Manaaki Whenua
Landcare Research

Review of methods and data used to develop target values for soil quality indicators

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Review of methods and data used to develop target values for soil quality indicators

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Contents

Summary

Project and client

- Soil quality monitoring for regional and national state of the environment (SOE) reporting has been carried out for about 25 years. Provisional soil quality target values were developed in 2000 through a series of workshops.
- This project reviews the basis of the target values currently used for soil quality monitoring programmes and provides recommendations for future updates of these targets.
- The project was undertaken for Otago Regional Council and the members of the Land Monitoring Forum Special Interest Group. Otago Regional Council sponsored this project through Envirolink funding (Envirolink Advice Grant 2333-ORC005) on behalf of all participating councils.

Objectives

- To review and document the basis of target values currently used for soil indicators monitored in soil quality monitoring programmes.
- To undertake a workshop with the Land Monitoring Forum to identify additional indicators that are currently being used, or for which there is interest in using.
- To identify data sources for the development of new target values.
- To produce a report that captures the findings of the project and includes recommendations for reviewing and updating the target values.

Methods

- A review was conducted of the literature relating to the development of the current target values in New Zealand soil quality monitoring. The results of the early workshops were summarised and critiqued, along with information used for the indicators and sources of information in the workshops. The results of the 2011 workshop and ones held since then were reviewed.
- A brief review was undertaken of the national and international literature on soil indicators, and the derivation and application of soil quality targets values.
- A workshop was held with regional and unitary councils in June 2023 to discuss the purpose of target values in the current regulatory environment, potential indicators, and the next steps for reviewing target values.

Results and conclusions

- Two expert workshops were originally held to establish target values for soil quality indicators. 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 (phosphorus), total carbon, total nitrogen, mineralisable nitrogen, macroporosity, and bulk density. It was concluded that there were limited environmental data to inform the development of provisional target ranges.

- In undertaking this review it became clear that there was no definitive source for the current target values, and that sometimes the reason for changes was unclear (e.g. for macroporosity). This report may fill that gap, as well as providing visibility of the original workshop processes and data used to underpin the current target values.
- Another observation of the target ranges used is that they tend to be set at the thresholds of the more extreme ends of the range (i.e. between the low/very low and high/very high ends), compared to more narrowly defining an optimal range. However, the parameters are predominantly based on production aspects, with data to underpin environmental considerations much more limited.
- The workshop in June 2023 was originally intended to focus on how the derivation of existing target values could be improved and identify new indicators and relevant data sources. However, comments from the workshop highlighted that in order to do this effectively there needs to be greater clarity around the context and purpose of using target values, including what actions should be taken as a result of falling outside the target ranges.
- Workshop participants expressed a clear desire to clarify those limits or thresholds that could lead to negative environmental impacts, particularly as regional councils are charged with being responsible for the environment.
- It was recognised that there is a tension between ensuring ongoing access to soil quality monitoring sites and effecting positive changes in soil health, particularly if punitive actions are taken as a result of sites falling outside the target ranges. ‘Behaviour-change approaches’ were considered to be preferable, but it was recognised that there is a variable appetite among individual councils to invest in such programmes.
- Participants saw value in continuing to monitor along the lines of existing SOE reporting, partly because of the investment and data that monitoring has provided over time. However, there was a clear desire to have clearer national direction on the objectives of monitoring, and actions that will result in improvements in soil quality.

Recommendations

Key recommendations arising from this project relate to two levels: SOE monitoring and national policy.

State of the Environment monitoring

We recommend:

- critically reviewing the performance of existing indicators used in SOE reporting, via existing trends and state analysis and literature studies, to evaluate whether to retain these as indicators for soil quality monitoring
- developing ‘living documents’ for those indicators that are retained

- critically reviewing new evidence (i.e. data available since the establishment of current target values) for the current suite of indicators, with a focus on developing thresholds, where possible, that define potential negative environmental impacts, taking into consideration variation across land use and soil order.

In terms of new indicators, we recommend:

- reviewing the evidence for and, if appropriate, confirming provisional thresholds or proposing alternative thresholds for hot-water carbon
- evaluating the current status of the use of biological indicators in monitoring programmes in New Zealand, and internationally, with a view to proposing potential indicators
- evaluating the status and value of an indicator for erosion at farm-scale (i.e. not highly erodible land).

More broadly, we recommend that:

- councils review how, or if, SOE soil quality monitoring and associated results are used to inform their resource management policies or plans, or the effectiveness of any relevant provision, which would provide an evaluation of the extent to which this intended original objective has been realised (arguably this is the most critical element of informing actions to improve soil quality/health)
- councils review opportunities to integrate soil quality monitoring with freshwater and groundwater monitoring to better inform holistic management.

National level

- We recommend that the Land Monitoring Forum advocate to the Resource Managers Group (RMG) and central government (Ministry for the Environment, Ministry for Primary Industries) to develop a national soils strategy that provides clear objectives for improving soil health across the multiple areas, integrates te ao Māori and mātauranga Māori, and recognises the key role that people play in improving soil health.

1 Introduction

Statutory requirements under the Resource Management Act 1991 (RMA) gave rise to the development of a national soil quality monitoring programme, initially through a Sustainable Management Fund Project (#5089) 'Implementing soil quality indicators for land', which began in 1999 and was completed in 2001. This project, commonly referred to as the 500 Soils project, collected new soil quality data from approximately 500 sites across New Zealand (Sparling et al. 2000, 2001a, b), building on an earlier Sustainable Management Fund Project (#5001) 'Trialling soil quality indicators for land' (Sparling et al. 1996, 1997, 1998). Sparling et al. (2004) provide an evaluation and overview of the programme's development and the trialling of different soil quality indicators. These studies provided the basis for current regional state of the environment (SOE) soil quality monitoring programmes.

Soil quality target values were established in the early 2000s (Lilburne et al. 2004; Sparling et al. 2003) to assist with interpreting the results of soil quality monitoring from these programmes (Sparling & Schipper 2002, 2004; Sparling et al. 2004). The 'provisional' values in Sparling et al. 2008,[1] with some subsequent modifications, provide the basis for current regional SOE reporting and national reporting (e.g. the Ministry for the Environment's *Our Land 2018* and *Our Land 2021*). After the original provisional target value document was published there has been occasional review and modification of some targets (e.g. Taylor & Mackay 2011), but no systematic review of the target values themselves.

This project fills that gap and collates the literature and background detail relating to the development of numerical target values used in council soil quality monitoring programmes. The aim is to help enable these values to be updated for regional and national reporting needs. This project draws on the findings of a previous review of target values (Stevenson & Drewry 2022) and soil health indicators (Stevenson 2022), and provides a first step towards a review and potential update of existing target values, and the development of target values for additional indicators. This work will be relevant to the ongoing development of the Natural and Built Environment Bill, which includes consideration of the setting of targets and limits for use under the National Planning Framework.

[1] Originally published in 2003, republished in 2008 with minor modification; hereafter only the 2008 version is referred to

2 Objectives

The objectives of this project are to:

- review and document the basis (method, data used) of target values currently used for soil indicators monitored in SOE soil quality monitoring programmes (other than contaminants)
- undertake a workshop with the Land Monitoring Forum (LMF) to identify additional indicators that are currently being used, or for which there is interest in using
- identify data sources for the development of new target values
- provide recommendations for review and update of the target values for SOE monitoring.

3 Methods

A review was conducted of the literature relating to the development of the current target values in New Zealand soil quality monitoring. The results of the early workshops were summarised and critiqued, along with information used for the indicators and sources of information in the workshops. The results of the 2011 workshop and ones held since then were reviewed. A brief review was undertaken of the national and international literature on soil indicators, and the derivation and application of soil quality targets values.

A workshop was held with regional and unitary councils in June 2023 to discuss the purpose of target values in the current regulatory environment, potential indicators, and next steps for reviewing target values.

4 Overview of the establishment of soil quality target values for the seven key indicators

The need for indicators for soil quality monitoring and SOE reporting was identified by the Ministry for the Environment in the late 1990s (MfE 1997, 1998) and was the underpinning basis for the development of the 500 Soils programme. It was also recognised that defining the desirable or normal limits for those indicators was required in order to interpret the monitoring results, and to identify soils that exceed expected ranges.

In 2000 the first efforts to develop such ranges were made. The approach was based on that used by Smith (1990) to define indices for water quality monitoring in New Zealand. Specifically, a structured approach was used to elicit, and evaluate, information drawn from an expert group to develop target ranges. This comprised two workshops, with the findings and evaluations outlined in reports (Sparling & Tarbotton 2000; Sparling et al. 2008) and a journal paper (Lilburne et al. 2004). Further details and discussion on the selection of indicators, and the development and use of these target values in soil quality monitoring programmes in New Zealand, are provided in Sparling & Schipper 2002, Sparling et al. 2003, Schipper & Sparling 2004, and Sparling et al. 2004.

The established target ranges were incorporated into LMF guidance on undertaking soil quality monitoring (LMF 2009). 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).

An overview of the timeline of the development of target values for the main soil quality indicators is presented in Table 1, with further detail provided below.

Table 1. Key steps in the development and review of soil quality indicator target values

Timeline	Overview of workshop and process	Reference
7/8 February 2000	An initial workshop was held with 24 New Zealand soil scientists, who were encouraged to draw non-linear response curves for soil quality indicators. After the workshop each curve was digitised and amalgamated, and response curve means and errors were calculated.	Lilburne et al. 2004; Sparling & Tarbotton 2000; Sparling et al. 2008
	In a 2nd workshop, a 6-member subgroup of the original panel reviewed the conclusions of the first workshop to resolve anomalies. The target values and ranges were regarded as provisional.	Sparling & Tarbotton 2000; Lilburne et al. 2004
2003 and 2008	Provisional targets were published based on the workshops of 2000 (originally published in 2003, but in 2008 re-issued with minor amendments).	Sparling et al. 2008*
2009	The LMF manual was published, including tables of target values.	LMF 2009
2011	Some targets were amended (AMN and Olsen P) in a workshop of 18 soil scientists and regional council staff in May. Four others contributed but did not attend. An email survey was first conducted to help set priorities for the workshop by identifying the issues and indicators of most concern. Recommendations were put forward to the LMF, who decided on the actions at a meeting in September. Changes to the target values for AMN and Olsen P were agreed.	Taylor & Mackay 2011
2013	'Soil Quality Indicators: The Next Generation' Envirolink Tools project was completed. The final report included the background papers and meeting minutes for the 2011 meetings, as well as exploring the use of ecosystem services framing for soil quality monitoring.	Mackay et al. 2013

* Sparling et al. 2008 was originally published in 2003, but was re-issued in 2008 with minor amendments.

Notes: AMN = anaerobically mineralisable nitrogen; Olsen P = phosphorus.

4.1 Establishment of target values

Two workshops were held to establish initial target values for soil quality indicators. A soil experts workshop in February 2000 involved 24 New Zealand soil scientists, and this was followed by a review workshop comprising a sub-group of the original panel. The process generally followed the methodology of Smith (1990), and the findings of the first workshop are captured in Sparling & Tarbotton 2000. The findings from the second workshop, including the establishment of target ranges, are captured in Lilburne et al. 2004 and Sparling et al. 2008. Details and outcomes from the process are summarised below.

4.1.1 Soil experts workshop 2000

During the first stage of this intensive, in-person, 2-day workshop, agreement was reached on the land-use categories and soil orders relevant to consider for individual parameters. The land-use categories were: intensive pasture, extensive pasture, pine plantation, cropping/horticulture, and indigenous forest (see Appendix 1 for the definitions used). Overall, 13 parameters for different soil orders and land uses were considered (Table 2). Cation exchange capacity was also discussed, but was felt to be unnecessary to measure because of the strong correlation with organic matter in topsoils. Microbial biomass, soil respiration, and soluble organic matter were not considered suitable soil quality indicators for routine monitoring programmes. Ultimately, the workshop attendees considered there was insufficient distinction between intensive and extensive pastures for any of the attributes considered (Table 2).

Table 2. Summary of soil properties, and soil order and land-use categories, considered for the development of target values

Soil property	Soil orders	Land-use categories
Soil pH	Organic All other soil orders	Pastures Cropping and horticulture Pines Indigenous
Organic carbon (C)	Allophanic and Oxidic Semiarid, Recent, and Pallic All other soil orders	Pastures Cropping and horticulture Forestry
C:N ratio	All soil orders	Pasture Cropping and horticulture Pines Indigenous
Mineralisable nitrogen (N)	All soil orders	Pasture Cropping and horticulture Pines Indigenous
Olsen P (phosphorus)	Allophanic Recent Organic and Pumice All other soil orders	Pasture Cropping and horticulture Pines Indigenous
Earthworms	All soil orders	Pastures Cropping and horticulture
Bulk density	All soil orders	All land uses
Aggregate stability	Allophanic and Oxidic All other soil orders	Cropping and horticulture All other land uses
Macroporosity	All soil orders	Pastures Cropping and horticulture Pines

Soil property	Soil orders	Land-use categories
Topsoil depth	All soil orders	All land uses (some question over pines)
Rooting depth	All soil orders	Pines and indigenous forest
C balance	Organic Allophanic and Oxidic Recent and Pallic Semiarid All other soil orders	All land uses
N balance	All soil orders	All land uses

For each parameter, individual scientists were encouraged to draw non-linear response curves. A template was provided, and the x-axis scale and units were written in before the curves were constructed so that individuals used the same scale and range. The group were free to interact after individuals had completed their response curves while working alone. Response curves were overlaid and discussed within the group, and then between groups, and modified with agreement.

A 'soil quality rating' (0–100%) was used on the y-axis, with units of the soil property on the x-axis. For each soil property the group reached a consensus on what the values would be along the x-axis. Then the group reached a consensus on whether the curves would be different for separate land-use categories, and then whether they would be different across soil orders.

Response curves were constructed using production considerations, while a second set of response curves used environmental considerations, as follows.

- Production criteria were agricultural productivity (plant dry matter, milk solids, logs for export), maximum economic yield, sustainable production, farm profitability, and impact on the rural economy, considered within a short-term time frame (<5 years).
- Environmental criteria were risks to air quality, water quality, loss of habitat, amenity and access, loss of diversity of indigenous species, invasions by weeds and pests, and contaminant accumulation. These were considered over a longer time frame (25 years).

However, beyond this generic description of production and environmental criteria it is unclear what or how data or information, particularly for the environmental criteria, was used to support evaluations for individual parameters.

No values for productivity or other criteria were specified because members defined their own values. Where considered appropriate, response curves were constructed for specific soil orders or groups of orders, and for specific land uses. In some cases there was insufficient knowledge to construct curves for all combinations.

At the end of the workshop all graph sheets were collected and the curves converted to numerical values by selecting regular values along the x-axis and reading the appropriate y-axis soil quality values. Intermediate values were obtained by linear interpolation.

Values were imported into a spreadsheet, and average soil quality values and errors calculated for each soil quality indicator.

Graphs were initially drawn using smoothed moving averages and sent to group members for further comment. The mean value and standard error of the mean were calculated and presented graphically. The majority of graphs showed the true mean value (only data cells included), and two further plots showing the mean plus or minus one standard error (Figure 1). Where there were too few contributors to calculate a standard error, data from individuals were plotted, with the soil type and land use designated in the graph legend.

