State of the environment soil quality monitoring, 2018–2025: state and trends

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Project and client

- The Ministry for the Environment (MfE) requires accurate, up-to-date information on the state of New Zealand's soil in order to update the environmental reporting 'Soil quality and land use' indicator, and to assess policy options for the mandatory soil domain in the proposed Natural Environment Act.
- MfE contracted the Bioeconomy Science Institute to collate regional council state of the environment (SOE) soil quality data and provide an assessment of these data against recently developed reference ranges for soil quality and trend analysis.
- A tabular data set and annotated code are provided alongside this report.

Objectives

- The objective of this project is to collate and analyse regional council SOE soil quality data up to 30 June 2025 to:
  - provide a tabular data set of core variables of soil quality, trace elements, and land-use type for the period 1995–2025
  - provide a tabular data set of any supplementary variables
  - undertake a comparison of core soil quality parameters against target ranges used for previous reporting and revised target ranges (renamed 'reference ranges')
  - undertake a comparison of trace elements against relevant guideline values
  - undertake a trend analysis of core and supplementary variables (such as hot-water-extractable carbon [HWEC] and aggregate stability) of soil quality and trace elements over the period 1995–2025, including an analysis of trends at individual sites and aggregation to relevant land-use or mixed land-use categories.

Methods

- Soil quality monitoring data were sought from all councils and collation was undertaken using the approach described in Stevenson et al. (2020), and included capture of the collated data in the National Soils Data Repository (NSDR). Land use was curated to provide consistent groupings prior to analysis.
- Data were analysed in two time-steps, 1 July 2018 to 30 June 2022, and 1 July 2022 to 30 June 2025 primarily to provide consistency with time periods covered in previous reporting.
- The collated data were compared with the relevant target and reference ranges and guideline values using R.
- Trend analysis was undertaken for soil quality indicators under each land use using linear mixed effect models, including sites that had not changed land use over the sampling period. This analysis included code based on previous trend analysis for SOE soil quality, data in addition to further analyses.

Results and conclusions

- Direct comparison between the number of sites not meeting target ranges or reference ranges, and conversion between reference ranges and target ranges for comparison with previous SOE monitoring reports, was confounded by the different land-use categories used, whether an upper or lower limit was specified, and the availability of values for different soil orders.
- Comparison of the monitoring data with reference ranges generally showed a higher number of results falling outside the ranges when compared with the target ranges. This was particularly the case for Olsen phosphorus (Olsen P) and bulk density, for which a much greater number of sites were above the reference range compared to target ranges, which largely reflects a ‘narrowing’ of the reference range for these indicators.
- Despite these differences, comparison of the monitoring data over the two monitoring periods using reference ranges provides results similar to those found in previous SOE reporting (MfE & Stats NZ 2018, 2021), as follows.
  - Total carbon is low in cropping soils, with about 20% of sites falling below the reference range and a decreasing trend over time.
  - Olsen P concentrations are high, and above reference ranges for dairy (68–71% of sites), cropping (30–60% of sites), and orchards (70–88% of sites). Drystock areas had approximately 50% of sites below the reference range.
  - Olsen P concentrations show increasing trends over time, particularly for vegetable cropping, but also for drystock and orchards.
  - There is evidence of widespread compaction (high bulk density and/or low macroporosity) for most land uses, but particularly dairy. That said, decreases in bulk density (i.e. improvement) under drystock, orchards, and vineyards, and increases in macroporosity (i.e. improvement) in short-rotation cropping, were the only significant trends identified for these indicators.
- Aggregate stability and HWEC results were collated for the first time, with the aggregate stability results providing clear evidence of soil structural degradation in cropping soils.
- Few sites exceeded the 95% protection-level ecological soil guideline values (Eco-SGVs), with copper concentrations in orchards most frequently exceeding the Eco-SGV in both monitoring periods. Significant increases in copper concentrations over time were most obvious for orchards, but were also significant for dairy sites.
- A moderate number of sites, predominantly dairy and drystock, had cadmium concentrations that exceeded the Tier 1 trigger value of 0.6 mg/kg, with decreasing trends for indigenous vegetation, plantation forestry, and dairy, and no increasing trends.
- The greater specificity of land use (e.g. vegetable cropping vs. vineyards) allows finer delineation of soil properties associated with different land-use classes. However, further improvements in the robustness of land-use classification between regions and over time is required to provide greater confidence in land-use associations, including the identification of real change in land use over time.

Despite challenges with the data, this collation has given rise to an extensive national data set of consistently collected and analysed data that provides the opportunity to undertake deeper analysis to better understand changes over time and the influence of other factors (e.g. climate, and land management, but particularly the spatial variability of soil properties).

Recommendations

- To improve the robustness of information provided, we recommend:
  - investing in the development of streamlined data collation processes to minimise both the time required for collation and data handling errors
  - that councils undertake an audit of land-use information held for all monitoring sites, and include classification of both land use at the time of sampling and farm system
- undertaking further analysis of the HWEC data to assess the potential influence of methodological influences on the observed trend over time
- undertaking a deeper analysis of this extensive national data set of soil quality data to provide a greater understanding of the factors (e.g. climate, land management) that influence soil quality.

1 Introduction

The Ministry for the Environment (MfE) requires accurate, up-to-date information on the state of New Zealand's soil in order to update the environmental reporting 'Soil quality and land use' indicator, and to assess policy options for the mandatory soil domain in the proposed Natural Environment Act. contracted the Bioeconomy Science Institute to collate regional council state of the environment (SOE) soil quality data and provide an assessment of these data against recently developed reference ranges for soil quality and trend analysis. A tabular data set and annotated code are provided alongside this report.

2 Objectives

The objective of this project is to collate and analyse regional council SOE soil quality data up to 30 June 2025 to:

- provide a tabular data set of core variables of soil quality, trace elements, and land-use type for the period 1995–2025
- provide a tabular data set of any supplementary variables
- undertake a comparison of core soil quality parameters against target ranges used for previous reporting (2024, 2021, 2018, and 2014) and revised target ranges (renamed 'reference ranges') for soil quality parameters
- undertake a comparison of trace elements against relevant guideline values
- undertake a trend analysis of core and supplementary variables (such as hot-extractable carbon [HWEC] and aggregate stability) of soil quality and trace elements over the period 1995–2025, including an analysis of trends at individual sites and aggregation to relevant land-use or mixed land-use category.

3 Methods

3.1 Data collation

Collation of data followed the approach described in Stevenson et al. (2020), which drew on the original data collation undertaken by Cavanagh et al. (2020) and included capture of the collated data in the National Soils Data Repository (NSDR). Briefly, Excel workbook templates were provided to councils to capture data not captured in the previous data collation, up to 30 June 2025 as a nominal endpoint. This included data from new site visits (i.e. re-sampling of existing sites, and sampling of new sites for the seven core variables of soil quality and land-use types, and for trace elements), as well as data for supplementary parameters that have previously not been collated: HWEC and aggregate stability. Files provided to individual councils included all data currently held in the NSDR.

Data provided by councils underwent a data check, including transfer to the template as required, before uploading to the NSDR. Data were exported from the NSDR for further cross-checking to ensure robustness and provide any further identified missing data (primarily approximate date of sampling, to month and year). Required corrections (primarily sampling date and land-use specification) and any further missing data were uploaded to the NSDR. Additional cross-checks of the data were undertaken before the final export of data.

Exported data are included from the 14 councils currently undertaking SOE monitoring, and the data captured extends from 1995 (the commencement of precursor studies to the '500 Soils' programme) to 30 June 2025 (as a nominal endpoint).

3.2 Indicators and trace elements

Data were collected for the following soil properties:

- seven core soil quality indicators – pH, total carbon (TC), total nitrogen (TN), anaerobically mineralisable nitrogen (AMN), Olsen phosphorus (Olsen P), bulk density, and macroporosity, which was measured as the difference between total porosity and volumetric water content of soil measured at a tension of –10 kPa
- eight trace elements – arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), fluorine (F), lead (Pb), nickel (Ni), zinc (Zn)
- two additional properties – hot-water extractable carbon (HWEC) and aggregate stability.

Sample collection typically followed that reported in the 'Soil quality and trace element' National Environmental Monitoring Standard (NEMS-SQ, NEMS 2022) and Hill & Sparling 2009. Briefly, at each site 10 cm depth soil cores were taken approximately every 2 m along a 50 m transect and bulked for soil chemical analyses. The transect should be a visually uniform strip and representative of the area to be sampled.

Three undisturbed soil samples were obtained along the transect for field bulk density and macroporosity by pressing stainless steel liners (10 cm in diameter and 7.5 cm in depth) into the soil. The three bulk density and macroporosity values were averaged to give an overall site value for the soil physical indicators. Aggregate stability was sampled by cutting an approximately 15 cm × 15 cm spade width into the soil to a depth of 10 cm and carefully extracting the intact sample. Soils were classified according to the New Zealand Soil Classification, and land-use information was also collected.

Analytical methods for all parameters reported here (except HWEC) followed those described in the NEMS-SQ, although variations are noted, specifically for the Olsen P analysis, as discussed below.

While the same general 'method' is used to analyse for Olsen P by a number of laboratories, there is a key difference in how the samples are analysed. Specifically, most *research* laboratories (including the Manaaki Whenua Environmental Chemistry Laboratory) analyse a known mass of soil and provide results on a gravimetric (per gram) basis, whereas most *commercial* laboratories utilise a scoop method to analyse a known volume of soil and report the results on a volumetric basis (i.e. per cubic centimetre of soil). The latter results in a variable mass of soil being analysed.

The preferred method for reporting at present is the gravimetric method, as outlined in the associated NEMS. To convert the values generated by the volumetric Olsen P method to the preferred gravimetric equivalent, we used a regression model based on a Gamma response generalised linear mixed effects model (GLMM), with the log-transformed volumetric Olsen P as a fixed effect and soil order as a random effect, as developed in Drewry et al. (2022).

Analysis of HWEC generally follows that described by Ghani et al. 2003. Briefly, water-soluble compounds are removed using a cold-water extraction step, prior to hot-water extraction at 80°C for 16 h. These extracts are filtered before analysis with a total organic C analyser. However, there has been some variation in the specific methods used by different laboratories, and over time this may result in some variability in the results received. In particular, there is variation in whether an initial cold-water extraction step is used, and whether this is analysed or discarded. Currently, commercial laboratories typically use hot-water extraction carried out on a dried and sieved (<2 mm) soil sample at 80°C for 16 h, followed by IR detection for non-purgeable organic carbon.

3.3 Metadata

Region, soil order, and land use (curated land use) are provided as metadata. Site location is not provided, because the required agreement between councils and MfE is not in place, but this information is held in the NSDR.

Land use has been variably captured among, and within, councils in relation to:

- the land-use categories used within a council
- the apparently subjective application of the categories
- the specific terminology used to refer to those categories (e.g. dairy, dairying, dairy farm, dairy pasture, etc.; Cavanagh et al. 2021, Cavanagh & Whitehead 2022, 2023).

Curation of land use, as captured by individual councils, was therefore required to provide consistent land-use categories that can be reported at a national level. Specifically, after the data were exported, further processing was undertaken to provide more consistent land-use categorisation based on information captured as vegetation cover, land use, and land-use notes.

A mapping approach was used to provide a normalised land-use classification scheme to identify a set of national land-use categories that are consistent with previous national reporting (i.e. curated land uses). The modelling exercise performed was semantic in nature, utilising the Simple Knowledge Organization Framework (SKOS) (Isaac & Summers 2009). A very basic relationship model was used to fit within the scope of the current project. This model identified links between variable terminologies and the specified categories, and a text-processing script was generated to utilise this mapping to populate the national land-use categories.

The initial validation script examines six input columns – vegetation, farm system, LU1, LU2, LU3, and land-use_notes – and compares their contents against reference terms in CSV files, built from the SKOS vocabulary, containing known land-use terminology. Matching uses a combination of fuzzy string matching (user defined; a 92% similarity threshold was used to accommodate minor spelling variations) and substring matching for common terms. The script identifies lifestyle blocks through a separate process, described below. All potential matches are collected, with results stored in intermediate columns for review.

Because input data often contain ambiguous or conflicting information, a post-processing step (see Figure 1) resolves cases where multiple land-use categories have been identified. This applies a priority hierarchy – dairy and drystock take precedence, followed by vineyard, kiwifruit orchard, tree orchard, and vegetable cropping – to determine the primary classification. Additional passes handle edge cases, such as Auckland-specific records[1] and reclassification of ‘unclassified pasture’, where supporting evidence (e.g. references to sheep, beef, or dairy) exists in other fields. We also note that scrub and tussock sites identified in the previous collation were recategorised by

[1] Where land use was sometimes captured as, for example, lifestyle-dairy, dairy-drystock.

Environment Canterbury during a recent review and updating of their soil quality monitoring programme. These sites were largely re-categorised as drystock sites of varying grazing intensity.

Some sites or sampling visits have been identified as lifestyle blocks, either through the land-use classification provided (e.g. lifestyle-dairy, lifestyle) or in notes captured about the land use of the site. These sites may also have some information on land-use activities (e.g. walnut grove, horse grazing). This information was used to assign lifestyle blocks to a ‘primary’ land use. We suspect there is variability within and between regions as to how consistently lifestyle blocks and/or the nature of any land-use activities have been identified. As such, lifestyle blocks with an identified primary land use are included in those categories for the main analysis, with rural residential land use being used to classify sites on which no agricultural or horticultural activities were identified. A separate analysis of sites identified as lifestyle blocks is provided in section 4.2.

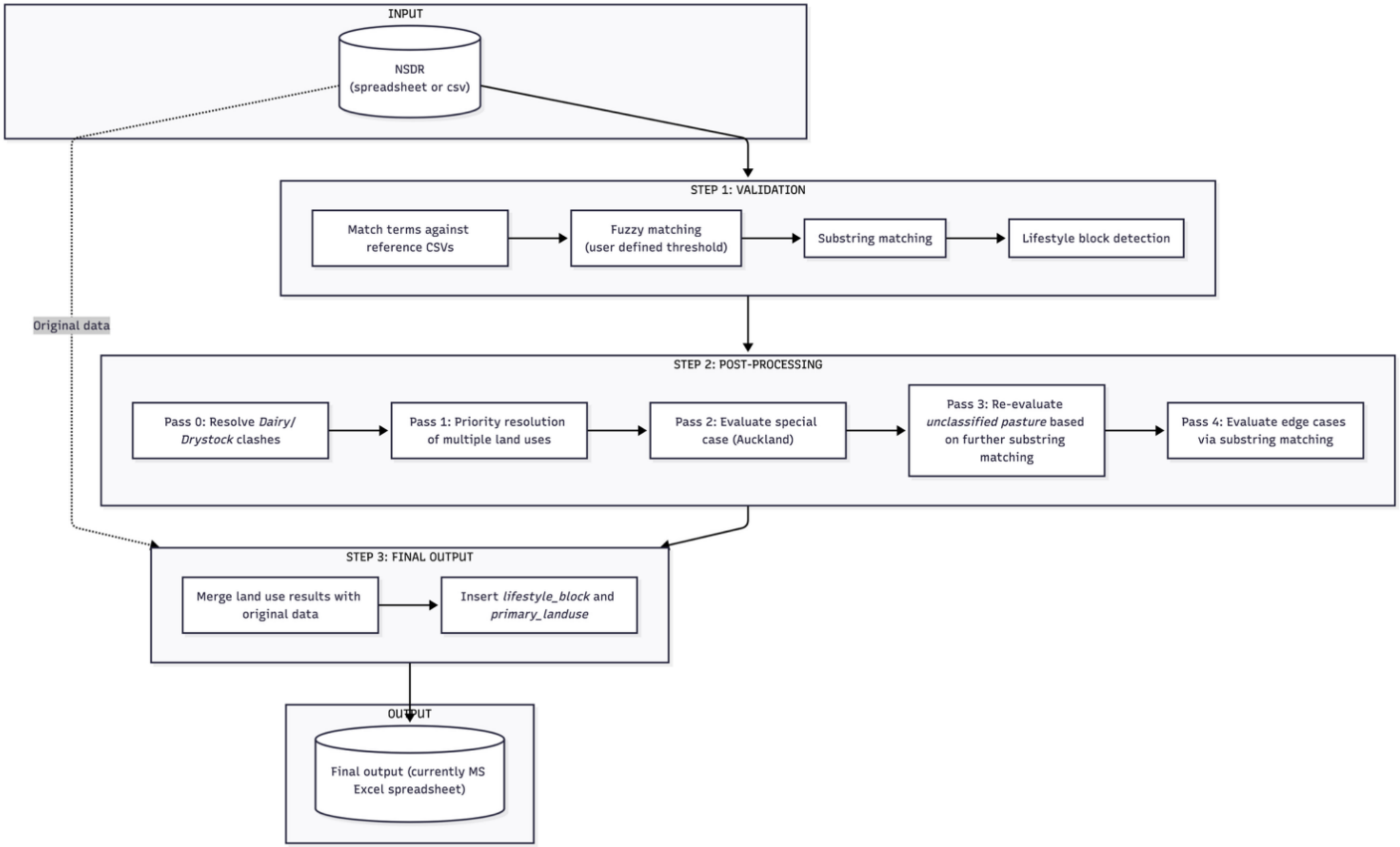

Figure 1. High-level land-use validation process.

Note: For an alternative diagram, see Appendix 1.

The curated land use, with examples of the varying terminologies captured under these land-use categories, is shown in Table 1. Curated land-use classes are matched, grouping as required, against the appropriate target values or reference ranges for the generation of compliance statistics (see section 3.5 for more detail). Reference ranges are provided for more detailed land-use classes than the previous target values, so the curated land use is more detailed than in previous reports.

Table 1. Curated land uses

Classification	Examples of specific terms included in each class
Dairy	Dairy, dairying, intensive grazing for dairy
Drystock	Sheep, beef, deer, pasture, pastoral farming, cut & carry pasture, intensive and extensive grazing for drystock
Vegetable cropping	Market garden, specific crops (e.g. potatoes, onions)
Short-rotation cropping	Arable, specific crops (e.g. maize, cut & carry maize), or cropping not otherwise identified as vegetable cropping
Kiwifruit orchard	Kiwifruit
Vineyard	Grapes, viticulture
Tree orchard	Specific tree crops (e.g. apples, pip fruit)
Orchard	Horticulture or any other orchard unable to be more specifically identified
Perennial horticulture	Perennial horticulture not able to be identified as orchard or vineyard
Plantation forestry	Exotic forestry, production forestry, woodlot, *Pinus radiata*
Indigenous vegetation	Native forest, indigenous forest, indigenous vegetation
Rural residential	Lifestyle block, additional terms (e.g. dairy-lifestyle, veg-lifestyle – mainly/only Auckland)
Urban open space	Urban park, including schools (mainly Auckland)
Other, unused	Land use not relevant for SOE reporting (e.g. waste-water disposal site, or unused)

3.4 R Script background, data manipulation, and formatting

Data for the soil quality data set were extracted from the NSDR into a set of site, sample, lab result, and other tables. SQL was then used to transpose the lab results into a standardised format containing measured properties as columns, and samples as rows, joined to site-related data at the time of the sample. The only manipulation of the data during extraction from the database involved averaging the three soil physical measurements per site for bulk density and macroporosity, when required (see section '3.2 Indicators and trace elements').

After being extracted from the database, any left-censored values (usually representing data below laboratory detection limits) were converted into half of the numeric string in the left-censored value. One negative AMN value and three Cd values equal to zero were removed from the data because they were determined to be erroneous data. Where sites had multiple measurements per site (e.g. orchard sites with measurements taken in inter-rows and tracks), these values were averaged to provide a single data point per site. Olsen P values in volumetric units (mg/L) for sites where no equivalent gravimetric data (mg/kg) were provided were converted to gravimetric units using equations developed in Drewry et al. 2021. These equations were preferred over a conversion process using the sample volume weight, because only a low number of samples contained the necessary volume weight data for this conversion.

Earlier generations of soil quality data (pre-2015) relied on spreadsheets to combine data from councils and generate soil quality statistics through simple look-up functions within the spreadsheets. It was difficult to document data manipulation, and the method for determining soil quality statistics was found to contain errors when dealing with missing data. For the 2015 report, R scripts were developed in association with MfE (Dr Ignatius Menzies), which were used to generate the soil quality statistics (e.g. the overall number of indicators and sites meeting target values and indicators that meet targets, grouped by land use). The same basic R coding was used in the 2018 and 2020 reports, and a slightly modified version (largely to accommodate changes in data structure from the NSDR download) is used here.

All data manipulation, formatting, and target value and reference range comparison steps performed on the data downloaded from the NSDR data are documented in the R markdown file included with the report.

3.5 Comparison with guideline values

Comparison with relevant guideline values was undertaken for two time-steps: 1 July 2018 to 30 June 2022, and 1 July 2022 to 30 June 2025. Two time-steps were used to provide greater consistency with the time frame used for previous reporting (typically 4 years) and to avoid re-sampled sites being captured in the same time-step (i.e. all sites were sampled once in each time-step).

The guideline values used were:

- existing target values for the seven core indicators (see Cavanagh et al. 2023 for a review and summary)
- recently developed reference ranges for the seven core indicators and HWEC (Cavanagh, Drewry et al. 2025)
- for trace elements, results were compared with ecological soil guideline values (Eco-SGVs; Cavanagh & Harmsworth 2023), and for Cd the Tiered Fertiliser Management System (FANZ 2019).

The regional distribution of sites is shown in Table 2, with distribution of sites across detailed land use and soil order provided in Appendix 2.

Table 2. Number of sites in each region used for comparison with guideline values for the two time-steps: 1 July 2018 to 30 June 2022 and 1 July 2022 to 30 June 2025

Region	Time-step	
	2018–2022	2022–2025
Auckland	75	119
Bay of Plenty	48	30
Canterbury	119	106
Gisborne	12	60
Hawke's Bay	37	17
Manawatu-Wanganui	75	44
Marlborough	72	60
Nelson	15	-
Northland	27	-
Otago	10	43
Southland	46	18
Taranaki	-	20
Tasman	-	37
Waikato	117	96
Wellington	81	59
Total*	**734**	**709**

* Other/unused land uses comprised an additional six and four sites in the 2018–2022 and 2022–2025 time-steps, respectively.

For comparison of collated data with target and reference ranges, detailed curated land-use categories were aggregated, as shown in Table 3. Details on further differences between individual indicators for target values and reference ranges are provided in sections 3.5.1 and 3.5.2 respectively.

Table 3. Aggregation of detailed land-use categories to enable comparison with target or reference ranges

Detailed land use	Target range land-use categories	Reference range land-use categories
Dairy	Dairy	Dairy
Drystock		
Unclassified pasture	Drystock	Drystock
Kiwifruit orchard		
Orchard		
Tree orchard	Orchard/vineyard	Orchard
Vineyard		Vineyard
Perennial horticulture		Orchard
Plantation forestry	Plantation forestry	Plantation forestry
Short-rotation cropping		Short-rotation cropping
Vegetable cropping	Cropping	Vegetable cropping
Indigenous vegetation	Indigenous vegetation	Indigenous vegetation
Rural residential	Rural residential	Rural residential
Urban open space	Urban open space	Urban open space
Other/unused	Other/unused	Other/unused

3.5.1 Soil quality indicator target values

The indicator target value ranges that have been used for previous SOE monitoring were first documented in Sparling et al. 2008, with some modifications proposed in Mackay et al. 2013. Review of the basis of these target ranges by Cavanagh et al. (2023) revealed that these ranges have been variably applied by individual councils. A summary of the target values used for SOE monitoring in *Our Land 2018* and *Our Land 2021* is provided in Table 4. These values are similar – but not identical – to the final 'agreed' ranges for the individual target ranges collated by Cavanagh et al. (2023), with the primary difference being the greater number of soil orders to which target ranges were applied (reflecting the wider range of soil orders covered by the monitored sites).

More significantly, Cavanagh, Drewry et al. 2025 identified that incorrect measurement units have previously been used for reporting Olsen P target ranges. Specifically, target ranges that were considered to be based on gravimetric measures of Olsen P (i.e. mg/kg) were actually based on laboratory volumetric measures (i.e. mg/L). This is partly because units associated with the table of updated Olsen P values discussions (section 3.4 of Mackay et al. 2013) were not included in the original document and have generally been assumed to be gravimetric measures (mg/kg) (e.g. Stevenson et al. 2020). However, Cavanagh, Drewry et al. (2025) confirmed through discussion with the original authors that these are laboratory-based volumetric measures (mg/L).[2]

We used the look-up tables provided in Drewry et al. 2022 to directly convert the target ranges in Table 4 to the 'correct' gravimetric values (Table 5), and used these corrected values to compare site data with target values.

