considerations; e.g. max biodiversity versus specialised organisms, redox conditions and SOM vs GHG
 - Intensification of land use
 - Resilience to stressors
 - Soil functions relating to ecosystem service delivery
 - Benchmarks from native/pristine areas useful but suggested having separate ranges for production goals – ranges likely don't apply for natural states
- b Agronomic production
 - Response curves – Olsen P, pH, crop-specific
 - Sustainable and efficient production – N and P
 - Structural indicators:
 - macroporosity – a better test that rural professionals can gather and is time-efficient
 - thresholds for density and porosity aligned to pastoral production
 - Slakes app from SHI (for AgStab, out of scope)
 - How to use C:N ratio to inform different soil functions
- c Typical range
 - Comparisons to reference soils and typical ranges for climate/soil type/land use combinations. Question asked on whether indicator ranges are climatically adjusted.
 - Useful for farmers to interpret their data
 - Use in research as a comparison

Out of scope

We seemed to be focused on finding existing data to define targets but why not have a research plan to experimentally determine relationship between targets and outcomes?

3 Which indicators / target ranges require revision/development and which are most useful?

Note: not sure whether people are saying these indicators require revision *or* are the most useful in some cases (e.g. HWEC)

Needs revision:

- macroporosity (and bulk density):
 - better alignment of macroporosity and bulk density
 - relevance for pumice-derived soils:
 - macroporosity and bulk density of subsoil, or other potential measure of compaction (subsoil is more indicative of long-term compaction than topsoil bulk density)

- bulk density seems unrelated to any issues because it never fails or is less than adequate, so the current criteria may not be relevant to topsoils)
- Olsen P:
 - addition of environmental consideration for different soil types
 - potentially a different measure for P
- HWEC:
 - There are extensive data sets on HWEC (and HWEON) that are closely related to PMN (soil N supply potential) and can be used to forecast climate/season variation in N supply for arable, vegetable, and lowland pastoral farming systems
- AMN:
 - poor understanding of relationship between anaerobic N and N losses
 - poor linkage with objective (biological health)
 - N story is complex and requires several parameters for adequate assessment
- Soil nutrients:
 - relationship with water quality targets – depends on non-soil factors, including depth of soils and connections to waterways

In context of agronomic production:

- Olsen P, total N: independent review of agronomic needs and in-depth cost–benefit analysis, e.g. is a 2% production loss reasonable for a 10% environmental improvement?
 - (We will take this forward into considerations for the qualitative CBA being undertaken as part of this work.)

General comments:

- split targets for production and environment
- good reference sites needed

Out of scope for the current project

- Better guidelines needed to prevent losses and increase soil C (focus on implementation not derivation of numeric criteria)
- Comments around trace elements, aggregate stability and need to consider pore connectivity (not included in the eight indicators)
- Depth of sampling – relates to questions around macroporosity and bulk density above

4 Any data people are aware of that could be used to help develop numeric criteria?

- NSDR
- Company commercial soil test data bases
- PFR's land management index programme

Out of scope

- Data from land-use change to strengthen learnings about how these metrics change in the real world; e.g. dairy to kiwifruit/apples or pasture to forestry

- Aggregate size distribution data from Land Monitoring Index
- 5 In the absence of sufficient data to develop environmentally based numeric criteria:
- a For which indicators might *production (yield)* be a useful proxy?
- C (upvoted)
 - pH
 - Effect of reduced macroporosity on reduced yield as %
 - Other comments:
- Show as data deficient as the purposes are different
 - It also depends –
 - on applications of values
 - on landowners – good production doesn't equal sustainability
 - When does high production suggest leakage of N and P into wider environment?