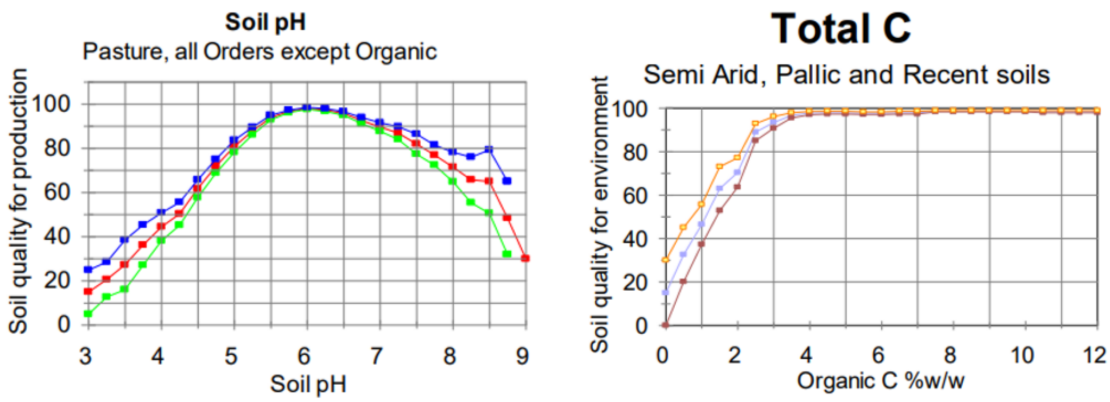

Figure 1. Examples of response curves produced from the workshop. Left: an 'optimal range' soil pH curve for pasture (production factors) for all soil orders, excluding Organic soils. Right: optimal values for total carbon on Semiarid, Pallic, and Recent soil orders based on environmental quality, following a 'more is better' pattern. (Source: Sparling & Tarbotton 2000)

4.1.2 Feedback on the process

As part of the overall process an evaluation of the approach was undertaken. This was done via an anonymous questionnaire to participants. In general there was satisfaction with the decision-making process, but some concern about the lack of precision, the potential for large errors, and misinterpretation by end-users when different soil orders and land uses were used and/or when the individual soil properties have inherently large variability (Sparling & Tarbotton 2000).

The general pattern of the response curves showed that the group were reasonably confident about what comprised an acceptable range for good quality and for production criteria. However, there was much less confidence about the shape of the response curves outside the 'acceptable' range, partly because there is much less experimental evidence available. Curves were also more varied for environmental criteria than for production criteria (Sparling & Tarbotton 2000).

Key summary comments from the soil experts 2000 workshop (reported in Sparling & Tarbotton 2000) include:

- ‘The confidence in the reliability of the Workshop information was much less than the acceptability of the process’
- ‘The pattern of response curves produced by the expert group showed a good degree of confidence in defining *optimum* levels of a particular soil attribute, but much less confidence in defining upper or lower acceptable limits.’

It was also observed that the reliability of, and confidence in, the response curves and suggested limits could be improved by repeating the process.

4.1.3 Review workshop 2000

Following the first workshop, a second was held with a six-member subgroup of the original panel to review the conclusions of the first workshop and resolve any anomalies. This included removing extreme outlier points, smoothing the amalgamated response curves, and aggregating soil and land-use categories where the curves were similar (Lilburne et al. 2004; Sparling et al. 2008).

Four soil quality categories along the response curves were defined:

- significant (adverse) impact
- potential impact (and therefore of concern)
- within the target range
- above-target range.

The workshop defined boundary points or thresholds along the response curves for each soil quality category (Lilburne et al. 2004). An upper and lower limit were defined for a target range. The acceptable range in a soil property was defined as being between the threshold of significant impact and the above-target range value. There was less confidence about the response curves outside the ‘acceptable’ range.

Where the production and environmental response curves showed different trajectories, the more conservative of the two responses was used (Sparling et al. 2008). Various sources of information were used in the workshop to define the category thresholds, and these are provided in Appendix 2. For soil fertility properties the yield response curves were used because these were well defined, especially for production (see later section for references). (For more details, see Lilburne et al. 2004 and Sparling et al. 2008, including combining the curves, and use of targets for ‘reporting by exception’.)

For soil fertility criteria (not specified but presumably Olsen P and pH), the expert opinion-derived response curves generally involved assuming a negative environmental impact once the plateau phase on the yield response curve had been exceeded (Lilburne et al. 2004; Sparling et al. 2008).

The target ranges were expected to be better defined as more data became available, and were considered to be better suited to assessing soil quality at a broad regional scale than for specific on-farm assessment (Lilburne et al. 2004). The final edited response curves are presented in Sparling et al. 2008. Examples of response curves for total nitrogen (N) and total carbon (C) developed in the workshop process are presented in Figure 2 to 4.

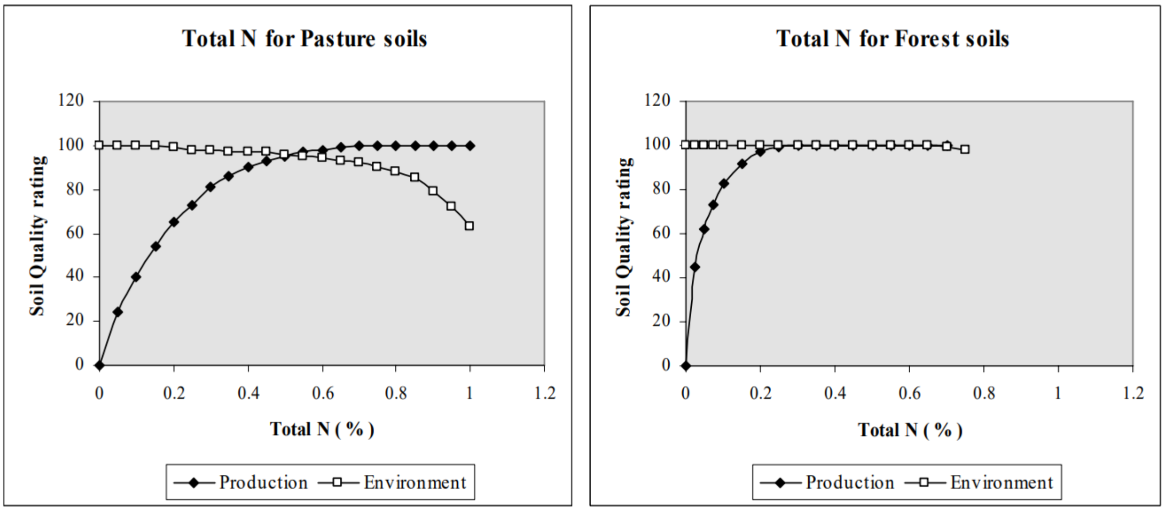

Figure 2. Response curves for total N on pasture (left) and forest soils (right), with separate curves for production factors and environmental quality (Source: Sparling et al. 2008). The environmental and production curves were combined to produce the combined curves, below (Figure 3).

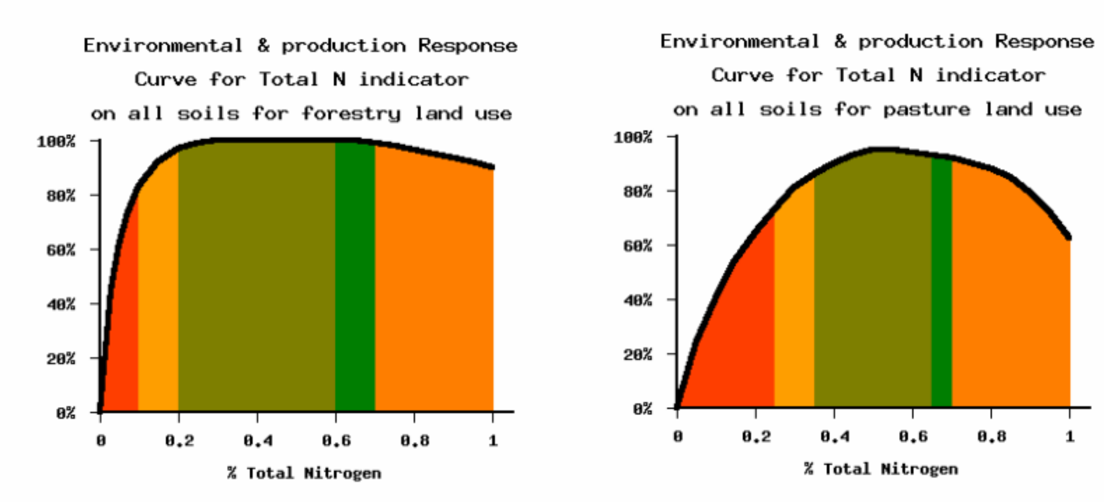

Figure 3. Combined (environment and production) soil quality response curves for total N. (Source: Sparling et al. 2008). These combined curves follow the 'optimal range' pattern. Legend colours were not explained, but are likely to be: very depleted, depleted, adequate, ample, and high. These classes were provided in their summary table of total N target values.

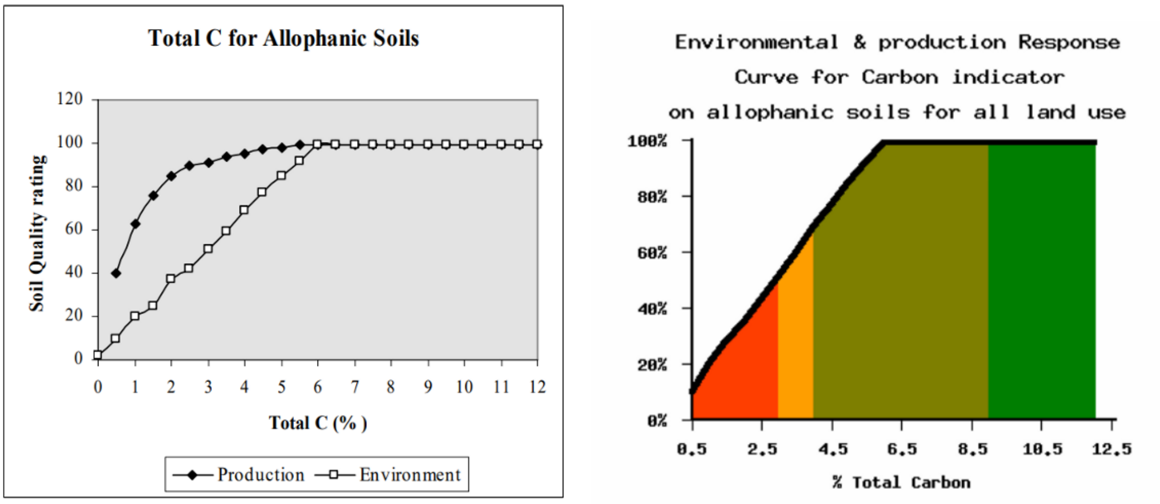

Figure 4. Separate curves for total C on Allophanic soils for production factors and environmental quality (left), combined to produce a single production and environmental response curve (right) (Source: Sparling et al. 2008). These curves follow the 'more is better' pattern. Legend colours were not explained, but are likely to be: very depleted, depleted, normal, and ample, as these classes were used in the summary tables of target total C values in Sparling et al. 2008.

4.1.4 Soil indicator review workshop 2011

A workshop organised by LMF to review the indicators used in soil quality monitoring and their target ranges in New Zealand was held in May 2011. There were 18 attendees, mainly from regional councils and Crown research institutes (CRIs). Prior to this workshop participants were sent briefing papers for the review of the soil quality indicators, additional information on soil invertebrate indicators, and upgrades of target ranges for macroporosity and Olsen P indicators (summarised in Appendices 7.4, 7.5 and 7.6 of Mackay et al. 2013).

Before the workshop an email survey was conducted to identify key aspects to be covered, and included questions such as, 'Are current processes robust?' and 'Are current target ranges correct?'. The priorities for discussion were:

- assess new indicators, including biological indicators (hot-water carbon, microbial communities using various genetic techniques, and soil invertebrates)
- review the existing indicators: AMN, total N, total C, Olsen P, aggregate stability and macroporosity (Taylor & Mackay 2011; Mackay et al. 2013).

A report from the workshop (captured in Taylor & Mackay 2011 and section 3.4 of Mackay et al. 2013) provided a summary of the main discussion points and presented a number of recommendations to the LMF. These recommendations were considered by the LMF at their meeting on 25/26 September 2011, with key decisions being:

- remove the upper limit for AMN
- reduce the upper limits of Olsen P to match the levels used by the agricultural and fertiliser industries

- investigate earthworm diversity and abundance and hot-water carbon as future soil quality indicators.

Taylor and Mackay (2011) noted an issue in relation to the reporting of results on a concentration vs volumetric basis. This arose from earlier national soil quality reporting typically using volumetric units (i.e. multiplying by bulk density for reporting volumetric values to provide comparisons between soils of different bulk density). For example, Sparling and Schipper (2004) reported total C and total N in volumetric units (mg/cm^3) with mineralisable N and Olsen P in µg/cm^3. Taylor and Mackay (2011) concluded that concentration was better for all indicators, excluding measuring C stocks.

Mackay et al. (2013) noted a further relating to gravimetric vs volumetric reporting of Olsen P, arising from the practice of research laboratories and organisations such as CRIs: they determine Olsen P on a gravimetric (weight) basis, while commercial laboratories determine Olsen P on a volumetric basis. This is discussed further in the section below on Olsen P (section 4.2.7).

4.2 Development of target ranges for the seven key soil indicators

This section presents details of the development of target values for the seven key indicators: soil pH, Olsen P, total C, total N, mineralisable N, macroporosity, and bulk density, particularly from Sparling et al. 2008, but including any subsequent updates. The reports/publications of Sparling and Tarbotton (2000), Lilburne et al. (2004), and Sparling et al. (2008) indicate that the targets are *provisional* targets.

Data for additional indicators (aggregate stability, earthworm numbers, topsoil depth, total rooting depth, C:N ratio, C balance and N balance) from the original workshops are also presented in Sparling et al. 2008, although, with the exception of aggregate stability, no combined curves or target ranges were defined for those properties. Information on some of these indicators is presented in section 5.

'Sources of information' (references) are given in Sparling et al. 2008 for individual parameters, although it is unclear how these references were used to inform the response curves or setting of target values. These references are captured in Appendix 2.

Finally, it useful to note that, in considering the responses of indicators, three broad scenarios are considered:

- less is better (e.g. contaminants)
- optimal (or acceptable) range (e.g. nutrients)
- more is better (e.g. soil carbon) (Moebius-Clune et al. 2016).

4.2.1 Bulk density

The bulk density response curves reported in Sparling et al. 2008 followed the 'optimal range' pattern. Separate curves were required for (1) Semiarid, Pallic, and Recent soils, (2) Allophanic Soils, (3) Organic Soils, (4) Pumice and Podzol soils, and (5) all other soil orders. A single curve was considered adequate to meet both production and environmental soil quality goals. Sparling et al. (2008) reported there were insufficient data to differentiate between land-use categories, so the target ranges are broad. It was noted that target ranges for cropping and horticulture were poorly defined. Nine references were provided as 'sources' of information in Sparling et al. 2008 (see Appendix 2).

Threshold values were based on quartile values from the National Soils Database (NSD) and 500 Soils project (Sparling et al. 2008), although no further information is given. The bulk density values were not revised at the 2011 workshop (Taylor & Mackay 2011; Mackay et al. 2013) and the values used are shown in Table 3.

Table 3. Bulk density target ranges (t/m^3 or Mg/m^3). Bold values indicate target values.

Soil type	Very loose		Loose	Adequate	Compact	Very compact
Semiarid, Pallic, and Recent soils	0.3	**0.4**	0.9	1.25	**1.4**	1.6
Allophanic soils		**0.3**	0.6	0.9	**1.3**	
Organic soils		**0.2**	0.4	0.6	**1.0**	
All other soils	0.3	**0.7**	0.8	1.2	**1.4**	1.6

Source: LMF 2009.