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

Table 4. Soil quality indicator target ranges used by MfE and Stats NZ in Our Land 2018 and Our Land 2021

Indicator	Soil order	Curated land use	Min.	Max.	Unit
AMN	All	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	50	NA	mg/kg
	All	Cropping, orchard/vineyard, plantation forestry	20	NA	mg/kg
Bulk density	Allophanic	All	0.5	1.3	g/cm^3
	Brown, Gley, Granular, Melanic, Oxidic, Podzol, Pumice, Raw, Ultic	All	0.6	1.4	g/cm^3
	Organic	All	0.2	1	g/cm^3
	Pallic, Recent, Semi-arid	All	0.7	1.4	g/cm^3
Macroporosity	All	All excl. plantation forestry	10	30	–10 kPa, %vol/vol
	All	Plantation forestry	8	30	–10 kPa, %vol/vol
Olsen P*	Raw	All, excl. plantation forestry	5	25	*mg/kg*
	Podzol	All excl. cropping and orchard/vineyard, forestry	5	25	*mg/kg*
	Podzol	Cropping, orchard/vineyard	20	50	*mg/kg*
	All soils	Plantation forestry	5	30	*mg/kg*
	Allophanic, Pumice	All excl. plantation forestry	20	50	*mg/kg*
	Brown, Gley, Granular, Melanic, Oxidic, Pallic, Recent, Semi-arid, Ultic	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	15	45	*mg/kg*
	Brown, Gley, Granular, Melanic, Oxidic, Pallic, Recent, Semi-arid, Ultic	Cropping, orchard/vineyard	20	45	*mg/kg*
	Organic	All excl. plantation forestry	20	40	*mg/kg*
	Organic	Plantation forestry	5	30	*mg/kg*
pH	Organic	Plantation forestry	3.5	7	−log(cH+/c0)
	All excl. Organic	Plantation forestry	3.5	7.6	−log(cH+/c0)
	All excl. Organic	Cropping, orchard/vineyard	5	7.6	−log(cH+/c0)
	All excl. Organic	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	5	6.6	−log(cH+/c0)
Total C	Pallic, Pumice, Raw, Recent, Semi-arid	All	2	NA	%C gravimetric
	Brown, Gley, Granular, Melanic, Oxidic, Podzol, Ultic	All	2.5	NA	%C gravimetric
	Allophanic	All	3	NA	%C gravimetric
	Organic	All	NA	NA	%C gravimetric
Total N	All	Plantation forestry	0.1	0.7	%N gravimetric
	All	Dairy, drystock, lifestyle, scrub, tussock, urban park/reserve	0.25	0.7	%N gravimetric
	All	Cropping, orchard/vineyard	NA	NA	%N gravimetric

Notes: Anthropic soils are ignored. See Table 4 for 'corrected' Olsen P values used for target range comparison in this report. These curated land uses were compared to the originally specified land uses as follows: dairy and drystock are measured against the pastoral target ranges, cropping and orchard/vineyard against the crop/hort target ranges, and plantation forestry against the forestry target ranges. Indigenous vegetation was not compared with target ranges because it is not a managed system. Exotic forestry is equivalent to plantation forestry used in this report. Urban park/reserve is the same as Urban open space

* italicised units indicate the units used for previous reporting - see text above this table for a discussion on units used for reporting Olsen P target ranges.

NA = not available.

Table 5. Gravimetric Olsen P values used for target range comparison to SOE data

Soil order	Land-use categories	Target min. (mg/kg)	Target max. (mg/kg)
Allophanic	Cropping, horticulture, dairy, drystock, urban park/reserve	27	67
Allophanic, Brown, Gley	Plantation forestry	7	40
Brown, Gley	Cropping, horticulture	27	60
Brown, Gley	Dairy, drystock, urban park/reserve	20	60
Granular, Oxidic	Cropping, horticulture	25	56
Granular, Oxidic	Dairy, drystock, urban park/reserve	19	56
Granular, Oxidic	Plantation forestry	6	37
Melanic, Pallic, Semiarid	Cropping, horticulture	28	63
Melanic, Pallic, Semiarid	Dairy, drystock, urban park/reserve	21	63
Melanic, Pallic, Semiarid	Plantation forestry	7	42
Organic	Cropping, horticulture, dairy, drystock, urban park/reserve	35	69
Organic	Plantation forestry	9	52
Podzol	Cropping, horticulture	33	83
Podzol	Dairy, drystock, urban park/reserve	8	42
Podzol	Plantation forestry	8	50
Pumice	Cropping, horticulture, dairy, drystock, urban park/reserve	38	94
Pumice	Plantation forestry	10	57
Raw	Cropping, horticulture, dairy, drystock, urban park/reserve	7	37
Raw	Plantation forestry	7	44
Recent	Cropping, horticulture	25	57
Recent	Dairy, drystock, urban park/reserve	19	57
Recent	Plantation forestry	6	38
Ultic	Cropping. Horticulture	28	62
Ultic	Dairy, drystock, urban park/reserve	21	62
Ultic	Plantation forestry	7	41

Aggregate stability is required in the NEMS-SQ (2022) framework for regional soil-quality monitoring. There has been no critical review of the provisional target value set in the early 2000s, although Cavanagh et al. (2023) provide an overview of values that have been used for SOE reporting, which includes values based on mean weight diameter (MWD), and the proportion of aggregates above different sizes. The bulk of the collated data reports aggregate stability as MWD, which is also specified in the NEMS-SQ.

In the original development of the provisional target values in the early 2000s aggregate stability was also considered, with response curves constructed for cropping and horticulture on Recent and Pallic Soils, although there was insufficient knowledge and confidence to construct response curves for other land uses and soil orders (Sparling et al. 2008). Aggregate stability >2 mm MWD was considered optimal for production and environmental criteria, with insufficient aggregate stability more detrimental to environmental quality rather than production. Values <1.5 mm MWD were noted as cause for concern, hence we use an MWD of <1.5 mm as a threshold value for comparison with collated data.

3.5.2 Soil quality indicator reference ranges

Cavanagh, Drewry et al. 2025 undertook an extensive review of available data to update the existing target ranges and proposed revised reference ranges for the seven core soil quality indicators and HWEC. The term ‘reference ranges’ was used to better reflect the fact that these numeric ranges largely provide context for measured results (are referred to, as opposed to representing values to aim for, i.e. targets). The approaches used to develop reference ranges were based on what was identified as being the most relevant for the individual indicators within the constraints of the available data.

Ultimately, the reference ranges were based on similar approaches used for the original target ranges, but utilising more extensive and/or recent data. In summary, these approaches were:

- for pH and Olsen P: a fixed range based on agronomic recommendations for agricultural land uses, and distribution-based ‘typical values’ for non-agricultural land uses
- for C, N, AMN, and HWEC: distribution-based ‘typical values’ (10^{th} to 90^{th} percentile of monitoring data set) for different land uses and soil order groupings, with a function-based (crop yield) minimum value of 2%C for non-Allophanic mineral soils under cropping
- for macroporosity and bulk density: reference distributions based on a currently small data set of soils from unimpacted controls for pastoral and forestry sites.

The reference ranges developed for the individual indicators are shown in Table 6.

Table 6. Reference ranges for soil pH

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

Table 7. Reference ranges for Olsen P for different land-use categories and soil orders

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

Note: Soil orders with similar gravimetric values have been grouped and rounded to the nearest 5 mg/kg for ease of use. The exact conversions are shown in Appendix 6 of Cavanagh, Drewry et al. 2025.

[a] Converted to gravimetric values using relationships developed by Drewry et al. (2022).

[b] The conversion of values for Raw Soils is based on limited data

[c] Developed from Nicholls et al. 2012 and Reid & Morton 2019; see Cavanagh, Drewry et al. 2025 for further details

[d] NZ Winegrowers 2024.

[e] Podzols only; no reference range for vineyards on Organic Soils.

[f] Developed from Reid & Morton 2019; see Cavanagh, Drewry et al. 2025 for further details.

[g] Depth-adjusted value for conversion of volumetric recommendations for pasture based on 7.5 cm depth (from Morton & Roberts 2024, Roberts & Morton 2023, and Morton et al. 2020), to 10 cm depth equivalent (based on Power et al. 2023: $OP_{10} = (OP_{7.5} - \beta_0)/\beta_1$, where $\beta_0 = 2.06$ and $\beta_1 = 1.64$. Applies to both volumetric and gravimetric values.

[h] Podzol.

[i] Organic soil (peat).

[j] For urban sites, the agronomic recommendation for pasture in sedimentary soils of 20 mg/L is used as an upper threshold from which gravimetric values were determined.

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

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

Table 8. Reference range for soil C (%) for different land-use categories and soil-order groups

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

[a] Values rounded to the nearest 0.5%.

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

Table 9. Reference range for total N (%) in mineral soils for aggregated land-use categories and soil orders

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

Table 10. Reference range for C:N ratio across all soil orders

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

Table 11. Reference range for AMN (mg/kg) for different land-use categories and soil-order groupings for mineral soils

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

* 16th percentile in non-Allophanic mineral cropping soils.

Table 12. Reference ranges for HWEC (mg/kg) for different land-use categories for all mineral soils[a]

Land-use group	Reference range (mg/kg)
Cropping	800[b]–1,500
Orchard	850–2,500
Vineyard	1,200–1,800
Dairy	1,400–4,000
Drystock	1,100–3,600
Plantation forestry	1,300–3,100
Indigenous vegetation	2,000–6,500

[a] Insufficient Organic Soils samples were available to develop reference ranges.

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

Table 13. Reference range for macroporosity (%, –10 kPa) for all soil orders

Land use	Reference range (%, –10 kPa)*
All land uses excluding forestry	10–21
Plantation forestry, indigenous vegetation	14–35

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

Table 14. Reference ranges for bulk density (g/cm^3) for soil-order groups

Land use	Soil order	Reference range (g/cm^3)	Upper limit (g/cm^3)
All land uses excl. plantation forestry	Organic	0.5–0.8	NA
	Soils (excl. Raw, Organic, Pumice[a])	0.7–1.0	1.4
All	Raw soils[b]	1.4	1.4
Plantation forestry	Allophanic	0.5–0.8	NA
	Pumice	0.7–0.9	NA
	Soils (excl. Raw[b], Allophanic, Pumice, Organic[a])	0.7–1.3	1.4

[a] No information available for this soil order for this land use.

[b] Higher bulk density is expected for Raw and Recent Soils derived from iron sands.

NA = not available.

3.5.3 Ecological soil guideline values (Eco-SGVs)

Currently there is no national approach or consensus for trace element concentrations in the context of national soil health reporting. Eco-SGVs, which were developed to protect terrestrial biota (soil microbes, invertebrates, plants, wildlife, and livestock), provide a useful way to readily assess the potential environmental impact from environmental contaminants, and thus provide an option for the future reporting of trace elements.

The development of Eco-SGVs for common soil contaminants to help protect environmental receptors (including microbes, invertebrates, plants, and higher animals) in soils and their associated ecosystems for New Zealand was funded through an Envirolink Tools Grant C09X1402 and completed in 2016. These Eco-SGVs were updated in 2019 in light of a national review undertaken in 2018 and international developments in the methodology for the development of such values since the completion of the Tools project. The detailed methodology and changes made during the update are provided in Cavanagh (2019a, b). Further updates were made in 2022 and 2023 in light of proposed changes under resource management reform. The Eco-SGVs provided in Cavanagh & Harmsworth 2023 include updates to background soil concentrations that underpin the Eco-SGVs. Further refinement of background soil concentrations by Cavanagh, Thompson-Morrison, McNeill et al. 2025 did not alter the Eco-SGVs.

These values are based on toxicological studies of the effect of different contaminants on different organisms and take into account spatial variation in naturally occurring background concentrations. Eco-SGVs have been developed with differing levels of protection that are applicable for use in the protection of soil quality and the management of contaminated land. For Cu and Zn sufficient information is available to provide Eco-SGVs for different soil types. These soil types are classified as typical, sensitive, and tolerant soils based on pH, clay content, organic C, and cation exchange capacity (CEC). Sensitive soils are those in which lower concentrations may give rise to negative effects on soil biota compared with typical or tolerant soils, and would have lower pH, C, and/or CEC. The properties of these soils were based on values of Brown, Recent and Allophanic Soils, determined from soils data held in the NSDR data to represent properties associated with typical, sensitive, and tolerant soils, respectively. The derived Eco-SGVs for commonly measured trace elements for different land uses are shown in Tables 15 and 16.

The 95% protection-level Eco-SGVs are those concentrations below which less than minor contaminant-related effects will occur, and they were used for comparison with the soil quality monitoring results. For Cu and Zn the 'sensitive' soil Eco-SGVs were also used at the 95% protection level.

Table 15. Eco-SGVs (mg/kg) developed for selected contaminants based on the estimated median ambient concentration

% protection[a]	As (mg/kg)	B (mg/kg)	B-HWS (mg/kg)	Cd_{BM}[b] (mg/kg)	Cr (mg/kg)	Pb_{BM}[b] (mg/kg)
95%	20	14	7	1.5	200	290
80%	60	22	15	12	400	900[1]
60%	150	25	17	35	660	2,500[1]

Source: Modified from Cavanagh & Harmsworth 2023.

[a] Differing levels of protection have been developed to assist both with the protection of soil quality and the management of contaminated land: the 95% protection level is used to indicate the concentrations below which less than minor contaminant-related effects are expected to occur; the 80% protection level is used to indicate the concentration at which more than minor effects may start to occur, and is suggested to be a trigger to indicate when ongoing deliberate inputs of contaminants (e.g. Cu fungicides) should cease (agricultural and horticultural land) and a site investigation should be carried out for potentially contaminated land; the 60% protection level is used to indicate the concentration at which more than minor effects are likely to occur and/or significant adverse effects are occurring, and is used in the management of potentially contaminated land for which there is a greater expectation of action to reduce risk.

[b] An extra 5% protection applied to each land use to provide protection against secondary poisoning.

Notes: BM = biomagnification; B-HWS = boron – hot-water soluble.

Table 16. Eco-SGVs (mg/kg) developed for Cu and Zn contamination in the three New Zealand reference soils based on the estimated median ambient concentration

% protection[a]	Cu typical soil (mg/kg)	Cu sensitive soil[b] (mg/kg)	Cu tolerant soil (mg/kg)	Zn typical soil (mg/kg)	Zn sensitive soil[b] (mg/kg)	Zn tolerant soil (mg/kg)
95%	110	**95**	135	200	**180**	250
80%	245	**190**	350	320	**285**	410
60%	430	**330**	640	510	**450**	645

Source: Modified from Cavanagh & Harmsworth 2023.

[a] Differing levels of protection have been developed to assist both with the protection of soil quality and the management of contaminated land: the 95% protection level is used to indicate the concentrations below which less than minor contaminant-related effects are expected to occur; the 80% protection level is used to indicate the concentration at which more than minor effects may start to occur and is suggested to be a trigger to indicate when ongoing deliberate inputs of contaminants (e.g. Cu fungicides) should cease (agricultural and horticultural land), and a site investigation should be carried out for potentially contaminated land; the 60% protection level is used to indicate the concentration at which more than minor effects are likely to occur and/or significant adverse effects are occurring, and is used in the management of potentially contaminated land for which there is a greater expectation of action to reduce risk.

[b] Suggested default Eco-SGV.

3.5.4 Tiered Fertiliser Management System

For Cd, which is a contaminant present in phosphate fertilisers, it is also useful to compare concentrations with those specified in the Tiered Fertiliser Management System (TFMS). The TFMS was developed as part of the National Cadmium Management Strategy (Cadmium Management Group 2019) to help minimise the accumulation of Cd in soil arising from fertiliser use. The TFMS sets out increasingly stringent restrictions on the choice and rate of phosphate fertiliser as soil Cd increases. The trigger values identifying the need to change to different management tiers, and the management actions required, are shown in Table 17.

Table 17. Summary of Tiered Fertiliser Management System tiers, trigger values, and management action required at different Cd concentrations

Tier number	Cd concentration (mg/kg)	Description
Tier 0	<0.6	Considered to be within naturally occurring background concentrations. A repeat soil Cd sampling in 5 years is recommended.
Tier 1	0.6	The choice of fertiliser product and rates is restricted to those that follow Tier 1 to Tier 3 recommendations presented in the TFMS document.
Tier 2	1.0	
Tier 3	1.4	
Tier 4	1.8	No net accumulation of soil Cd.

3.6 Trend analysis

The objective of the trend analysis was to determine whether soil quality indicators have changed over time under different land uses. The detailed methodology and the steps taken to clean, transform, and analyse the data are found in the R markdown (Rmd) file included as a separate file. Trend analyses include code based on previous trend analysis and described in Stevenson & McNeill 2020, in addition to further analyses described here. Summary parameters of the data set used for trend analysis are provided in Table 18.

Table 18. New Zealand regions with the number of valid data points within each region

Region	No. samples	No. sites	First year	Last year	Sites with missing soil order	Sites missing land use
Auckland	660	184	1996	2024	0	0
Bay of Plenty	369	87	1999	2025	3	3
Canterbury	374	279	1996	2025	0	0
Gisborne	72	72	2021	2023	0	0
Hawke’s Bay	237	115	2000	2025	0	0
Manawatu-Wanganui	176	102	2015	2024	0	0
Marlborough	360	100	2000	2024	0	0
Nelson	15	15	2018	2018	0	0
Northland	130	29	2001	2022	0	0
Otago	56	56	2022	2024	0	0
Southland	121	57	2010	2024	0	0
Taranaki	128	60	1999	2022	0	0
Tasman	86	37	2001	2023	0	0
Waikato	707	161	1996	2024	1	0
Wellington	550	118	2000	2025	0	0
Total	**4,041**	**1,472**			**4**	**3**

For each indicator, data were filtered to contain only sites that had been sampled more than once. In total, 923 sites were repeat sampled, and of these 774 did not change land use over the sampling period (1996–2025) while 149 changed land use.

Sites with Raw and Oxidic Soils were filtered out of the data set due to low numbers (two and one, respectively), and urban open space and rural residential land uses were also excluded due to low sampling numbers in these land uses. Any sites classified as ‘other’ or ‘unused’ land use were also excluded from the trend analysis. One outlier data point was removed for total C, total N, and C:N ratio, as the C and N concentrations of 0.3% and 10.1%, respectively, were judged to be erroneous data. Where land-use categories contained only two sampling time-points for any indicator, these categories were excluded for that indicator.

Indicator data were transformed, where necessary, to stabilise the variance (Table 19). Following this, linear mixed effects models (or repeated measures analysis of variance [ANOVA]) were fitted to the data using the *lme4* package (Bates et al. 2015). In each model the fixed effects comprised sampling year, land-use category, and the interaction between these two variables. For each indicator a model-fitting process was undertaken using different combinations of random effects, including soil order, site, and region, to select the correct random effects structure. These random effects were chosen to control for the effects of soil order and sampling site on indicator status, recognising that some soil orders may have inherently different indicator status (e.g. Organic Soils naturally contain higher C than other soil orders), and that site-specific conditions can affect soil quality measures (e.g. iron sand naturally contain higher particle density, increasing bulk density).

Region was included to control for pedoclimatic variation influencing soil quality indicator status. Random effects were set with random intercepts only. ANOVA was used to determine whether there was a significant difference between the models compared, and final models were chosen based on the Akaike information criterion (AIC; a standard model selection tool was used to evaluate the relative goodness of fit of statistical models to data). Only random effects that resulted in a significantly improved model fit were used. Any model fits that produced warnings were excluded as options. The random effects used for each indicator are detailed in Table 19, with explained variances detailed in Appendix 3. Other assumptions of the linear mixed effect models were assessed, including normality of random effects, constant variance of errors, and no multicollinearity; no problematic violations of these assumptions were identified, except for HWEC and fluorine (see sections 4.4.9 and 4.4.10, respectively).

Table 19. Model details for each indicator, including the number of sites included for the trend analysis over 1996–2025, if and how the data were transformed to improve normality, and the random effects included in the model

Indicator	No. sites in trend analysis	Data transformation	Model random effects
Olsen P	731	Log	Soil order, site, region
Total C	733	Log	Soil order, site, region
Total N	733	Log	Soil order, site, region
AMN	731	Square root	Soil order, site
pH	731	None	Soil order, site, region
Bulk density	731	None	Soil order, site, region
Macroporosity	708	Square root	Soil order, site, region
C:N ratio	733	Log	Soil order, site, region
HWEC	219	Log	Soil order, site, region
As	658	Log	Soil order, site, region
Cd	715	Log	Soil order, site, region
Cr	660	Log	Soil order, site, region
Cu	658	Log	Soil order, site, region
Ni	658	Log	Soil order, site, region
Pb	658	Log	Soil order, site, region
Zn	658	Log	Soil order, site, region
F	289	None	Soil order, site, region

Using the models derived for each indicator, changes over time for each land-use category were quantified using the emtrends function from the *emmeans* package (Lenth 2025). Statistically significant changes over time were represented by confidence intervals around the trend that did not include zero and a $P < 0.05$.

Modelled trends and 95% confidence intervals were computed for each land-use category based on the derived models for each indicator using the *ggeffects* package (Lüdecke 2018). These trends and confidence intervals were plotted alongside measured data for each indicator.

Trend analysis for sites that were identified as having changed land use over the sampling period was investigated using the same approach as described above and using land-use change categories. These categories included ‘subtle’ changes such as consistent change in classification between dairy and drystock, or vegetable cropping and short-rotation cropping, as well as more obvious changes between dairy/drystock and cropping or dairy/drystock and plantation forestry (Table 20).

As can be seen from Table 20, there is a high number of ‘other’ types of land-use change. Along with the variable duration of the time since land-use change, which may influence the extent to which any changed land management practices have influenced soil indicators, and uncertainty about whether an actual land-use change occurred (e.g. between short-rotation cropping and vegetable cropping, dairy and drystock), this meant there was low confidence in the value of the trend analyses. Therefore the results of these exploratory analyses are not included in this report. This trend analysis for sites that have changed land use could be revisited in the future, taking into account the time since land-use change occurred and using this as a model parameter.

Table 20. Numbers of sites in each land-use change category

Land-use change	Number of sites
Dairy to drystock	18
Drystock to dairy	8
Vegetable cropping to short-rotation cropping	26
Short-rotation cropping to perennial horticulture	11
Plantation forestry to pasture	9
Pasture to plantation forestry	5
Other	72
Total	**149**

4 Results

4.1 Comparison between target ranges and reference ranges for core indicators

Direct comparison between the number of sites not meeting target ranges or reference ranges is confounded by the different land-use categories used, whether an upper or lower limit was specified, and the availability of values for different soil orders. Table 3 illustrates the different land-use categories used, while Table 21 provides a summary of the availability of target ranges and reference range values. Table 22 provides a qualitative indication of the significance of sites falling outside the target or reference range.

A further difference is that indigenous vegetation has not been compared with target ranges in previous reporting because it is not a managed system. The different approach used in the development of reference ranges allowed these to be developed for indigenous vegetation. However, for most of the comparisons below, information relating to indigenous vegetation has been excluded to provide greater comparability. Parameters for which both target ranges and references are compared (i.e. HWEC and aggregate stability) are not discussed here, but are covered in section 4.2.

Table 21. Overview of differences in the availability of target ranges or reference ranges for individual indicators*

Indicator	Target ranges	Reference ranges
pH	All soil orders and land uses	All soil orders and land uses
Olsen P	All soil orders and land uses	No values for Organic Soils on vineyards; no lower limits for urban open space and no upper or lower limits for plantation forestry
Total C	No values for Organic Soils; no upper limits	All soils and land use; no upper limit for Organic Soils or Allophanic Soils for vineyards
Total N	No target ranges for cropping, orchard/ vineyard land use	All soils and land use, except Allophanic Soils for vineyards
AMN	All soil orders and land uses; no upper values	No values for Organic Soils
HWEC	None	No values for Organic Soils
Macroporosity	All soil orders and land uses	All soil order and land use
Bulk density	All soil orders and land uses	No values for Pumice Soils for all land uses except forestry; no values for Organic Soils for forestry; no upper limit for Organic, Allophanic or Pumice Soils

* Target ranges were not used for comparing indigenous vegetation sites because they are not part of managed systems; the different approach used for the development of reference ranges allowed these to be developed for indigenous vegetation sites.

Table 22. Traffic light indication of the significance of parameter values falling outside target or reference ranges. Green: continue to monitor; orange: review to verify if values are acceptable for the site and/or if management practices can improve production or environmental outcomes; red: investigate and implement land management practices to improve soil quality or mitigate potential negative environmental (or production) outcomes

Indicator	Target range				Reference range			
	Below	Within	Above	Investigation level	Below	Within	Above	Investigation level
pH	Production		Production		Production		Production	
Olsen P – vegetable cropping	Production		Environment		Production		Environment	Environment
Olsen P – all other land uses	Production		Environment		Production		Environment	
Total C – cropping, dairy, drystock	Environment and production		NL	Environment and production	Environment and production			
Total C – all other land uses	Environment and production		NL		Environment and production			
Total N	NL	NL	NL				Environment	
AMN	Environment and production		NL		Environment and production			
HWEC	NA	NA	NA		Environment and production			
Macroporosity	Environment and production		Environment and production		Environment and production		Environment and production	
Bulk density	Environment and production		Environment and production		Environment and production		Environment and production	Environment and production
Aggregate stability	Environment		NL		Environment		NL	

NL = no limit; NA = not applicable.

Notwithstanding the difference in the exact number of results assessed, comparison with reference ranges generally results in a higher number of results being identified as falling outside the range (Table 23).

Table 23. Sum of the number of results falling below, within or above, and percentage within, target or reference ranges for all indicators (includes indigenous land use)

Time-step	Target range					Reference range				
	Below	Within	Above	Total	% within	Below	Within	Above	Total	% within
2018–2022	548	3,684	316	4,548	81	785	2,865	1,091	4,741	60
2022–2025	487	3,388	310	4,185	81	748	2,662	1,060	4,470	60

Note: The total is the total number of results compared to a target or reference range.

This difference is partly due to the absence of upper values for target ranges for AMN and total C, and the absence of target ranges for total N for cropping. However, bulk density and Olsen P have markedly fewer sites falling within the reference range, arising from the markedly higher number of sites above the specified reference ranges compared to the target ranges (Tables 24 and 25). These changes are, in turn, largely a result of a ‘narrowing’ of the reference range for these indicators. We note that the Olsen P reference range is largely based on agronomic recommendations.

