Soil Quality and Trace Elements in the Auckland Region, 2018-2022

State of the Environment Reporting

Danilo Guinto

September 2025

Technical Report 2025/23

aucklandcouncil.govt.nz

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Auckland Council
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ISSN 2230-4525 (Print)
ISSN 2230-4533 (Online)

ISBN 978-1-991377-83-8 (PDF)

The Peer Review Panel reviewed this report
Review completed on 11 September 2025 Reviewed by two reviewers
Approved for Auckland Council publication by: Name: Paul Klinac Position: General Manager, Engineering, Assets and Technical Advisory
Recommended for approval/publication by:
Name: Dr Jonathan Benge Position: Head of Environmental Evaluation and Monitoring
Name: Jacqueline Lawrence-Sansbury Position: Team Manager, Air, Land and Biodiversity, Environmental Evaluation and Monitoring Unit, EEMU
Date: 11 September 2025

Recommended citation
Guinto, D. (2025). Soil quality and trace elements in the Auckland region, 2018-2022. State of the environment reporting. Auckland Council technical report, TR2025/23

Image credits
Cover: A soil landscape in Algies Bay
Page 2: A recently tilled vegetable paddock in south Auckland
Photographs by Danilo Guinto

Executive summary

The soil is a non-renewable natural resource that provides several functions through maintaining environmental quality and supporting plant, animal and human health. The importance of the soil in supporting primary production is highlighted in the economic contribution of the Pukekohe horticulture industry estimated to be around $261 million per annum. Thus, soils need to be managed carefully to ensure sustainable production and minimise environmental degradation. Changes in the capacity of soil to function are reflected in soil properties that change in response to management or climate. These soil quality indicators are important in focusing conservation efforts or maintaining and improving the condition of the soil and in evaluating soil management practices.

As part of its State of the Environment (SoE) reporting, Auckland Council has been continuously monitoring topsoil quality (0-10 cm) since 1995. Periodic sampling is done under various land uses that include horticulture (outdoor vegetable and orchard sites), pasture (dairy, drystock and lifestyle block converted sites), urban (mainly parks), plantation forestry and native vegetation sites. Seven soil quality indicators are measured: pH, total carbon (C), total nitrogen (N), anaerobically mineralisable nitrogen (AMN), Olsen phosphorus (P), bulk density (BD) and macroporosity (MP). In addition, seven trace elements, namely total recoverable arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn) are included.

The present report covers the current monitoring data from 2018-2022 and compares it with the 2013-2017 base period.

Many horticulture sites (65 per cent) have elevated Olsen P levels due to excessive P fertilisation. This presents a high risk of runoff into waterways and may lead to the eutrophication of surface water bodies. About 71 per cent are also compacted as reflected in their low macroporosity. In terms of bulk density, however, only 24 per cent are considered compacted which shows that bulk density is a less sensitive indicator of soil compaction. Soils under horticulture also have high proportions of total C (41 per cent) and AMN (47 per cent), respectively below their guideline values indicating low potential for mineralisation of nutrients like, N, P and sulphur (S).

Pasture soils are less enriched in Olsen P compared to horticulture soils, with only 37 per cent having elevated concentrations. However, like the horticulture soils, 70 per cent of samples are compacted. All sites passed the total C and AMN guideline values, although 30 per cent are outside the total N guideline range.

At urban sites, 50 per cent of samples failed the guideline range for Olsen P suggesting about half of the urban parks are receiving high P application. Under forestry land use, 73 per cent of soil samples have failed the guideline range for Olsen P. However, this is not an environmental concern because the samples that failed were below the lower limit of the guideline value which means that inadequate P fertiliser is being applied under plantation forestry to potentially benefit tree growth.

For all trace elements, the percentages of samples that are outside guideline ranges are 26 per cent or less with fails for Cu, Zn and Cd being most noticeable under pasture and horticulture land uses. For As and Ni, about 6 per cent or less of the sites were outside their respective guideline ranges under all land uses. In urban parks, about 17 per cent each of Cr and Pb fell outside their respective guideline range.

Mean concentrations of trace elements were generally within their guideline values and varied by land use, except for As. Horticulture and pasture soils had significantly higher Cd levels, attributed to long-term phosphate fertiliser application since Cd is an unavoidable impurity in phosphate fertilisers. Horticulture and urban sites had the highest mean concentrations of Cu, likely due to its use as a fungicide in horticulture. Urban soils had significantly higher mean Pb concentrations than other land uses, possibly due to historic vehicle emissions.

Comparisons between the 2018-2022 current period and the 2013-2017 base period across all land uses indicated only slight changes in soil quality indicators and trace elements and their differences were not statistically significant. This indicates the same issues of extreme P fertility, compaction and low organic resources in the more intensive land uses like outdoor vegetable production remain at the present.

While it is challenging to improve soil quality in intensive farming due to practices that exposes soil organic carbon to be lost to the atmosphere via microbial respiration, there is scope to adopt sustainable practices such as cover cropping, crop rotation, reduced tillage, composting, and promoting biodiversity. Within Auckland, several programmes and initiatives are now in place to address soil quality issues as well as water quality issues. These include the "Empowering Farmer Compliance for Auckland" guide packaged by Perrin Ag and funded by Auckland Council, and projects under the Te Tautara o Pukekohe Trust, such as freshwater and soil health monitoring, crop stacking, and sediment management. It is hoped that all current and future efforts to stem increasing soil quality degradation will ensure that highly productive soils support our primary land uses and enhance environmental sustainability.