Out of scope

- VSA, effective rooting depth (out of scope)
- b For which indicators might *typical values* be a useful proxy?
- Physical indicators, not chemical indicators
 - Chemical indicators are arguably modified more, and their targets for production are different, whereas physical indicators' typical range aligns better between production and reference state
 - Other comments:
- If typical values are treated as default values, then they will be useful for all indicators in the absence of data. But once specific data become available, then they need to be used instead.
 - The use of typical values will depend on land use: at what point are values atypical and imply negative environmental outcomes?
- c When might *typical values* be most useful?
- To get a baseline-assessment / reference state
 - To place a site or farm in relation to others
- 6 What factors will influence values and should be considered in the development of numeric criteria?
- Pedoclimatic factors
 - Soil order, age, climate, texture, depth to groundwater, bypass flow potential, CEC and AEC, geology, slope
 - Distance to groundwater, surface water and sensitive areas
 - In relation to risk levels for nutrients, the vulnerability of the site to leaching (as indicated by shallow groundwater oxidation, and rapid permeability, and proximity to waterway) should be considered as an on-off switch for the relevance of high levels to water quality or overland flow, but with different risk factors for the on/off switch

- Off-site impacts, the size, spatially and the potential magnitude of the impact
 - Land use
- Including land-use change
 - Management
- Seasonal extremes e.g. pugging, pine harvest, tillage
- Cropping intensity – SQMS/cropping index on compaction and OM indicators
 - Other comments:
 - temporal and spatial variability in normal circumstances
 - confidence intervals
 - erosion can change values
 - climate change
 - uniformity is needed between testing labs

7 Land use – what land uses should numeric criteria be developed for?

- LUs in the newly developed classification 2024 (3 upvotes)
- Existing LU classes with more consideration of sub-classes (e.g. cropping, vineyards, orchards, urban green space)
- Separate market garden and arable cropping classes if sufficient data exist
- PFR would have this in their land management index programme
- Urban soils
- Dairy, drystock, cropping, horticulture, and forestry
- High-intensity LUs with biggest environmental impact
- Organic soils / drainage of peat soils – may require separate monitoring programme for peat subsidence/impacts
- Land where effluent is applied
- Are the values going to be restricted to land use where there is long term consistency with no change? E.g. pasture crop rotations may present a problem in interpretation
- Other comments (out of scope, implementation focused)
- Sample according to an 8 x 8 km grid
- Land-use conversion risk assessment checklist to mitigate impacts

Summary of responses to questions (including those entered in the chat for those who didn't receive the polls)

8 What sector or industry do you represent?

a	Regional council	12	41%
b	Research (CRI, uni)	7	24%
c	Central govt (MPI, MfE)	4	14%
d	Forestry industry	3	10%
e	Fertiliser industry	2	7%
f	Agricultural industry	1	3%

9	Have you used the SoE soil quality indicator target ranges?		
a	Yes	22	67%
b	No	11	33%
10	How have you used one or more of the SoE target ranges?		
a	National or regional SoE soil quality reporting	16	43%
b	Soil quality assessment (journal publication)	7	19%
c	Consenting or compliance	5	14%
d	Other soil quality assessment	5	14%
e	Other	2	5%
f	Industry on-farm quality assurance	2	5%
11	Which target ranges might require the greatest revision (from an environmental perspective)?		
a	Olsen P	10	33%
b	Macroporosity	6	20%
c	Total N	5	17%
d	AMN	3	10%
e	Bulk density	3	10%
f	Total C	3	10%
g	pH	0	0%