The bulk density reference range is based on a relatively small data set, but the number of sites above the reference range is more consistent with the findings of the macroporosity results, which show a similar number of sites below the macroporosity reference range (this is also based on a relatively small data set). For bulk density, a less restrictive upper limit of 1.4 g/cm^3 based on function was also proposed for some soil orders (Table 14). This value is similar to the upper values for the target range, and, not surprisingly, the number of sites exceeding this upper limit is more similar to those exceeding upper values for the target range (Table 26).

Table 24. Comparison of the number of results falling below, within or above target or reference ranges for individual indicators over the first time-step period, 1 July 2018 to 30 June 2022

Indicator	Target range				Reference range*			
	Below	Within	Above	Total	Below	Within	Above	Total
pH	3	668	16	687	83	505	99	**687**
Olsen P	185	341	161	687	143	202	342	**687**
Total C	49	625	NA	674	93	528	66	**687**
Total N	13	365	74	452	68	551	68	**687**
AMN	18	669	NA	687	81	532	60	**673**
Macroporosity	266	390	22	678	274	311	93	**678**
Bulk density	14	626	43	683	43	236	363	**642**

* Excluding results for indigenous vegetation to facilitate greater comparability.

Table 25. Comparison of the number of sites falling below, within or above target or reference ranges for individual indicators over the second time-step period, 1 July 2022 to 30 June 2025

Indicator	Target range				Reference range*			
	Below	Within	Above	Total	Below	Within	Above	Total
pH	2	611	19	632	55	473	118	**646**
Olsen P	177	280	175	632	127	200	316	**643**
Total C	39	577	0	616	112	471	63	**646**
Total N	14	328	74	416	89	483	74	**646**
AMN	23	608	0	631	99	455	74	**628**
Macroporosity	211	385	33	629	223	340	80	**643**
Bulk density	21	599	9	629	47	246	326	**619**

* Excluding results for indigenous vegetation to facilitate greater comparability.

Table 26. Number of sites with bulk density equal to or below and above the upper limit of 1.4 g/cm^3

Land-use category	2018–2022			2022–2025		
	Equal or below	Above	NA	Equal or below	Above	NA
Cropping	121	30	5	113	3	5
Dairy	146	7	4	125	1	6
Drystock	195	3	3	158	6	3
Indigenous vegetation	40	-	3	54	-	2
Orchard	36	1	1	46	-	2
Plantation forestry	38	-	12	52	-	19
Rural residential	6	-	-	1	-	-
Vineyard	32	3	-	43	-	-
Urban open-space	-	-	-	37	NA	NA
Total	**614**	**44**	**28**	**629**	**10**	**37**

NA = not applicable: a limit of 1.4 g/cm^3 is not applicable to certain soil orders (e.g. Organic Soils, Pumice Soils); hyphen indicates no sites fell into this category.

4.2 Comparison with guideline values

4.2.1 Core soil quality indicators

This is the first time aggregate stability results have been collated. The two most commonly measured parameters are shown in Table 27, with the initial analysis showing reasonable availability of results for cropping sites and much more limited data available for non-cropping sites across the different time points. For this reason, a discussion on aggregate stability is only provided in the cropping sites section below.

Table 27. Number of results for aggregate stability (MWD and %>1 mm) and total number of sites in the soil quality monitoring data set for all land uses, cropping and non-cropping sites, over the previous time period and the individual time-steps considered in this report

Time-step	All land uses			Cropping sites			Non-cropping sites		
	No. of measures for MWD	No. of measures for % >1 mm	Total	No. of measures for MWD	No. of measur es for % >1 mm	Total	No. of measures for MWD	No. of measures for % >1 mm	Total
Pre-2018	241	18	**2,577**	47	2	**352**	194	16	**2,225**
2018–2022	225	73	**740**	133	47	**160**	92	26	**580**
2022–2025	220	156	**713**	103	70	**124**	117	86	**589**

A summary of the percentage of sites within the reference ranges for the individual land uses is shown in Tables 28–34. This does not include rural residential (lifestyle blocks) as a specific land-use class, given the low numbers (six and one) in the two monitoring periods. However, further discussion on lifestyle blocks is provided below (see also Tables 34 and 35).

Cropping sites

Cropping sites were generally within the refence range for most indicators for both monitoring periods, although a moderate (c. 30%) to high (>50%) percentage of sites were above the Olsen P reference ranges for vegetable or short-rotation cropping (Table 28). A moderate percentage of sites were below the reference ranges for organic matter-related indicators (total C, total N, AMN, and HWEC). A high percentage of sites were above the reference range for bulk density and below the aggregate stability threshold of 1.5 mm MWD (Table 29), indicating degradation of the soil physical structure. This was less evident in the macroporosity results, where the sites were relatively evenly distributed between below, within, and above the reference range (2018–2022) or mostly within the reference range (2022–2025). However, this may reflect anecdotal observations of the influence of cultivation at the time of sampling, which is expected to more significantly influence (increase) macroporosity measurement. In contrast to the cropping sites, there is a much greater percentage of non-cropping sites that were equal to or above the aggregate stability threshold of 1.5 mm MWD.

Table 28. Percentage of sites falling outside and within the reference ranges in the cropping land-use category over the two monitoring periods, and number of sites (*n*) for which measurements are available

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	1	84	15	160	0	87	13	123
Olsen P – vegetable cropping	2	65	33	63	3	48	50	40
Olsen P – short-rotation cropping	1	38	61	97	1	38	61	82
Total C	16	78	6	160	20	75	5	123
Total N	18	80	2	160	24	73	3	123
AMN	14	80	6	155	25	68	7	117
HWEC	31	60	9	122	35	56	9	101
Macroporosity	25	43	33	159	16	61	23	122
Bulk density	3	13	85	156	2	13	85	121

Table 29. Percentage of sites falling below, equal to, or above the mean weight diameter 'threshold' of 1.5 mm

Time period	Cropping			Non-cropping		
	% below	% equal or above	*n*	% below	% equal or above	*n*
2018–2022	60	40	133	16	84	92
2023–2025	65	35	103	9	91	117

Dairy sites

Dairy sites were generally within the refence range for most indicators for both monitoring periods, although a high percentage of sites were above the Olsen P reference range and were also compacted (as indicated by a high percentage of sites below the macroporosity reference range and a high percentage above the bulk density reference range) (Table 30).

Table 30. Percentage of sites falling within the reference ranges in the dairy land-use category over the two monitoring periods

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	12	73	15	177	10	67	23	150
Olsen P	12	16	71	177	19	13	68	150
Total C	15	75	10	177	14	75	11	150
Total N	7	81	11	177	5	77	18	150
AMN	13	81	6	173	19	70	10	144
HWEC	11	89	-	102	6	91	3	111
Macroporosity	65	32	3	176	52	37	11	150
Bulk density	6	40	54	157	7	45	48	132

Hyphen indicates no sites fell into this category

Drystock sites

Drystock sites were generally within the refence range for most indicators for both monitoring periods, although only a low proportion of sites were within the Olsen P reference range (Table 31). In contrast to dairy land use, a slightly higher proportion of sites were below the Olsen P reference range compared to those that were above. A moderate percentage of sites showed signs of compaction, with a moderate percentage below the macroporosity reference range and a moderate to high percentage above the bulk density reference range.

Table 31. Percentage of sites falling within the reference ranges in the drystock land-use category over the two monitoring periods

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	23	64	13	218	16	63	21	170
Olsen P	45	19	36	218	49	17	34	168
Total C	13	77	10	218	25	65	10	170
Total N	8	79	13	218	22	68	10	170
AMN	9	86	5	215	14	79	7	167
HWEC	3	91	6	97	6	89	5	132
Macroporosity	37	53	10	214	41	51	8	169
Bulk density	8	45	47	201	8	39	52	166

Orchard sites

Orchard sites were generally within the refence range for most indicators for both monitoring periods, although a high percentage of sites were above the Olsen P reference range (Table 32). There was an even distribution of sites falling within and above the pH reference range. A moderate percentage of sites showed signs of compaction, with a moderate percentage below the macroporosity reference range and a moderate to high percentage above the bulk density reference range.

Table 32. Percentage of sites falling within the reference ranges in the orchard land-use category over the two monitoring periods

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	-	53	48	40	-	56	44	50
Olsen P	3	10	88	40	-	30	70	50
Total C	8	73	20	40	16	70	14	50
Total N	3	65	33	40	6	80	14	50
AMN	5	64	31	39	15	73	13	48
HWEC	10	76	14	29	11	86	3	36
Macroporosity	23	67	10	39	50	48	2	50
Bulk density	11	54	35	37	10	40	50	48

Hyphen indicates no sites fell into this category

Vineyard sites

Vineyard sites were generally within the refence range for most indicators for both monitoring periods (Table 33). However, a high percentage of sites showed signs of compaction, with a high percentage below the macroporosity reference range and a high percentage above the bulk density reference range. Most sites fell outside the references ranges for Olsen P, with a large number of sites falling both below and above the ranges. While most sites were within the total C and total N reference ranges for both time periods, a moderate percentage were above or below the AMN reference range. Only a small number of sites had results for HWEC.

Table 33. Percentage of sites falling within the reference ranges in the vineyard land-use category over the two monitoring periods

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	9	91	-	35	11	84	5	44
Olsen P	40	20	40	35	34	27	39	44
Total C	0	91	9	35	2	86	11	44
Total N	3	94	3	35	2	93	5	44
AMN	17	57	26	35	2	59	39	44
HWEC	14	71	14	7	0	75	25	8
Macroporosity	60	29	11	35	30	49	21	43
Bulk density	0	9	91	35	0	14	86	43

Hyphen indicates no sites fell into this category

Plantation forestry

Plantation forestry sites were generally within the refence range for all indicators for both monitoring periods (Table 34). There was a moderate percentage of sites lower than the bulk density reference range in both timepoints.

Table 34. Percentage of sites falling within the reference ranges in the plantation forestry land-use category over the two monitoring periods

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	8	88	4	51	8	83	8	71
Olsen P	-	84	16	51	-	82	18	71
Total C	14	75	12	51	17	76	7	71
Total N	10	84	6	51	14	82	4	71
AMN	14	68	18	50	14	73	13	70
HWEC	5	81	14	21	30	61	9	54
Macroporosity	16	73	10	49	13	75	13	71
Bulk density	20	74	6	50	20	76	4	71

Hyphen indicates no sites fell into this category

Indigenous vegetation

Indigenous vegetation sites were generally within the refence range for most indicators for both monitoring periods (Table 35). However, there was a high percentage and a moderate percentage of sites that were above the Olsen P reference range for the first and second monitoring time-points, respectively. Approximately half of the sites were within the bulk density reference range, with a low to moderate percentage above or below the reference range. In the first monitoring period a moderate percentage of sites were above the macroporosity reference range, while in the second monitoring period a moderate percentage of sites were below the macroporosity reference range. Some of this variability may be associated with the differing nature of indigenous vegetation sites, which can include riparian plantings (i.e. retirement of pastoral land) as well as undisturbed native forest.

Table 35. Percentage of sites falling within the reference ranges in the indigenous vegetation land-use category over the two monitoring periods

Indicator	2018–2022				2022–2025			
	% below	% within	% above	*n*	% below	% within	% above	*n*
pH	16	73	11	44	10	81	8	59
Olsen P	-	50	50	44	-	73	27	59
Total C	5	77	18	44	14	76	10	59
Total N	5	73	23	44	8	78	14	59
AMN	5	80	15	41	9	77	14	57
HWEC	15	76	9	33	35	65	-	20
Macroporosity	5	69	26	42	24	69	7	59
Bulk density	44	44	12	41	20	45	36	56

Hyphen indicates no sites fell into this category

Urban open space

Urban open space sites were only monitored in the second monitoring period. The majority of sites fell within the reference ranges for most parameters (Table 36), but the majority were above the Olsen P reference range, and a moderate percentage were also above the total N reference range. Some of this variability may be associated with a differing intensity of management of the urban open space sites.

Table 36. Percentage of sites falling within the reference ranges in the urban open-space land-use category over 1 July 2022 to 30 June 2025 period

Indicator	2022–2025			
	% below	% within	% above	*n*
pH	3	92	5	37
Olsen P	-	43	57	37
Total C	5	78	16	37
Total N	5	57	38	37
AMN	-	81	19	37
HWEC	27	70	3	37
Macroporosity	8	70	22	37
Bulk density	3	92	5	37

Note: No urban open-space sites were sampled in the 1 July 2018 to 30 June 2022 period. Hyphen indicates no sites fell into this category

Lifestyle blocks

The variable identification of lifestyle blocks, combined with the small number of sites that have been identified as such, means it is not possible to undertake any further analysis of any difference in soil quality between commercial operations and ‘hobby’ farmers for a given land use. To provide visibility of the soil quality at sites that have been identified as lifestyle blocks, Tables 37 and 38 present the number of lifestyle blocks with a different ‘primary’ land use that fall below, within or above relevant reference ranges for the first and second monitoring period, respectively.

Table 37. Summary of the number of lifestyle blocks with different 'primary' land uses that fall below, within or above relevant reference ranges for the monitoring period 1 July 2018 to 30 June 2022

Indicator	Primary land use	Below	Within	Above
AMN	Cropping	-	3	-
AMN	Drystock	-	2	-
AMN	Perennial horticulture	-	3	-
AMN	Rural residential	1	5	-
Bulk density	Cropping	-	3	-
Bulk density	Drystock	-	2	-
Bulk density	Perennial horticulture	1	2	-
Bulk density	Rural residential	-	6	-
Macroporosity	Cropping	2	1	-
Macroporosity	Drystock	1	1	-
Macroporosity	Perennial horticulture	3	-	-
Macroporosity	Rural residential	2	3	1
Olsen P	Cropping	2	1	-
Olsen P	Drystock	1	1	-
Olsen P	Perennial horticulture	-	2	1
Olsen P	Rural residential	5	1	-
Total C	Cropping	-	3	-
Total C	Drystock	-	2	-
Total C	Perennial horticulture	-	3	-
Total C	Rural residential	-	6	-
Total N	Drystock	-	-	2
Total N	Rural residential	-	5	1
pH	Cropping	-	3	-
pH	Drystock	-	2	-
pH	Perennial horticulture	-	3	-
pH	Rural residential	-	6	-

Hyphen indicates no sites fell into this category

Table 38. Summary of the number of lifestyle blocks with different ‘primary’ land uses that fall below, within or above relevant reference ranges for the monitoring period 1 July 2022 to 30 June 2025

Indicator	Primary land use	Below	Within	Above
AMN	Dairy	1	3	1
AMN	Orchard	1	3	-
AMN	Rural residential	1	-	-
Bulk density	Dairy	1	5	1
Bulk density	Orchard	1	2	1
Bulk density	Rural residential	-	-	1
HWEC	Rural residential	-	1	-
Macroporosity	Dairy	2	5	-
Macroporosity	Orchard	3	1	-
Macroporosity	Rural residential	-	-	1
Olsen P	Dairy	1	2	4
Olsen P	Orchard	-	2	2
Olsen P	Rural residential	-	-	1
Total C	Dairy	3	2	2
Total C	Orchard	-	3	1
Total C	Rural residential	-	1	-
Total N	Dairy	1	4	2
Total N	Orchard	-	3	1
Total N	Rural residential	-	1	-
pH	Dairy	-	3	4
pH	Orchard	-	3	1
pH	Rural residential	-	1	-

Hyphen indicates no sites fell into this category

Multiple exceedances

Table 39 presents the number of monitored sites with data that fall outside the reference ranges (i.e. sites that did not meet the reference ranges) for multiple indicators. Only the seven core soil quality indicators (pH, Olsen P, total C, total N, AMN, bulk density, and macroporosity) are included. Also, only soil orders and land uses with derived reference ranges are included (i.e. sites with no specified reference ranges, such as total N measures for vineyards on Allophanic Soils, are not included in counts). Furthermore, some sites had data measured for only some of the seven core indicators. The minimum number of indicators measured per site was two. These data are visualised, and land-use categories included, in Figure 2 (2018–2022) and Figure 3 (2022–2025).

Table 39. Number of sites not meeting reference ranges for multiple indicators for the two time-steps considered in this report

Core indicator reference ranges not met	No. sites, 2018–2022	No. sites, 2022–2025
0	25	34
1	132	114
2	207	191
3	168	74
4	99	105
5	56	57
6	24	26
7	12	5
Total	**723**	**706**

Note: Indicators considered are the seven core indicators (i.e. pH, Olsen P, total C, total N, AMN, bulk density and macroporosity).

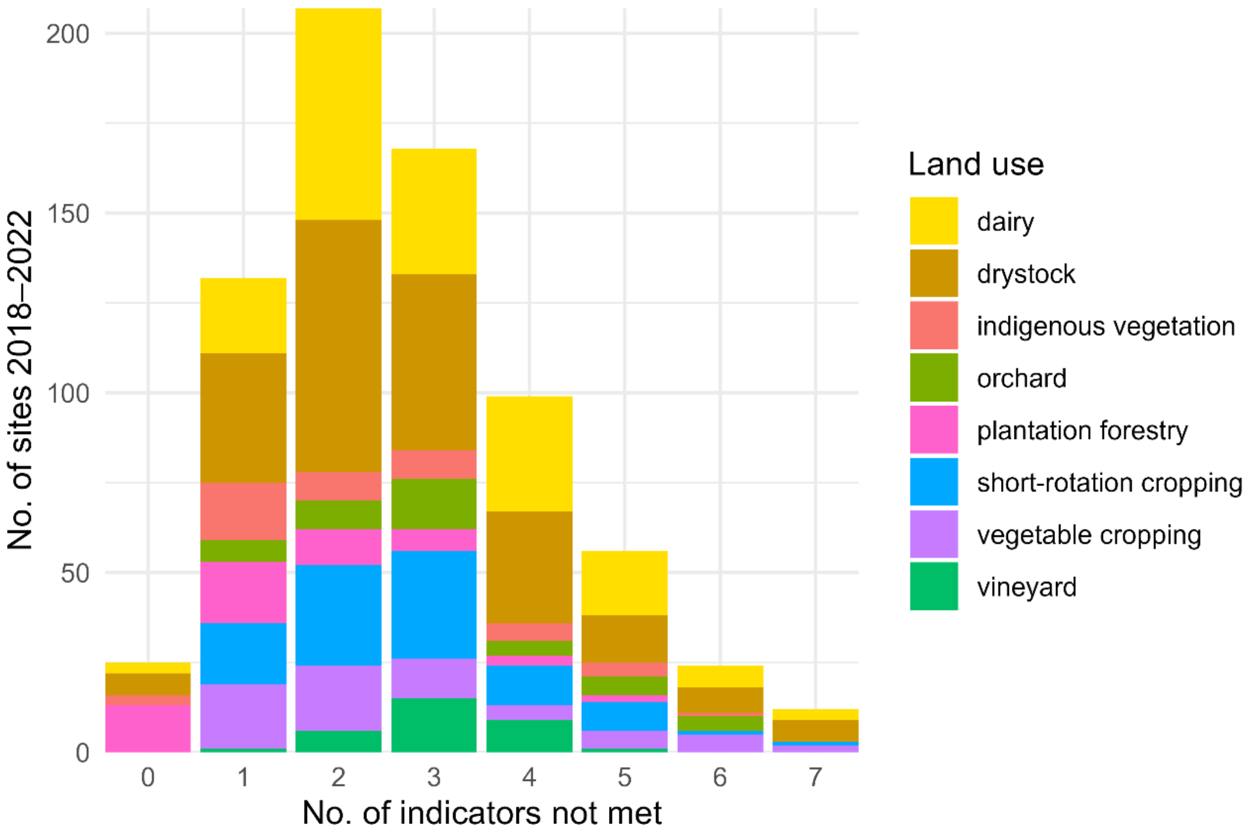

Figure 2. Number of sites not meeting reference ranges for multiple indicators between 2018 and 2022.

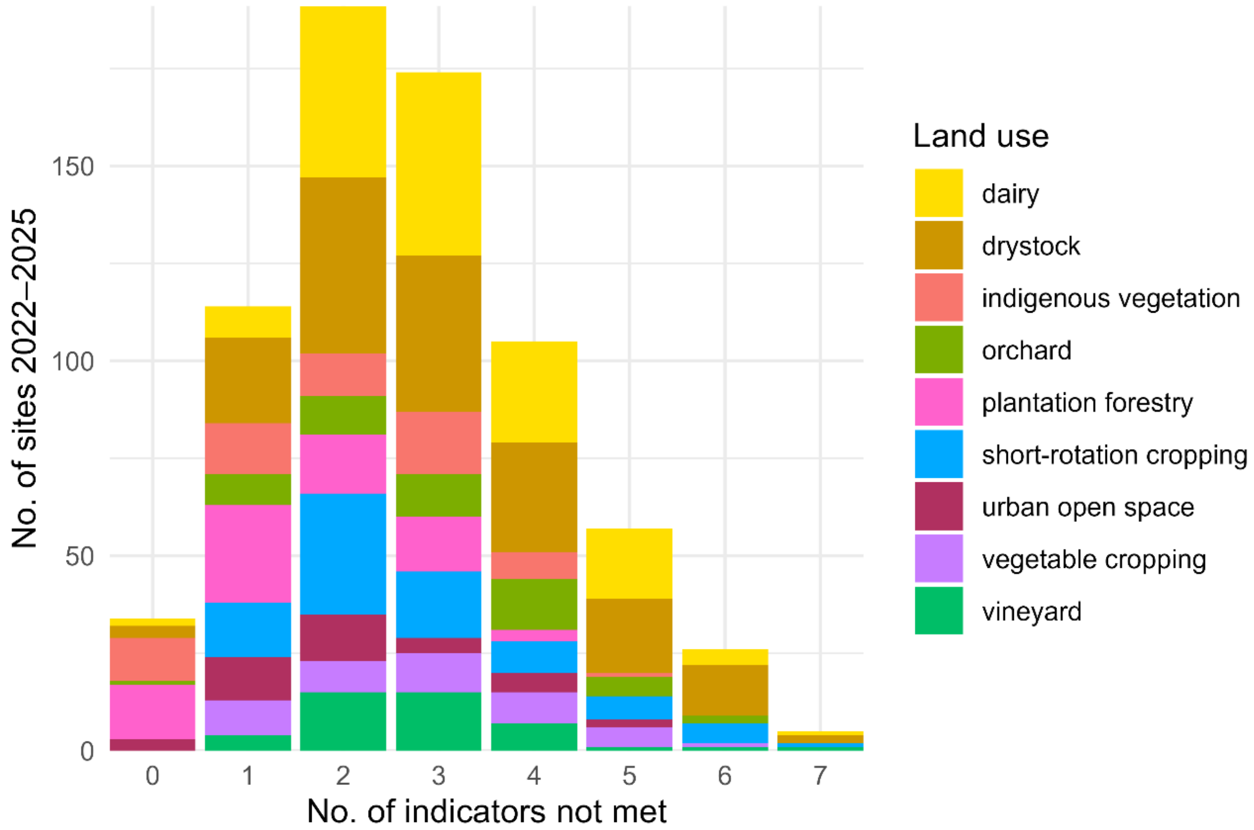

Figure 3. Number of sites not meeting reference ranges for multiple indicators between 2022 and 2025.

4.2.2 Trace elements

There were few sites that exceeded the 95% protection-level Eco-SGVs, with Cu concentrations in orchards most frequently exceeding the Eco-SGV in both monitoring periods (Tables 40 and 41).

Table 40. Number of sites in land-use categories that included at least one site that exceeded the 95% protection-level Eco-SGV for a trace element, for sites sampled 1 July 2018 to 30 June 2022.

Trace element	Land-use category	No. sites above or below 95% protection Eco-SGV	
		Below	High
As	Dairy	176	1
	Orchard	36	3
	Rural residential	5	1
Cd	Dairy	176	1
Cu	Drystock	217	1
	Orchard	31	8
	Vineyard	34	1
Pb	Cropping	158	1
Zn	Dairy	176	1

Note: Refer to Tables 15 and 16 for the value of the different Eco-SGVs.

Table 41. Number of sites in land-use categories and trace elements that included at least one site that exceeded the 95% protection-level Eco-SGV for a trace element, for sites sampled 1 July 2022 to 30 June 2025

Trace element	Land-use category	No. site above or below 95% protection Eco-SGV	
		Below	High
As	Dairy	139	3
	Drystock	161	3
	Indigenous vegetation	56	1
	Urban open space	36	1
Cd	Dairy	149	1
	Orchard	49	1
Cu	Drystock	163	1
	Indigenous vegetation	56	1
	Orchard	42	7
	Urban open space	35	2
Zn	Dairy	141	1
	Drystock	163	1
	Orchard	48	1
	Urban open space	36	1

Note: Refer to Tables 15 and 16 for the value of the different Eco-SGVs.

A moderate number of sites, predominantly dairy and drystock, had Cd concentrations that exceeded the Tier 1 trigger value of 0.6 mg/kg, with a smaller number of sites exceeding Tier 2 or Tier 3 trigger values (Table 42). No sites exceeded the Tier 4 trigger value in either time-step.