Because of the importance of organic matter and the role that soil organisms play in crop production and environmental protection, future soil monitoring needs to consider the use of biological soil indicators, include the assessment of subsoil conditions, and conduct measurements of emerging contaminants like pesticide residues and microplastics.

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1 Introduction

Soil quality is the capacity of soil to function within ecosystems and land-use boundaries to sustain: (i) biological productivity, (ii) environmental quality, and (iii) plant and animal (including human) health (Doran et al., 1996). This definition involves the linkage between soil functions and soil ecosystem services (Bünemann et al., 2018). Soil functions represent “what the soil does” or “how the soil behaves”, rather than simply describing what the soil is. Soil functions are groups of soil attributes and processes, which link together to serve a role (Figure 1). The soil’s capacity to function influences the extent to which ecosystem services are provided. Ecosystem services, many of which are directly and indirectly provided by soils, support the very survival and quality of all life. Given the complex relationship soils have to ecosystem services, it is not surprising that pinpointing exactly what represents good quality or healthy soil is challenging.

No single soil measurement quantifies soil quality, rather it must be inferred from several soil attributes, processes, and contexts. Changes in the capacity of soil to function are reflected in soil properties that change in response to management or climate. These soil quality indicators are important in focusing conservation efforts or maintaining and improving the condition of the soil and in evaluating soil management practices. Indicators are also important to relate soil quality to that of other natural resources (e.g. water). These help to determine trends in the condition of soils and can also serve as guides in policy land management decisions and policy formulation. Soil health has now become an important term in soil science and sustainable agriculture circles. As defined by the Food and Agriculture Organization of the United Nations (FAO), soil health is the ability of the soil to sustain the productivity, diversity and environmental services of terrestrial ecosystems (FAO, 2020). Today, the terms soil quality and soil health are commonly used as synonyms — distinguished mostly by preference rather than meaning.

Monitoring and reporting on the state of all or part of the environment by regional and unitary councils is a requirement under Section 35 of the Resource Management Act 1991. As part of its State of the Environment (SoE) reporting, Auckland Council has been monitoring topsoil quality (0-10 cm) since 1995, starting with the Soils 500 programme led by Manaaki Whenua Landcare Research (MWLR). The data accumulated to date show the state and trends of key indicators, reflecting changing soil health status, tracking the impacts of human activities over time and identifying soil quality-related issues to be addressed (e.g. excessive soil fertility, compaction, contamination, etc.). Curran-Cournane (2020) reported the status of the region’s soil quality during the period 2013-17 and identified trends from the three periods covering 1995-2000, 2008-2012, and 2013-17 according to land use.

This report covers the current monitoring data from 2018-2022, and compares it with the 2013-2017 base period. The specific objectives of this report were to identify any soil quality issues arising from the current monitoring data (2018-2022), compare soil quality under broad land use and under rural land use activity, and analyse data trends during the periods 2013-2017 and 2018-2022 across all land uses.