Appendix 4 – New Zealand Land Use Management classification system

1 Conservation and minimal use of natural environments	2 Production agriculture and plantations	3 Built environment
1.1.0 Biodiversity protection 1.1.1 High degree of biodiversity protection 1.1.2 Moderately high degree of biodiversity protection 1.1.3 Moderate degree of biodiversity protection 1.1.4 Moderately low degree of biodiversity protection 1.1.5 Low degree of biodiversity protection	2.1.0 Plantation forests 2.1.1 Exotic plantation forestry 2.1.2 Indigenous plantation forestry 2.1.3 Other production uses 2.1.4 Planted environmental & infrastructure protection 2.1.5 Permanent carbon forest	3.1.0 Residential 3.1.1 High-density residential 3.1.2 Medium-density residential 3.1.3 Low-density residential 3.1.4 Rural residential
1.2.0 Cultural and natural heritage 1.2.1 Indigenous cultural heritage 1.2.2 Cultural heritage 1.2.3 Natural heritage	2.2.0 Grazing modified pasture systems 2.2.1 Dairy 2.2.2 Intensive dry stock 2.2.3 Extensive dry stock	3.2.0 Public recreation and services 3.2.1 Outdoor recreation 3.2.2 Indoor recreation 3.2.3 Community services
1.3.0 Minimal use from relatively natural environments 1.3.1 Surface water supply 1.3.2 Ground water 1.3.3 Grazing native vegetation 1.3.4 Production from indigenous vegetation 1.3.5 Customary use 1.3.6 Defence land 1.3.7 Environmental & infrastructure protection 1.3.8 Carbon forest	2.3.0 Short-rotation and seasonal cropping 2.3.1 Arable cropping 2.3.2 Arable and mixed livestock cropping 2.3.3 Short-rotation horticulture 2.3.4 Seasonal flowers and bulbs, and turf-farming	3.3.0 Commercial 3.3.1 Retail 3.3.2 Office 3.3.3 Hospitality 3.3.4 Entertainment 3.3.5 Healthcare 3.3.6 Transportation & warehousing
1.4.0 Unused land and land in transition 1.4.1 Unused land 1.4.2 Land undergoing rehabilitation	2.4.0 Perennial horticulture 2.4.1 Tree crops 2.4.2 Vine fruits 2.4.3 Other perennial horticulture	3.4.0 Manufacturing and industrial 3.4.1 General purpose factory 3.4.2 Food processing factory 3.4.3 Major industrial complex 3.4.4 Sawmill 3.4.5 Farm buildings/infrastructure 3.4.6 Abattoirs
	2.5.0 Intensive horticulture 2.5.1 Production nurseries 2.5.2 Glasshouses/shadehouses	3.5.0 Utilities 3.5.1 Fuel powered electricity generation 3.5.2 Hydro electricity generation 3.5.3 Wind electricity generation 3.5.4 Solar electricity generation 3.5.5 Electricity substations and transmission 3.5.6 Gas treatment, storage and transmission 3.5.7 Water extraction and transmission
	2.6.0 Intensive animal production 2.6.1 Animal containment 2.6.2 Poultry farms 2.6.3 Piggeries 2.6.4 Horse studs 2.6.5 Aquaculture	3.6.0 Transport and communication 3.6.1 Airports/aerodromes 3.6.2 Roads 3.6.3 Railways 3.6.4 Ports and water transport 3.6.5 Navigation and communication
	2.7.0 Water and wastewater 2.7.1 Stock water 2.7.2 Effluent pond 2.7.3 Water treatment - land application 2.7.4 Water treatment - wetland 2.7.5 Irrigation reservoirs and canals	3.7.0 Mining 3.7.1 Mines 3.7.2 Quarries 3.7.3 Tailings 3.7.4 Evaporation basins 3.7.5 Extractive Industry not in use
	2.8.0 Land in transition 2.8.1 Unused degraded land 2.8.2 No defined use 2.8.3 Land undergoing rehabilitation 2.8.4 Abandoned land	3.8.0 Waste treatment and disposal 3.8.1 Landfills 3.8.2 Transfer stations and recycling facilities 3.8.3 Municipal wastewater 3.8.4 Wastewater treatment - land application 3.8.5 Stormwater management
		3.9.0 Vacant and transitioning land 3.9.1 Vacant land 3.9.2 Greenfield development 3.9.3 Brownfield development

Figure A4.1. Overview of the draft New Zealand Land Use Management classification system

(Source: Law et al. 2024)

Appendix 5 – Sector matrices

Pastoral matrix

Table A5.1. Identification of peer-reviewed publications on soil quality indicators and environmental outcomes, and extensive datasets for pastoral land use in NZ