Table 42. Number of sites at the different tiers of the Tiered Fertiliser Management System for the two time-steps

Land-use category	2018–2022				2022–2025			
	Tier 0	Tier 1	Tier 2	Tier 3	Tier 0	Tier 1	Tier 2	Tier 3
Cropping	149	4	-	-	119	4	-	-
Dairy	138	35	3	1	126	22	1	1
Drystock	195	16	7	-	157	11	1	-
Orchard	27	3	2	-	39	7	3	1
Vineyard	35	-	-	-	43	1	-	-
Plantation forestry	50	1	-	-	71	1	-	-
Rural residential	5	1	-	-	1	-	-	-
Urban open space	1	-	-	-	37	-	-	-
Indigenous vegetation	44	-	-	-	59	-	-	-

Hyphen indicates no sites fell into this category

4.3 Data visualisation

Alternative ways of displaying the monitoring data can provide additional insights into how individual indicators may compare across and within different land uses. Two examples of violin plots are shown in Figures 4 and 5. Figure 5 includes an overlay of a boxplot specifically showing the interquartile ranges and medians of the data for each land use.

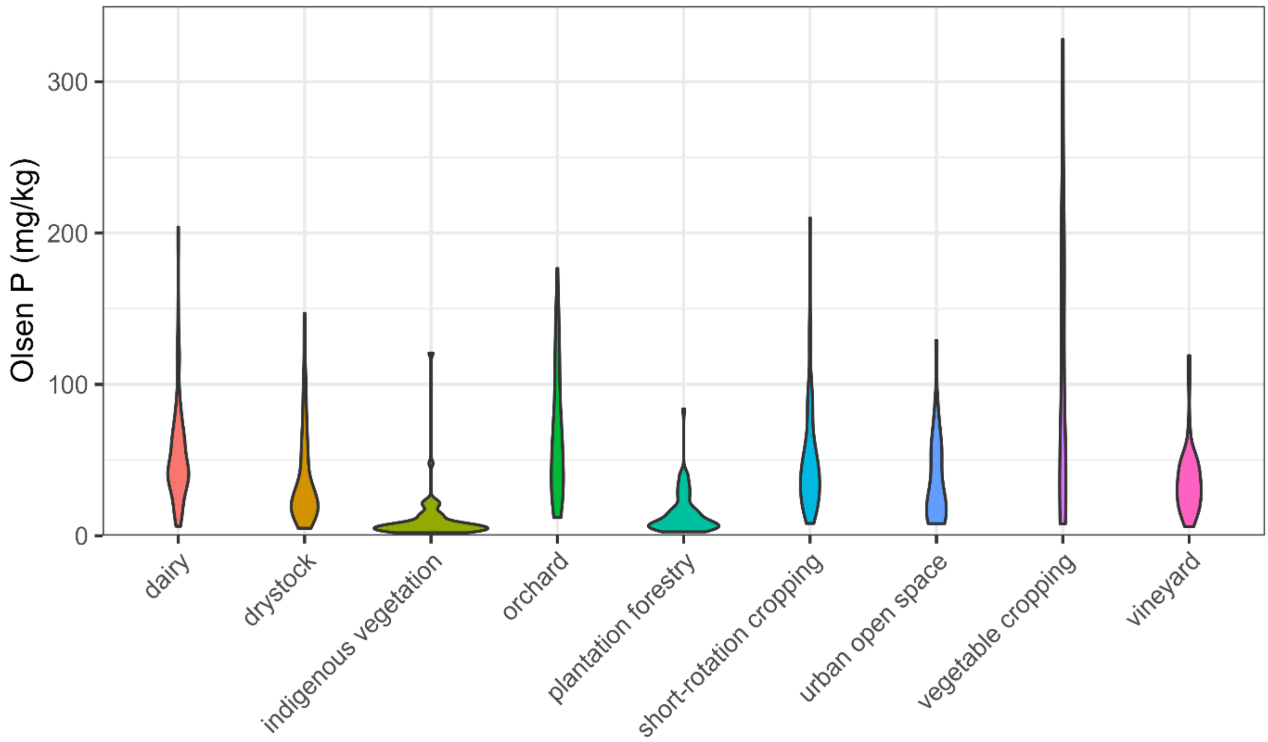

Figure 4. Example of a violin plot showing SOE monitoring data for Olsen P collected between 2022 and 2025.

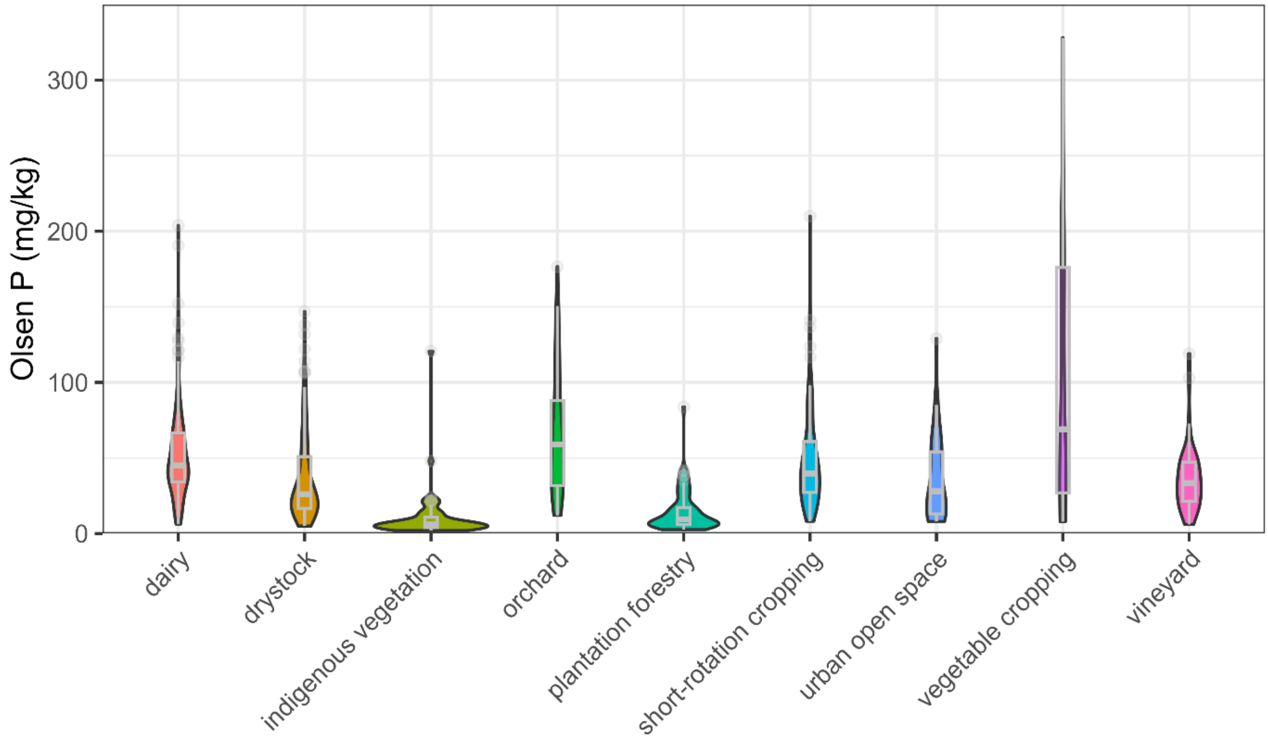

Figure 5. Example of a violin plot with an overlying boxplot showing SOE monitoring data for Olsen P collected between 2022 and 2025.

For the majority of indicators it is not possible to indicate the reference ranges for each land use on a single violin plot because the reference ranges also depend on soil order, and each land use contains many soil orders with different reference ranges. Soil pH, C:N ratio, HWEC, and macroporosity are the exceptions, because their reference ranges vary solely by land use. A violin plot for macroporosity with reference ranges indicated by shaded areas is presented in Figure 6.

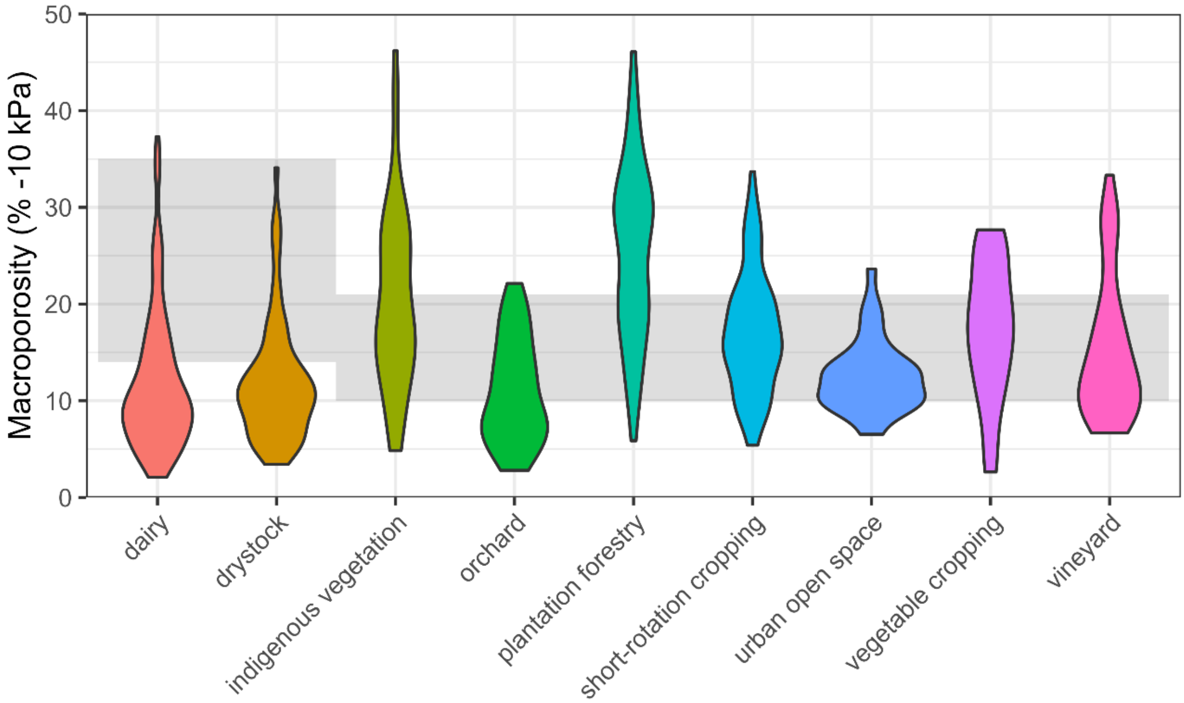

Figure 6. Example of a violin plot including land-use-specific reference ranges for macroporosity SOE data collected between 2022 and 2025. The shaded area indicates the reference ranges for each land use.

A more typical boxplot for macroporosity, and including reference ranges as a shaded area, is presented in Figure 77. This plot shows the interquartile ranges and medians of the monitored data but gives less visibility to the spread of the data along the distribution compared to the violin plot, above. As shown in Figures 5 & 6Figure 5, there are various ways of combining these plots depending on the output desired.

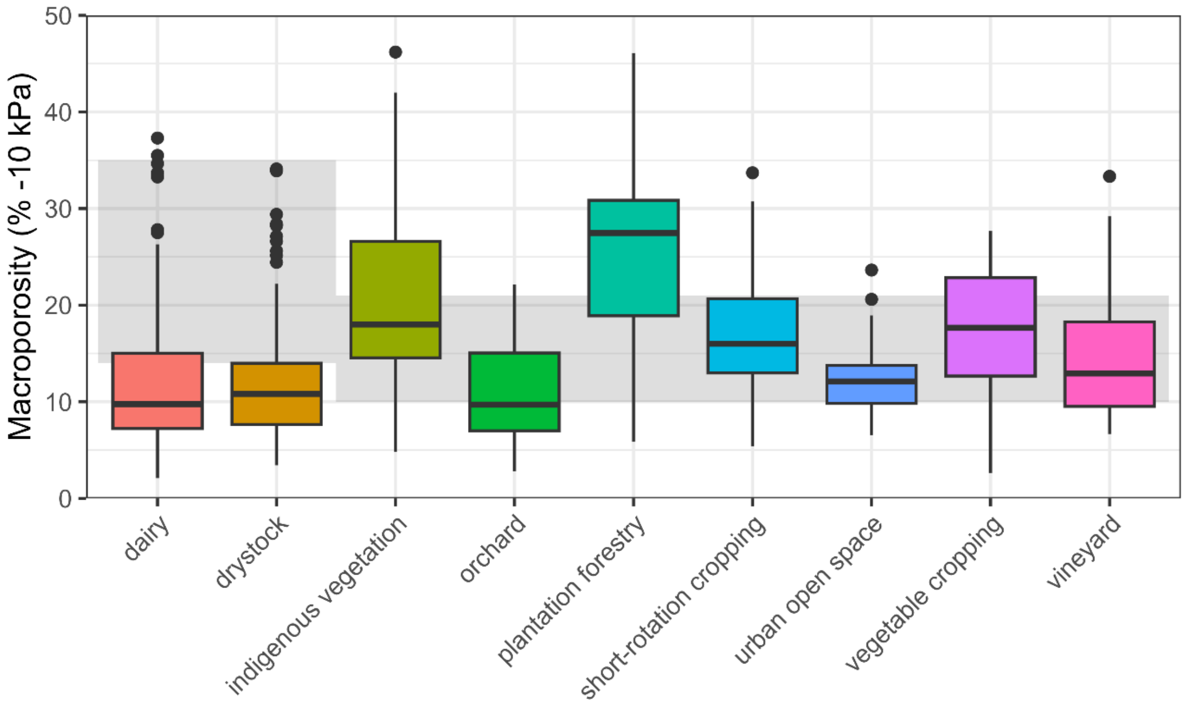

Figure 7. Example of a boxplot including land-use-specific reference ranges for macroporosity SOE data collected between 2022 and 2025. The shaded area indicates the reference range for each land use.

4.4 Trend analysis

Table 43 summarises the slope and confidence intervals for each indicator and land use. If the confidence interval includes 0, the slope of the trend line is not significantly different from 0 (i.e. there is no identified trend, either negative or positive, for that land use and indicator, over time). Significant land-use trends are indicated with bold confidence intervals: these indicate changes in the status of these indicators under the relevant land uses over time. Positive confidence intervals indicate an increasing trend and negative confidence intervals indicate a decreasing trend.

Figures for temporal trends for each indicator (by land use) are shown in the relevant indicator subsections. These include graphs of the measured data and land-use trends for individual indicators over time for individual land uses, which illustrate the variability of measured results at an individual site over time, alongside the general trend for that land use. These general trends for individual land uses are compiled into a single figure for each indicator to allow ready comparison between land uses.

Of the 774 sites included in the trend analysis that did not change land use over the course of the sampling period, only 150 have been sampled right through from 2000 or earlier until the current sampling round (i.e. 2022 or later). It is therefore possible that the trend analysis places undue emphasis on these sites. One hundred and forty-nine sites were identified as having changed land use. Due to the variable nature of the distribution of sites sampled over time, some of the identified land-use trends may reflect this limitation of the sampling network. This is particularly the case for trace elements that are not generally applied in land management, such as As, Cr, and Ni, for which small, statistically significant increases were observed in some land uses, and for trends under indigenous vegetation, for which increases or decreases in trace elements would not typically be expected.

Table 43. Table of 95% confidence intervals of rate of change in the transformed property over time for each model and land use

Indicator	Indigenous vegetation	Drystock	Dairy	Orchard	Vineyard	Short–rotation cropping	Vegetable cropping	Plantation forestry
Olsen P	–0.010, 0.002	0.010, 0.019	0.002, 0.011	0.008, 0.026	0.002, 0.024	0.001, 0.019	0.014, 0.046	–0.007, 0.004
Total C	–0.004, 0.002	0.000, 0.004	–0.002, 0.002	–0.006, 0.003	–0.001, 0.009	–0.011, –0.002	–0.008, 0.006	–0.004, 0.002
Total N	–0.002, 0.003	0.002, 0.006	0.000, 0.004	–0.004, 0.005	–0.002, 0.008	–0.009, –0.001	–0.003, 0.011	–0.006, –0.001
C/N ratio	–0.003, –0.000	–0.003, –0.001	–0.004, –0.002	–0.004, <0.001	–0.002, 0.003	–0.004, –0.000	–0.008, –0.002	0.001, 0.004
AMN	–0.029, 0.025	–0.011, 0.027	–0.038, –0.001	–0.032, 0.047	0.013, 0.105	0.023, 0.099	–0.136, –0.008	–0.041, 0.01
pH	–0.002, 0.007	–0.002, 0.004	–0.001, 0.005	–0.009, 0.004	–0.009, 0.006	–0.014, –0.002	–0.031, –0.010	–0.004, 0.004
Bulk density	–0.002, 0.001	–0.002, –0.000	–0.002, <0.001	–0.005, –0.001	–0.008, –0.002	–0.002, 0.002	–0.005, 0.003	–0.000, 0.002
Macroporosity	–0.000, 0.024	–0.003, 0.014	–0.003, 0.013	–0.019, 0.015	–0.009, 0.038	0.002, 0.036	–0.036, 0.023	–0.006, 0.018
HWEC	–0.038, –0.012	–0.036, –0.021	–0.03, –0.017	–0.032, –0.000	—	–0.033, –0.002	—	–0.027, –0.006
As	–0.001, 0.010	–0.002, 0.006	–0.002, 0.006	0.005, 0.019	0.005, 0.023	–0.010, 0.005	–0.001, 0.024	–0.002, 0.009
Cd	–0.014, –0.001	–0.006, 0.003	–0.014, –0.005	–0.012, 0.006	–0.013, 0.010	–0.011, 0.007	–0.008, 0.024	–0.035, –0.021
Cr	0.001, 0.010	–0.006, 0.001	–0.004, 0.003	0.003, 0.015	–0.010, 0.006	–0.008, 0.005	–0.006, 0.016	–0.008, 0.002
Cu	–0.016, –0.006	–0.008, –0.000	0.000, 0.008	0.011, 0.025	–0.000, 0.017	–0.009, 0.005	–0.009, 0.016	–0.013, –0.002
Ni	–0.001, 0.010	–0.006, 0.002	–0.003, 0.005	–0.006, 0.009	–0.016, 0.003	–0.013, 0.002	0.005, 0.032	–0.011, 0.001
Pb	–0.008, 0.001	–0.004, 0.002	–0.001, 0.005	–0.003, 0.009	–0.011, 0.003	–0.007, 0.004	–0.007, 0.013	–0.002, 0.007
Zn	–0.011, –0.001	–0.008, –0.001	0.002, 0.009	0.005, 0.018	–0.008, 0.009	–0.010, 0.003	0.002, 0.026	–0.016, –0.005
F	–1.198, 4.312	1.013, 3.911	–3.465, –0.862	0.145, 5.781	–11.379, 8.06	–0.907, 4.256	–6.557, 8.777	–2.772, 1.798

Notes: Confidence intervals that are significant (i.e. that do not include zero) are shown in bold. For these bold values, $P < 0.05$. Bold values indicate significant change over time in the direction of the sign of the confidence intervals (i.e. negative intervals indicate a decreasing trend in transformed value, and positive intervals indicate an increasing trend).

4.4.1 Olsen P

There were significant increases under dairy, drystock, orchards, vineyards, short-rotation cropping, and vegetable cropping. No other land-use trends were significant for Olsen P.

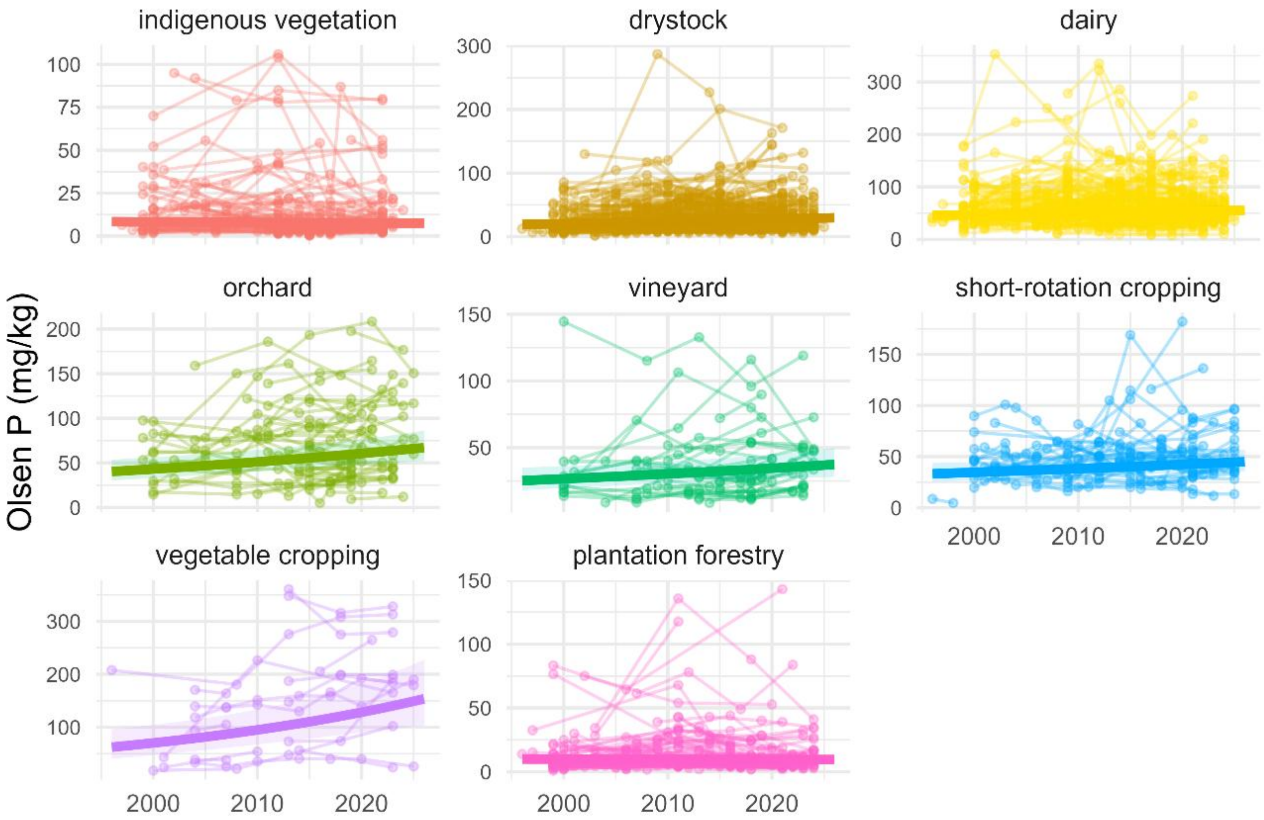

Figure 8. Measured data and land-use trends for Olsen P over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

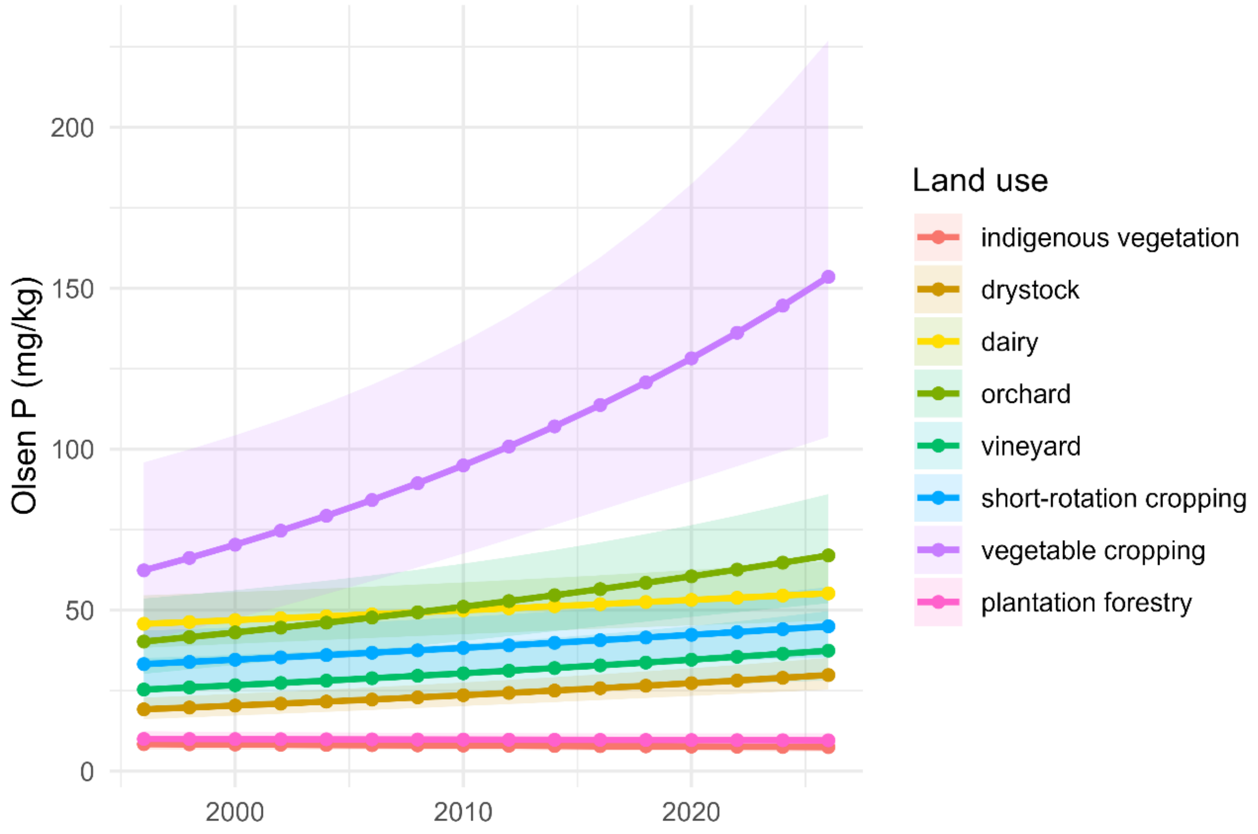

Figure 9. Land-use trends for Olsen P over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.2 Total C

There was a significant increase under drystock and a significant decrease under short-rotation cropping. No other land-use trends were significant for total C.