4.2.2 Macroporosity

Sparling et al. (2008), based on the workshops held in 2000, considered that macroporosity falls into the optimal range response. A single response curve was considered adequate for all soil orders, and for pasture, horticulture, and cropping soils, but a different curve was obtained for forestry land use. These two curves were also considered adequate to cover both production and environmental criteria.

There appears to be little specific evidence presented for the difference in forestry soils vs pasture, and there were no forestry references specified in the reference list, only pastoral-based studies (Appendix 2). These studies are supposedly the basis for the thresholds established, although no further detail is provided. It was noted that there were few data for cropping and horticulture. The target ranges for macroporosity developed by Sparling et al. (2008) are shown in Table 4.

Table 4. Macroporosity target ranges from Sparling et al. 2008, based on response curves associated with % pores over 60 µm

Land use	Very low		Low	Adequate	High
Pastures, cropping and horticulture	0	**6**	8	**30**	40
Forestry	0	**8**	10	**30**	40

However, there are several points of potential confusion in the establishment and use of target values or range for macroporosity. First, there is confusion about the terminology, and the use of different definitions of macroporosity. For example, Sparling et al. (2008) describe macroporosity as the measure of the number of large pores – those with a 'diameter greater than 60 µm', which is measured at a –5 kPa tension (Mackay et al 2006). However, under the description of the methodology used, Sparling et al. (2008) refer to 'θ as the volumetric water content at −10 kPa tension', which is considered to measure pores with a diameter of 30 µm (Mackay et al. 2006; Drewry, Carrick et al. 2021). Some rationale is provided by Mackay et al. (2006), who noted that 'the term macroporosity has in the past been defined as the number of pores in the soil with a diameter >60 µm, but in more recent times usage has been expanded to include pores with a diameter down to 30 µm.' They reference Gradwell (1971, cited in Mackay et al 2006) as the source of the definition of macroporosity as the pore volume calculated from the volumetric soil moisture content at –5 kPa tension, and air capacity as the pore volume calculated from the volumetric soil moisture content determined at –10kPa, and highlight the need to specify the tension at which macroporosity is determined.

In the 500 Soils studies (Sparling et al. 2001a, b), water release was measured at 5, 10, 100, and 1,500 kPa, with 'macroporosity' provided in the reports. The tension used is not stated but is understood to be –5 kPa, based on the original definitions of Gradwell (1971). Manaaki Whenua – Landcare Research laboratories continue to use macroporosity as measured at a tension of –5kPa, and air capacity to refer to macroporosity measured at a tension of –10kPa. This terminology has led to some historical confusion in the reporting of macroporosity results by councils, particularly as the LMF manual (Hill & Sparling 2009) refers to macroporosity as measured at –10kPa (page 70). The Manaaki Whenua – Landcare Research laboratories now make it clear on results sheets which matric potential the measurements are completed at.

Macroporosity is perhaps more widely accepted as being the volumetric percentage of large soil pores >30 µm (measured at –10 kPa matric potential), and this has been adopted as the primary measure for macroporosity in regional and national environmental reporting and research studies, including much of the earlier pasture production-based macroporosity research (e.g. Drewry et al. 2004). Further, recent studies typically use macroporosity measured at –10 kPa matric potential (e.g. Drewry, Carrick et al. 2021; Drewry et al. 2015; Hu et al. 2021). A further point is that Mackay et al. (2006) noted that the term macroporosity has 'been defined as the number of pores', but the term is more correctly referred as to the *volumetric quantity of pores* of a specific diameter, *not the number*. Further technical explanation is given in Drewry, Carrick et al. (2021).

Notwithstanding the confusion in terminology and the tension at which macroporosity is measured, there is also a lack of clarity about what the target ranges or values are based on, and when they changed for use by councils.

Mackay et al. (2006) drew on additional macroporosity data obtained since 2000 to undertake a review of the macroporosity target ranges provided in the 2003 version of 'Provisional soil quality target values' (Sparling et al 2008; Figure 5). For pasture and cropping soils they suggest that 'As a consequence of redrawing the curve the low and adequate quality classes need to be changed to 8–20% and 20–30%, respectively', and noted a production 'lift' for macroporosity at about 10%. These recommendations were considered to apply to horticultural crops, since few new data had been generated. For forestry they stated that the majority of forest soils (imperfectly to well drained) show a linear increase in productivity for macroporosity over 10%, and to at least 30% before flattening off or decreasing. The revised target ranges are provided in Table 5, but they don't strictly match the text provided in the document. The same material is repeated in Beare et al. 2007.

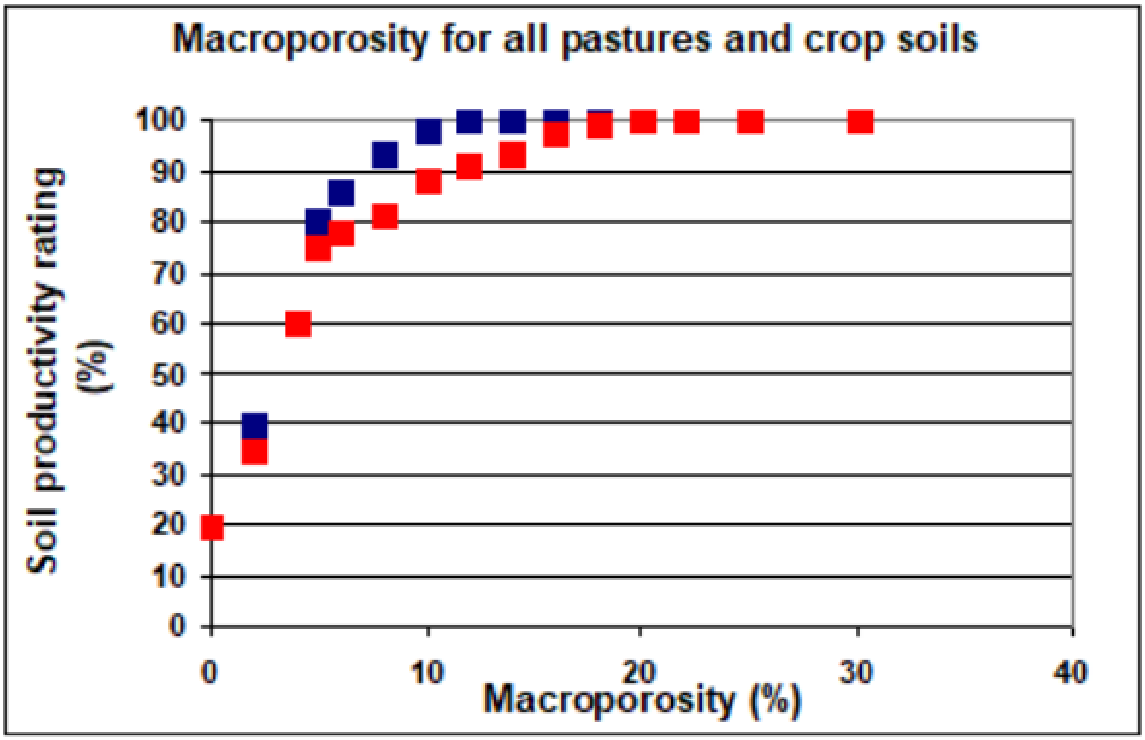

Figure 5. An updated provisional soil productivity response curve for macroporosity for all pasture and crop soils (red dots), based on macroporosity, measured at –10kPa, compared to the original soil quality response curve for macroporosity (blue dots). (Source: Mackay et al. 2006)

Table 5. Revised macroporosity target ranges from Mackay et al. 2006; tension not stated but assumed to be –10 kPa*

Land use	Very low		Low	Adequate	High
Pastures, cropping, & horticulture	0	5	10	20	>30
Forestry (timber production)	0	5	10	20	>35
Pine seedlings	0	10	20	30	>40

* The Very low, Low, etc. classes were added to provide consistency with the other tables.

The LMF manual (Hill & Sparling 2009) provides target ranges for macroporosity (at – 10 kPa), largely based on Sparling et al. 2008, but attributes a change from 8 to 10% for low for pasture, cropping, and horticultural soils to Mackay et al. (2006) (Table 6).

Table 6. Macroporosity target ranges (% v/v at –10 kPa)

Land use		Very low		Low		Adequate		High	
Pastures, cropping, and horticulture	0		**6**		10		**30**		40
Forestry	0		**8**		10		**30**		40

Source: Hill & Sparling 2009.

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). It was considered there wasn't sufficient evidence, and that further explanation of why results are inside or outside the targets may be needed in reporting the results, particularly for certain soil types and land uses. An example given was that 20% is low for Pallic soils but high for Melanic soils. The current forestry target range was indicated to be 8–30% (Taylor 2011; section 7.4 in Mackay et al. 2013), which accords with the values shown in Table 6.

4.2.3 Total carbon

Total C was considered to be a good measure of organic matter, given New Zealand soils typically contain very little carbonate, and organic matter was considered important for soil quality because it helps soils retain moisture and nutrients, and gives good soil structure for water movement and root growth.

Soils were recognised as differing in the amount of organic matter they contain depending on their mineralogy, climate, and land use. As such, Semiarid, Pumice, and Recent soils formed one distinct group, and Allophanic Soils another distinct group, with the Organic soil order, which by definition contains more than 16% C, excluded from consideration (Sparling et al. 2008).

Total C response curves for environmental protection were higher than those for production. Three references were identified as sources of information (Appendix 2).

Sparling et al. (2008) reported that thresholds for total C (and N, anaerobically mineralisable N) were obtained from interquartile ranges of long-term pasture sites, grouped by soil order, using data from the New Zealand National Soils Database (NSD) and the 500 Soils project, and cite Sparling et al. (2003). However, Sparling et al. (2003) indicate that a 90% cut-off value on the response curves was used to identify the organic C content below which soil quality was considered to be degraded.

Sparling et al. (2008) also stated that long-term pasture sites were used as the 'optimum' target range for organic matter content, because the total C content of New Zealand pasture topsoils has been found to be similar to that of long-term indigenous forest sites, citing Sparling & Schipper 2002 as the source for this information. However, 'long-term pasture' does not appear to be defined by Sparling and Schipper (2002); rather, there is reference to combining sites on pastoral land use for dairy, sheep & beef, and deer production, as aerial photography was unable to distinguish between those land uses.

No upper limits were determined, but desirable lower ranges were identified. These values were not changed at the 2011 workshop, although there was discussion that the lower target may not apply for some land uses and could be raised for some soil orders (Mackay et al. 2013). The target range values for total C derived for different soil orders are presented in Table 7.

Table 7. Total carbon target ranges (% w/w). Bold values indicate target values.

Soil type	Very depleted	Depleted	Normal	Ample	
Allophanic	0.5	**3**	4	9	12
Semi-arid, Pallic, & Recent	0	**2**	3	5	12
Organic			excluded		
All other soil orders	0.5	**2.5**	3.5	7	12

Source: LMF 2009.

4.2.4 Total nitrogen

Response curves for total N developed during the workshops showed two distinct patterns, with production curves following a 'more is better' pattern while environmental ones followed a 'less is better' pattern (Sparling et al. 2008). Curves were produced only for pasture and forestry because there were insufficient data for cropping and horticulture. As for total C, it was suggested that the thresholds for total N be obtained from interquartile ranges of long-term pasture sites, grouped by soil order, using data from the NSD and the 500 Soils project (Sparling et al. 2003). Five references were listed as sources of information (see Appendix 2).

Total N targets were not changed at the 2011 workshop. There were few other details or reference sources provided (e.g. in Taylor & Mackay 2011), but they reported there was some doubt about the usefulness of total N as an indicator of N loss. Target value ranges for total N derived for pasture, forestry, cropping, and horticulture are presented in Table 8.

Table 8. Total nitrogen target ranges (% w/w). Bold values indicate target values.

Land use	Very depleted	Depleted	Normal	Ample	High	
Pasture	0	**0.25**	0.35	0.65	**0.70**	1.0
Forestry	0	**0.10**	0.20	0.60	**0.70**	
Cropping and horticulture			excluded			

Source: LMF 2009.

4.2.5 Anaerobically mineralisable nitrogen

Separate response curves were constructed for environmental and production targets, and for pasture, forestry and horticulture (Sparling et al. 2008). As for total C, the thresholds for anaerobically mineralisable nitrogen (AMN) were indicated to be obtained from interquartile ranges of long-term pasture sites, grouped by soil order, using data from the NSD and the 500 Soils project (Sparling et al. 2008). Seven references were identified as sources of information (Appendix 2).

At the 2011 workshop it was recommended that the lower AMN targets stay the same but the upper target be removed because it was not considered to be a good indicator of environmental risk (essentially leaching) (Taylor & Mackay 2011; Mackay et al. 2013). These reports indicated that LMF agreed that the upper AMN targets should be removed, and the LMF manual should be updated. There were few other details or reference sources provided (e.g. in Taylor & Mackay 2011). Table 9 presents target values for AMN after the removal of the upper target.

Table 9. AMN target ranges (mg/kg). Bold values indicate target values.

Land use		Very low	Low	Adequate	Ample	High	Excessive
Pasture	25	**50**	100	200	200	250	300
Forestry	5	**20**	40	120	150	175	200
Cropping and horticulture	5	**20**	100	150	150	200	225

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

4.2.6 pH in water

Separate curves were developed for mineral and organic soils, with different curves for pasture, for crop and horticulture, for forestry, and for indigenous vegetation (Sparling et al. 2008). The response curves for production showed a marked 'optimum range', but less so for environment (Sparling et al. 2008). Five sources of information were identified by Sparling et al. (2008) (Appendix 2).

The briefing paper sent to participants of the 2011 workshop in advance (Mackay et al. 2013, section 7.4) presented a table of optimal pH ranges for selected crops and recommended a target pH range for forestry on Organic soils (3.5–7.6). However, at the 2011 workshop the values were considered acceptable as they were, and the recommendation for forestry on Organic soils was not adopted (Table 10) (Taylor & Mackay 2011; Mackay et al. 2013).

There were few other details provided in Taylor & Mackay 2011, although the briefing paper contained in the appendix of Mackay et al. (2013) noted that the target ranges were based on both expert opinion estimates and measured production responses. Several sources of information for optimal pH ranges for production were identified in section 7.4 of Mackay et al. (2013) (see Appendix 2).

Table 10. Soil pH target ranges. Bold values indicate target values.

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.

4.2.7 Olsen P

Sparling et al. (2008) reported that separate curves were required for Allophanic, Pumice, and Organic soils, corresponding to the Volcanic, Pumice, and Peat soil categories used by the fertiliser industry and related research. The other soil orders were combined. Sparling et al. (2008) reported that the upper limit for all land uses and soil categories was 100 µg P/cm^3, and they identified six sources of information (see Appendix 2).

At the May 2011 workshop it was proposed that the Olsen P target values be changed so that the upper values were similar to agricultural and fertiliser industry values. A record of the May 2011 workshop discussions (section 3.4 in Mackay et al. 2013) suggests the values shown in Table 11 were the agreed values. These values are based on providing for 97% of maximum production but more environmental protection than the limits provided in Sparling et al. 2008 and Hill & Sparling 2009.

Table 11. Suggested Olsen P target ranges (mg/kg) from Mackay et al. (2013). Units not specified but assumed to be mg/kg.

Land use	Soil type	Suggested Olsen P targets	
		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*	5	5
Pasture; horticulture and cropping	Raw sands and Podzols with medium and above AEC*	15	25
Pasture; horticulture and cropping	Other soils	20	45
Pasture; horticulture and cropping	Hill country	15	20
Forestry	All soils	5	30

* AEC = anion exchange capacity.