Sector: Pastoral agriculture								
Outcome	Soil quality indicator							
	pH	Total C	Total N	AMN	Olsen P	HWEC	Macroporosity (-10kpa)	Bulk density
Soil function – infiltration							1, 3, 6, 8, 10, 22, 40, 43, 51	1, 3, 6, 8, 10, 41, 51
Soil function – nutrient cycling		2, 15, 47, 50	15, 16, 21, 50		39, 49	4, 5	40	41
Soil biodiversity	38	16, 17, 37, 38	17, 37, 38		37, 38		22, 37	
Pest and disease regulation		16, 17	17					
GHG emission (CO ₂ , N ₂ O, CH ₄ , etc)	7, 46	15, 19, 20, 46, 50	9, 15, 46, 50		46, 48, 49	4, 5, 24	8, 10, 18, 23, 50	8, 10, 18, 46
Water quality (N& P loss)		2, 13, 15, 19, 20	16, 21	10	10, 11, 39, 40, 42, 45		3, 6, 8, 10, 11, 12, 25, 26, 40, 43, 51	3, 6, 8, 10, 12, 41, 51
Production	32, 35, 44	11, 47	11, 16, 21, 44		11, 12, 16, 33, 34, 44, 45,	24	11, 12, 22, 27, 28, 29, 30, 31, 36	11, 27, 28, 29, 32, 35
Extensive data set								
Long-term P fertiliser and sheep grazing experiment at Ballantrae (1975–2024)	X	X	X	X	X	X	X	X
Long-term experiment examining the effect of elevated CO ₂ on pastoral system. Free-Air Carbon dioxide Enrichment (FACE) facility at Flockhouse	X	X	X		X			

AgResearch Winchmore P fertiliser under irrigation	X	X	X	X	X	X	X	X
Pasture response under non-limiting P fertiliser × N fertiliser × irrigation: 4 sites	X	X	X		X			
Effect of compaction on pasture response to P fertilisers					X		X	X
Effect of grazing on labile organic carbon and pastures	X	X	X	X	X		X	X

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Short-rotation and perennial horticulture

Table A5.2. Number of peer-reviewed publications on soil quality indicators and environmental outcomes for arable, vegetable, and perennial horticulture sectors (black symbol: NZ study; red symbol: international study)

Sector: arable, forage, vegetables								
Outcome	Soil quality indicator							
	pH	Total C	Total N	AMN	Olsen P	HWEC	Macroporosity (-10 kpa)	Bulk density
Soil function – infiltration		2, 8	2				5, 6, 7, 13, 15	5, 6, 7, 8, 13, 15
Soil function - nutrient cycling	1, 4, 10, 11; 7, 25	1, 2, 4, 10, 11, 12; 24	1, 2, 4, 10, 11; 24		4	1		11, 17
Soil biodiversity								
Pest and disease regulation	14	14	14		14			
GHG emission (CO ₂ , N ₂ O, CH ₄ , etc.)	1, 4, 9, 10, 11; 18, 19	1, 4, 9, 10, 11	1, 4, 10, 11		4	1	6	6, 9, 11
Water quality (mainly nitrate leaching)	17, 20	13; 20, 21			20		3, 5, 6, 7, 8, 13, 15	3, 5, 6, 7, 8, 13, 15; 17, 20, 21
<i>Extensive data set</i>								
Production	16	2, 16, 22, 23	2				5, 7, 13, 15; 22	5, 7, 13, 15; 22

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Table A5.3. Number of peer-reviewed publications on soil quality indicators and environmental outcomes for arable, vegetable, and perennial horticulture sectors (black symbol: NZ study; red symbol: international study)

Sector: Perennial Horticulture								
Outcome	Soil quality indicator							
	pH	Total C	Total N	AMN	Olsen P	HWEC	Macroporosity (-10kpa)	Bulk density
Soil function – infiltration		7					5	2, 5; 7, 9
Soil function – nutrient cycling						3		
Soil biodiversity								
Pest and disease regulation								
GHG emission (CO ₂ , N ₂ O, CH ₄ etc)	10	1; 10					1,5	
Water quality (mainly nitrate leaching)	4, 10	4					4,5	5
<i>Extensive data set</i>								
Production	6, 8, 10	6, 7, 8, 10	6, 8					6,7

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Table A5.4. Description of extensive datasets identified for arable, vegetable, and perennial horticulture sectors