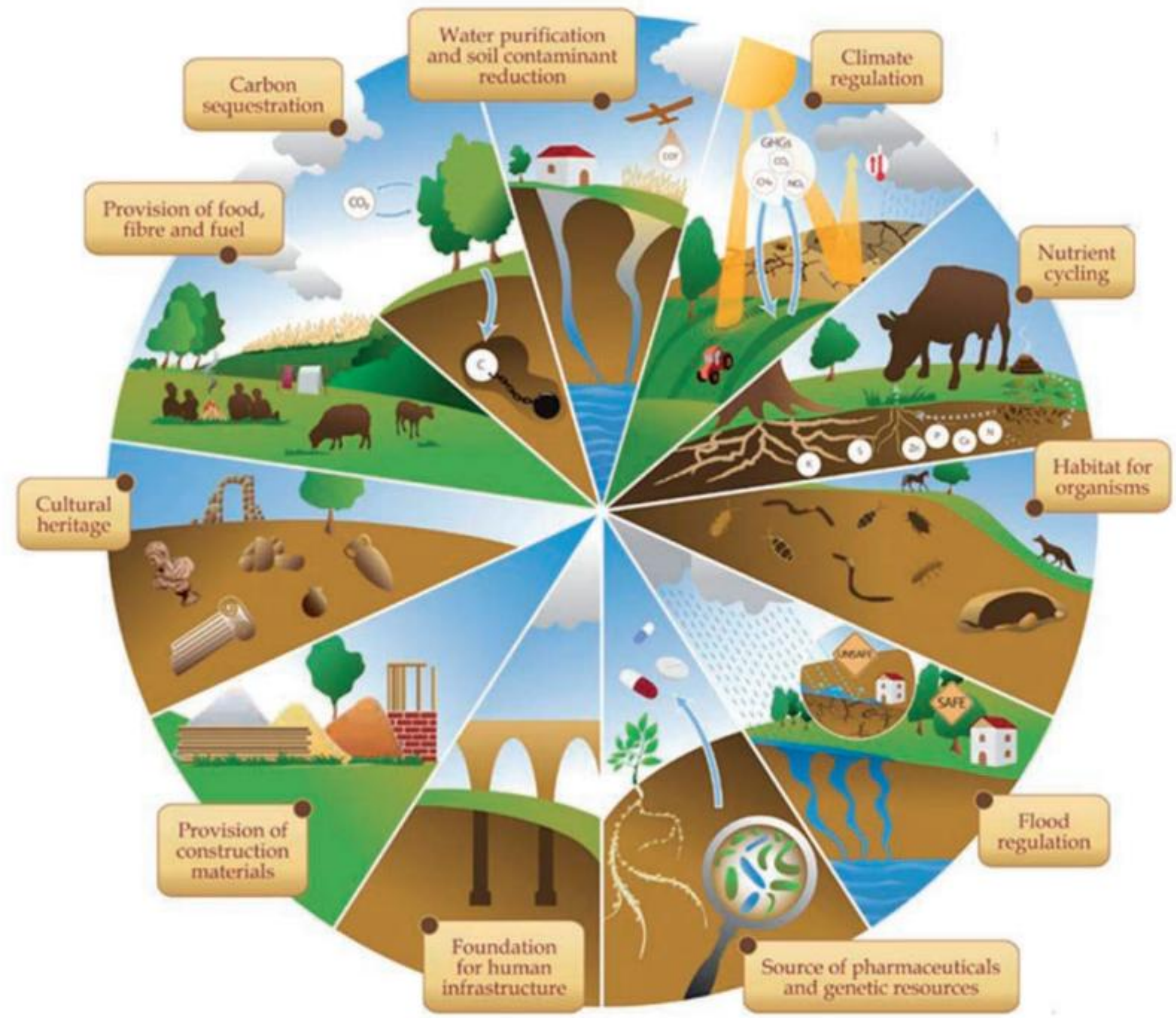

Figure 1. The multiple functions of soil (Source: Food and Agriculture Organization of the United Nations).

1.1 Primary production land use in Auckland – special focus

Although Auckland is a rapidly urbanising region, primary rural production that depends on the soil resource continues to be valuable and important. It contributes to local and national food supply and export markets. In particular, south Auckland's Franklin district is a primary production hub undergoing rapid land use change owing to population growth and the conversion of farmlands with elite and prime soils into residential and rural lifestyle blocks as documented in various studies by Curran-Cournane et al. (2014; 2018; 2021), Deloitte (2018) and Richardson (2021). The area is known for its highly versatile soils recognised for their contribution to the New Zealand's food production particularly outdoor vegetable production (Orbell, 1977; Molloy, 1998) and the provision of other ecosystem services (Curran-Cournane et al. 2014).

There are a range of crops and animals grown in the Auckland region but not all data from these enterprises are collected and reported in Stats NZ's Agricultural Production Surveys especially for minor crops and livestock (e.g. deer). Thus, selected available data sets are provided to describe trends in primary production land use in the region. Since 2002, the number of livestock in Auckland follows a declining trend (Figure 2). From 2002 to 2023, dairy cattle and beef cattle numbers declined by 35% and 36%, respectively, while sheep numbers declined by 45%. However, in the more recent period from 2013 to 2023, the declines were much smaller, with dairy cattle numbers declining by only 12%, and both beef cattle and sheep numbers declining only by 5%.

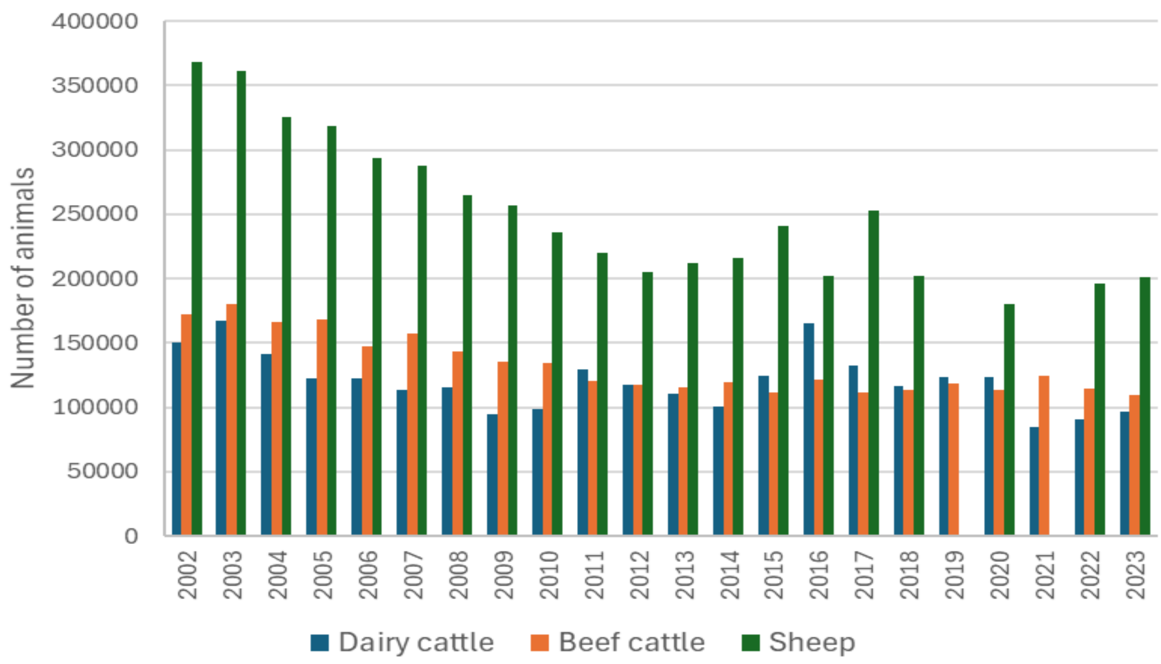

Figure 2. Livestock numbers in the Auckland region, 2002-2023 (Statistics NZ Agricultural Production Survey).