At the September 2011 LMF meeting it was agreed to reduce Olsen P values, but it was noted that the targets were still based on productivity rather than environmental impacts, and that further work (such as specific soils, e.g. raw sands) might be required (Taylor & Mackay 2011; Mackay et al. 2013).

Additional suggested target values were also presented in the briefing paper for the May 2011 meeting (section 7.4 of Mackay et al. 2013) but were not selected for use. This briefing paper did contain other additional sources of information on optimal Olsen P ranges for production, some of which are summarised in Table 12, with associated references in Appendix 2.

Table 12. Suggested Olsen P target values from various sources referenced in Mackay et al. 2013, section 7.4

Target relevance	Land use or site characteristics	Suggested Olsen P concentration	Reference
Near maximum pasture production	0–20° and 30–40° slopes in Waikato hill pasture	10 µg P/ml (summer-dry steep slopes)	Gillingham et al. 1984
Maximum pasture production	0–20° and 30–40° slopes in Waikato hill pasture	15 µg P/ml (gentle slopes)	Gillingham et al. 1984
97% maximum pasture production	All soil groups	12–50 mg/kg, depending on soil type	Edmeades et al. 2006
Near maximum pasture production	Sheep & beef pastures located on the east coast of both Islands	<20 µg P/ml	Gillingham et al. 2007
Relative production	Forestry	25 mg/kg	Watt et al. 2008
97% maximum pasture production	Sedimentary soil	20 µg P/ml	Roberts & Morton 2009
97% maximum pasture production	Volcanic ash soil	22 µg P/ml	Roberts & Morton 2009

The notes from the September 2011 meeting also flag an issue associated with the difference in extraction methods and reporting of Olsen P between commercial laboratories and research (CRI) laboratories (Mackay et al. 2013). Specifically, commercial laboratories extract and report Olsen P on a volumetric (volume) basis while CRI laboratories extract and report on a gravimetric (weight) basis. This issue has been extensively explored in Drewry et al. 2013, 2015, and Taylor et al. 2016, 2018, with a robust statistical analysis using historical soil quality monitoring data reported in Drewry, Cavanagh et al. 2021.

Drewry, Cavanagh et al. (2021) concluded that there is a significant difference in Olsen P concentrations determined by volumetric and gravimetric methods, and that the relationships vary with soil order. They provided several recommendations for regional and national reporting. Given that for regional and national reporting the gravimetric method is currently the cited method, a key recommendation was to ensure that when volumetric analyses are requested, the volume-weight (the mass of a known volume of dried-ground soil, which is measured in laboratories that report results on a volumetric basis but may not be provided to clients) is also requested. (Note that volume-weight is not soil bulk density.)

To assist with the conversion of historical data where volume-weight may not be available, Drewry, Cavanagh et al. (2021) provide detailed look-up tables (two Excel sheets) of comparative values for converting between gravimetric and volumetric Olsen P in the supplementary material. The soil orders Allophanic, Brown, Recent, Gley, Ultic, Granular, Pumice, Pallic, Organic, Raw, Podzol, and Melanic were included in the spreadsheet. The spreadsheet provides conversion for gravimetric (volumetric) Olsen P concentrations from 1 mg/kg (1 mg/L) to the corresponding volumetric (gravimetric) concentration, for the soil orders, in steps of 1 unit up to the maximum for the data.

The study also examined conversion using bulk density and 'volume weight', and concluded that bulk density values were generally significantly different from, and greater than, volume weight. Conversion using bulk density was originally suggested in the September 2011 LMF meeting and probably relates to earlier reporting of Olsen P by volumetric 'stocks' (e.g. Sparling et al. 2004). However, Drewry, Cavanagh et al. (2021) reported that bulk density conversion introduced greater variability in reporting, as changes over time in both Olsen P concentration and bulk density can occur.

5 Additional indicators and soil quality programmes

In addition to the seven main indicators, some other indicators have been commonly used and/or specified in the National Environmental Monitoring Standard for Soil Quality and Trace Element Monitoring (NEMS-SQ) (2022). This section provides an overview of these additional indicators, including discussion of the basis of any target value, if used. A brief discussion on some other selected monitoring programmes that provide a long history of monitoring is also provided to indicate either the data available, or the use of additional indicators and/or identification of target values.

5.1 Additional indicators

5.1.1 Aggregate stability

Aggregate stability is required in the NEMS-SQ (2022) framework for regional soil quality monitoring, in addition to the seven indicators specified by the LMF for land uses involving soil disturbance. Aggregate stability was also considered in the workshop held in 2000, with response curves constructed for cropping and horticulture on Recent soils (Sparling & Tarbotton 2000). These curves followed the 'more is better' approach. The indicator was considered to be applicable to all soils, but there was insufficient knowledge and confidence to construct response curves for other land uses and soil orders. Sparling and Tarbotton (2000) noted that for Recent soils, aggregate stability >2 mm mean weight diameter (MWD) was optimal for production and environmental criteria, but insufficient aggregate stability was more detrimental to environmental quality rather than to production. Values <1.5 mm MWD were noted as cause for concern.

In the 2011 workshop (Taylor & Mackay 2011; Mackay et al. 2013), limited information on target values was again noted and a need identified to establish critical limits for other soils, particularly sandy soils. Beare et al. (2005) was cited in section 7.4 of Mackay et al. (2013) as a source of information for aggregate stability targets, showing that at <1.5 mm MWD production decreases. However, Beare et al. (2005) cite Beare et al. (2004) as the source of this information, and this reference is inaccessible. Other sources of information on potential aggregate stability target values are listed in Appendix 2.

Aggregate stability is analysed by all councils that undertake soil quality monitoring (except one), and is often only measured for cropping/horticultural soils (Cavanagh et al. 2017). All councils use a 'more is better' approach (Table 13). Different sources for the target values cited in council reports are listed in Appendix 2 (including those identified in Table 13).

An alternative measure of aggregate stability, expressed as a percentage of total soil aggregates that are less vulnerable to erosion based on average aggregate size distribution (e.g. Beare & Tregurtha 2004), was also discussed at the 2011 workshop, with the proportion of soil <0.85 mm considered to be a better assessment of erosion risk than aggregate stability in mm MWD (Mackay et al. 2013). The LMF, however, concluded that these were two separate indicators, neither of which would become part of the core soil quality indicator suite, but both are useful 'environmental indicators' that could later be developed for regional council use (Taylor & Mackay 2011). The average size distribution measurement has since been used in some regional council monitoring, in different forms (Table 13). Only aggregate stability expressed as mm MWD is required under the NEMS-SQ (2022).

Table 13. Details of aggregate stability measured by regional councils in New Zealand

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

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

5.1.2 Trace elements

A suite of trace elements – arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), fluoride (F), lead (Pb), nickel (Ni), zinc (Zn) – are also required to be monitored under the NEMS-SQ. The development of soil guideline values to protect ecological receptors (Eco-SGVs) for these trace elements, except Ni, is outlined in Cavanagh & Munir 2019, and a brief description is provided below. No Eco-SGVs for Ni have been derived in a New Zealand context, although Canadian authorities have derived an environmental guideline value for Ni (CCME 2015).

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

The ACLs are developed through a process of:

- collating, screening and standardising toxicity data to an EC30 toxicological endpoint[2]
- incorporating ageing or leaching factors, and normalising to three New Zealand reference soils (copper and zinc only)
- using the BurrliOZ programme[3] to derive ACLs from species sensitivity distribution using the collated toxicity data (the BurrliOZ programme allows for the selection of different levels of protection of species).

The ACLs were then added to median background concentrations determined by Cavanagh et al. (2015) to develop Eco-SGVs provided in Cavanagh & Munir 2019 and Cavanagh & Harmsworth 2022. The latter authors outlined the use of Eco-SGVs for the protection of soil quality and the management of contaminated land, with Eco-SGVs based on protection of 95% of species proposed for use in SOE soil quality monitoring programmes.

National background concentrations of trace elements have recently been updated) and used to update the Eco-SGVs (Cavanagh et al. 2023 while the implementation of Eco-SGVs under different policy and regulatory settings was evaluated in an Envirolink Tools project (Cavanagh and Harmsworth 2023).

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[2] EC30 = effective concentration at which there is a 30% decrease in the endpoint being assessed.

[3] https://research.csiro.au/software/burrlioz/

5.1.3 Hot water carbon

Hot water carbon (HWC) was discussed at the 2011 workshop (Taylor & Mackay 2011; Mackay et al. 2013) as a potential soil quality indicator to measure soil biological activity and, potentially, to replace AMN. Research was presented at the workshop on the potential use of HWC as a soil quality indicator, and potential targets for certain soil types and land uses, but further work was required to develop these for all soils and land uses.

In the years following the 2011 workshop a number of regional councils, including Marlborough District Council, Greater Wellington Regional Council, and Environment Canterbury, incorporated HWC into their monitoring programmes. Several sources have been used for target values, including Taylor et al. 2017, 2022 (Appendix 2).

A provisional target of 1,800 mg/kg was developed by Taylor et al. (2017) and represented the value below which soil degradation was observed, from four regions of New Zealand trialling this soil quality indicator (Taylor et al. 2022).

In 2022 two new targets were proposed by Taylor et al. (2022). A target of >1,700 mg/kg, termed a 'background low target', was 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 HWC data against VSA scores for the same soils and taking the HWC 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 HWC targets (>1,700, >1,800 and >2,000 mg/kg) identified degraded soils and were acceptable targets for soil quality monitoring.

5.1.4 C:N ratio

The C:N ratio has been used by some regional councils to help interpret soil quality data, although target values are not always used. C:N ratios were considered in the original workshops held in 2000, with separate curves constructed for pasture, cropping/horticulture, and forestry production on all soil orders, and a single curve constructed for environmental outcomes for all land uses and soil orders (Sparling & Tarbotton 2000; Sparling et al. 2008). All curves followed an optimal range pattern, with the optimal ranges for pasture, cropping/horticulture, and forestry determined to be 8–12, 8–20, and <15, respectively. The optimal range for environmental quality was 7–30. Upper and lower 'cut-off limits' of 5 and 40, respectively, for C:N ratio were noted for production factors, and a lower 'cut-off limit' of 5 for environmental quality. It is not clear if these 'cut-off limits' represent the absolute limits of the target value, or whether this represents the range of values possible in soil.

Multiple sources of information and values for optimal C:N ratios for environmental quality were presented in section 7.4 of Mackay et al. 2013 and are listed in Appendix 2.

C:N ratio was discussed at the 2011 LMF workshop in the context of interpreting total N and AMN data, although it was noted that a lower limit for C:N ratio was unclear (Taylor & Mackay 2011; Mackay et al. 2013).

Additional information on target values for C:N ratios is available in SINDI (Soil INDIcators) (https://sindi.landcareresearch.co.nz/Content/HelpTotalN.html, discussed further in section 5.3.2), as it relates to the interpretation of total N in soils (Table 14). These data appear to be from the 500 Soils data set, as ranges are described as 'typical of soils in the 500 Soils data set' or 'at the higher range of soils in the 500 Soils data set', etc.

Table 14. C:N ratio target values from SINDI

Land use	Interpretation	C:N ratio range
Pasture and horticulture	High N	≤10
	Ample N	10–12
	Adequate N	12–14
	Low N	15–25
	Very low N	>20
Plantation forestry and indigenous ecosystems	High N	≤12
	Ample N	10–15
	Adequate N	15–17
	Low N	(not specified)
	Very low N	>25

As noted above, C:N ratio has been used by some regional councils to help interpret soil quality data. For example, Environment Canterbury has used the value ranges from SINDI, reporting sites as meeting the soil quality indicator target if they fall within the adequate or ample ranges, and either high or low if they fall above or below these ranges, respectively (Thompson-Morrison 2023). Some other councils (e.g. Taranaki Regional Council, Stevenson & Laubscher 2018) report C:N ratios but do not compare them to target values.

5.1.5 Earthworms

The responses of exotic earthworms were considered in the 2000 workshop, and response curves were constructed for optimal earthworm numbers (#/m^2) in soils under pasture and horticulture, with separate curves constructed for production and environmental outcomes. Production curves followed the 'more is better' pattern, while environmental curves had an optimal range. Organic soils were considered to be a separate category. Insufficient data about earthworm numbers under plantation forestry and indigenous vegetation was noted as the reason they were not selected as a soil quality indicator.

Subsequently, earthworm abundance and diversity as soil quality indicators were discussed at the 2011 LMF workshop, where a briefing paper was presented (section 7.5 of Mackay et al. 2013). The briefing paper presented provisional thresholds for earthworm functional group numbers and a field identification and sampling protocol for earthworms, with several listed sources of information (Appendix 2).

Earthworms were not incorporated into the core soil quality indicators due to potential difficulties associated with deriving an indicator and the 'variable nature of earthworms'.

A 2020 report (Schon & Roberts 2020, discussed in section 0) used earthworm abundance and diversity as indicators of soil health under pasture and forestry land uses. In 2022 an update to the proposed use of earthworms as soil quality indicators was published in Schon et al. 2022 (Appendix 2). The updated proposed indicator values are detailed in Table 15. Both abundance and diversity are considered as part of the proposed indicator, and diversity is achieved by having the target number of each of all three earthworm functional groups (epigeic, endogeic and anecic).

Nonetheless, Schon et al. (2022) note that exotic earthworm absence from some soils may be a result of previous land use (e.g. pine forest), or may reflect the accidental nature of the arrival of exotics into New Zealand. They further note that large areas of agricultural soils have limited ecological diversity of exotic earthworms, and provide the example that North Island hill country and much of the South Island contain only two ecological groups of earthworms.

Table 15. Proposed earthworm abundance and diversity targets

Indicator	Target value (#/m^2)
Earthworm abundance	>400
Epigeic earthworms	>25
Endogeic earthworms	>25
Anecic earthworms	>25

Source: Schon et al. 2022

5.2 Additional monitoring programmes

Some additional monitoring programmes are mentioned here to provide further insight into data availability and indicators selected.

5.2.1 Environment Canterbury's Arable and Pastoral Soil Quality Monitoring Programme

In addition to the continuation of the 500 Soils soil quality monitoring programme, Environment Canterbury runs an Arable and Pastoral Soil Quality Monitoring Programme (APSQMP), targeting productive soils of the Canterbury plains and downs. The APSQMP has run since 1999, although the sampling strategy employed was adjusted in 2002 to conform with the Land Management Index (LMI) project (Lawrence-Smith et al. 2014). The LMI is a model developed by Crop & Food Research (now Plant & Food Research) to predict changes in soil quality and associated productivity on cropping farms, based on crop and soil management information (Beare et al. 2005). The APSQMP has therefore measured the indicators required by the LMI, which include the seven LMF indicators as well as aggregate stability, total porosity (although this has not been compared against target ranges), aggregate size distribution (to report potentially erodible aggregates), penetration resistance, and HWC (Lawrence-Smith et al. 2014).

The target values used for aggregate stability and potentially erodible aggregates were sourced from New Zealand studies, while the target value used to assess penetration resistance was determined by the authors for the purposes of the monitoring programme (Lawrence-Smith et al. 2014; Table 16). The cited sources of information are listed in Appendix 2.