Study (citation ie Drewry et al 2023) / Dataset	Region (s), or national	Land use/s (dairy, drystock, pastoral, short-rotation)	Soil orders Specify soil orders if limited number of soil orders assessed in study	# sites (specify # if <20)	Sampling method	Soil properties measured (ONLY consider pH, Olsen P, total C, total N, AMN, Macroporosity, bulk density, HWEC)	Sample depth	One-time or multi-year ?	Measure of state or change over time? Y/N	Potential environmental linkage e.g. leaching)?	Production outcome? Y/N	Data location
Rootzone reality Flux meter (Norris et al., 2023)	National	arable cropping	multiple	12	other	all except HWEC	0-100 at 20 interval	multi-year	Y, change over time	nitrate leaching	Y	MfE, PFR (Matt Norris) and FAR (Dirk Wallace)
SLURI (Mike Beare)	National	multiple	multiple	>20	other	Total C, Total N, AMN, Macroporosity, Aggregate Stability, others likely, but needs confirming	Variable, depending on indicator.	one-time	Y, state	not directly assessed	Y, in some cases	PFR, AgR, MWLR
SLUI (Mike Beare)										not assessed		PFR

LMI (Mike Beare)	National	multiple	multiple	>20	single sample	all except macro-porosity	0-15, 15-30 (only for bulk density, total C, total N)	one-time	Y, state	not directly assessed	N	PFR
Ecan Arable & Pasture (Mike Beare, Craig Tregurtha)	Canterbury	multiple	multiple	>20	single sample	all inc HWEC	0-15, 15-30 (only for bulk density, total C, total N)	multi-year	Y, change over time	not directly assessed	N	PFR (with approval from Ecan)
SVS (Hamish Brown)	National (2 research sites+ 10 commercial sites)	vegetable cropping	multiple	12 (2 scientific sites+ 10 commercial sites)	plot composite			multi-year	Y, change over time	nitrate leaching	Y	PFR
MBIE Soil health & Smap projects (Fu et al., 2021, 2023, Hu et al., 2022, and many others)	National (mainly Canterbury, Waikato)	multiple	multiple	>20	single sample	all inc HWEC	0-10, 10-20, 20-30	one-time	Y, state	not assessed	N	MWLR, PFR
MTT (Fraser et al., 2013 SSSAJ, Mike Beare)	Canterbury	arable cropping	pallic	1	plot composite	bulk density, macroporosity, total C, total N, pH, Olsen P, AMN, Aggregate stability	0-30	multi-year	Y, state or over time	nitrate leaching, soil C change, some soil biodiversity data, Pest & disease monitoring.	Y	PFR

LUCI project (Curtin, Beare et al 2017, SSSAJ)	National (Waikato, Auckland, Hawkes Bay and Gisborne, Canterbury, Southland)	multiple	multiple	>20	single sample	pH, total C, total N, AMN, HWEC	0-15	one-time	Y, state	not assessed	N	PFR
SQMS projects (Beare)	Canterbury, Southland (mostly)	multiple	multiple	>20 each region	transect composite	pH, Olsen P, Total C, total N, Bulk Density, plus many others	Depth varies with indicators measured	multi-year	Y, change over time	not directly assessed	Y	PFR
Restorative and degradative project (Francis et al., 1999; 2001)	Canterbury	arable cropping	pallic	1	plot composite	bulk density, macroporosity, total C, total N, pH	0-20 with various intervals	multi-year	Y, state or over time	infiltration capacity	Y	PFR
FRNL project (winter forage trial, compaction trial, treading trial)	Canterbury	arable cropping	multiple	2	plot composite	bulk density, macroporosity	0-30 (25) with various intervals	one-time	Y, state or over time	nitrate leaching, N2O emission	Y	PFR
FRST/ARGO S project (Carey et al., 2009)	BoP, Northland, Tasman	orchards	2-3	36	other	bulk density, pH, Olsen-P, total N	0-15	multi-year	Y, state	not assessed	Y	?

(Goh et al., 2000)	Canterbury, Otago	orchards	2-3	5 (3 research sites, 2 commercial sites, different management - 11 total)	transect composite	bulk density, pH, Olsen-P, total C, total N	0-5, 5-15, 15-30	one-time	Y, state	infiltration	N	LU?
Sustaining Soil Services (Vogeler et al., 2006, Deurer et al., 2008, 2009)	Hawke's Bay	orchards	recent	2	other	macroporosity, bulk density, pH, total C, HWEC	0-10, 10-20, 20-30	one-time	Y, state	gas diffusion; infiltration & water retention; compaction; air permeability; leaching	N	PFR
OSUG-project (Müller et al., 2019)	BoP	orchards	allophanic	2	single sample	bulk density, macroporosity, total N, total C, pH	0-10	one-time	Y, state	leaching	N	PFR
Rahman et al., 2011	BoP	orchards	allophanic	4	single sample	bulk density, pH, total N	0-15	one-time	Y, state	not assessed	Y	GroPlus ?