In addition, data from NZ Dairy Statistics show that since 2002, effective dairy farm area decreased by 38% while average herd size increased by 47%. Average stocking rate decreased only slightly by 0.85% (Table 1). When considering the more recent decade (2013/14 to 2023/24), however, the decline in effective farm area is only 22% and the increase in herd size is only 11%. The increase in stocking rate is about 2.2%. Increases in herd size and stocking rate indicate more intensive use of the land under dairy use which have implications for how soils are used and managed.

The picture is different for the more intensive horticultural land uses such as orchard and outdoor vegetable crops. For orchard crops, Figure 3 shows that areas planted under kiwifruit increased from 2014 to 2022, while areas under avocado show an increasing trend since 2009. Areas under wine grape cultivation were variable, increasing from 2012 and peaking in 2017, declining in 2019-2020, before increasing again in 2022. For vegetable crops, over a thousand hectares are harvested periodically under onions and over 700 hectares under potatoes. In general, the area harvested for onions was larger than that for potatoes from 2002 to 2014, except in 2017 and 2020, when the area harvested for potatoes was much higher than that for onions.

The 4,359-hectare so-called Pukekohe hub is an area of intensive horticultural production. The horticulture industry within this area is a wealth creating industry which makes a strong economic contribution, largely through the production of onions, potatoes, carrots, leafy greens, brassicas, tomatoes, and kiwifruit. Deloitte (2018) has estimated the economic contribution of the hub's horticulture industry to be $261 million per annum. This relatively small growing area, 0.01% of the Auckland region, contributes a respectable 0.3% to Auckland's economy.

Table 1. Changes in effective dairy farm area, average herd size and average stocking rate in the Auckland region, 2001/02 to 2023/24 (from NZ Dairy Statistics)

Year	Effective farming area (ha)	Average herd size	Average stocking rate (cows/ha)
2001/02	61,393	199	2.34
2002/03	59,762	205	2.33
2003/04	56,846	216	2.39
2004/05	53,650	221	2.4
2005/06	50,381	224	2.41
2006/07	48,358	233	2.43
2007/08	46,361	240	2.46
2008/09	47,383	245	2.43
2009/10	45,672	244	2.4
2010/11	46,947	248	2.36
2011/12	46,282	249	2.37
2012/13	48,655	260	2.3
2013/14	48,826	262	2.27
2014/15	47,063	272	2.42
2015/16	48,041	271	2.31
2016/17	43,549	264	2.4
2017/18	43,619	273	2.42
2018/19	40,937	281	2.43
2019/20	39,178	283	2.45
2020/21	38,376	289	2.47
2021/22	38,140	291	2.45
2022/23	35,310	283	2.42
2023/24	38,084	292	2.32
% change (2002-2024)	-38	47	-0.85
% change (2014-2024)	-22	11	2.2