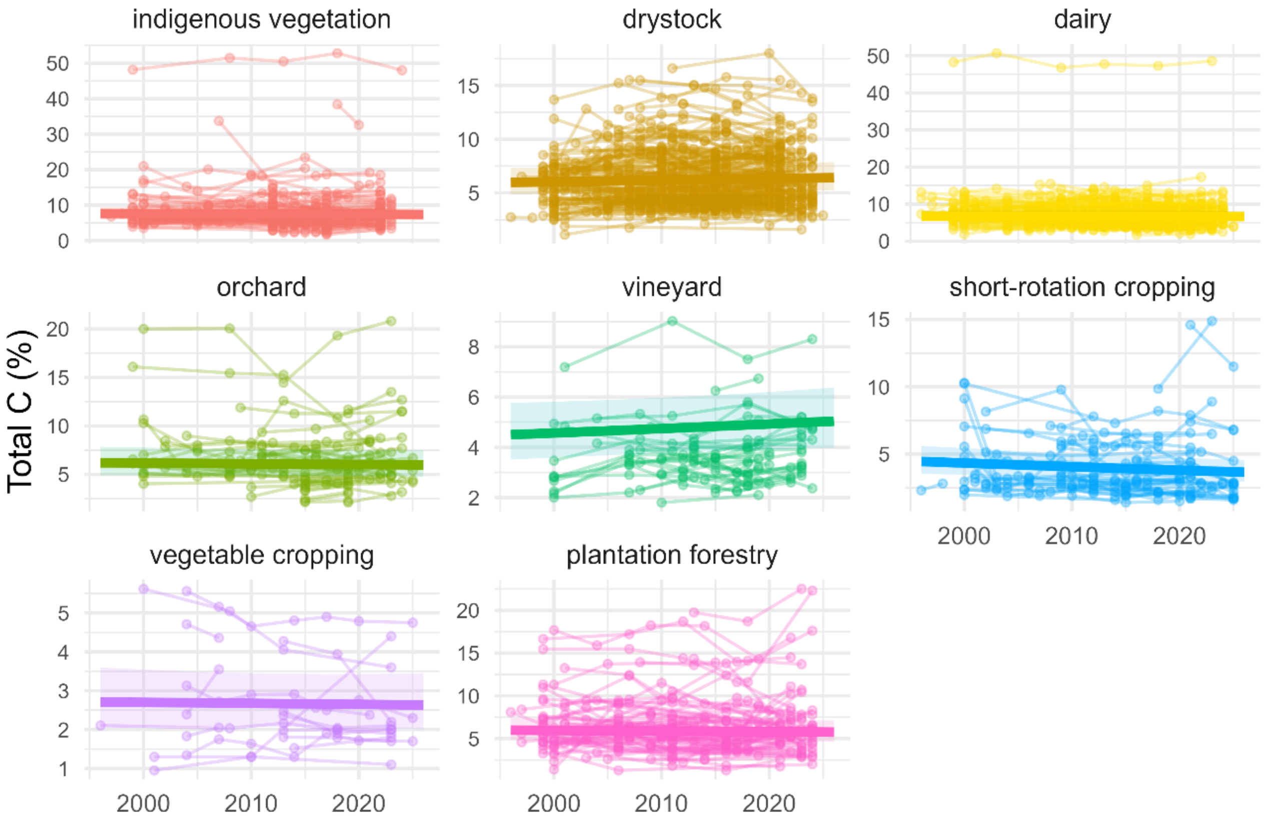

Figure 10. Measured data and land-use trends for total C over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

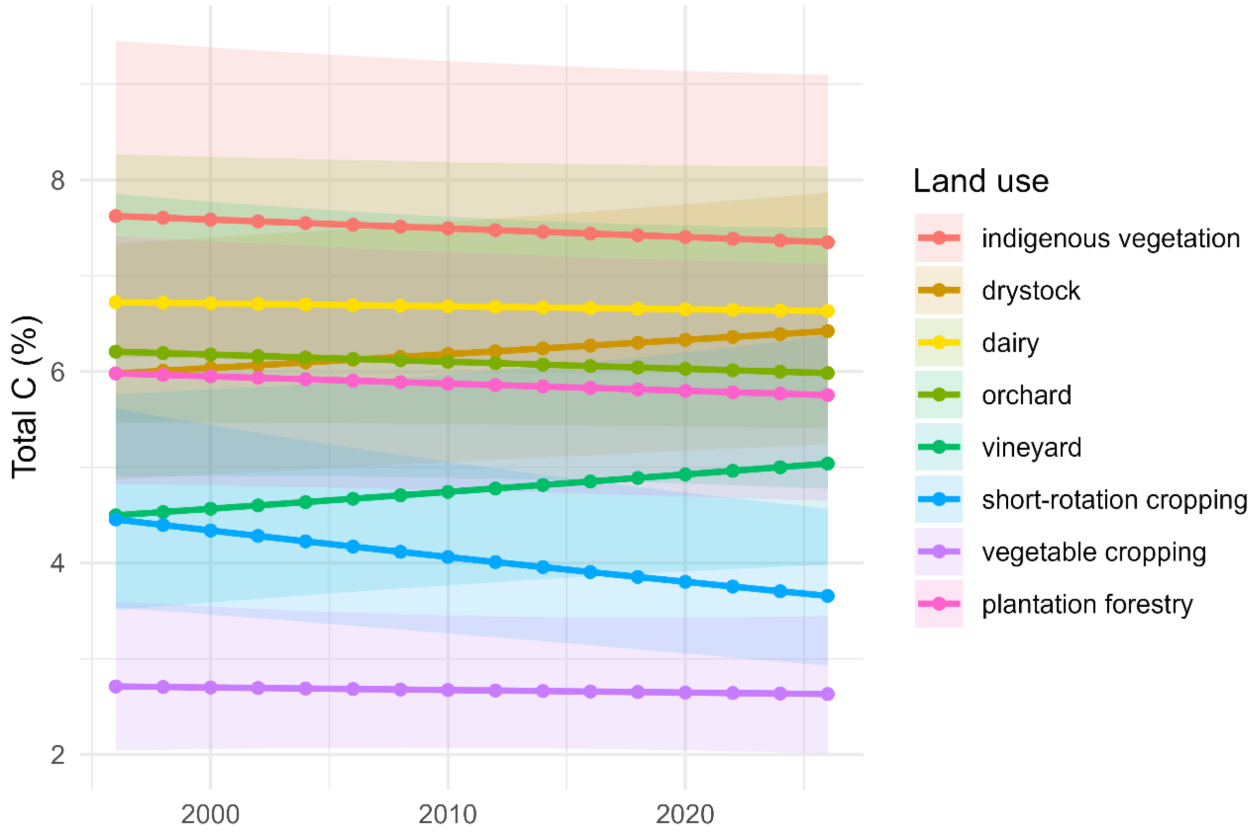

Figure 11. Land-use trends for total C over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.3 Total N

There were significant increases under drystock and dairy, and a significant decrease under short-rotation cropping. No other land-use trends were significant for total N.

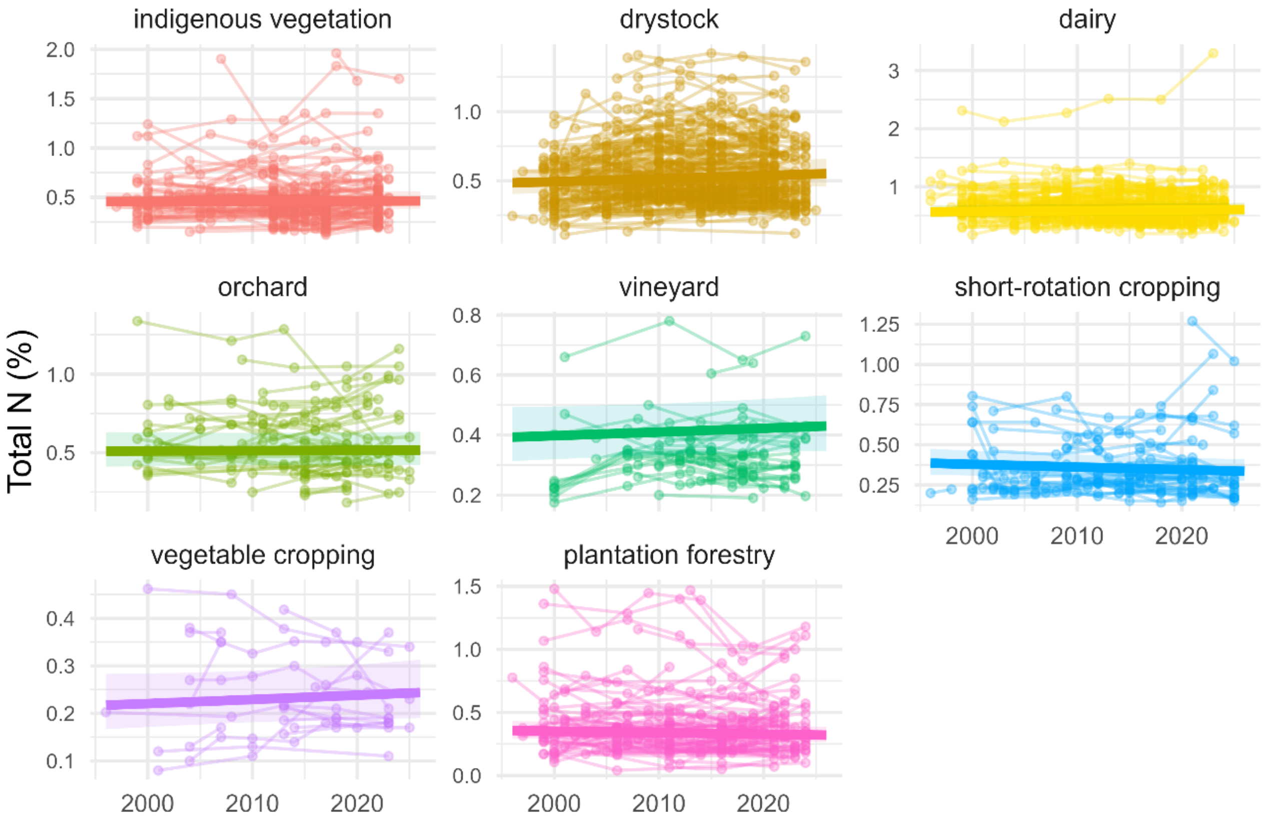

Figure 12. Measured data and land-use trends for total N over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

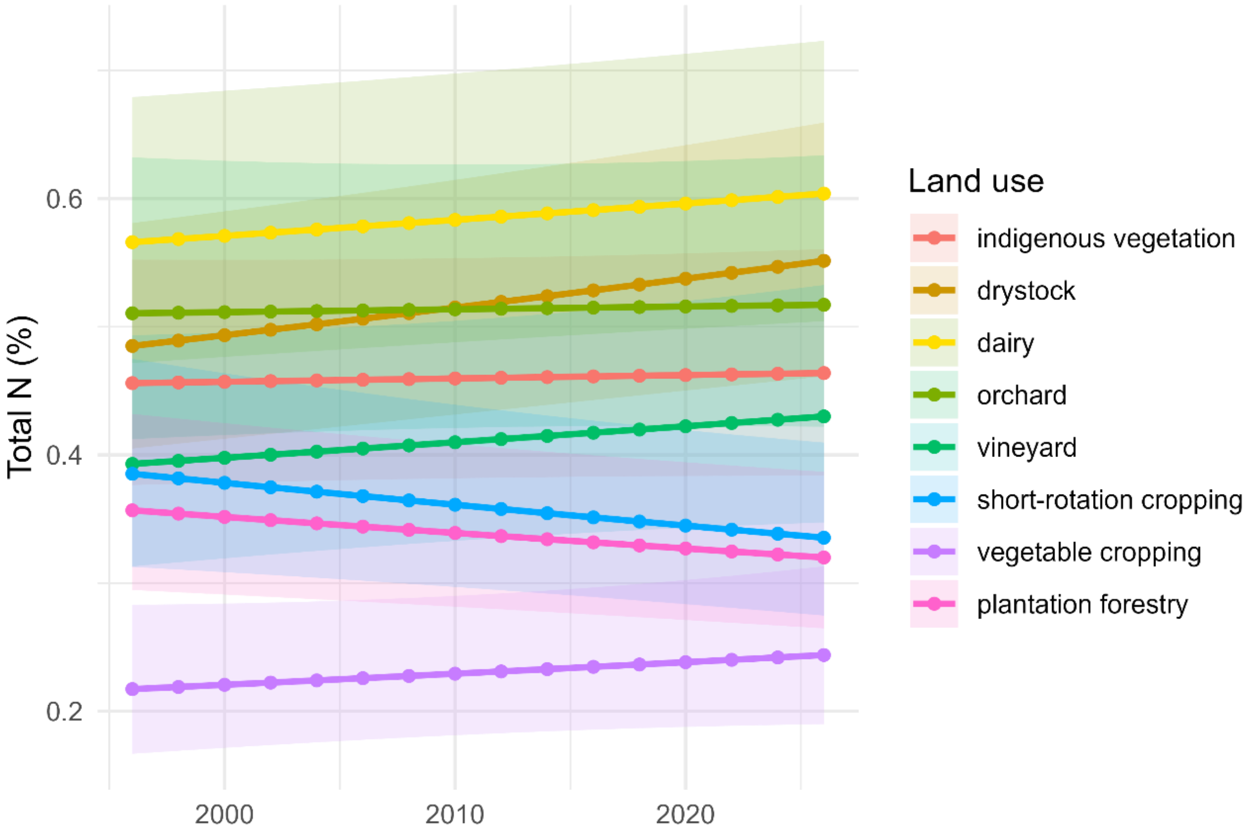

Figure 13. Land-use trends for total N over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.4 C:N ratio

Most land uses exhibited significant trends for C:N ratio. There were significant decreases under indigenous vegetation, drystock, dairy, short-rotation cropping, and vegetable cropping, and a significant increase under plantation forestry.

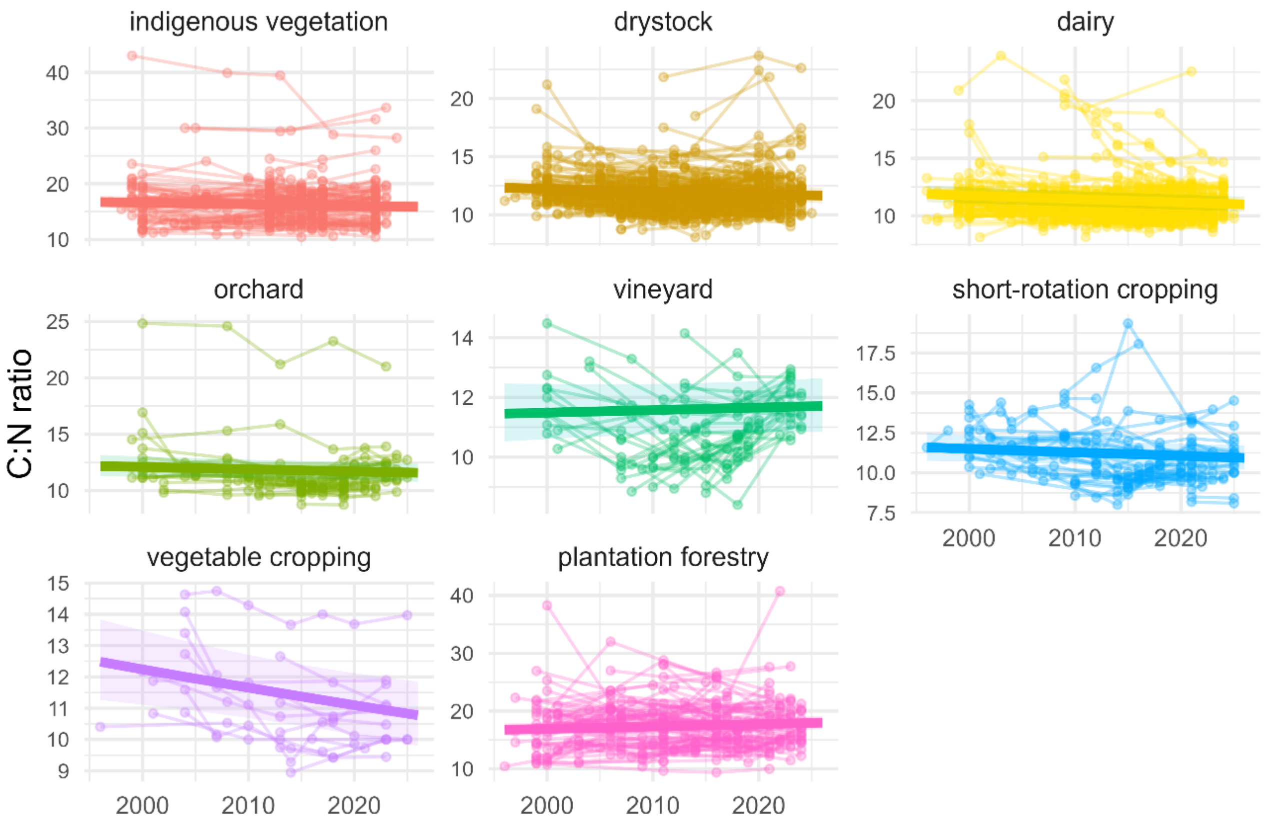

Figure 14. Measured data and land-use trends for C:N ratio over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

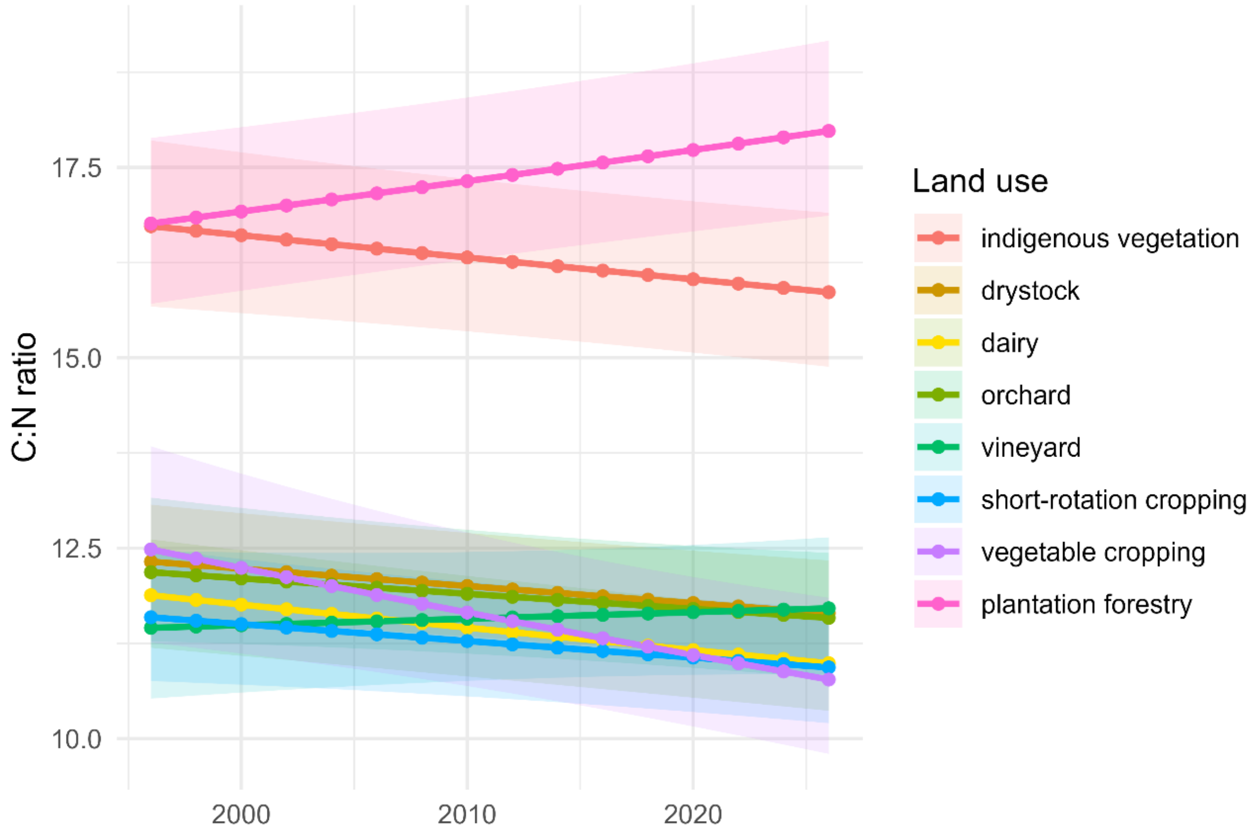

Figure 15. Land-use trends for C:N ratio over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.5 AMN

There were significant increases under vineyards and short-rotation cropping, and significant decreases under dairy and vegetable cropping. No other land-use trends were significant for AMN.

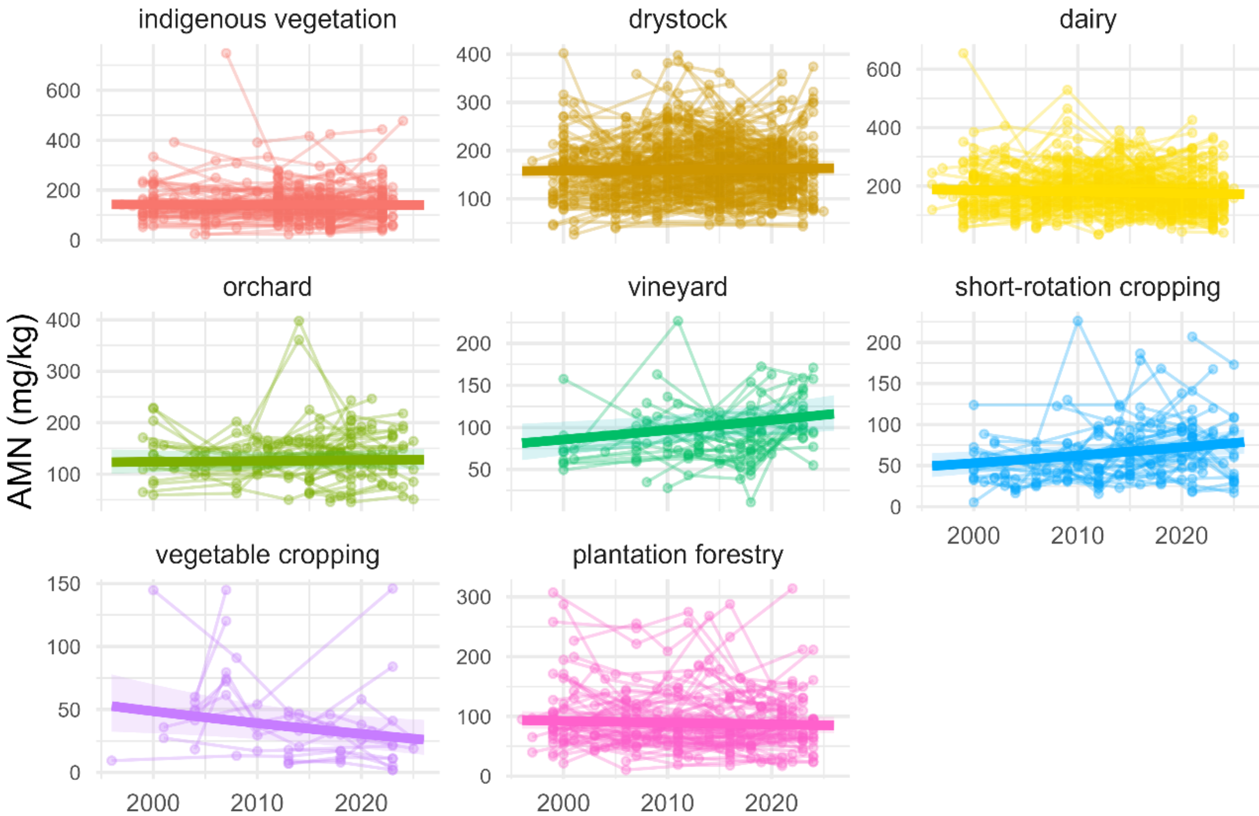

Figure 16. Measured data and land-use trends for AMN over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

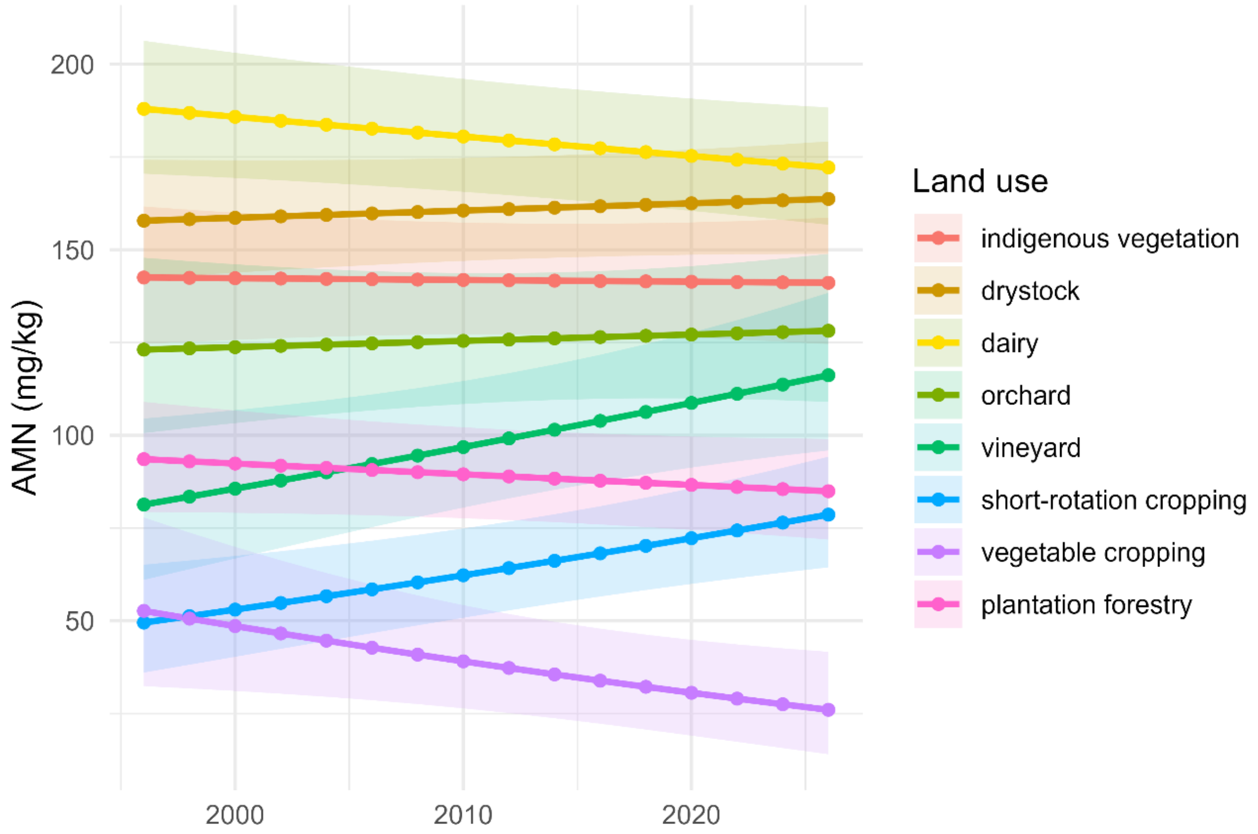

Figure 17. Land-use trends for AMN over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.6 pH

There were significant decreases under vegetable cropping and short-rotation cropping. No other land-use trends were significant for pH.