Forestry matrix

Table A5.5. Identification of NZ publications on soil quality indicators and environmental outcomes for exotic forestry

Sector: Forestry								
Outcome	Soil quality indicator							
	pH	Total C	Total N	AMN	Olsen P	HWEC	Macroporosity (-10kpa)	Bulk density
Soil function – infiltration								
Soil function – nutrient cycling								
Soil biodiversity	1, 2, 4, 22	1, 2, 4, 22	1, 2, 4, 22		22			22
Pest and disease regulation								
GHG emission (CO ₂ , N ₂ O, CH ₄ etc)								
Water quality (mainly nitrate leaching)	5, 6, 17	17	17, 21					
<i>Extensive data set</i>	7, 11, 12, 16, 20, 24	7, 11, 12, 13, 14, 15, 16, 20, 24	7, 11, 12, 13, 14, 15, 16, 20, 24		11, 24		11	7, 11, 15, 13, 14, 15, 20
Production	3, 12, 18, 19, 23	3, 9, 10, 12, 18, 19, 23	3, 9, 10, 12, 18, 19, 23		23		23	9, 10, 12, 23

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Table A5.6. Description, and prioritisation, of extensive datasets identified for exotic forestry

Trial ID	Trial ID	Top priority studies for soil quality indicator targets review	Study (e.g. Drewry et al. 2023) / Dataset	Region (s), or national	Land use/s	Soil orders (Specify soil orders if limited number of soil orders assessed in study)	# Sites	Sampling method	Soil properties measured	Sample depth (cm)	One-time or Multi-year?	Measure of state or change over time (Y/N)	Potential environmental linkage	Production outcome (Y/N)	Raw data published (Y/N)	Citation of published raw data for top priority studies
		Yes	(McMahon et al 1999)	Regional	Forestry	Pumice		Plot composite	Bulk density, Macroporosity	0-80, 12-20 (subsoil)	One-time	Y	Not assessed	N	N	
		No	Simcock et al unpublished	Regional	Forestry	Multiple		Plot composite	Bulk density, Macroporosity	0-10, 10-20 (subsoil)	One-time	N	Not assessed	N	N	
		Yes	(Simcock et al 2006)	Regional	Forestry	Ultic		Plot composite	Bulk density, Macroporosity	1-10, 10-20 (subsoil)	Multi-year	N	Not assessed	N	N	
FR380	FR380	Yes	(Watt et al., 2008)	National	Forestry	Multiple	>20	Plot composite	pH, Total C, Total N, Olsen P, Macroporosity, Bulk density	0-10	One-time	N	Not assessed	Y	Y	(Garrett et al., 2022b)

	FR380		(Ross et al., 2009)	National	Forestry	Multiple	>20	Plot composite	pH, Total C, Total N	0-10, the first sub-horizon	One-time	N	Not assessed	Y	Y	
	FR380		(Garrett et al., 2022b)	National	Forestry	Multiple				0-10, then by horizon		N	Not assessed	N	Y	
	FR380		(Davis et al., 2012)	National	Forestry	Multiple						N	Assessed	N	N	
FR561	FR561	Yes; additional dataset	(Smaill et al., 2023)	National	Forestry	Multiple	6	Plot composite	pH, Total C, Total N, Bulk density	0-10, 10-20, 20-30, 30-50, 50-100	One-time	N	Not assessed	N	Y	(Smaill et al., 2023)
FR531	FR531	Yes; additional dataset	(Paul et al., 2024)	National	Pastoral	Multiple	4	Plot composite	Total C, Total N, Macroporosity, Bulk density	0-10, 10-20, 20-30	One-time	N	Not assessed	N	Y	(Paul et al., 2024)
Harvest residue and removal and fertiliser addition Trials	Harvest residue and removal and fertiliser addition Trials		(Garrett et al., 2021a)	National	Forestry	Multiple	6					N	Not assessed	Y	N	
	Harvest residue and removal and fertiliser addition Trials	Yes	(Garrett et al., 2021b)	Auckland, Bay of Plenty, Otago	Forestry	2-3	3	Plot composite	Total C, Total N, Bulk density	0-10	One-time	N	Assessed	Y	N	