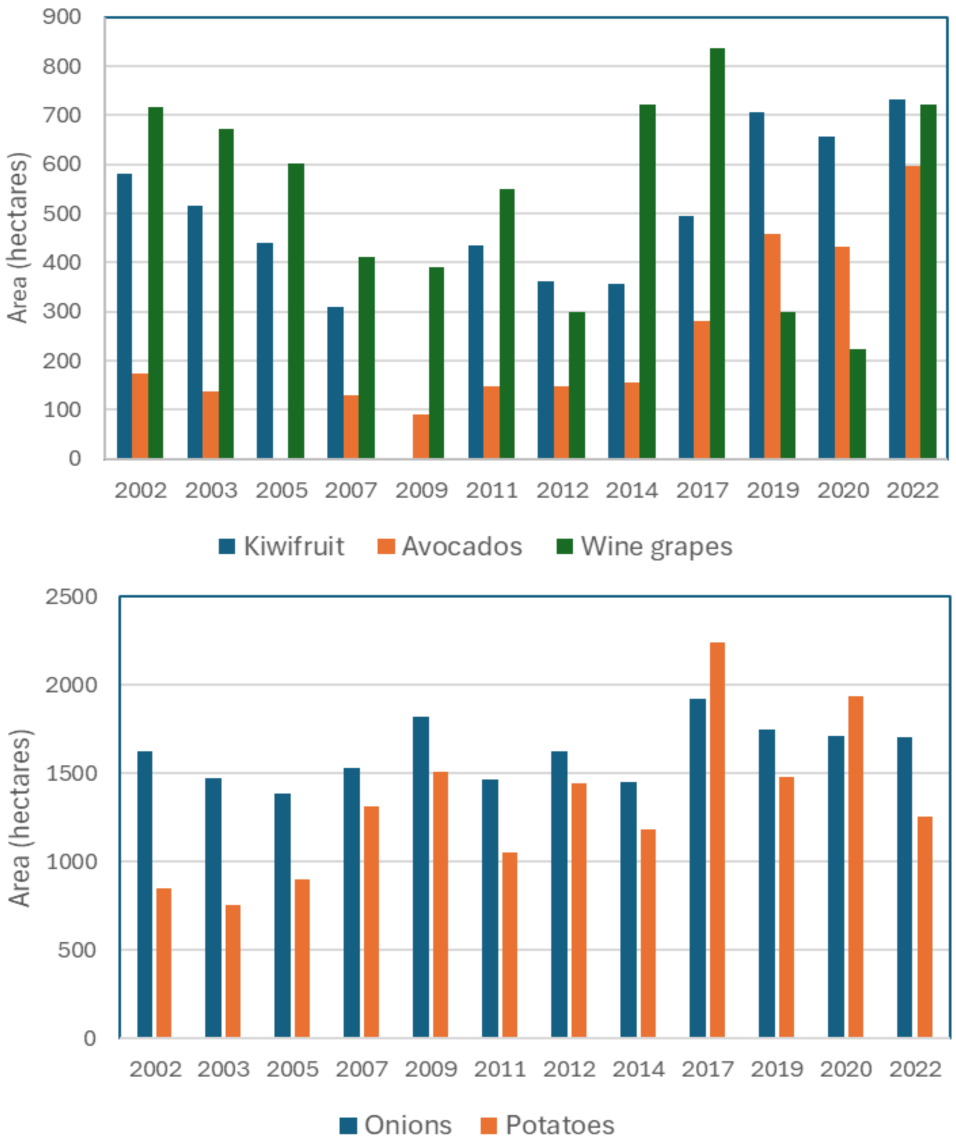

Figure 3. Areas planted under selected orchard crops (top) and areas of harvested onions and potatoes (bottom) in Auckland, 2002 to 2022 (Statistics NZ Agricultural Production Survey)

1.2 Brief description of Auckland's soil quality monitoring programme

The full background to Auckland's soil quality monitoring programme has been provided by Curran-Cournane (2020). To date, there are a total of 157 soil quality monitoring sites (Figure 4) across the region representing the five land-use types of interest:

- 19 horticulture sites (outdoor vegetable and orchard sites),
- 49 pasture sites (dairy, drystock and lifestyle block converted sites),
- 15 plantation forestry sites,
- 36 urban park sites,
- 38 indigenous or native vegetation sites.

Figure 4. Map of Auckland's soil quality monitoring sites.

The diversity of soil types is also accounted for in the monitoring sites. In terms of soil classification (New Zealand soil order level), the soil classes belong to 47 Ultic, 25 Granular, 24 Allophanic, 18 Recent, 17 Brown, 10 Gley, 10 Anthropic and 6 Organic soil orders (Appendix 1). Sampling occurs every year during spring generally on a five-year cycle by land use so that for every year at least one land use category Is sampled. Thus, for the period 2018 to 2022, sampling was conducted as follows: 2018 – horticulture; 2019 – dairy, 2020 – drystock; 2021 – forestry; and 2022 – native and urban.

Seven topsoil (0-10 cm) quality indicators are measured: pH, total carbon (C), total nitrogen (N), anaerobically mineralisable nitrogen (AMN), Olsen phosphorus (P), bulk density (BD) and macroporosity (MP). In addition, seven trace elements, namely total recoverable arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn) are included.

1.3 Supporting information

This report is one of a series of technical publications prepared in support of *Te oranga o te taiao o Tāmaki Makaurau – The health of Tāmaki Makaurau Auckland's Natural Environment in 2025: a synthesis of Auckland Council State of the Environment reporting*.

All related reports (past and present) are published on the Knowledge Auckland website.

All data supporting this report can be requested through our Environment Auckland Data Portal. Here you can also view live rainfall data and use several data explorer tools.

2 Materials and Methods

2.1 Soil sampling and analysis

Monitoring follows standard protocols for New Zealand soil quality sampling. Full details of the sampling protocols are given in Land Monitoring Forum (2009) and National Environmental Monitoring Standards (NEMS) (2022) and are described briefly here. A georeferenced 50 m transect was established in each sampling site. For chemical analyses, topsoil samples (0-10 cm) were collected with a step-on soil sampler at 2-m intervals along the 50 m transect. The individual samples collected were labelled, composited and mixed thoroughly in a plastic bag (Figure 5). It should be noted that the standard 0-10 cm topsoil sampling depth represents a compromise for pasture and horticultural land uses, since pasture soils are normally sampled at 0-7.5 cm while horticultural soils are sampled at 0-15 cm. For physical analyses (i.e., bulk density and macroporosity), three stainless steel soil cores (10 cm diameter, 7.5 cm high) were driven into the soil at 15, 30 and 45 m along the transect.

The collected samples were submitted to Landcare Research laboratories for the analysis of seven standard soil quality indicators, namely: pH, total C, total nitrogen N, AMN, Olsen P, bulk density (BD) and macroporosity (MP). For chemical analyses, the composited samples were submitted to the Palmerston North laboratory while for physical analyses, soil cores were sent to the Hamilton laboratory.

For trace element analysis, composited samples were submitted to Hill Laboratories in Hamilton for the analysis of As, Cd, Cu, Cr, Pb, Ni, and Zn. The soils were air-dried at 35°C and screened to pass a 2-mm sieve. Trace element concentrations were determined by digesting the samples in nitric/hydrochloric acid and analysing the trace elements in the digest by inductively coupled plasma mass spectrometry (also known as US Environmental Protection Agency Method 200.2). The concentrations were reported as total recoverable metals in mg/kg dry soil.

It is acknowledged that some constraints are present in the most recent soil quality data collected that resulted in fewer data points. Between 2018 and 2022, several scheduled soil quality sites across different land uses could not be sampled due to access restrictions, land use changes, or biosecurity concerns. These issues, beyond the control of Auckland Council staff, have affected the completeness and consistency of soil quality reporting. This resulted in a total of only 144 sites being used. Hopefully these limitations can be rectified once the concerned authorities/landowners provide site access in future samplings so that these sites do not become permanently lost.