Table 16. Additional soil quality indicators measured in Environment Canterbury's APSQMP, with relevant source references for target values

Indicator	Target value	Relevant references
Aggregate stability	>1.5 mm MWD (0–15 cm)	Beare et al. 2003; Beare & Tregurtha 2004
Potentially erodible aggregates (soil aggregates <0.85 mm in diameter)	<40% (0–10 cm)	Eastwood 2001; Leys et al 1996
Penetration resistance	<2.5 MPa (soil moisture standardised to 35% w/w) (0–15 cm)	da Silva et al.1994 (proposed <2 MPa for soils at field capacity)
HWC	None used	—

Source: Lawrence-Smith et al. 2014

5.2.2 Ngāi Tahu soil health report

An assessment of the health of soils under forestry and pasture, and land transitioning from forestry to pasture, was commissioned by Ngāi Tahu in 2019 (Schon & Roberts 2020). As well as the seven LMF indicators, available potassium, C:N ratio, HWC, available water capacity, microbial respiration, earthworm abundance and earthworm diversity were used as soil health indicators (Table 17). Available potassium was measured as QT (quick test) potassium, while earthworm diversity was determined using the abundance of each of the three classes of earthworms that perform different functional roles in the soil (epigeic, endogeic, and anecic earthworms).

Table 17. Additional soil quality indicators measured in the Ngāi Tahu soil health report

Indicator	Target		Relevant references
	Optimal range	High-producing pasture	
QT potassium	7–10	—	Roberts & Morton 2016
C:N ratio	8–12	9–11	Roberts, pers. comm. **
HWC (mg/kg)	>1,400	—	Drewry et al. 2017
Available water capacity (mm/100 mm)	>6	>20	Roberts, pers. comm. **
Microbial respiration (µg/g/h CO2-C)	1.25–5	—	Doran et al. 1997
Earthworm abundance (#/m^2)	>400	—	van Groenigen et al. 2014
Epigeic earthworms (#/m^2)	>25	—	—
Endogeic earthworms (#/m^2)	>350 *	—	—
Anecic earthworms (#/m^2)	>25	—	—

* Updated in Schon et al. 2022 to >25/m^2

** No other identifying information was provided in this report on these personal communications

The report listed several sources of information for the target values used (Appendix 2), but it was not clear which reference was used for which indicator, other than those identified in Table 17.

5.3 Additional 'target value' assessments

5.3.1 Soil quality indicator 'ratings'

'Rating' criteria for soil chemical and physical parameters were included as an appendix in Hewitt et al. 2021. The chemical criteria are based on Blakemore et al. 1987, and are similar to LMF 2009, which defines qualitative descriptions of soil indicator data based on quantitative ranges for each indicator (e.g. very high, high, medium). However, distinctions were not made for soil type or land-use activities. The chemical ratings were intended to be a guide to the interpretation of chemical analyses on 'type' samples collected during soil survey work in New Zealand by the New Zealand Soil Bureau. Metson (1956) is cited as the source for some of the ratings – although it is not specified which ones.

The chemical ratings were developed to indicate the range of values encountered in New Zealand soils for the chemical analyses specified in Blakemore 1987. It is suggested that the data set should not be biased towards sampling in an agricultural context, and Blakemore notes that while some deficiency levels have been taken into account, the ratings shouldn't be used to provide fertiliser recommendations. Blakemore also notes that while the ratings were derived for topsoils, they were being (sometimes inappropriately) applied to subsoils.

Ratings are provided for some of the key soil quality indicators, notably pH, total C, N, and Olsen P, as well as other chemical parameters including P-retention, cation-exchange capacity, oxalate-extractable aluminium, and iron.

The ratings for soil physical properties from the appendix of Hewitt et al. 2021 included potential rooting depth, dry bulk density, total porosity, macroporosity, penetration resistance, degree of packing, permeability, profile readily available water (over a potential rooting depth or 1.5 m depth), and soil depth. Several sources were cited, though not for every parameter: potential rooting depth and profile readily available water were from Wilson & Giltrap 1984; penetration resistance was adapted from Griffiths (1984); degree of packing was specified as determined using a Singleton blade and 6 mm tip penetrometer after Griffiths (1984); and permeability was adapted from S-map ratings (Appendix 2).

5.3.2 SINDI

Soil INDIcators (SINDI)[4] is an online tool developed by Manaaki Whenua – Landcare Research to assist in the interpretation of soil quality data. SINDI was developed in the early 2000s as a means to compare soil quality indicator data for the seven core LMF indicators, with target ranges based on Sparling et al. 2008. Land use- and soil-order-specific interpretations are given. Data can also be compared with the distribution of data present in the Soil Quality Database or the NSD held by Manaaki Whenua – Landcare Research. Also, information sheets containing the response curve, how the indicator is measured, how to improve the status of the indicator, and associated references are provided for each of the seven soil quality indicators.

Both Hawke's Bay Regional Council and Environment Southland indicated that they use SINDI to interpret their soil quality monitoring data for all indicators in Cavanagh et al. 2017. The information sheet on total N has also been used by Environment Canterbury to interpret C:N ratio data, and at a recent workshop other councils also indicated they referred to SINDI for some data interpretation.

Some recent statistics were obtained for the use of the SINDI website, demonstrating use of the SINDI tool. For example, for 1 January 2022 to 31 December 2022 there were 2,295 page views, with 573 page views of the calculator page, and users spent about 2 minutes with the calculator tool.

Stevenson and Drewry (2022) noted suggestions from the LMF regarding SINDI, which included communicating SINDI more and possibly refurbishing the website, adding interpretative information, or automating updates, including adding new soil quality data collected for S-map, etc. SINDI is built on a very old web platform and has not been updated to include results from soil quality sampling since 2014, so any revamping or updating would require significant redevelopment.

The Australian soil quality website https://www.soilquality.org.au/ provides an example of the display of information from soil quality monitoring sites (Figure 6), as well as information to assist in the interpretation of results and to improve soil quality (Figure 7).

[4] https://sindi.landcareresearch.co.nz/

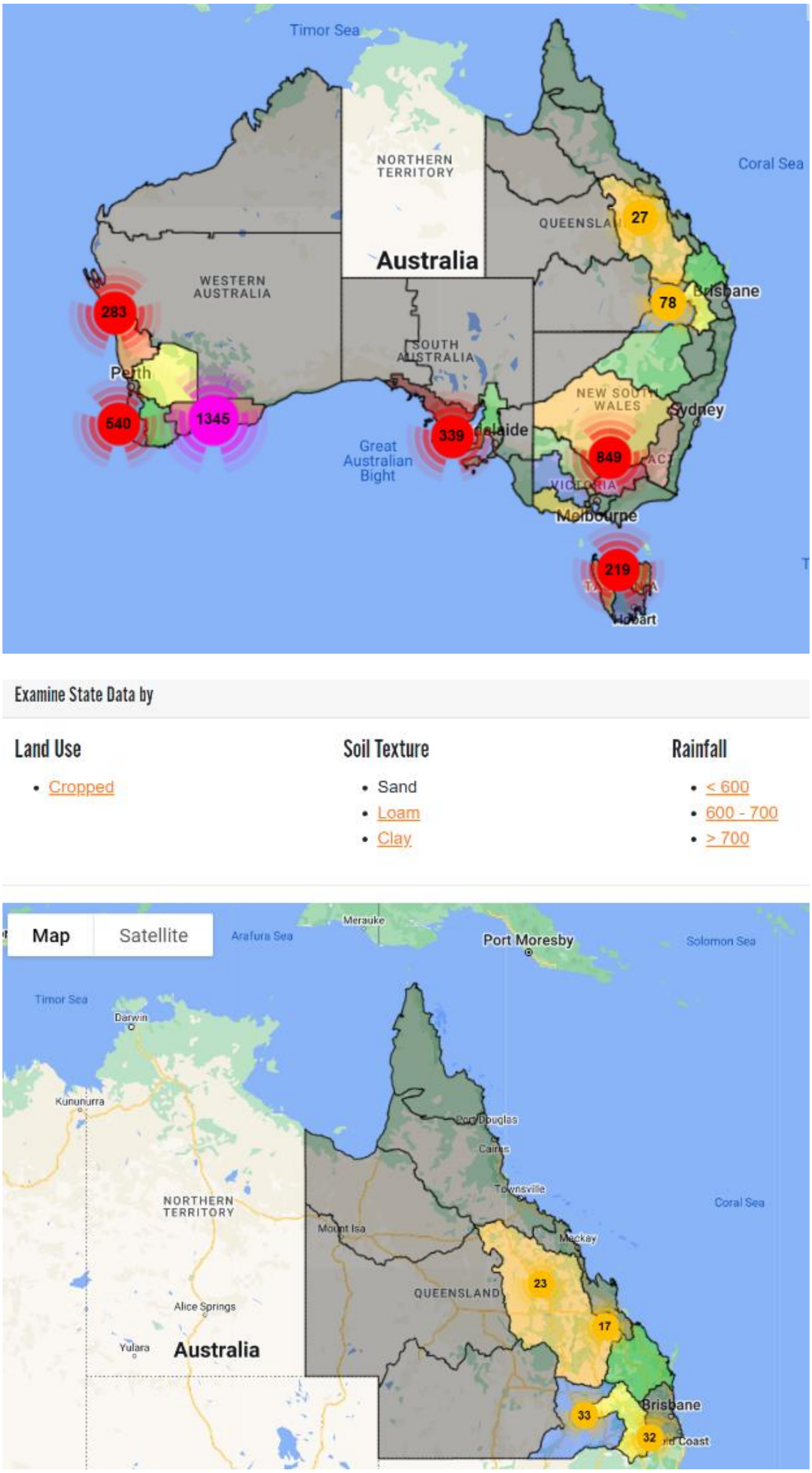

Figure 6. Display of the location of soil quality monitoring sites across Australia, and within Queensland. (Source: https://www.soilquality.org.au/)

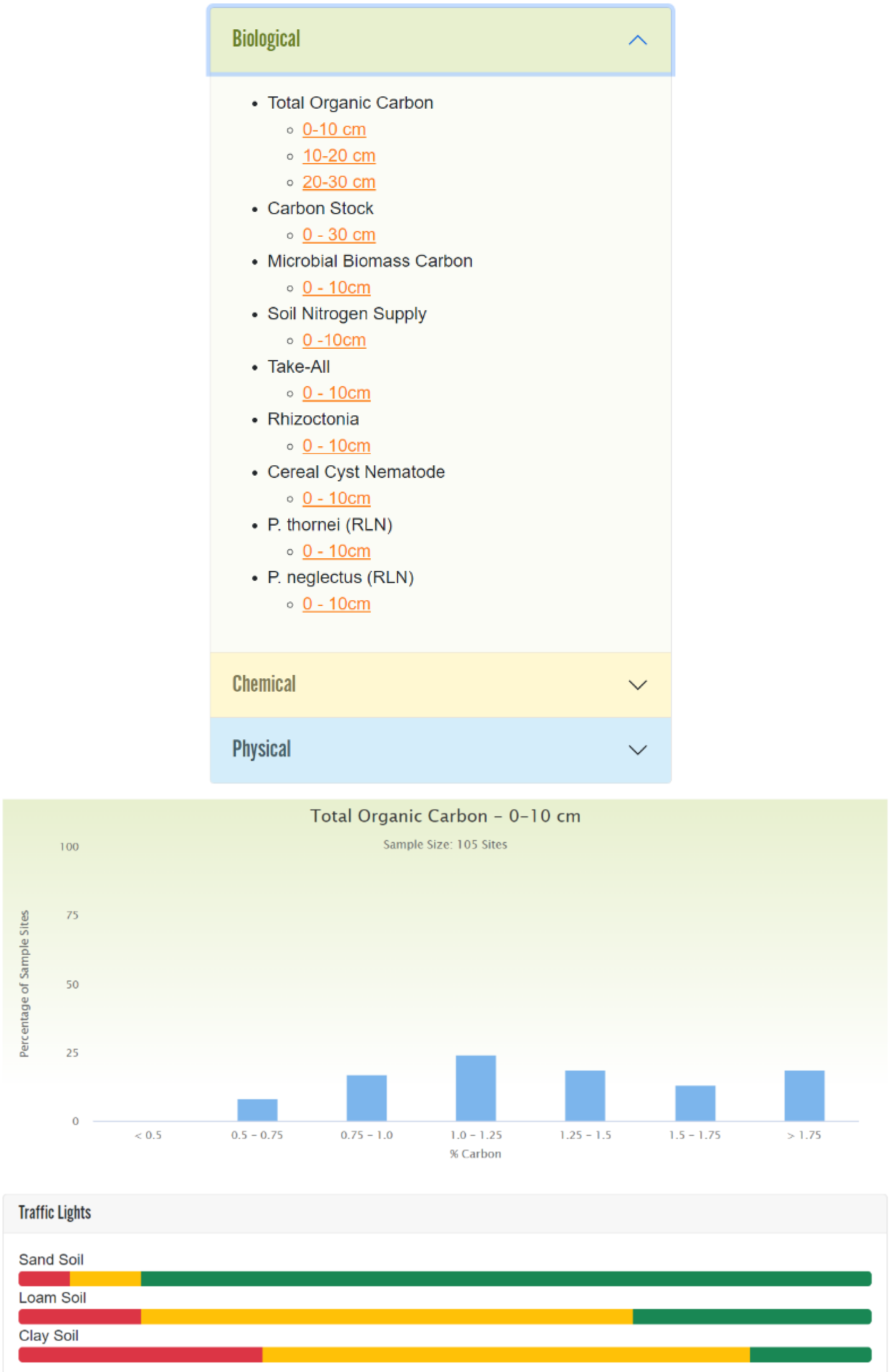

Figure 7. Example of indicators for which results are available (top), and the display of results (bottom).

6 Purpose of target values in the context of SOE, current legislation, and international approaches to soil quality monitoring

6.1 State of the environment reporting

The Resource Management Act 1991 (RMA) provides the current driver for soil quality monitoring. Specifically, section 30 empowers regional councils to control land for the purposes of soil conservation. In this context, soil conservation includes both soil health and soil intactness (erosion). Section 35 also requires local authorities to collect information about the state of the environment. In addition, the Environmental Reporting Act 2015 requires regular reporting on the land domain, which comprises soil and underlying rock, animals, plants, and structures associated with the land. However, no specific objectives for the purpose of that reporting are given.

The LMF (Hill & Sparling 2009) considered the primary regional objectives for soil quality monitoring to be to:

- provide an early-warning system to identify the negative effects of primary land uses on long-term soil productivity (physical, chemical, biological)
- track specific, identified issues relating to the effects of land use on long-term soil productivity (which may also be district- or area-specific)
- utilise these results for SOE reporting and policy development
- integrate with other regional monitoring (e.g. water, especially groundwater).

A similar set of objectives has been included in the NEMS-SQ as potential regional programme objectives, including to:

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

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

- structural decline
- nutrient depletion
- organic matter depletion
- nutrient saturation / excess, biological activity

- soil acidification (Sparling et al. 2001).

Land-use priorities were structural decline, nutrient saturation, and biological activity, particularly under dairy, intensive beef rearing, horticulture, forestry, and deer farming, while nutrient depletion and acidification were potential concerns under forestry (Sparling et al. 2001). It is interesting to note that lacking from both the LMF and NEMS-SQ objectives is a clear statement on what actions (e.g. policy response, land management response) are intended to be taken if soil quality is observed to deteriorate. It is further noted that organic matter depletion (i.e. low soil C), nutrient excess (Olsen P), and structural decline (reduced macroporosity) are key issues still reported on today, with low macroporosity being dominant (MfE 2022).