Harvest residue and removal and fertiliser addition Trials	(Garrett et al., 2021c)	National	Forestry	Multiple	4	Plot composite	Total C, Total N, Bulk density	0-10	One-time	N	Assessed	Y	Y
Harvest residue and removal and fertiliser addition Trials	(Jones et al., 2008)	Bay of Plenty	Forestry	Recent	1	Plot composite	Total C, Total N	0-10	One-time	N	Assessed	N	N
Harvest residue and removal and fertiliser addition Trials	(Jones et al., 2011)	Waikato	Forestry	Pumice	1	Plot composite	Total C, Total N	0-10	One-time	N	Assessed	N	N
Harvest residue and removal and fertiliser addition Trials	(Smith et al., 1994a)	Auckland	Forestry	Recent	1						Assessed	Y	N
Harvest residue and removal	(Smith et al., 1994b)	Auckland	Forestry	Recent	1	Plot composite	Total N	0-10	One-time	N	Not assessed	Y	N

	and fertiliser addition Trials															
	Harvest residue and removal and fertiliser addition Trials	Yes	(Garrett et al., 2019)	National	Forestry	Multiple	6	Plot composit e	pH, Total C, Total N, Bulk density	0-10	One- time	Y	Not assessed	Y	Y	(Garrett et al., 2019)
	Harvest residue and removal and fertiliser addition Trials	Yes	(Addison et al., 2019)	Auckland , Bay of Plenty	Forestry	2-3	2	Plot composit e	pH, Total C, Total N	0-10	One- time	N	Assessed	N	N	
	Harvest residue and removal and fertiliser addition Trials	Yes	(Addison et al., 2021)	Otago	Forestry	Pallic	1	Plot composit e	pH, Total C, Total N	0-10	One- time	N	Assessed	N	N	
LUCAS National Planted Forest Inventory Plots	LUCAS National Planted Forest Inventory Plots		(Beets et al., 2019)	National	Forestry	Multiple	>20	Plot composit e	pH, Total C, Total N	0-5	One- time	N	Not assessed	Y	N	

	LUCAS National Planted Forest Inventory Plots		(MfE, 2021)	National	Forestry	Multiple	>20	Plot composite	Total C, Total N	0-5	Multi-year				
	LUCAS National Planted Forest Inventory Plots	Yes; additional dataset	(MfE, 2021)	National	Forestry	Multiple	>20	Plot composite	Total C, Total N, Bulk density	0-10, 10-20, 20-30	One-time	N	Assessed	Y	N
Puruki Experimental Forest	Puruki Experimental Forest		(Garrett et al., 2021d)	Waikato	Forestry										
	Puruki Experimental Forest		(Beets et al., 2004)	Waikato	Forestry	Pumice	1	Plot composite	pH, Total C, Total N	0-10	One-time	N	Not assessed	Y	N
	Puruki Experimental Forest	Yes	(Beets et al., 2002)	Waikato	Forestry	Pumice	1	Transect composite	Total C, Bulk density (not published; Total N, Olsen P, pH)	0-5, 5-10, 10-50	One-time	N	Assessed	N	N
	Puruki Experimental Forest		(Ross et al., 1999)	Waikato	Forestry	Pumice	1	Transect composite	Total C, Total N, Bulk density	0-10	One-time	N	Assessed	N	N
	Puruki Experimental Forest		(Byers et al., 2023)	Waikato	Forestry	Pumice	1	Transect composite	pH, Total C, Total N	0-10	One-time	N	Assessed	N	N