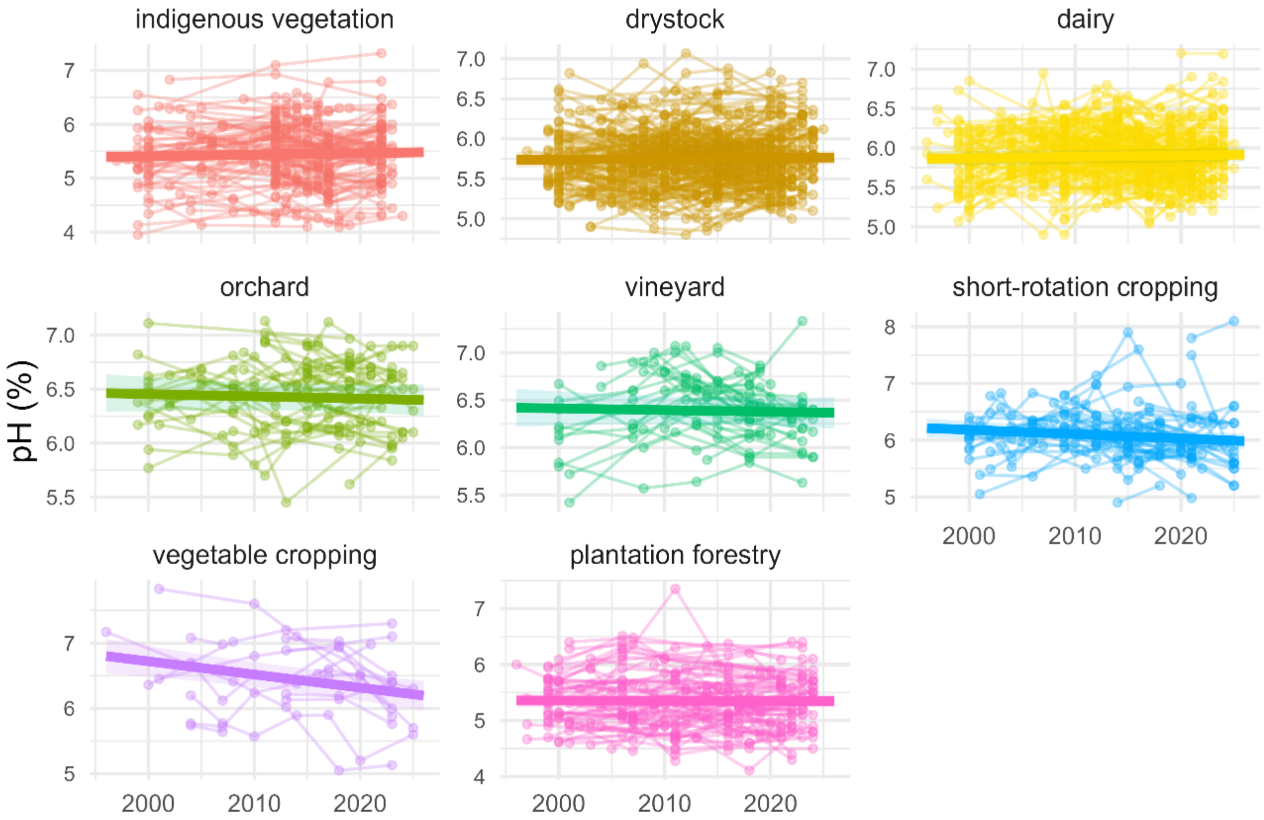

Figure 18. Measured data and land-use trends for pH over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

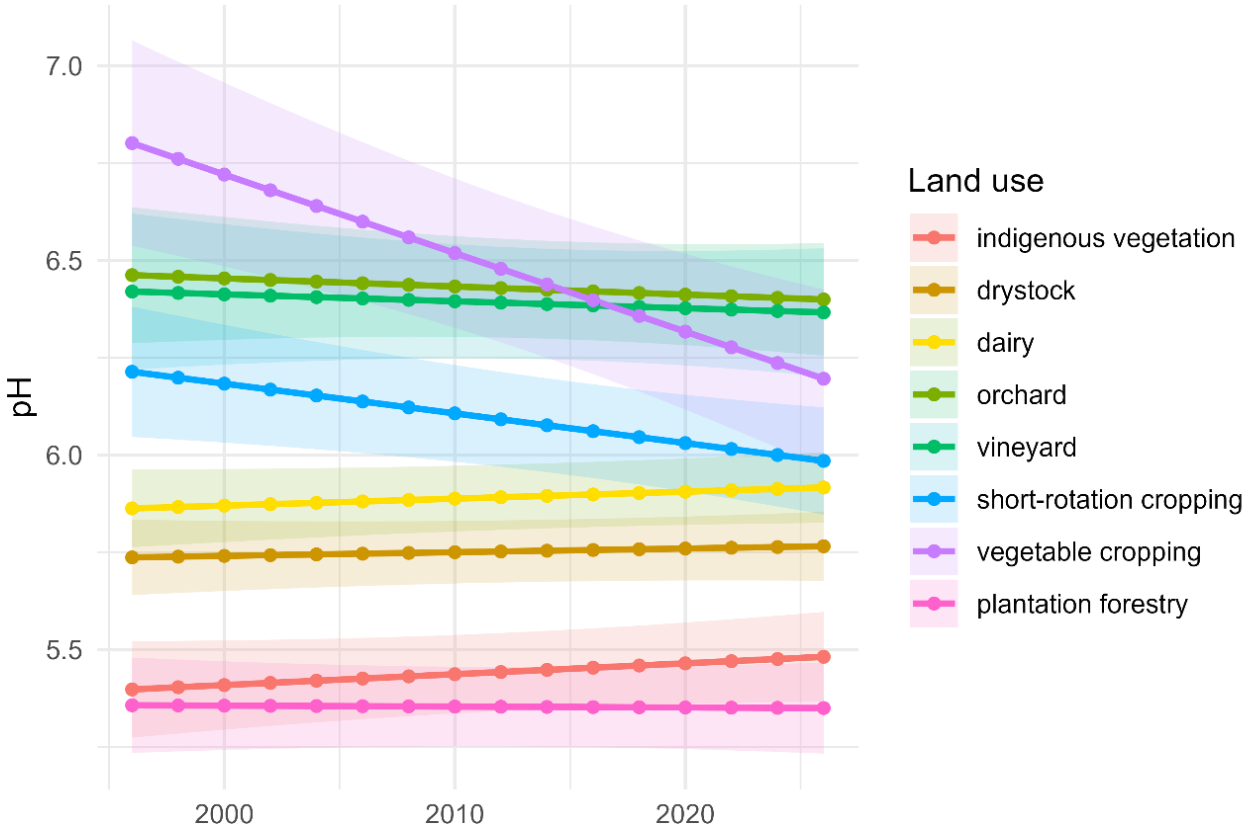

Figure 19. Land-use trends for pH over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.7 Bulk density

There were significant decreases under drystock, orchards, and vineyards. No other land-use trends were significant for bulk density.

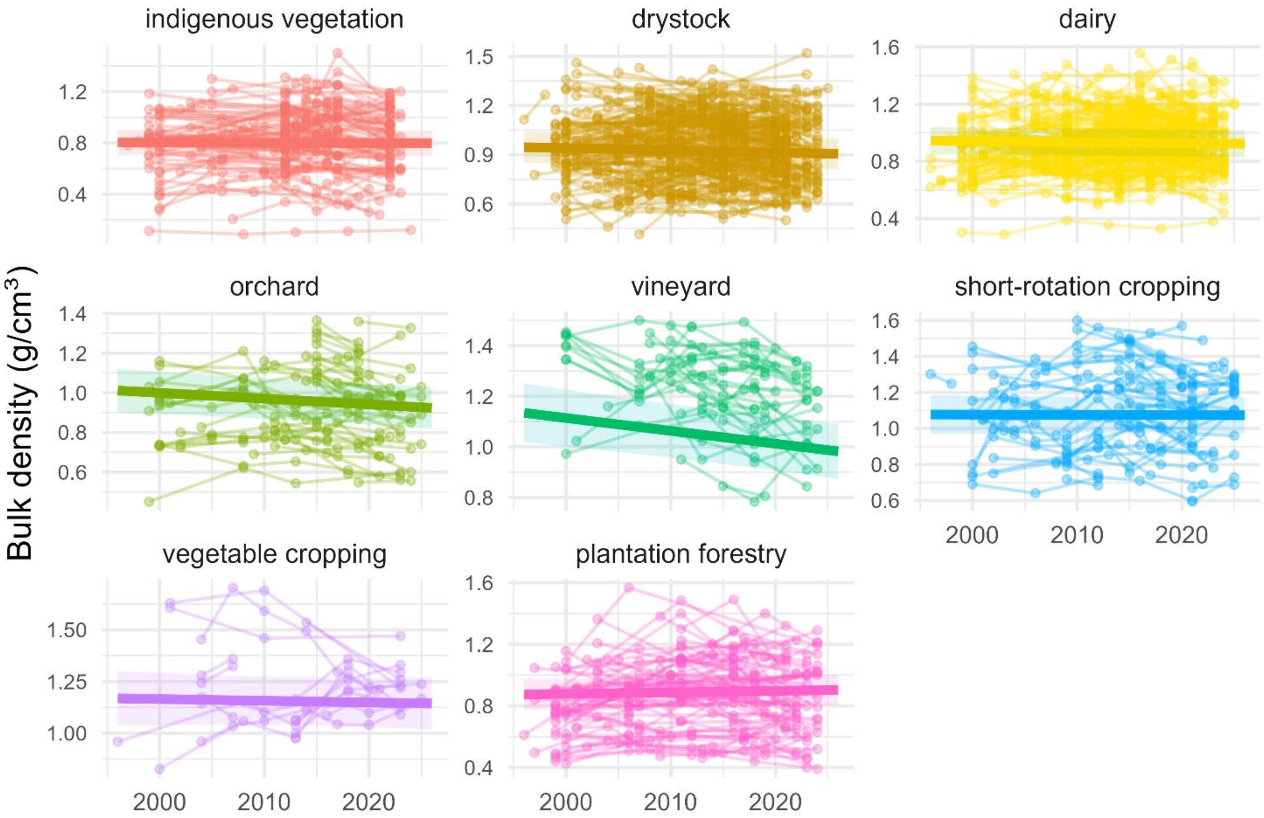

Figure 20. Measured data and land-use trends for bulk density over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

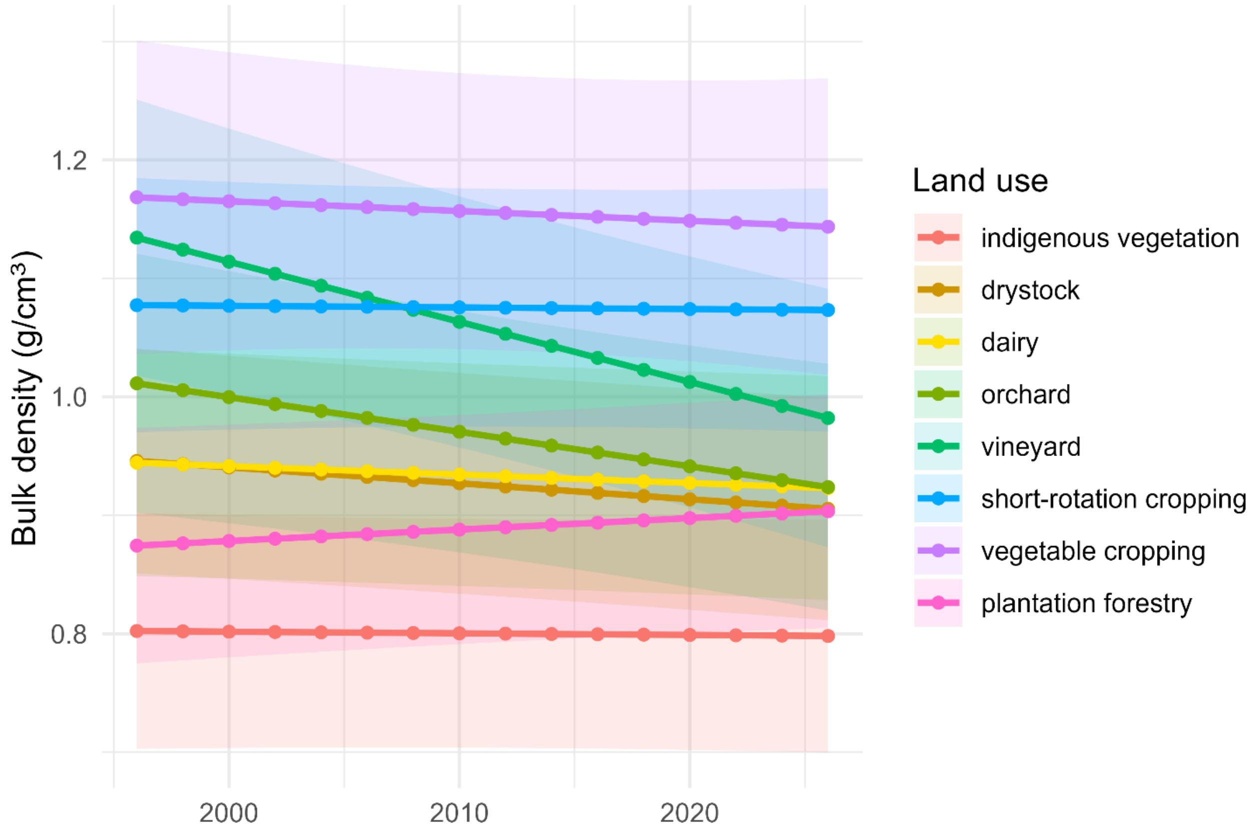

Figure 21. Land-use trends for bulk density over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.8 Macroporosity

There was a significant increase under short-rotation cropping. No other land-use trends were significant for macroporosity.

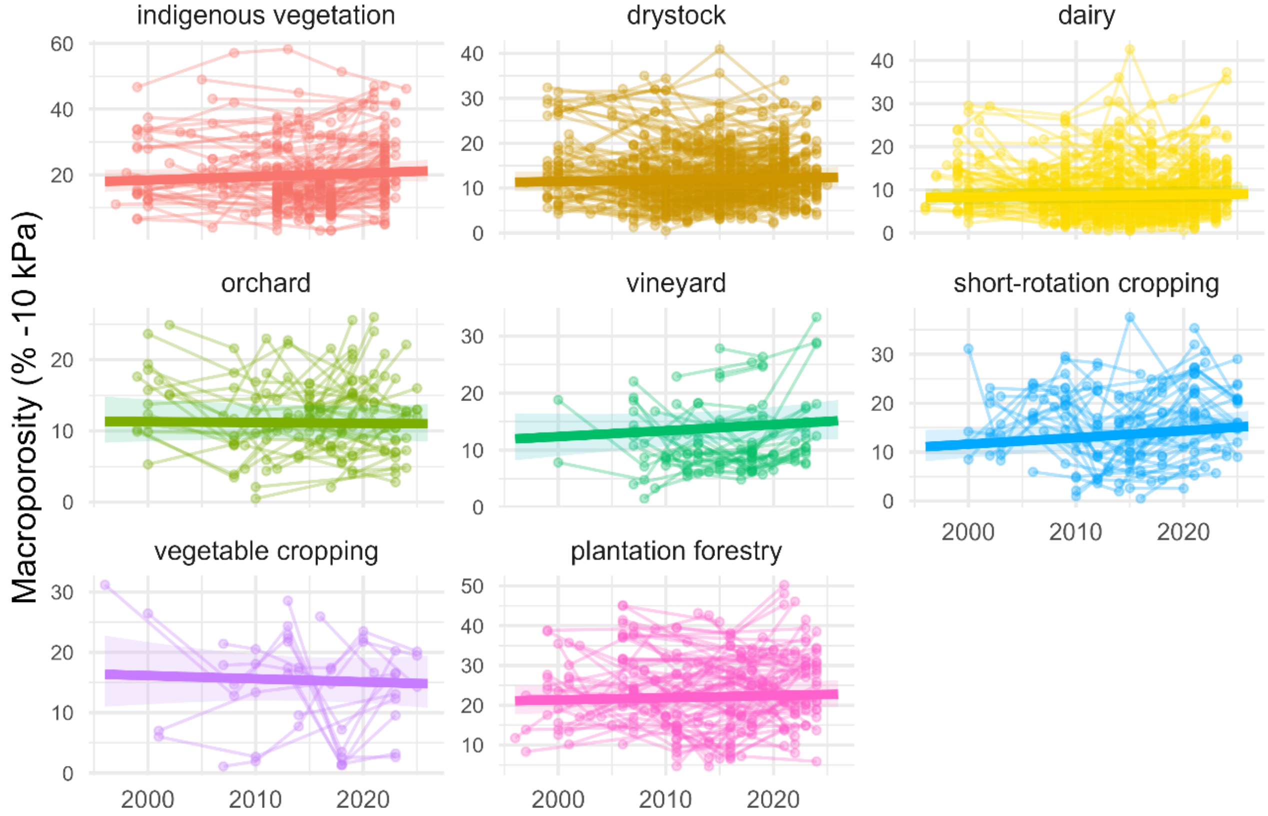

Figure 22. Measured data and land-use trends for macroporosity over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

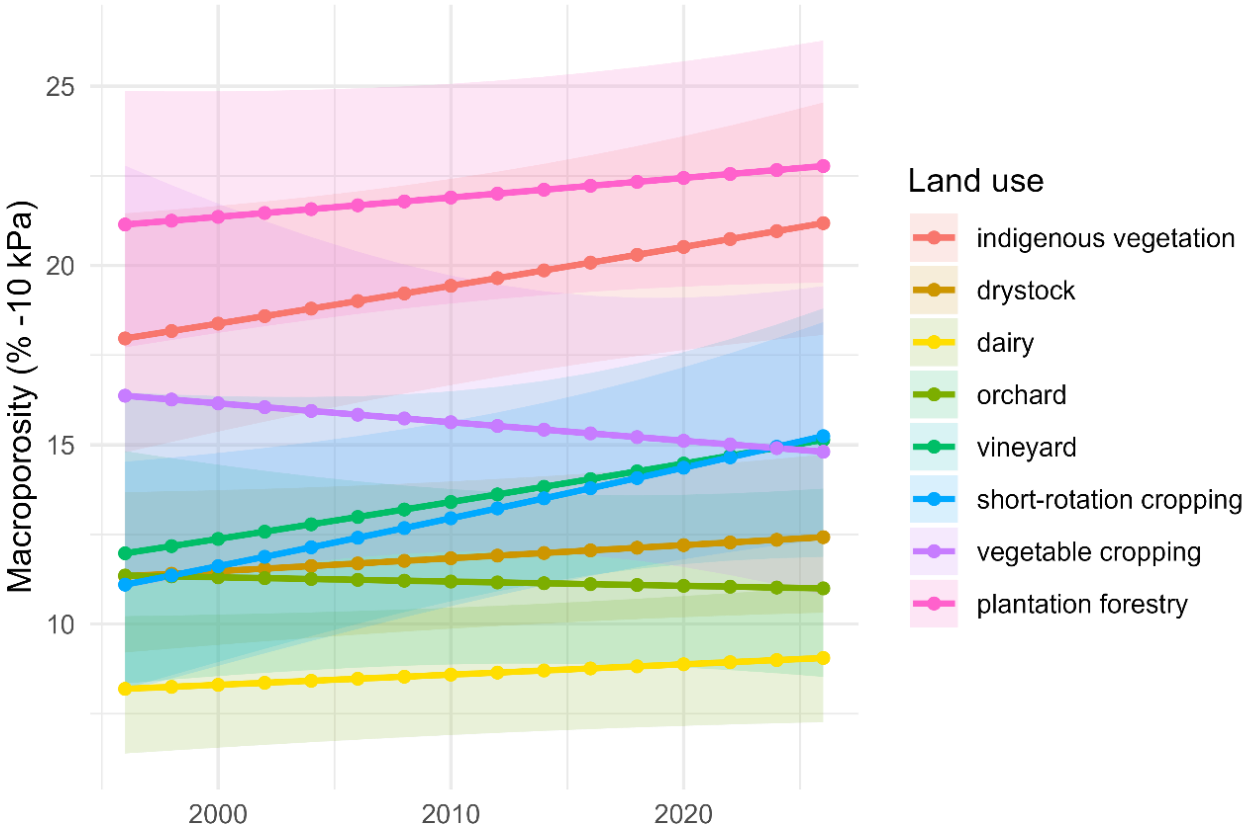

Figure 23. Land-use trends for macroporosity over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

4.4.9 HWEC

There were significant decreases in all land uses that had repeated measures of HWEC. However, given the known variations in methodologies between laboratories and over time (see Cavanagh, Thompson-Morrison, Drewry et al 2025), further evaluation of the HWEC data is required to confirm that these trends are real and not an artefact of methodological differences. Also, there is a greater density of measurements from 2015 onwards being greater than that of the preceding time period, which may also influence the observed trend. Finally, this model showed a high degree of multicollinearity. We therefore recommend caution when interpreting the trends shown here.

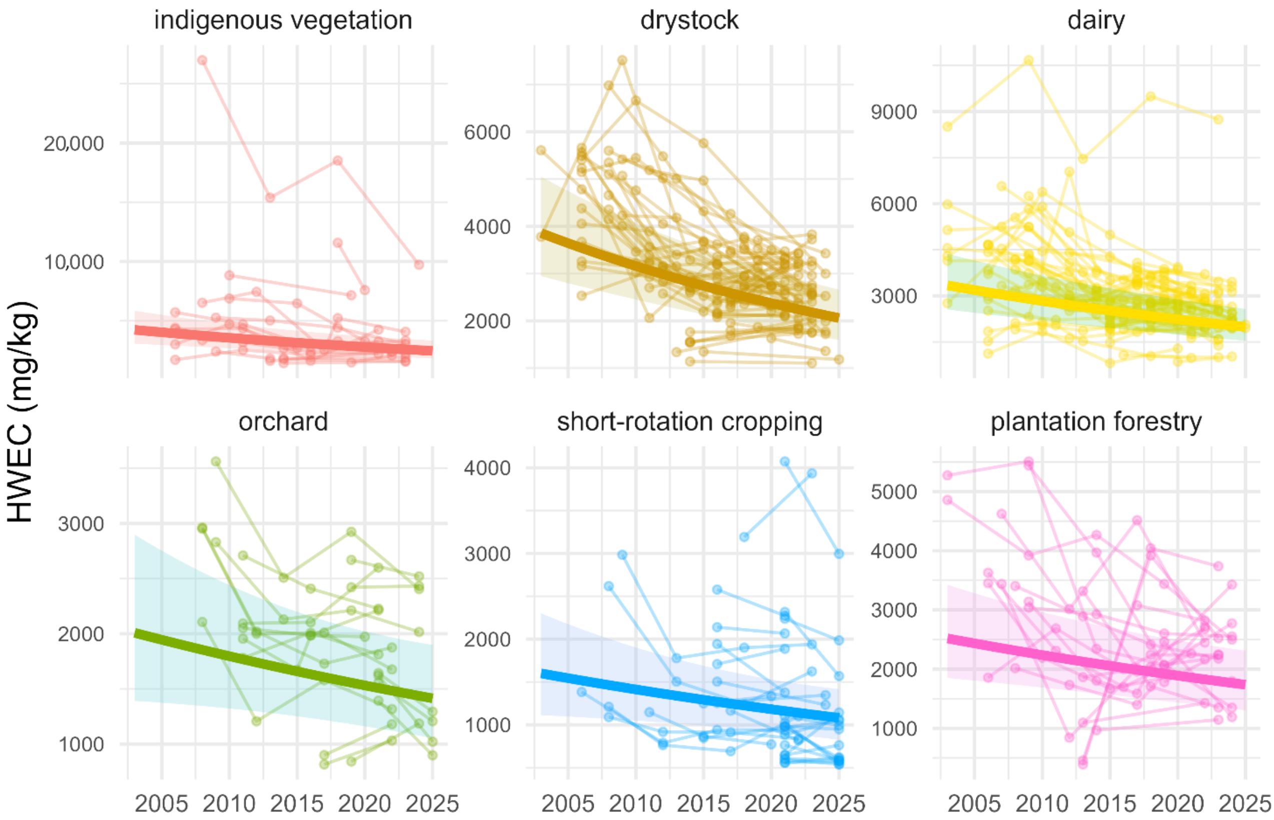

Figure 24. Measured data and land-use trends for HWEC over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time. HWEC has been only been measured since 2003, so the x axis of this plot differs from that of other indicators.