6.2 Legislative setting

6.2.1 Current setting

As noted above, section 30 of the RMA empowers regional councils to control land for the purposes of soil conservation. Section 35 outlines the responsibility of local authorities to collect information about the state of the environment. The Environmental Reporting Act 2015 requires regular reporting on the land domain, which comprises soil and underlying rock, animals, plants, and structures associated with the land. However, no specific objectives for the purpose of that reporting are given.

6.2.2 Natural and Built Environment Bill

The Natural and Built Environment (NBE) Bill is one of three key pieces of legislation that make up current resource management reform. Under this reform, and in particular the Natural and Built Environment Act, environmental limits and targets are a primary means to prevent further environmental degradation and drive environmental improvements. Limits and targets will be set across six mandatory matters: air, soil, indigenous biodiversity, freshwater, estuaries, and coastal waters, and they may also be set for other matters. The purpose of environmental limits is to protect human health and prevent the ecological integrity of the natural environment degrading from its current state.

The purpose of the Act is to:

a *enable the use, development, and protection of the environment in a way that—*

- *i* *supports the well-being of present generations without compromising the well-being of future generations; and*
- *ii* *promotes outcomes for the benefit of the environment; and*
- *iii* *complies with environmental limits and their associated targets; and*
- *iv* *manages adverse effects; and*

b *recognise and uphold te Oranga o te Taiao.*

To assist with achieving the purpose of the Act, the National Planning Framework and all plans must provide for various system outcomes (s.5), with the following most relevant in the context of the management of soils:

a) the protection or, if degraded, restoration, of—

i the ecological integrity, mana, and mauri of .....soils....

c) well-functioning urban and rural areas that are responsive to the diverse and changing needs of people and communities in a way that promotes—

ii the use and development of land for a variety of activities, including for housing, business use, and primary production; and ....

d) [the availability of highly productive land for land-based primary production...]

It is noted for [d] above that there is no specification regarding the quality of this highly productive land (which is based on an assessment of land-use capability and is independent of the current quality of that land).

Ecological integrity is defined in the Bill as the:

.... ability of the natural environment to support and maintain the following:

- *representation: the occurrence and extent of ecosystems and indigenous species and their habitats; and*
- *composition: the natural diversity and abundance of indigenous species, habitats, and communities; and*
- *structure: the biotic and abiotic physical features of ecosystems; and*
- *functions: the ecological and physical functions and processes of ecosystems.*

The purpose of setting environmental limits is to prevent the ecological integrity of the natural environment from degrading *from the state it was in* at the commencement of the relevant part of the Act, or to protect human health. However, minimum-level targets may be set if the associated environmental limit is set at a level that represents unacceptable degradation of the natural environment (s.50).

Environmental limits may be set in relation to the ecological integrity of the natural environment or to human health, and must be set as a minimum biophysical state, or the maximum amount of harm or stress to the natural environment that may be permitted in a management unit. They may be qualitative or quantitative, and set at different levels for different management units – although management units are currently not defined. Environmental limits must also be set in a way that integrates more than one of the aspects of the natural environment (air, indigenous biodiversity, coastal waters, estuaries, freshwater, soil).

The purpose of setting targets is to assist in improving the state of the natural and built environment. There is greater flexibility in what a target may look like with it being specified that a target —

c is able to be measured; and

d must be achieved by a specified time; and

e is designed to assist in achieving—

i a system outcome; or

ii a framework outcome; or

iii in relation to a target set in a plan, a plan outcome specified in the plan.

Further, a target may be expressed as a series of steps, each with a time limit, designed to achieve progressive improvement over time. *Mandatory* targets 'must … be set for each aspect of the environment for which a limit is set … and at a level equal to or better than that of the associated environmental limit'; *discretionary* targets may be set for other matters if they are relevant for achieving a system outcome, a framework outcome, or a plan outcome.

Considerations in the implementation of the NBE

The introduction of the NBE Bill provides a different perspective on the selection and use of soil quality indicators and target ranges or values. In particular, the framing of ecological integrity (a nature-centric perspective) contrasts with previous considerations of soil and soil quality in the context of ecosystem services (a human-centric view; e.g. Mackay et al. 2013; Dominati et al. 2010; Dominati 2013), or, internationally, a focus on soil function (e.g. Büneman et al. 2018; Creamer et al. 2022).

Ecological integrity appears to place an emphasis on attributes of soil that tend towards a return to a system undisturbed by human activity as being the desired outcome to effect protecting or restoring the ecological integrity of soil. However, this is not easily reconciled with our high dependence on our use of soil (e.g. food production, platform for building) and the different system outcomes specified in the NBE Bill of

- protecting or, if degraded, restoring, of the ecological integrity, mana, and mauri of soils

with

- having well-functioning urban and rural areas that are responsive to the diverse and changing needs of people and communities in a way that promotes the use and development of land for a variety of activities, including for housing, business use, and primary production.

Not all of these uses are conducive to restoring or even protecting the ecological integrity of the soil.

A further system outcome specified in the NBE is the availability of highly productive land; the productiveness of this land is integrally related to the health of the associated soils.

6.3 Frameworks and indicators

While consideration of frameworks for indicators was largely beyond the scope of the current project, it became evident during preparation for the council workshop that it was useful to provide some contrasting examples of the use of indicators to help test thinking about the purpose of indicators and target values, and indeed, whether the current indicators are the 'right' indicators, given legislative change.

Stevenson and Drewry (2022) and Stevenson (2022) have previously provided an overview and consideration of some alternative frameworks within which to consider soil quality indicators, including a framework developed for New Zealand incorporating mātauranga Māori (Figure 8). Further publications by Harmsworth (2022a, b) provide some basis for recognising and upholding Te Oranga o te Taiao for soil (as required under the NBE).

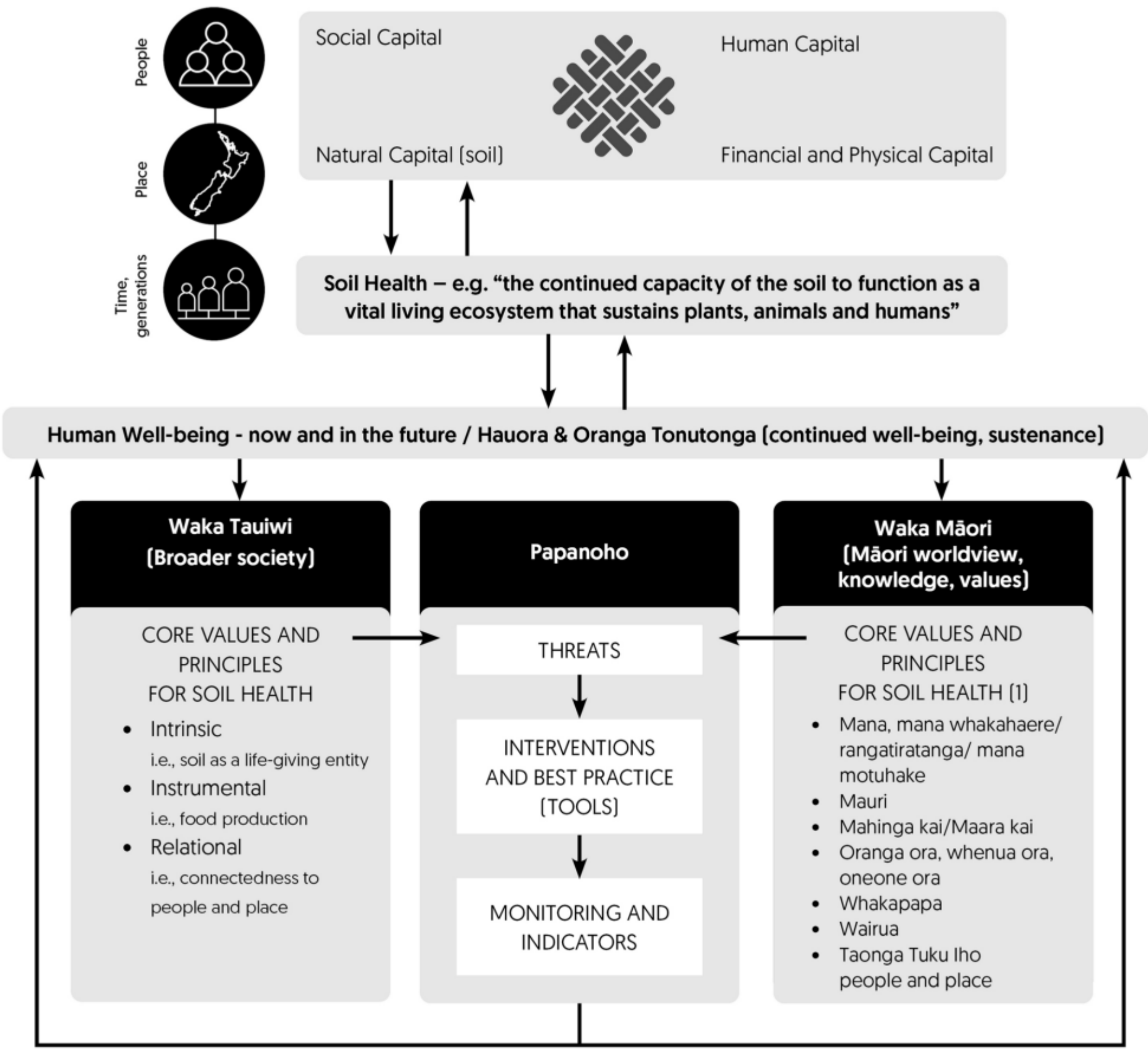

Figure 8. Soil health and well-being framework. (Source: Stronge et al. 2023)

Internationally, the targets, objectives and indicators promoted for the European Soil Health and Food Mission (Table 18) provide a useful example of targets and indicators that could be useful in the context of the NBE. The EU soil observatory provides another example of the use of indicators, this time to assess the status of soil degradation across the EU (Figure 9).[5] The website provides further details on the individual indicators, and the source of threshold values used to indicate degradation.

Table 18. The objectives, targets, and indicators for the Soil Health and Food Mission*

Mission Goal: 75% of all soils healthy by 2030 as indicated by no decline in any of 6 soil health indicators according to benchmarks for healthy soils for each local context			
Specific Targets and Indicators			
Objectives	**Land Management Targets**	**Soil Health Targets**	**Six Soil Health Indicators**
Land degradation and desertification	*50% degraded land restored*	*Strong reduction in degradation and desertification*	*All 6 soil health indicators*
Soil organic carbon	*Conservation of high carbon soils and a reverse of carbon loss in croplands.*	*A switch from a 0.5 % loss per year to a 0.1-0.4% increase in SOC concen-tration in cropland soils* *30-50% reduced area of peatland losing carbon*	*Soil organic carbon stock* *Vegetation cover*
Soil sealing and net land take	*Urban recycling of land from 13 to 50%* *No net land take by 2050*	*Switch from 2.4% to no net soil sealing*	*Soil structure including soil bulk density and absence of soil sealing and erosion* *Vegetation cover*
Soil pollution	*25% of land under organic farming* *Doubling of rate of remediated sites prioritising brown field sites*	*5-25% additional land (i.e. over and above the 25% in full organic) with reduced risk from a range of pollutants*	*Presence of soil pollutants, excess nutrients and salts*
Erosion	*50% degraded land restored*	*Prevention on 30-50% of land with unsustainable erosion risk*	*Soil structure including soil bulk density and absence of soil sealing and erosion.* *Vegetation cover*
Soil structure	*50% degraded land restored*	*Reduction by 30-50% of soil with compaction*	*Soil bulk density and other measures of soil structure*

* Source: EC 2020. EC 2021, which updates EC 2020, refers to eight soil health indicators – the extra indicators being landscape heterogeneity and forest cover.

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

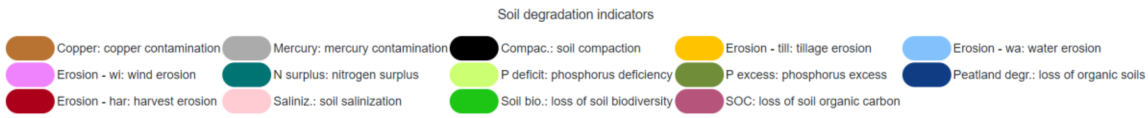

Figure 9. Soil degradation indicators used by the EU soil observatory.

More generally, soil indicators and measures of soil health is an active area of current research in Europe and the USA, primarily in relation to agroecosystems. Recent publications include a minimum suite of soil indicators in the North American Project to Evaluate Soil Health Measurements (Bagnall et al 2023):

- organic C
- potentially mineralisable C
- aggregate stability
- available water-holding capacity.

There are multiple papers and reports arising from the EU H2020-funded programme 'Landmark', for which the overall scientific aim was to 'Comprehensively quantify the current and potential supply of soil functions across the EU, as determined by soil properties (soil diagnostic criteria), land use (arable, grassland, forestry) and soil management practices', with relevance for farmers and farm advisors, legislators, and policy-makers.[6] This programme was the pre-cursor to Benchmarks,[7] a 5-year, €12 million programme that commenced in January 2023 and includes testing and validating the Soil Health and Food mission indicators (shown in Table 18), as well as some alternative/additional indicators, and establishing context-specific thresholds for these indicators. Feeney et al 2023 is one of the few studies that also indicators soil health benchmarks for the wider semi-natural environment. These authors developed soil health soil health benchmarks using soil organic matter, pH, bulk density and earthworm abundance for managed and semi- natural landscapes.

6.4 Development and use of target values internationally

Stevenson and Drewry (2022) provide an overview of approaches for deriving target values, drawing on Taylor (2021), with the following provided as examples of methodologies:

- expert panels
- percentiles
- natural state
- reference soils

[6] https://landmark2020.eu/project-details/

[7] Benchmarks: Building a European Network for the Characterisation and Harmonisation of Monitoring Approaches for Research and Knowledge on Soils - WUR

- calibration to risk, a risk index or threshold of contamination
- agronomic optimums
- comparison with field observations
- demarcation of critical thresholds or triggers for specific soil functions
- biological indicator approach
- scoring curves
- decision expert models (using weightings for attributes).

Some international examples of the use of 'target values' are the scoring indicator approach used in the Cornell Soil Health Assessment Framework (Figure 10, and a traffic light system (Figure 11).

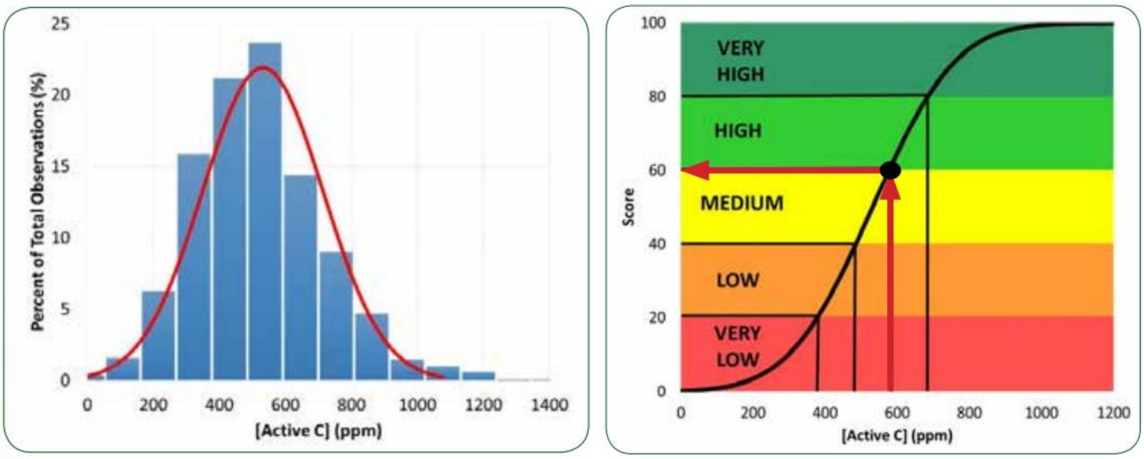

Figure 10. Example of the development and use of scoring indicators for assessing the results of Moebius-Clune et al. (2016). Left: the mean and standard deviation derived from the normal distribution describing the frequency distribution of active carbon is used to calculate the cumulative normal distribution (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 active C content lower than or equal to the sample being scored.