	ntal Forest															
	Puruki Experimental Forest		(Dyck et al., 1987)	Waikato	Forestry	Pumice	1	Transect composite	pH, Total C, Total N, Bulk density	0-10	One-time	N	Assessed	Y	N	
	Puruki Experimental Forest		(Parfitt et al., 2001)	Waikato	Forestry	Pumice	1	Plot composite	pH, Total C, Total N	0-5/5-10	One-time	N	Not assessed	Y	N	
	Puruki Experimental Forest		(Parfitt et al., 2002)	Waikato	Forestry	Pumice	1	Plot composite	pH, Total C, Total N	0-5/5-10	One-time	N	Assessed	N	N	
	Puruki Experimental Forest		(Quinn, 2005)	Waikato	Forestry	Pumice	1		-				Assessed		N	
Pakurahi Paired Catchment Land Use Study	Pakurahi Paired Catchment Land Use Study	Yes	(Heaphy et al., 2014)	Hawke's Bay	Forestry	2-3	1	Plot composite	pH, Total C, Total N, Bulk density	0-10	One-time	N	Not assessed	Y	N	
	Pakurahi Paired Catchment Land Use Study		(Fahey and Marden, 2006)	Hawke's Bay	Forestry		1		pH				Assessed	N	N	
	Pakurahi Paired Catchment Land		(Eyles and Fahey, 2006)	Hawke's Bay	Forestry		1		pH				Assessed	N	N	

Use Study															
Whatawhata Catchment	Whatawhata Catchment	(Hughes and Quinn, 2019)	Waikato	Forestry		1							Assessed	N	
Other	Other	(Davis, 2014)	National	Forestry									Assessed	N	
	Other	(Baillie and Neary, 2015)	National	Forestry									Assessed		
	Other	Yes; additional dataset	(Garrett et al., 2022a)	National	Forestry	Multiple	>20	multiple	pH, Total C, Total N	0-10	One-time	N	Not assessed	N	N
	Other	Yes; additional dataset	(Xue et al., 2013)	Canterbury, Bay of Plenty	Forestry	2-3	2		pH, Total C, Total N, Olsen P	0-10		N	Not assessed	N	N
	Other		(Olykan et al., 2008)	Canterbury, Waikato	Forestry	2-3	2		pH, Total C, Total N	0-10		N	Not assessed	N	N
	Other		(Wakelin et al., 2021)	West coast, Canterbury	Multiple	2-3	4	Transect composite	pH, Total C, Total N, Bulk density, Olsen P	0-5	One-time	N	Assessed	N	N

Appendix 6 – Summary of coefficients for Olsen P conversion

Table A6.1. Summary of generalised linear mixed effects model coefficients for volumetric-to-gravimetric Olsen P conversion using all New Zealand soil orders

Type	Term	Coefficient
Fixed effects	Intercept	0.4228
	log(Olsen P)	0.9927
Random effects	Allophanic	-0.1088
	Brown	-0.1138
	Gley	-0.1137
	Granular	-0.1829
	Melanic	-0.0591
	Organic	0.1485
	Pallic	-0.0518
	Podzol	0.1098
	Pumice	0.2408
	Raw	-0.015
	Recent	-0.1627
	Ultic	-0.0798

Source: Drewry et al. 2022

Notes: Units of Olsen P are mg/L (volumetric) or mg/kg (gravimetric).

Appendix 7 – Olsen P conversions

Table A7.1. Conversion of selected volumetric Olsen P values into gravimetric measures, based on Drewry et al. 2022

Volumetric Olsen P (mg/L)	Gravimetric Olsen P (mg/kg)											
	Allophanic	Brown	Recent	Gley	Ultic	Granular	Pumice	Pallic	Organic	Raw	Podzol	Melanic
10	13	13	13	13	14	13	19	14	17	15	17	14
17	23	23	22	23	23	21	32	24	29	25	28	24
20	27	27	25	27	28	25	38	28	35	29	33	28
27	36	36	34	36	37	34	51	38	47	40	45	38
30	40	40	38	40	41	37	57	42	52	44	50	42
31	41	41	39	41	43	38	59	44	54	45	52	43
35	47	46	44	46	48	43	66	49	60	51	58	49
40	53	53	51	53	55	50	76	56	69	59	66	56
45	60	60	57	60	62	56	85	63	78	66	75	63
50	67	66	63	66	68	62	94	70	86	73	83	70
60	80	79	76	79	82	74	113	84	103	88	99	84
70	93	92	88	92	96	86	132	98	120	102	116	98

Notes: The volumetric values shown are those used in section 7.2.2 and are based on agronomic recommendations, allowing for depth adjustment for pastoral land uses, as discussed in section 7.2.2.