Table 2 provides a summary of the standard soil quality indicators and trace elements used in SoE reporting and their significance in relation to primary production and environmental outcomes. Appendix 2 shows further detailed information on the seven trace elements reported in soil quality monitoring.

Figure 5. Soil quality sampling on the 50-m transect line.

2.2 Data presentation and statistical analysis

The analysis focused on the most recent soil quality data collected (2018-2022). The data for soil quality indicators and trace elements were presented graphically and expressed as the percentage of sites falling below, within, and above the guideline ranges. Mean values were compared with environmental guideline values and presented in tabular form, showing the number and percentage of sites outside the guideline values for both soil quality indicators and trace elements.

Soil quality guideline ranges are numerical values of soil quality indicators deemed desirable either from a production or from an environmental protection standpoint (Sparling et al., 2008; MacKay et al., 2013). Both soil quality and trace element guidelines provide an early warning system whereby values falling outside the recommended ranges can pose a risk to the environment and/or soil productivity.

At the time of writing, the recommended guideline ranges for the soil quality indicators are being revised for use in SoE reporting (Cavanagh et al., 2025). Therefore, the recommended guideline ranges by land use and soil order from Curran-Cournane (2020) were retained (Table 3). An adjustment for the Olsen P guideline range was required, because while the values were reported gravimetrically (in mg/kg), the target guideline range that the site values were reported against were actually in volumetric units (mg/L) (See Soil quality and land use | Stats NZ). This requires converting the volumetric guideline range to gravimetric range using the conversion table provided by Drewry et al. (2022). For example, the original guideline range for Olsen P was thought to be 15-50 mg/kg

(Curran-Cournane, 2020) which now converts to 20-65 mg/kg. Any future revisions in guideline ranges that will significantly differ numerically from the current guideline ranges will have a bearing on the number and percentage of sites falling within or outside these ranges. It should be noted that for native vegetation sites, no current guideline ranges exist for any soil quality indicators or trace elements.

Table 2. Alphabetical list of soil quality indicators used in State of the Environment reporting and their significance.

Indicator [Unit]	What is it?	Significance
Anaerobically mineralisable nitrogen (AMN) [mg/kg]	A measure of the amount of nitrogen (N) that can be readily supplied to plants from the decomposition of soil organic matter under ideal conditions.	An indicator of biologically active soil N which is crucial for understanding substrate quality and N dynamics. Since the actual amount of N that will mineralise in the field depends on factors such as soil moisture and temperature, caution is needed when interpreting the results.
Bulk density (BD) [g/cm^3]	Dry mass of soil divided by its total volume. Soils typically have about half of their volume comprised of voids or pore spaces. The voids hold water and air and allow them to move through soil. If these pores are lost through compaction, bulk density increases.	Compacted soils have poor aeration, are slow draining, and roots find it difficult to grow and push through such soil. Bulk density is influenced by the amount of soil organic matter, texture, type of soil minerals and porosity.
Macroporosity (MP or MP10), Measured at -10kPa suction [%]	A measure of the proportion of large pores in soil, measured at a suction of -10kPa. Large pores are defined as those with a diameter greater than 30 microns.	Macropores are important for air penetration into soil and are the first pores to be lost when soils are compacted. Low macroporosity reduces soil aeration, resulting in less clover growth and N fixation and decreased pasture yields.
Olsen P [mg/kg]	The standard method of assessing soil P availability to plants. Phosphate is the only form of P taken up by plants. There is very little phosphate in the soil solution as most 'available' phosphate is adsorbed onto clays and organic matter.	The Olsen extractant (dilute sodium bicarbonate) mimics the ability of a plant to remove solution and adsorbed phosphates from soil and hence get a measure of the P status for plant nutrition. Olsen P is used to calculate rates of P fertiliser application.
pH [unitless]	Soil pH is an indication of the acidity or alkalinity of the soil. It is a measure of the amount of hydrogen (H^+) ions in solution. A pH of 7 is	Most plants and have an optimum pH range for growth and pH affects which species will grow best by influencing the availability of soil nutrients. Most forest

Indicator [Unit]	What is it?	Significance
	termed neutral, below 7 is acidic, and above 7 is alkaline or basic.	soils in New Zealand are acidic, and indigenous forest plants are generally tolerant of acid conditions. Introduced exotic pasture and crop species require higher pH. Excess soil acidity is normally corrected by liming to raise the pH.
Total C [%]	Measures the amount of carbon in soil. This includes carbonates and soil organic matter C, but New Zealand soils typically contain very little carbonate, so total C is a good measure of organic matter.	Organic matter helps soils retain moisture and nutrients and gives good soil structure for water movement and root growth. Carbon is a food source for a diverse range of microbes that play important roles in mineralisation of nutrients like N, P and sulphur. Once depleted, organic matter takes many years to replace, and its careful conservation is recommended by most agronomists and soil scientists.
Total N [%]	A measure of the total amount of all forms of nitrogen in soil. Typically, in topsoils, organic matter N makes up more than 90% of the total N.	N is an essential major nutrient for plants and animals, and the store of organic matter N is an important measure of soil fertility. Organic N needs to be mineralised to inorganic forms (ammonium and nitrate) by soil micro-organisms before it can be used by plants.
Trace Elements [mg/kg] (See Appendix 2 for details)	Seven trace elements (As, Cd, Cr, Cu, Ni, Pb and Zn) are measured and reported as total recoverable elements.	These trace elements are regarded as potential or actual contaminants in soil arising from rural and urban land use activities. Excessive levels can pose toxicity problems to plants and animals and even to humans.