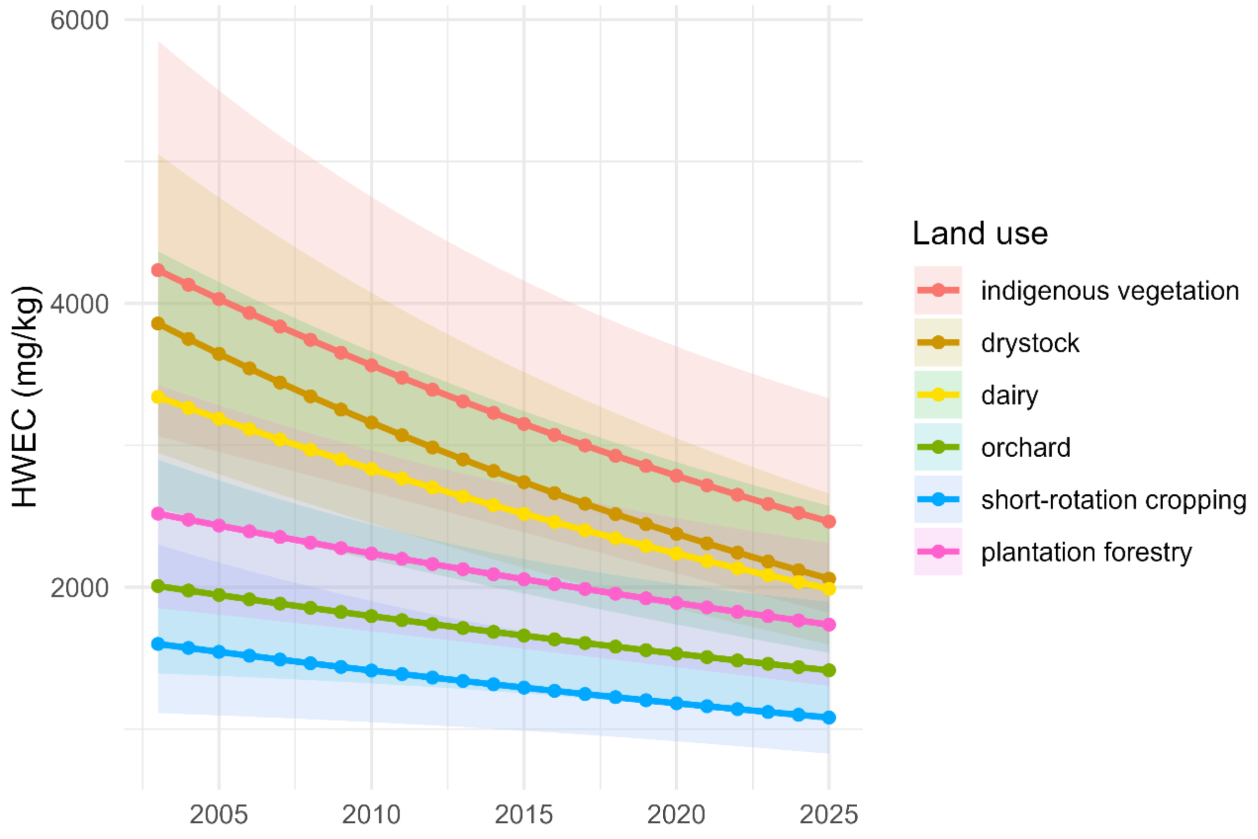

Figure 25. Land-use trends for HWEC over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends. HWEC has been only been measured since 2003, so the x axis of this plot differs from that of other indicators.

4.4.10 Trace elements

Trace elements applied in agriculture: copper, zinc, cadmium, fluorine

Cu and Zn are intentionally applied as pest-control agents to agricultural systems, Cu as a fungicide primarily used in horticulture, and Zn primarily as a facial eczema treatment for livestock. Cd and F are contaminants in phosphate fertilisers, so although they aren't intentionally applied they enter agricultural systems as a consequence of the use of these fertilisers.

Copper

There were significant decreases under indigenous vegetation, drystock, and plantation forestry, and significant increases under dairy and orchards. Copper is commonly used as a fungicide in orchards and as a pasture or animal supplement in dairy systems, which may explain its increasing trend under these land uses over time. Significant increases were also seen in As and Cr in orchards, which, taken together, may reflect the use of copper-chromium-arsenic (CCA) treated wood in this land use.

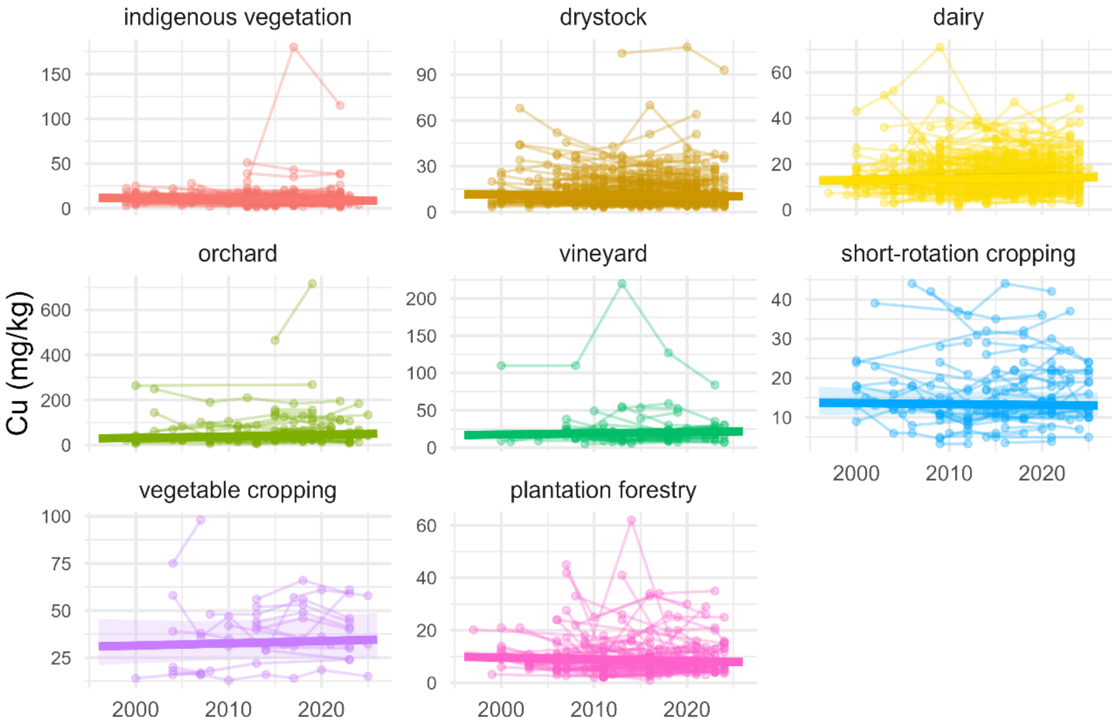

Figure 26. Measured data and land-use trends for Cu over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

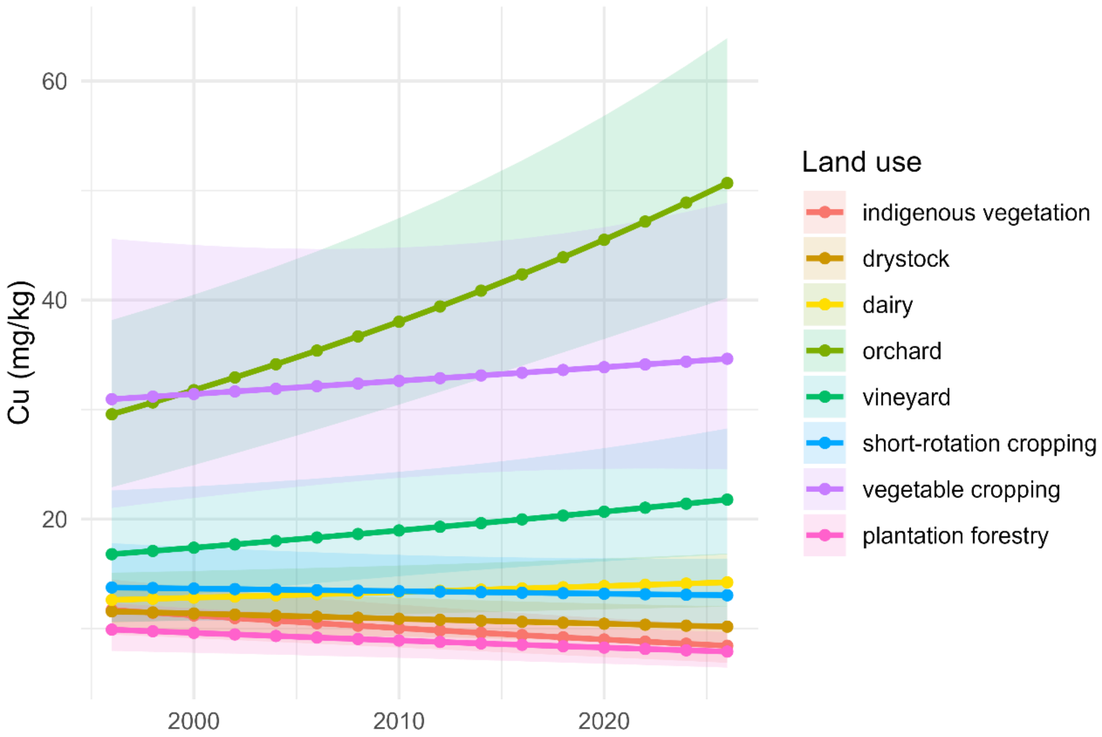

Figure 27. Land-use trends for Cu over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

Zinc

The trends for Zn were the same as those for Cu, with the addition of a significant increase under vegetable cropping over time.

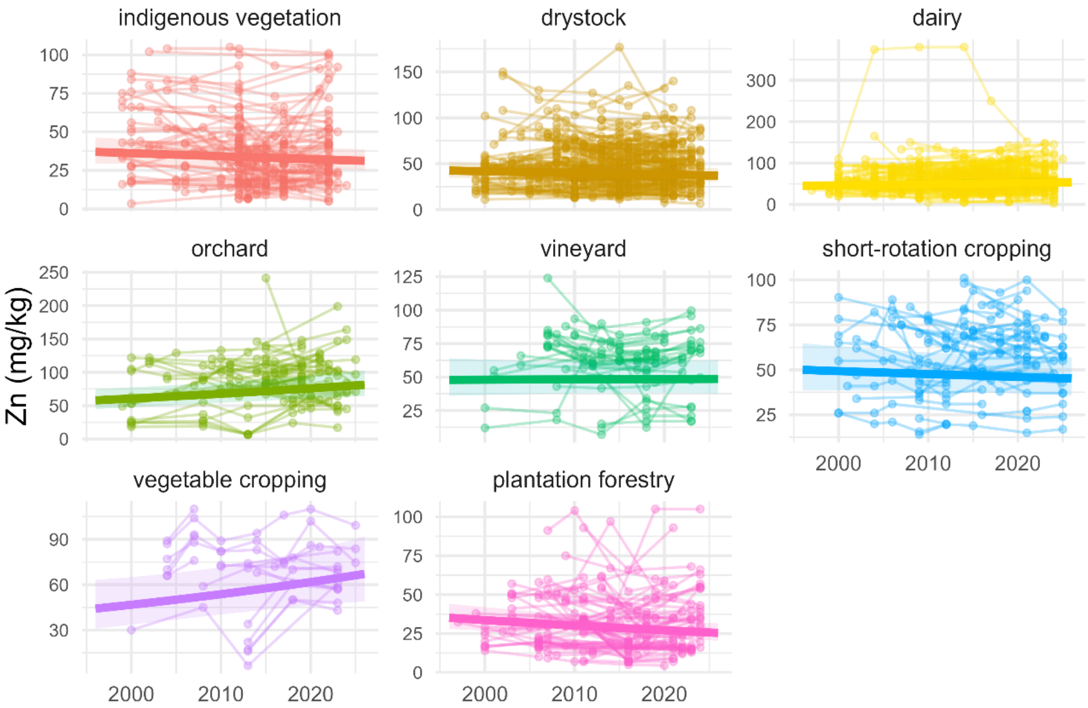

Figure 28. Measured data and land-use trends for Zn over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

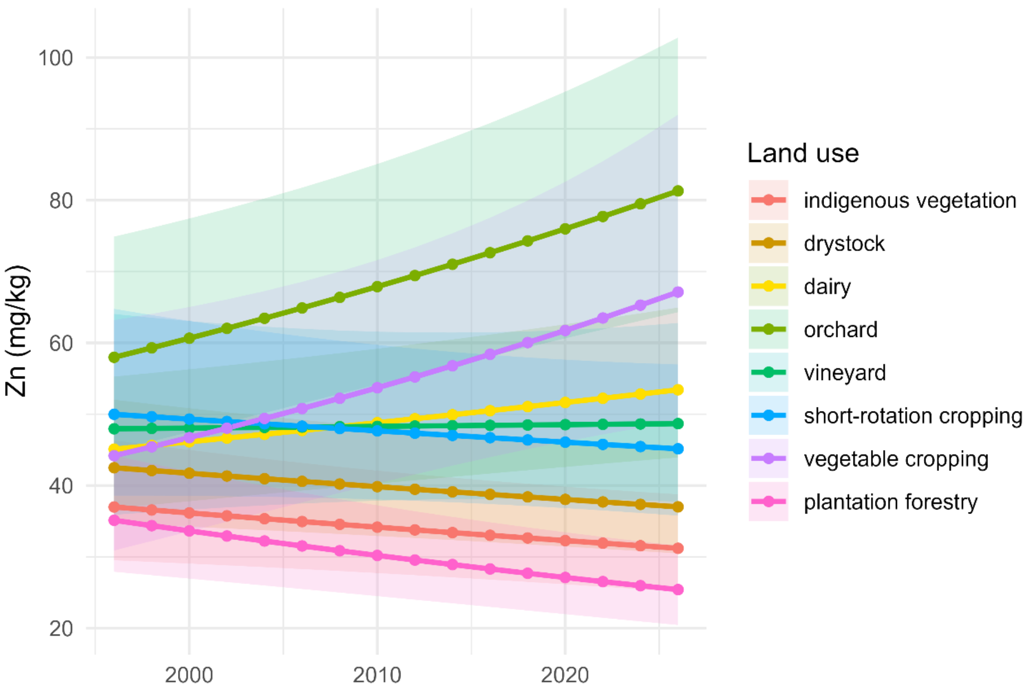

Figure 29. Land-use trends for Zn over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

Cadmium

There were significant decreases under indigenous vegetation, plantation forestry and dairy. No land uses showed significantly increasing trends for Cd.

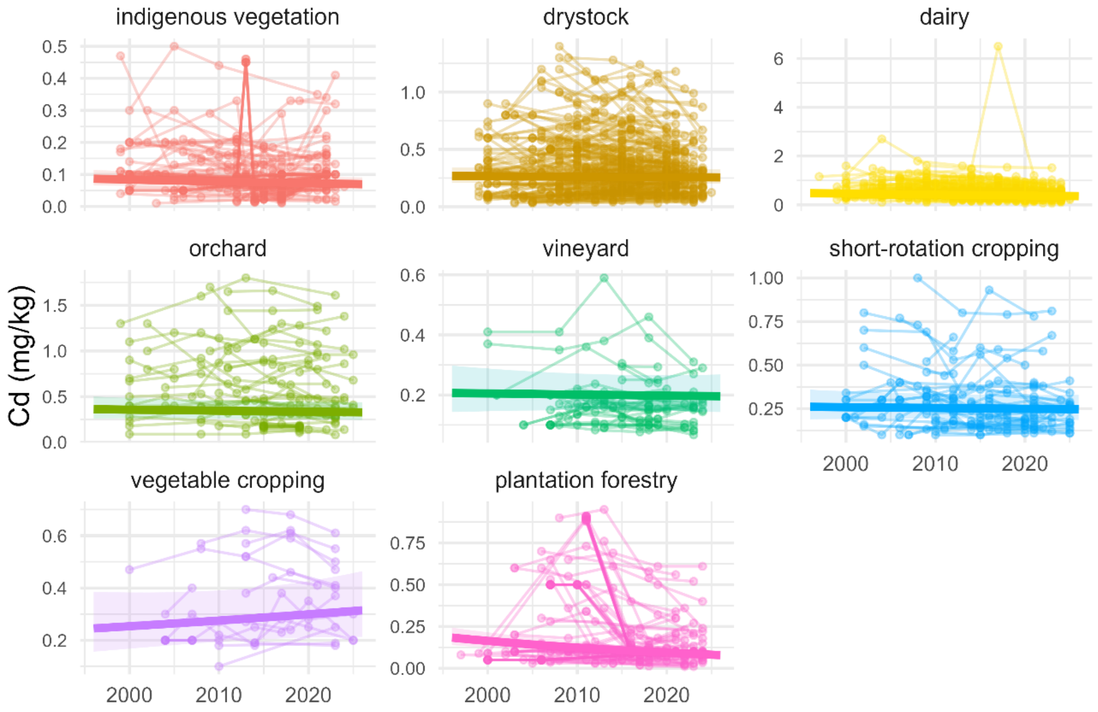

Figure 30. Measured data and land-use trends for Cd over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

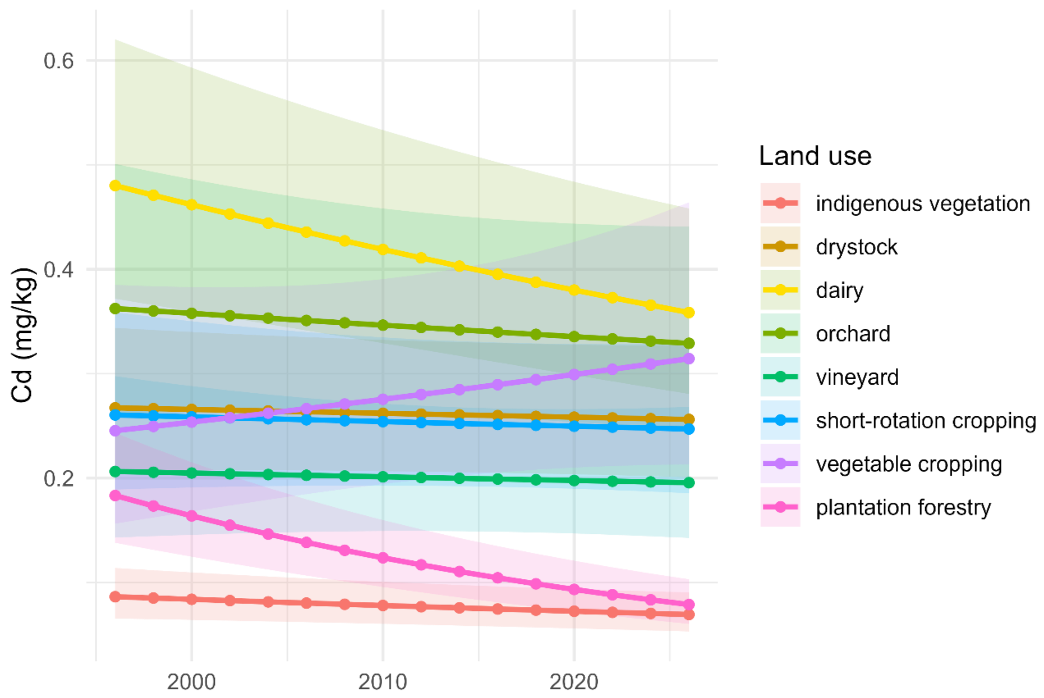

Figure 31. Land-use trends for Cd over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

Fluorine

There were significant increases under drystock and orchards, and a significant decrease under dairy. No other land-use trends were significant for F. This model faces similar limitations to that for HWEC, in that sampling is biased for most sites for the time period post-2005 and the model showed a high degree of collinearity. Thus we recommend caution in interpreting the trend presented here.

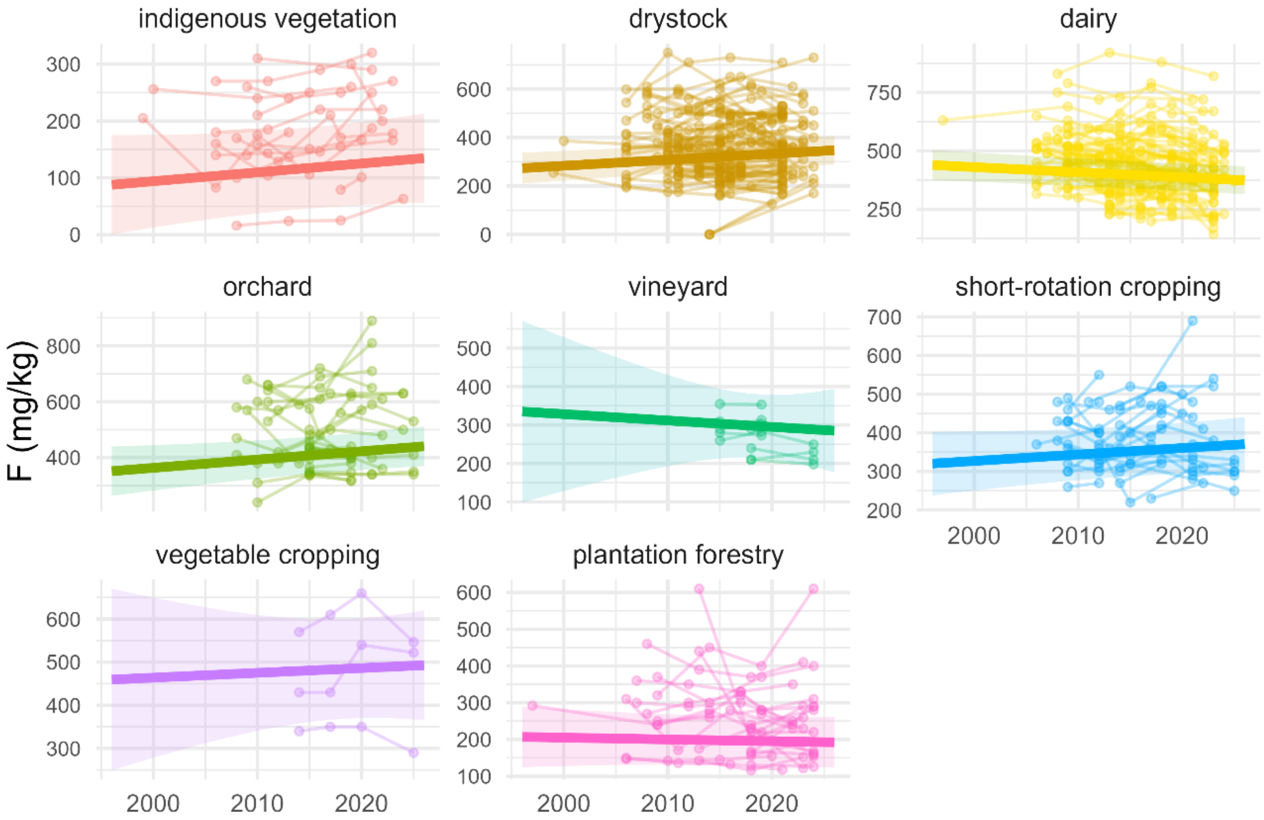

Figure 32. Measured data and land-use trends for F over time.

Notes: Thick lines indicate modelled land-use trends, and shaded areas around these represent 95% confidence intervals, while thin lines represent individual sites over time.