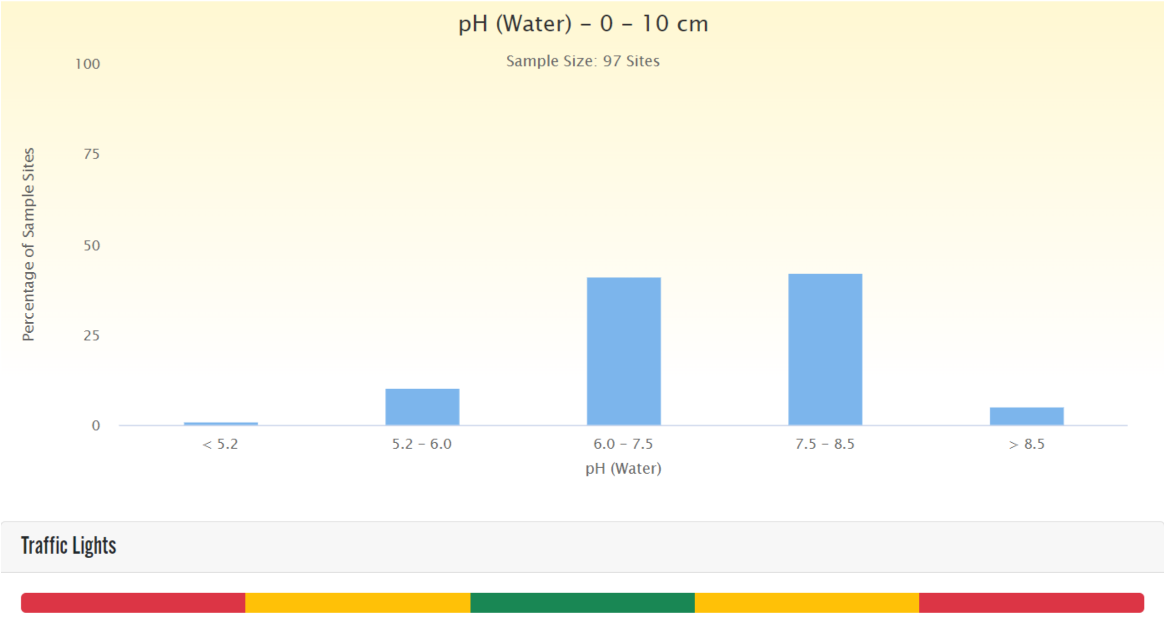

Figure 11. Example of the use of the traffic light system for presenting results from soil quality monitoring. (Source: https://www.soilquality.org.au/)

While no formal analysis was undertaken, Stevenson and Drewry (2022) largely agreed with the view of Taylor (2021) that, no matter which method was adopted, some level of expert opinion via an expert panel would probably still be needed. It is also worth highlighting here the significant investment in Europe through Benchmarks (mentioned above) in testing and validating indicators and establishing context-specific thresholds for these indicators. In Australia, approximately $18 million was provided for soils research[8] in 2022, including research useful for informing the use of different indicators – particularly biological indicators.

7 Workshop with Land Monitoring Forum, June 2023

7.1 Workshop overview

A virtual workshop was held on 8 June 2023 with the LMF and included 15 regional council representatives as well as representatives from the Ministry for the Environment, Ministry for Primary Industries, and StatsNZ. The workshop explored various aspects of the use of soil quality indicators and, more specifically, the target values/ranges used for the various indicators.

An initial overview of the development of target values (and ranges) was provided, noting that:

[8] https://www.agriculture.gov.au/agriculture-land/farm-food-drought/natural-resources/soils#:~:text=The%20National%20Soil%20Strategy%2C%20released,for%20the%20next%2020%20years.

- these values were derived as provisional target values
- they were developed through consideration of both production and environmental aspects
- there were very limited data on environmental considerations.

The focus for the workshop was to address the following questions:

- What is the purpose / desired intent / role of soil quality target values?
- Is 'soil quality target values' the right terminology?
- Are the current indicators the 'right' indicators?
- Are there new indicators that should be considered?
- What are key data sources?
- What methods might be appropriate to derive numeric values?

Mural whiteboard was used to capture people's comments, alongside discussion and comments in Teams chat. The 'raw' comments from Mural are provided in Appendix 4. This workshop summary also draws in some additional information from the literature review that helps inform the recommendations made.

What is the purpose / desired intent / role of soil quality target values?

To facilitate discussion, a short presentation provided an overview of the intent behind the development of the original target values and the existing objectives of the soil quality monitoring programme, plus an overview of current (RMA) and future (NBE) legislation (the content was largely that presented in section 6.2, above).

The majority of participants from councils that have long-term established soil quality monitoring programmes perceived that there had been little or no improvement over time in soil quality parameters, and that soil quality monitoring was simply monitoring a decline or documenting degraded soil quality. It is relevant to note that at least three of the key issues identified during the establishment of the monitoring programme – organic matter depletion, soil structure decline, nutrient excess – remain the key issues identified currently. One council observed that some positive changes were occurring, although it was unclear if this was related to climatic changes or changes in management practices.

It was further noted that soil quality monitoring programmes had arguably 'missed' the point of most significant change: indigenous vegetation being converted to agricultural use. In this context there was debate over the extent to which soil quality monitoring did actually provide 'an early-warning signal', as per the objectives.

There was a clear call for a greater focus on 'environmental impacts' given the 'environmental' mandate of regional councils, although it was also noted that biomass production is a key service of soils and needs to be recognised.

There was also a clear call for a greater connection between information obtained from monitoring and actions to effect improvements in soil quality. However, there was tension noted in potentially using SOE monitoring results (and even results from the National Soil

Carbon monitoring programme) to inform policy instruments, because their use in policy instruments compromises the integrity of these sampling programmes, given this sampling occurs on private land (and access to land could be denied). Arguably, this is more likely to be the case if punitive action (e.g. enforcement action) is taken as a result of falling outside any established target values or limits, and less so if non-regulatory 'behaviour-change' approaches were adopted.

One council reflected that some change can be effected by working with the individuals at the monitoring site locations. While 'behaviour change' programmes were recognised as perhaps a better approach (than enforcement or compliance) to improve soil quality through changed management practices, it was also recognised that there is likely to be variable appetite among councils to do this – and also perhaps that more definitive information on the connection between changed management practices and improved soil health is lacking. It is also arguable whether the development of 'behaviour change' programmes should be the responsibility of councils, given the extent of use of land for primary production.

Overall, there was a sense that it is time to reframe what is intended to be achieved though soil quality monitoring, but that there is value in continuing at least some monitoring along the lines of the current monitoring programme.

Is 'soil quality target values' the right terminology?

There was a fairly unanimous view that 'target values' is no longer the appropriate terminology to be using, particularly in the context of defining targets in the NBE Bill. 'Critical limits' or 'thresholds' was more favoured, reflecting a greater emphasis on the environmental implications of land-use practices, although some participants noted that acknowledgement needed to be given to the fact that the land is used for primary production and that some balance is required.

Are the current indicators the 'right' indicators? Are there new indicators that should be considered?

Some alternative views of indicators were presented to workshop participants to illustrate the use of different indicators (and targets), and these are captured in section 6.3. Specifically, the targets, objectives and indicators promoted for the European Soil Health and Food Mission were presented as Table 18 above, followed by indicators used by the EU soil observatory and the minimum suite of indicators arising the from the North American Project to Evaluate Soil Health Measurements.

Discussion summary

The resulting discussion focused on the inclusion of more specific biological indicators, and erosion (farm-scale rather than highly erodible land). Internationally there is a focus on erosion from agricultural land (harvest, wind, and water), whereas in New Zealand a greater focus has been placed on major erosion sources such as shallow landslips, because this is the dominant source of sediment in rivers.

Final questions

The final two questions, 'What are key data sources? and 'What methods might be appropriate to derive numeric values?' were not further discussed, as the preceding discussion revealed that such fundamental questions about the purpose and intent of target values and indicators became largely redundant.

8 Discussion and conclusions

The current project had a relatively narrow focus on reviewing the basis for numerical values of existing target values and identifying new indicators and data sources. In undertaking the review it became clear that there was no definitive source for the 'current' target values, and that sometimes the reason for changes was unclear (e.g. for macroporosity). This report fills that gap, as well as elucidating the original workshop processes and the data used to underpin the target values currently used.

A suggestion arising after the workshop was that each indicator could have a 'living document' that sets out, and assesses, the strengths, weaknesses, interpretation, and other nuances for the indicator, using some evidential basis. One international example of this concept is the 'fact sheets' provided on the Australian soil quality website.[9]

Another observation of the target ranges used is that they tend to be set at the threshold or more 'extreme' ends of the range (i.e. between the low/very low and high/very high ends) compared to more narrowly defining an optimal range. The parameters are predominantly based on production aspects, with data to underpin environmental considerations much more limited. It also has to be emphasised that the original target values were considered to be only provisional, with the intent that they would be updated when more data became available (Sparling et al 2008; Lilburne et al. 2004).

Although the focus of the workshop in June 2023 was originally intended to be on how the derivation of existing target values could be improved, and to identify new indicators and relevant data sources, comments from the workshop highlighted that in order to do this effectively there needs to be greater clarity about the context and purpose of target values, including any actions that could or should arise from results falling outside these values. Supporting this were observations that over 20 years of monitoring there had been little change in results, and little movement towards improving degraded soil quality.

It is relevant to note that at least three of the key issues identified during the establishment of the monitoring programme – organic matter depletion, soil structure decline, and nutrient excess – remain the key issues identified currently, although now there are perhaps data to provide the evidence for these effects occurring. The Environment Aotearoa report (MfE 2022) also notes that over half the SOE soil quality monitoring sites fail to meet the macroporosity target ranges. This observation is supported by the analyses of Stevenson and McNeill (2020), which showed no overall

[9] https://www.soilquality.org.au/factsheets

improving trend in soil quality observed over the period 1994–2018 in New Zealand. Over this time there have also been changes in the land-use and land management activities, which probably also confounds trend assessment.

From the workshop there was a clear desire to have greater clarity around limits or thresholds that could lead to negative environmental impacts, particularly because regional councils are charged with being responsible for the environment. However, this focus can't be completely divorced from considerations relating to primary production – particularly when it is estimated that approximately 95% of our food comes from soil (FAO 2015).

There was recognition of a tension between ensuring ongoing access to soil quality monitoring sites and effecting positive changes in soil health, particularly if punitive actions are taken as a result of sites falling outside the target ranges (an issue that could arise from the use of environmental limits in the NBE, although limits will be set on the current state). 'Behaviour-change approaches' were considered to be preferable, but there was recognition that there is a variable appetite among councils to invest in such programmes. Further, while Hill and Sparling (2009) also indicated that soil quality monitoring objectives aim to utilise results for policy development (and in so doing potentially provide drivers for intervention to improve soil health), the extent to which this has occurred is unclear.

A further point identified was that the results of SOE soil quality programmes are not integrated with other regional monitoring (e.g. water, especially groundwater), which is arguably a failure of one of the original (Hill & Sparling 2009) and current (NEMS-SQ) objectives of the programme.

Several regional councils have recently undertaken, or are undertaking, reviews of their soil quality monitoring programmes (e.g. Marlborough District Council, Greater Wellington Regional Council), and this information would be useful to inform evaluations of many of the above points (if covered).

There was considered to be value in continuing to monitor along the lines of existing SOE monitoring, partly because of the investment and data that monitoring has provided over time. However, there was a strong desire to have clearer national direction on the objectives for monitoring, and, specifically, actions that result in improvement of soil quality.

More generally, there are questions as to whether this should be the role of regional councils, compared to perhaps the primary sector, and whether the SOE monitoring programme should be the primary way to effect that change. Various international soil strategies and underpinning programmes (e.g. the EU Soil strategy,[10] the EU Mission 'A

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

Soil Deal for Europe',[11] and the Australia National Soil Strategy[12]) recognise the critical importance of working in partnership with multiple stakeholders to realise improvements in soil health.

On reflection of the key challenges raised in the workshop – and recognising that outside of the SOE soil quality monitoring programmes, there are calls for the development of a national policy statement on contaminated land management and soil re-use (Mayhew 2023), and the recently released Waste Minimisation Strategy includes the goal of reducing the volume of soil disposed to landfill[13] (MfE 2023). Also, the Parliamentary Commissioner for the Environment is undertaking further investigation of the use of urban soils, following an assessment of urban green-space (PCE 2023). It therefore seems clear that a higher-level strategic approach is required to generate the impetus and clear objectives for managing soils, so that soils are better protected and valued, and improved soil health is realised.

The development of a National Soil Strategy would help provide a framework for attributes for soil under the NBE, but would also explicitly provide a connection with other aspects of the environment that can be influenced by soils, including climate change, fresh- and ground-water quality, and, importantly te ao Māori. Steps toward a framework incorporating te ao Māori and mātauranga Māori have already been taken (Stronge et al. 2023; Harmsworth 2022a, b; Sevicke-Jones et al. 2021). Such an approach could provide a wider impetus and momentum for changing management practices to effect improved soil health more effectively than potentially disconnected and variable programmes operated by individual councils.

9 Recommendations

Key recommendations arising from this project relate to two levels.

SOE soil quality monitoring

We recommend:

- critically reviewing the performance of existing indicators in SOE reporting, via existing trends, state analysis, and literature studies, to evaluate whether to retain these as indicators for soil quality monitoring
- developing 'living documents' for those indicators that are retained
- critically reviewing new evidence (i.e. data available since the establishment of current target values) for the current suite of indicators, with a focus on developing thresholds, where possible, that define potential negative

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

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

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

environmental impacts, taking into consideration variation across land use and soil order.

In terms of new indicators, we recommend:

- reviewing evidence for and, if appropriate, confirming provisional thresholds or proposing alternative thresholds for hot-water carbon
- evaluating the current status of the use of biological indicators in monitoring programmes, in New Zealand and internationally, with a view to proposing potential indicators
- evaluating the status and value of an indicator for erosion at farm-scale (i.e. not highly erodible land).

More broadly, we recommend that:

- councils review how, or if, SOE soil quality monitoring and the associated results are used to inform their resource management policies or plans, or the effectiveness of any relevant provision, which would provide an evaluation of the extent to which this intended original objective has been realised (arguably, this is the most critical element in informing actions to improve soil quality/health)
- councils review opportunities to integrate soil quality monitoring with freshwater and groundwater monitoring to better inform holistic management.

National level

- We recommend that LMF advocate to Resource Managers Goup and central government (Ministry for the Environment, Ministry for Primary Industries) for the development of a national soils strategy that provides clear objectives for improving soil health across the multiple areas, integrates te ao Māori and mātauranga Māori, and recognises the key role that people play in improving soil health.

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Appendix 1 – Land-use categories used for workshops held in 2000

The following land-use definitions are taken from Sparling & Tarbotton 2000.

Crop and horticulture: Soils (typically Granular, Recent, Pallic, Melanic) used for orchards, vineyards, arable cropping and market gardening. A very diverse land use but tends to have some form of tillage, high agrichemical use, and reduced organic matter returns.