Table 3. Guideline ranges for soil quality and trace elements by land use and soil order (Curran-Cournane, 2020). (Broad refers to the range for all land uses except those land use and/or soil order combinations below it).

Indicator or Trace Element	Range
pH	Broad 5.5-7.5 Pasture (excl. Organic) 5.5-6.6; Pasture (Organic) 5.0-6.7; Horticulture (excl. Organic) 5.5-7.5; Horticulture (Organic) 5.0-7.5; Forestry (Excl. Organic) 4.0-7.5
Total carbon (%)	Broad >3 Allophanic: >4; Recent >3; Brown, Gley, Granular and Ultic >3.5; Excl. Organic
Total N (%)	Broad 0.35-0.70 Pasture 0.35-0.70; Forestry 0.2-0.7; Excl. Horticulture (No guideline)
Olsen P (mg/kg)	Broad 20-65 Pasture and Horticulture (Brown, Gley, Organic, Granular and Ultic) 26-46; Pasture and Horticulture (Allophanic and Granular) 26-65; Forestry 7-39
AMN (mg/kg)	Broad >40 Pasture >60; Horticulture and Forestry >40
Macroporosity (%)	Broad: 10-30 Forestry: 5-30
Bulk density (g/cm^3)	Broad 0.6-1.3 Allophanic 0.6-1.2; Brown, Gley, Granular and Ultic 0.7-1.3; Organic 0.2-1.0; Recent 0.8-1.3
As (mg/kg)	0.4-12
Cd (mg/kg)	<0.1-0.65
Cr (mg/kg)	Non-volcanic 2-55; Volcanic (Allophanic and Granular) 3-125
Cu (mg/kg)	Non-volcanic 1-45; Volcanic (Allophanic and Granular) 20-90
Ni (mg/kg)	Non-volcanic 0.9-35; Volcanic (Allophanic and Granular) 4-320
Pb (mg/kg)	1-65
Zn (mg/kg)	Non-volcanic 9-180; Volcanic (Allophanic and Granular) 54-1,160

When there are analytical results below the limit of detection (e.g., some trace elements), they were replaced by half the limit of detection as is standard procedure outlined in Berthouex and Brown (2002). Differences in soil quality indicators and trace elements under different land uses were compared by analysis of variance (ANOVA) using Genstat 24th edition. Mean separation was done using the least significant difference (LSD) procedure at P=0.05. Due to variance heterogeneity for most parameters, the data were natural log-transformed prior to analysis (except for pH and bulk density). The P values for log-transformed data were the ones reported. However, following Curran-Cournane, the untransformed means were presented for ease of interpretation. For temporal trend analysis, the 2018-22 data collected were compared with the data from the base reference period of 2013-2017 using a t-test.

3 Results

3.1 Indicators outside guideline ranges across land uses

Across all land uses, 51% of sites failed (those below and above) the macroporosity guideline range while 49% of sites failed the Olsen P guideline range. These results are similar to the past monitoring from 2013-2017, which identified compaction and excessive Olsen P fertility to be the main soil quality issues for the region (Curran-Cournane, 2020). About 25% of the sites failed the guideline range for total N (excluding horticulture sites which have no guideline range for this parameter). Sixteen per cent of sites failed the guideline range for pH, while only around 10% of sites failed the guideline range for total C, AMN, and bulk density.

The percentage of soil quality indicators within each land use that fall below, within and above their respective guideline ranges are shown in Figure 6. For horticulture land use, 70% of the sites were below the macroporosity guideline range indicating these soils are compacted. This, however, is not reflected in the bulk density, where 76% of sites are within the guideline value. This shows that macroporosity is a more sensitive indicator due to large pores being the first to be lost during compaction. Nearly half (47%) of horticulture sites have elevated Olsen P values indicating excessive phosphate fertiliser application under this land use which poses a risk to stream P contamination during runoff events carrying eroded topsoil containing high concentrations of P which could eventually result in eutrophication. More than 40% of horticulture sites have total C and AMN below their respective guideline range, which indicates reduced mineralisation of the soil's native organic matter to supply the needs of crops. For pH, only about 6% of horticulture sites have pH values below the guideline range with the majority of sites falling with the pH guideline ranges. This is an indication that acidity is not an issue for horticulture soils.

Like horticulture land use, 70% of pasture sites were below the macroporosity guideline range indicating compaction. Again, bulk density was not a sensitive measure of compaction. with no sites above its guideline range. For Olsen P, only 15% were above the guideline range suggesting that excessive P fertility is less of a problem than in horticulture sites. About 22% of sites were below the guideline range. This is a consequence of the adjustment of the Olsen P guideline range from 15-50 mg/kg to 20-65 mg/kg because of its conversion from volumetric to gravimetric expression. Statistics NZ reported that, nationally, this error has resulted in an overestimation of sites falling above the Olsen P target range and an underestimation of sites below the target range (See Soil quality and land use | Stats NZ). Thus, the correction applied should better reflect the proportion of sites that fail the guideline range. All of the pasture sites have total C and AMN within their guideline ranges. However, for total N, about 25% of the sites were above the guideline range. For pH, about 17% the sites fell below the guideline range, indicating pasture soils were more acidic than horticulture soils.