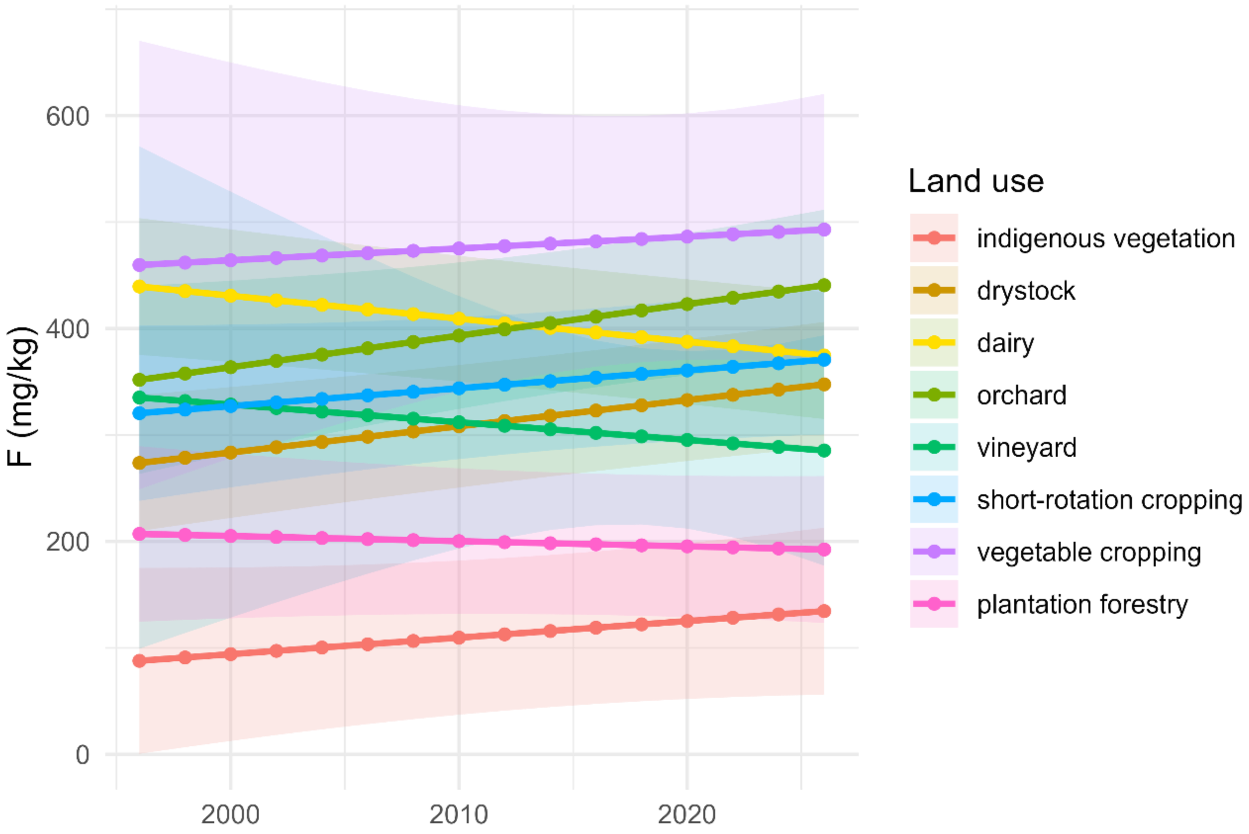

Figure 33. Land-use trends for F over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

Other trace elements: arsenic, chromium, nickel, and lead

As, Cr, Ni, and Pb are not currently used in land management, but they may be present in soils from diffuse sources or as a result of legacy uses (e.g. sheep dip sites, lead arsenate pesticide in orchard sites, or copper-chromium-arsenate treated timber).

There were significant increases in As under orchards and vineyards. No other land-use trends were significant for this trace element.

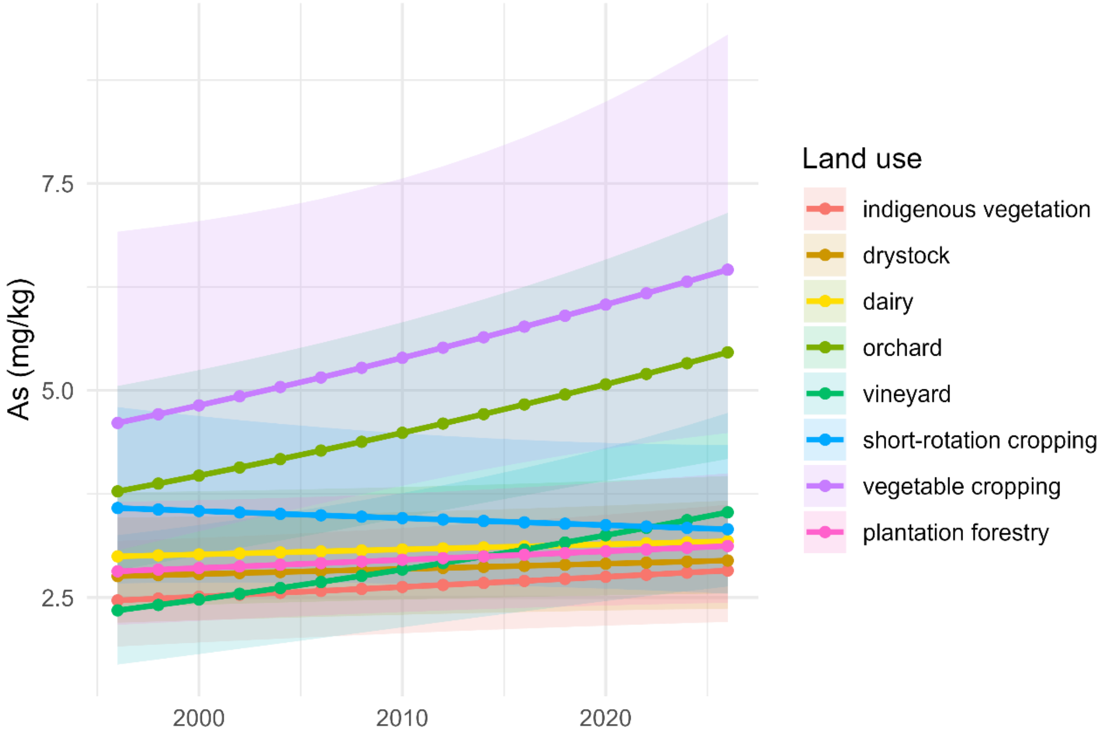

Figure 34. Land-use trends for As over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

There were significant increases in Cr under indigenous vegetation and orchards. No other land-use trends were significant for this trace element.

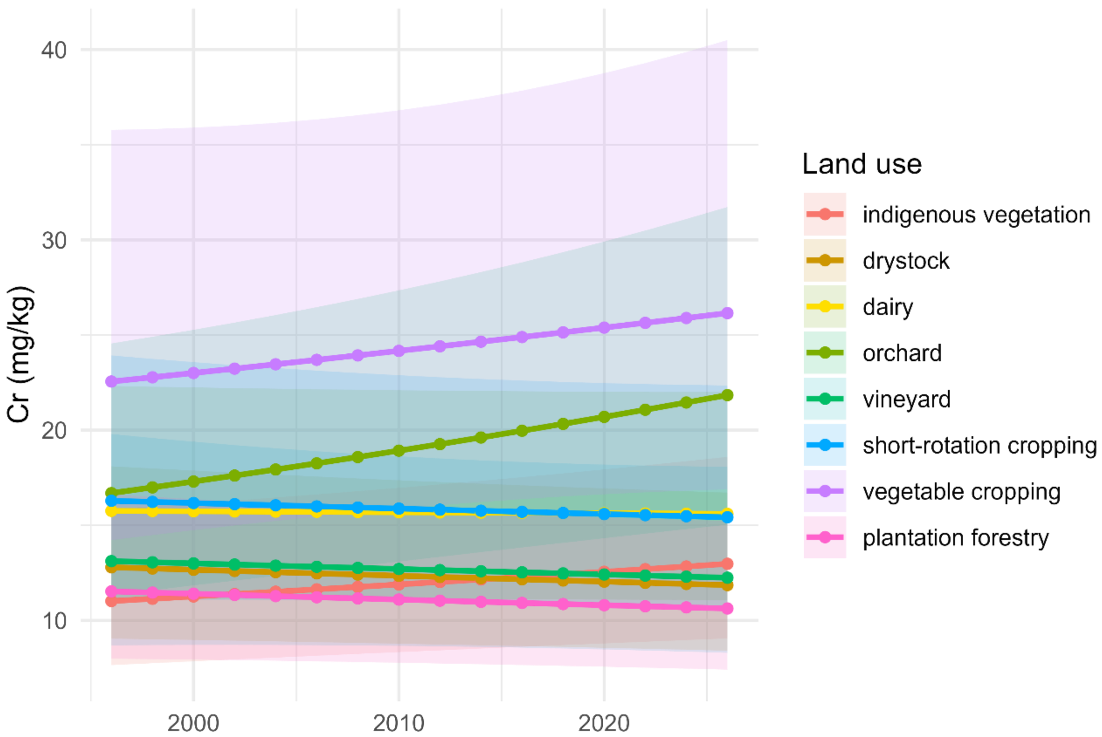

Figure 35. Land-use trends for Cr over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

There was a significant increase in Ni under vegetable cropping. No other land-use trends were significant for this trace element.

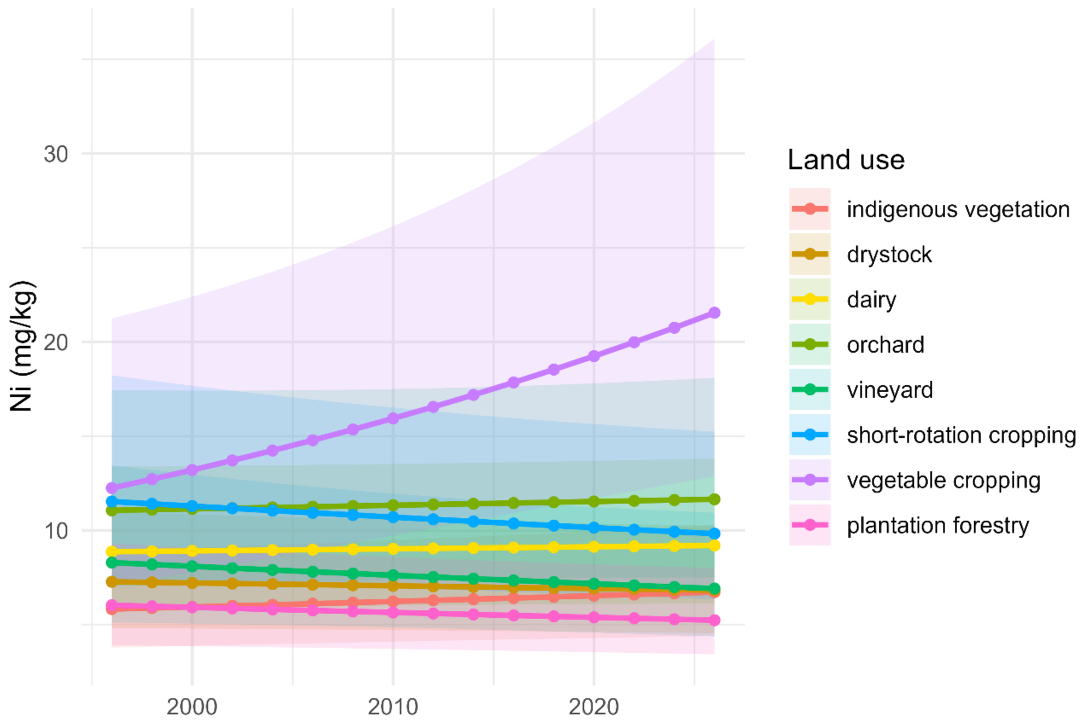

Figure 36. Land-use trends for Ni over time.

Shaded areas indicate 95% confidence intervals around the trends.

There were no significant land-use trends for Pb.

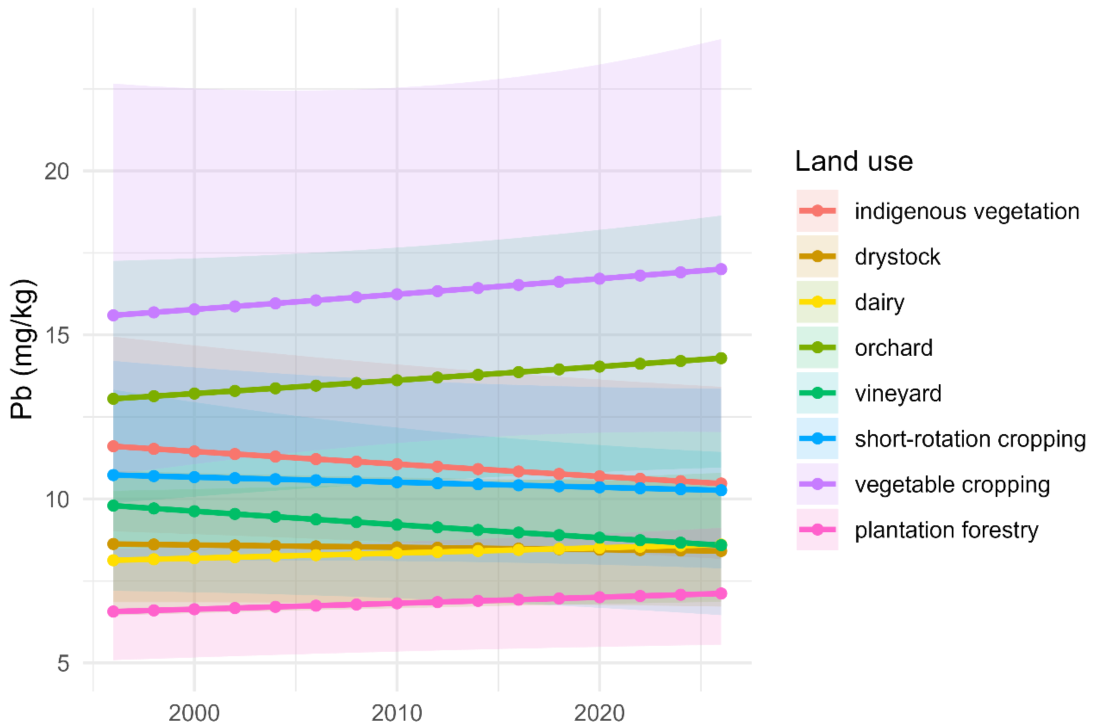

Figure 37. Land-use trends for Pb over time.

Notes: Shaded areas indicate 95% confidence intervals around the trends.

5 Conclusions

Direct comparison between the number of sites not meeting target ranges or reference ranges, or conversion between reference ranges and target ranges for comparison with previous SOE monitoring reports, is confounded by the different land-use categories used, whether an upper or lower limit was specified, and the availability of values for different soil orders.

Comparison of the monitoring data with reference ranges generally results in a higher number of results being identified as falling outside the range as when compared with the target ranges. This is particularly the case for Olsen P and bulk density, for which a much greater number of sites were above the reference range compared to the target ranges, which largely reflects a ‘narrowing’ of the reference range for these indicators.

Despite these differences, comparison of the monitoring data over the two monitoring periods with reference ranges provides findings similar to those found in previous SOE reporting (MfE & Stats NZ 2018, 2021). The following results were notable.

- Total C is low in cropping soils, with c. 20% of sites falling below the reference range and a decreasing trend is observed over time
- Olsen P concentrations are high, and above reference ranges for dairy (68–71% of sites), cropping (30–60% of sites), and orchards (70–88% of sites). The main exceptions to this were that plantation forestry sites were mostly within the reference range, and drystock sites had approximately 50% of sites below the reference range. No Olsen P reference ranges were developed for vineyards.
- Olsen P concentrations show increasing trends over time, particularly for vegetable cropping, but also for drystock and orchards.
- There is evidence of widespread compaction (high bulk density and/or low macroporosity) for most land uses, but particularly dairy. That said, decreases in bulk density (i.e. improvement) under drystock, orchards, and vineyards, and increases in macroporosity (i.e. improvement) in short-rotation cropping, were the only significant trends identified for these indicators.

Aggregate stability and HWEC results were collated for the first time, with aggregate stability results providing clear evidence of soil structural degradation in cropping soils.

There were few sites that exceeded the 95% protection-level Eco-SGVs, with Cu concentrations in orchards most frequently exceeding the Eco-SGV in both monitoring periods. Significant increases of Cu concentrations over time were most obvious for orchards, but increases were also significant for dairy sites. A moderate number of sites, predominantly dairy and drystock, had Cd concentrations that exceeded the Tier 1 trigger value of 0.6 mg/kg.

There were other significant trends for trace elements, such as:

- an apparent increase in As under orchard/vineyards
- increasing trends in Zn under orchards, dairy, and vegetable cropping
- generally decreasing trends in Cu and Zn for cropping, drystock, plantation forestry, and indigenous land uses
- decreases in Cd for indigenous vegetation, plantation forestry, and dairy, and no increasing trends.

The greater specificity of land use (e.g. vegetable cropping vs. vineyards) allows finer delineation of soil properties associated with different land-use classes. However, further improvements in the robustness of land-use classification between regions and over time is required to provide greater confidence in land-use associations, including the identification of real change in land use over time.

Despite challenges with the data, this collation has given rise to an extensive national data set of consistently collected and analysed data, which provides the opportunity to undertake deeper analysis to better understand changes over time, and the influence of other factors (e.g. climate, land management, but particularly the spatial variability of soil properties).

6 Recommendations

- To improve the robustness of information provided, we recommend:
  - investing in the development of streamlined data collation processes to minimise both the time required for collation and data handling errors
  - that councils undertake an audit of land-use information held for all monitoring sites, and include classification of both land use at the time of sampling and farm system
- undertaking further analysis of the HWEC data to assess the potential influence of methodological influences on the observed trend over time
- undertaking a deeper analysis of this extensive national data set of soil quality data to provide a greater understanding of the factors (e.g. climate, land management) that influence soil quality.

7 Acknowledgements

Thanks to Stephen McNeill (BSI) Nina Koele and Fiona Curran-Cournane (MfE), and Kate Lee, David Harris, and Lindsay Morris (Stats NZ) for comments on the draft report (Lance Morrell (MfE). Thanks to Ray Prebble (BSI) for editing assistance and Carrie Innes (BSI) for formatting assistance.

Declaration of the use of generative AI / AI-assisted technologies

This research work included the use of OpenAI's ChatGPT, including GPT-4- and GPT-5-family models, to assist with efficient data wrangling using the R language.

After using this tool, the content was reviewed and edited as needed by the authors.

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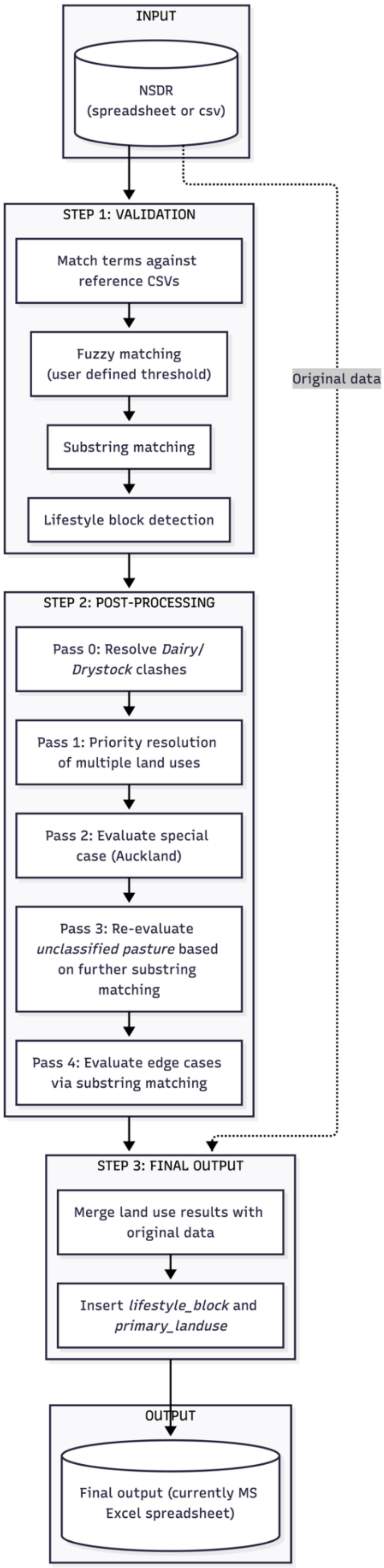
Appendix 1 – Alternative diagram showing the high-level land-use validation process (cf. Figure 1)



Appendix 2 – Distribution of sites across soil orders

Table A2.1. Distribution of sites across different soil orders for the time-step 1 July 2018 to 30 June 2022

Land use	Allophanic	Brown	Gley	Granular	Melanic	Organic	Pallic	Podzol	Pumice	Recent	Ultic	Semiarid	Oxidic	Raw	Total
Dairy	14	49	32	5	2	4	22	1	20	22	6	-	-	-	**177**
Drystock	20	59	19	9	3	3	28	4	16	26	9	2	-	-	**198**
Unclassified pasture	-	3	2	-	-	-	10	-	-	5	-	-	-	-	**20**
Kiwifruit orchard	6	-	-	1	-	-	1	-	1	1	-	-	-	-	**10**
Orchard	4	1	4	-	-	-	1	-	-	9	1	-	-	-	**20**
Tree orchard	1	-	1	-	-	-	-	-	-	-	-	-	1	-	**3**
Vineyard	-	5	9	-	-	-	10	-	-	7	4	-	-	-	**35**
Perennial horticulture	2	-	-	-	-	1	-	-	1	4	-	-	-	-	**8**
Short-rotation cropping	3	17	22	2	-	5	27	-	3	16	2	-	-	-	**97**
Vegetable cropping	6	17	11	9	-	-	18	-	-	2	-	-	-	-	**63**
Plantation forestry	8	16	-	3	-	-	5	1	4	6	7	-	-	1	**51**
Indigenous vegetation	7	11	2	-	-	3	5	1	3	12	1	-	1	-	**46**
Rural residential	1	1	1	2	-	-	-	-	-	1	-	-	-	-	**6**
Other	-	-	2	-	-	-	2	-	-	2	-	-	-	-	**6**
Total	**72**	**179**	**105**	**31**	**5**	**16**	**129**	**7**	**48**	**113**	**30**	**2**	**2**	**1**	**740**

Hyphens indicate no sites were present on that soil order for that land use

Table A2.2. Distribution of sites across different soil orders for the time-step 2 July 2022 to 30 June 2025

Land use	Allophanic	Brown	Gley	Granular	Melanic	Organic	Pallic	Podzol	Pumice	Recent	Ultic	Anthropic	Semiarid	Raw	Total
Dairy	16	33	17	2	2	6	29	3	18	16	8	-	-	-	**150**
Drystock	16	43	23	5	3	3	30	3	3	25	2	3	-	-	**159**
Unclassified pasture	-	1	1	-	1	-	9	-	-	2	-	-	-	-	**14**
Kiwifruit orchard	2	-	-	1	-	-	-	-	1	4	-	-	-	-	**8**
Orchard	5	2	-	-	-	1	1	-	-	2	2	-	1	-	**14**
Tree orchard	2	1	2	-	-	-	-	-	-	8	-	-	-	-	**13**
Vineyard	-	7	7	-	2	-	14	-	-	6	4	-	4	-	**44**
Perennial horticulture	5	2	1	-	-	1	-	-	1	5	-	-	-	-	**15**
Plantation forestry	9	29	-	-	2	-	6	2	11	12	-	-	-	1	**72**
Short-rotation cropping	4	11	20	-	1	5	19	-	1	20	1	-	-	-	**82**
Vegetable cropping	-	4	4	13	1	-	9	-	-	9	-	1	-	-	**41**
Indigenous vegetation	4	17	1	9	-	2	1	1	3	5	16	-	-	-	**59**
Rural residential	-	1	-	-	-	-	-	-	-	-	-	-	-	-	**1**
Urban open space	11	-	1	2	-	-	-	-	-	6	7	10	-	-	**37**
Other	-	-	3	-	-	-	-	-	-	-	-	-	-	-	**3**
Unused	-	-	1	-	-	-	-	-	-	-	-	-	-	-	**1**
Total	**74**	**151**	**81**	**32**	**12**	**18**	**118**	**9**	**38**	**120**	**40**	**14**	**5**	**1**	**713**

Hyphens indicate no sites were present on that soil order for that land use

Appendix 3 – Variation explained by random effects in trend analysis

Table A3.1. Variation explained by random effects in the trend analyses for each indicator

Indicator	Variance component	Variance explained (on the scale of the transformed response)
Olsen P	Site	0.340
	Region	0.034
	Soil order	0.012
	Residual	0.155
Total C	Site	0.090
	Region	0.023
	Soil order	0.094
	Residual	0.035
Total N	Site	0.088
	Region	0.025
	Soil order	0.064
	Residual	0.034
AMN	Site	3.083
	Region	0.617
	Soil order	2.953
pH	Site	0.103
	Region	0.003
	Soil order	0.007
	Residual	0.078
Bulk density	Site	0.017
	Region	0.005
	Soil order	0.020
	Residual	0.009
Macroporosity	Site	0.295
	Region	0.138
	Soil order	0.097
	Residual	0.474
C/N ratio	Site	0.015
	Region	0.003
	Soil order	0.005
	Residual	0.007
HWEC	Site	0.073
	Soil order	0.058
	Region	0.037
	Residual	0.063
As	Site	0.251
	Soil order	0.050
	Region	0.058
	Residual	0.083

Indicator	Variance component	Variance explained (on the scale of the transformed response)
Cd	Site	0.213
	Region	0.111
	Soil order	0.042
	Residual	0.136
Cr	Site	0.230
	Soil order	0.052
	Region	0.258
	Residual	0.068
Cu	Site	0.287
	Soil order	0.034
	Region	0.017
	Residual	0.080
Ni	Site	0.305
	Soil order	0.033
	Region	0.392
	Residual	0.095
Pb	Site	0.225
	Soil order	0.051
	Region	0.069
	Residual	0.052
Zn	Site	0.165
	Soil order	0.043
	Region	0.043
	Residual	0.074
F	Site	6747
	Soil order	3239
	Region	2510
	Residual	3017