Extensive pasture: pasture used typically for beef and sheep (includes deer and goats). Introduced grasses include Brown-top, Fescue, Fog. Clover content variable. Rolling to hilly country. Includes some steeplands and some tussock. Aerial top-dressed as farm finances allow. Includes examples on most Soil Orders.

Indigenous: ideally includes any uncleared and unimproved land under the original vegetation, secondary regrowth and other diverse natural habitats (wetlands, alpine areas, tussock country, foreshore). Typically characterised by acidic soils with low nutrient contents, and with vegetation dominated by NZ native species. Could (hopefully) occur on all Soil Orders.

Intensive pasture: pasture used mainly for dairy farming, typically ryegrass-clover, receiving lime and fertiliser on a regular (annual or less) basis. Flat to rolling country. Might be irrigated. Typically Allophanic soils in Waikato and Taranaki, but also other Soil Orders in Southland and Northland.

Plantation forests: typically *Pinus radiata*. Soils (steep, rolling, flat) used to grow Radiata pine. This land use is wide ranging, including various Soil Orders ranging from Recent (dunes), ex-sheep and beef pastures and former indigenous forest (Brown, Pumice, Allophanic, Pallic, Oxidic, etc.)

Appendix 2 – References cited as sources of information for establishment of soil quality target values

Sources of information for standard indicators

Bulk density

References cited as sources of information in the workshops held in 2000

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Appendix 3 – Additional data sources

NSD and NSDR

Soil observations are available from the National Soils Database (NSD), which is a data set within the National Soils Data Repository (NSDR). The NSD is a 'point' database containing descriptions of about 1,500 New Zealand soil profiles, together with their chemical, physical, and mineralogical characteristics. The information is obtained from excavated pits, usually up to 1.5 m deep but sometimes deeper, from which the soil scientists collect samples for chemical and physical analyses.

A first data repository, the NSD was introduced by the NZ Soil Bureau in the 1980s, discontinued in 1992 due to funding restrictions, then re-established by Manaaki Whenua – Landcare Research as the NSDR in 2015. The processing and upload of soil 'legacy' data into the NSDR is an ongoing and labour-intensive process. The bulk of New Zealand soil information is collected from private land and is subject to the Privacy Act 2020. This limits the amount of soil data that can be made available to the public.

A web viewer is available for soil observations from the NSD: https://viewer-nsdr.landcareresearch.co.nz/getting-started

Future research to develop target values could utilise the significant resources of NSDR from S-map and other Manaaki Whenua – Landcare Research sampling data in recent years. We reported in Soil Horizons (2020) that:

> For the S-map Next Generation project alone, over the last 3 years, over 1000 new soil physical samples were collected at 173 new sites across New Zealand and analysed in the laboratories. *This resulted in over 20,000 soil physics measurements and over 5,000 soil chemistry measurements.*

Carbon monitoring data sets

Mudge PL, Kelliher FM, Knight TL, O'Connell D, Fraser S, Schipper LA 2017. Irrigating grazed pasture decreases soil carbon and nitrogen stocks. Global Change Biology 23(2): 945-954.

Mudge PL, Millar J, Pronger J, Roulston A, Penny V, Fraser S, et al. 2021. Impacts of irrigation on soil C and N stocks in grazed grasslands depends on aridity and irrigation duration. Geoderma 399: 115109.

Other sources

Potentially, AgResearch and Plant & Food Research may have data sets that are useful. However, this would need the relevant permissions to use the data, and sufficient funding to be able to adequately deal with a wide range of formats, methods, depths, circumstances, issues, etc. (data cleaning and preparation can be very time consuming and costly).

Publications

A range of publications from New Zealand studies since those reported by Sparling and Tarbotton (2000), Lilburne et al. (2004), and Sparling et al. (2008) are potentially available to help inform an update of the soil quality targets. Selected publications since the 2000 workshop are listed below as useful examples, including production and environmental components, but there are likely to be others, especially for carbon. There is an emphasis on New Zealand studies, but several relevant international studies are also listed.

Macroporosity and bulk density

Curran-Cournane F, McDowell R, Littlejohn R, Condron L 2011. Effects of cattle, sheep and deer grazing on soil physical quality and losses of phosphorus and suspended sediment losses in surface runoff. Agriculture, Ecosystems and Environment 140(1–2): 264–272.

Donovan M, Monaghan R 2021. Impacts of grazing on ground cover, soil physical properties and soil loss via surface erosion: a novel geospatial modelling approach. Journal of Environmental Management 287: 112206.

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Note: a previous 2002 Fertiliser and Lime Research Centre conference paper was reported by Lilburne et al. (2004) and Sparling et al. (2008), but further statistical analysis on macroporosity pasture production response curves was done on that data set and published in: Drewry JJ, Littlejohn RP, Paton RJ, Singleton PL, Monaghan RM, Smith LC 2004. Dairy pasture responses to soil physical properties. Australian Journal of Soil Research 42(1): 99–105.

Drewry JJ, Cameron KC, Buchan GD 2008. Pasture yield and soil physical property responses to soil compaction from treading and grazing: a review. Australian Journal of Soil Research 46(3): 237–256.

Drewry JJ, Carrick S, Penny V, Dando JL, Koele N 2022. Effect of irrigation on soil physical properties on temperate pastoral farms: a regional New Zealand study. Soil Research 60(8): 760–771.

Drewry JJ, Paton RJ, Monaghan RM 2004. Soil compaction and recovery cycle on a Southland dairy farm: implications for soil monitoring. Australian Journal of Soil Research 42(7): 851–856.

Houlbrooke DJ, Drewry JJ, Laurenson S, Hu W, Carrick ST 2021. Soil structure: its importance to resilient pastures in New Zealand (review). Resilient pastures symposium of New Zealand Grasslands Association. Agricultural Practice Series 17: 271–281.

Hu W, Drewry J, Beare M, Eger A, Müller K 2021. Compaction induced soil structural degradation affects productivity and environmental outcomes: a review and New Zealand case study. Geoderma 395: 115035.

McDowell RW, Drewry JJ, Paton RJ, Carey PL, Monaghan RM, Condron LM 2003. Influence of soil treading on sediment and phosphorus losses in overland flow. Australian Journal of Soil Research 41(5): 949–961.

Romero-Ruiz A, Monaghan R, Milne A, Coleman K, Cardenas L, Segura C, Whitmore AP 2023. Modelling changes in soil structure caused by livestock treading. Geoderma 431: 116331.

Total carbon

Beare MH, McNeill SJ, Curtin D, Parfitt RL, Jones HS, Dodd MB, Sharp J 2014. Estimating the organic carbon stabilisation capacity and saturation deficit of soils: a New Zealand case study. Biogeochemistry 120: 71–87

Kelliher FM, Condron LM, Cook FJ, Black A 2012. Sixty years of seasonal irrigation affects carbon storage in soils beneath pasture grazed by sheep. Agriculture Ecosystems & Environment 148: 29–36.

Lawrence-Smith EJ, McNally S, Beare M, Curtin D, Lehto K 2018. Updating guidelines for the interpretation of soil organic matter (carbon and nitrogen) indicators of soil quality for state of the environment monitoring. Envirolink project 1801-MLDC132. Plant and Food Ltd SPTS No. 16215.

McNally S, Beare M, Curtin D, Meenken E, Kelliher F, Calvelo Pereira R, et al. 2017. Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. Global Change Biology 23(11): 4544–4555.

Mudge PL, Kelliher FM, Knight TL, O'Connell D, Fraser S, Schipper LA 2017. Irrigating grazed pasture decreases soil carbon and nitrogen stocks. Global Change Biology 23(2): 945–954.

Mudge PL, Millar J, Pronger J, Roulston A, Penny V, Fraser S, et al. 2021. Impacts of irrigation on soil C and N stocks in grazed grasslands depend on aridity and irrigation duration. Geoderma 399: 115109.

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Schipper LA, Parfitt RL, Fraser S, Littler RA, Baisden WT, Ross C 2014. Soil order and grazing management effects on changes in soil C and N in New Zealand pastures. Agriculture, Ecosystems & Environment 184: 67–75.

Stevenson BA, Sarmah AK, Smernik R, Hunter DW, Fraser S 2016. Soil carbon characterization and nutrient ratios across land uses on two contrasting soils: their relationships to microbial biomass and function. Soil Biology and Biochemistry 97: 50–62.

Whitehead D, Schipper LA, Pronger J, Moinet GYK, Mudge PL, Calvelo Pereira R, et al. 2018. Management practices to reduce losses or increase soil carbon stocks in temperate grazed grasslands: New Zealand as a case study. Agriculture, Ecosystems & Environment 265: 432–443.

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AMN

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Appendix 4 – Comments from Mural digital whiteboard

Comments from Mural digital whiteboard used during the workshop and emails subsequently received are provided below.

Mural digital whiteboard notes

Q1- What is the purpose/intent of 'target values? / What action is anticipated as a result of being outside the range' and by whom?

Q2- Are these the 'right' indicators? / What are other indicators?

Table 19. Summary of mural comments:

Question	Individual comments
q1	we want to monitor in order to inform policy in order to minimise adverse effects of land use on the environment
q1	depends on scale, but, at a regional- or national- scales, perhaps they are tool for simplifying a lot of indicator data for identifying some emerged issues. not sure science is at a level where it can support demonstration of effects (production, environment)
q1	im concerned about how seasonal climate variation can make soil parameters decline or increase significantly when land management practises haven't changed, but make the landowners non compliant due to not being allowed to have a state decrease under the new act
q1	If a site fell out of a target range we used to have land managers relay such results to landowners to inform on the land management practices (until the team dissolved) then it was up to the land and soil scientist to disseminate results - not sure how effective this was though wrt influencing land management
q1	Valuable for context and interpretation of the results, especially for feeding back to landowners.
q1	I think the targets are important for the monitoring programme to give an indication of how sites are doing. I think it is important to keep these separate from environmental limits that may be imposed by new regulation, which will need to be managed accordingly
q1	Confidence that we have some national consistency and support of science community
q1	Long term issue of different councils using different processes. Just need to get everyone on the same page. This includes LCR and Hill labs talking to each other and standardising lab tests.
q1	ER can use data showing state and trends. The more complete the data set the better. Identifying place is also helpful.
q1	seems like they currently tell you if the result is an outlier on some value scale (production optimisation or environmental risk)?
q1	Need to reframe what is being achieved
q1	MO - Marlborough - distinctive that no change over long term - some parameters show steep decline shortly after conversion, others none. Difference between unfarmed vs cropping - bounces at 2%C
q1	Adding to Fiona's point it is important to differentiate/keep separate soil quality monitoring from regulatory enforcement of hard limits. Otherwise the SQM will no longer exist
q1	Note my comment on the responsibilities of RCs

Question	Individual comments
q1	action is to improvement of soil health
q1	Is it suitability for just healthy for production that we are targeting, or also ecological integrity? Similar to approach for water and other ecosystems
q1	Need to understand indicators use - bulk up
q1	Need to set higher level objectives for soil to be achieved
q1	Monitoring stuff that is within the control of landowners etc....
q1	critical limits useful - not targets
q1	use freshwater attributes - a, b, c
q1	current monitoring Â is telling the same story every year - no change being effected
q1	Regional council need to report to ratepayers - WRC have seen positive change - could be landuse change or simply environmental change
q1	some responses are engagement/awareness via good practice guide
q1	Climate action driving change roadmap being written
q1	very hard to get outreach etc programmes funded etc etc needs higher level policy drivers to effect change...
q1	climate vs
q1	critical review of results to date
q1	Shift to greater focus on environmental
q1	The soil is a dynamic system which changes based on the inputs, such as land use, climate (short and long) etc
q1	limits/targets need to un
q1	need to avoid perverse outcomes of limits etc with different targets
q1	Perhaps attempt to arrive at an overall index that incorporates the individual indicators
q1	We need a means for interpreting indicator data. Do we interpret it for the purpose of giving catchment context to freshwater farm plan development? or to an extension officer working with a land manager? or a policy maker?
q1	do we need a list/matrix of attributes that make an indicator right/suitable> e.g. quality of its information for a given land use, its short-term variability to climate, its spatio-temporal variability, cost, land use versus land use management sensitivity, etc.
q1	and then, knowing the benefits and constrains of each indicator - you then you map the relevant value from your objectives framework (production or else) to some result range, or a limit
q2	Would be good if we could advance a biological indicator such as earthworms, whether it is via destructive sampling or eDNA
q2	Definitely support some kind of bio indicator
q2	Biological indicators OK to add but must be technically sound, biologically meaningful, sensitive to soil management and interpretable
q2	Can look at enzyme activities or permanganate oxidisable carbon; pesticide residues in soils
q2	biological chemical physical[soil loss]
q2	Like the idea of earthworms as a bio indicator as these are currently used for VSA's
q2	research still required [for biological indicators]

Question	Individual comments
q2	i (ogi) thinks that biomass production is a key service provided by soils, but agree that we need to capture the environmental effects better
q2	HWC - interpretation alongside other measurements
q2	microplastics

Post-workshop email

I think the loose purpose of soil quality target values is to interpret the indicator data. But, stepping back from understanding how targets should be designed to best assist in improving our environment at regional- and national- scales, I suspect that we've overstepped, and I don't think we've maintained a very close eye on the limits of our existing indicators, or their target range values. I don't think we necessarily need numerical limits, ranges, or thresholds, provided we have good evidence that the target is strongly linked to some outcome, and we want to track change over time. But, then we need to review indicators themselves. So, I think we need a more robust framework for holding indicators and target ranges together although I think the chances of receiving funding for its development are slim..

Anyway, the following has been sitting in my draft notes for a while, and while it's larger in scope than your report, and I have probably shared it earlier, it doesn't hurt to raise it (again).

It would be helpful to develop a framework for proposing and tracking the addition, or alteration, of soil indicators used by Land Monitoring Forum members. As one component of the framework, each indicator would have a "living document", that sets out, and assesses the strengths, weaknesses, interpretation, and other nuances for the indicator, using some evidential basis. At the minimum, every indicator in NEMS should have such a document.

Indicator documentation could be framed by a set of criteria, such as:

- Evidence of indicator's association with soil function. This involves maintaining an agreed list of soil functions we're looking to monitor, such as biomass production, nutrient cycling/filtering, carbon storage, resilience to structural breakdown; but there will be others, including ecological and cultural services. This should also discuss the basis and strength of the association between the indicator and value (how faithful is the correlation?).
- Suitability of indicator for different land uses. What land uses is the indicator best suited for and why? How sensitive is it to short-term land management events, versus long-term land management effects. Includes guidance on how often it needs to be monitored (to estimate state, or trend).
- Originality and complementarity. Does the indicator provide new information or if it's closely related to an existing one. Does it complement the existing set?

- Robustness: temporal stability & spatial-scale applicability. Assessment of seasonal, spatial, and depth-wise variability in results. Indicators that have high variability in small units of space or time are likely to be expensive to implement.
- Discussion of sampling and analysis methodology, including consideration of equipment needs, cost, robustness to different soils (e.g. stony conditions), training requirements, laboratory reproducibility, laboratory availability, etc
- Interpretation and communication. Existence of data, or models, or, relationships, that link its results with the provision of service it is a proxy for. Is existing data sufficient to fit a critical threshold, or optimal range, for a range of relevant land uses? Numerical values may not be necessary if indicator is very closely linked to a function or effect, and trends over time are of high interest. How easy is it to communicate, assuming audience does not have a strong science background?
- Status: summary and a recommendation of use: e.g. More research needed. Recommended for SoE, farm-level land management, or for tracking a specific local/regional issue.