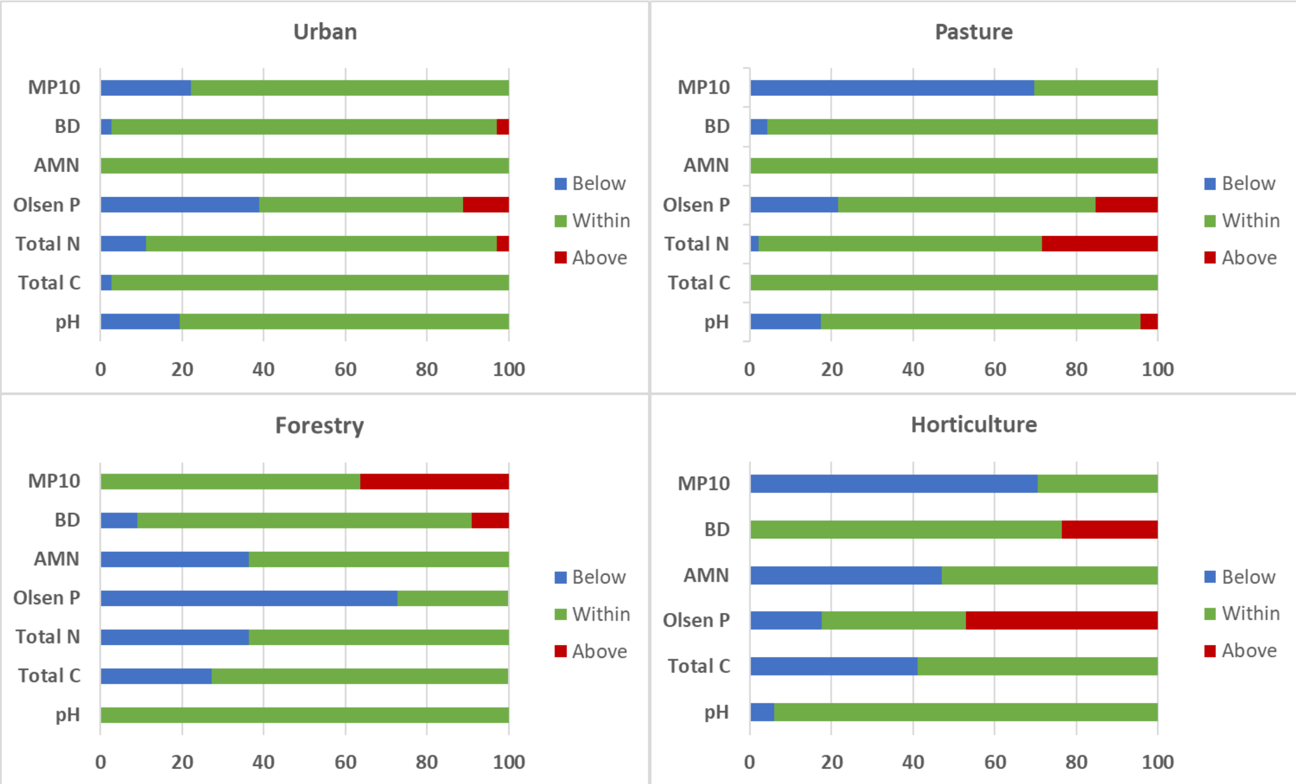

Figure 6. Percentage of soil quality indicators by land use falling below, within and above guideline ranges. 2018-2022. Abbreviations: BD=bulk density, AMN=anaerobically mineralisable nitrogen, MP10=macroporosity at -10 kPa (Note: Total N for horticulture is excluded since there is no available guideline range).

Soil compaction is not an issue under plantation forestry land use. In fact, about 36% of the sites fall above the macroporosity guideline range indicating these soils are porous. This is also reflected in bulk density where only about 9% of the sites were above the guideline range, i.e. these soils have low bulk density. Forestry soils have low Olsen P with about 73% of the sites below the guideline range. The low Olsen P values could be limiting tree growth and is a silvicultural issue rather than an environmental issue. For both total N and AMN, about 36% of sites were below their respective guideline range. About 27% of sites were below the guideline range for total C. This is not surprising, since forestry soils are generally considered less fertile compared with horticulture and pasture soils. None of the forestry sites have any soil acidity or alkalinity issue.

In urban soils, about 22% of sites were below the guideline range for macroporosity. For bulk density, only 3% of the sites were above the guideline range. About 39% of sites were below the Olsen P guideline range and only 11% were above the guideline range, indicating excessive P fertility is not an important issue under urban park land use. For total C and total N, only 3% and 11% of sites, respectively, were below their guideline ranges. Almost 20% of the sites are acidic and fall below the guideline range for pH.

3.2 Trace elements outside guideline ranges by land use

Across all land uses, around 19% of the sites failed the guideline range for Cu while about 12% of the sites failed the guideline range for Cd. Copper is widely used as a fungicide in farming operations, while Cd is inadvertently applied on pasture and horticulture land because it is an unavoidable contaminant in the manufacture of phosphate fertilisers. Fortunately, phosphate fertilisers sold in New Zealand now have low levels of Cd as a contaminant (Abraham et al., 2016) but the issue of continuous heavy application of phosphate fertiliser on pasture and horticultural sites remains due to the cumulative nature of its effects. About 4% of the sites failed the guideline range for Ni. For Pb, about 6% of sites failed the guideline range. Less than 1% of sites failed the guideline range for Cr. About 15% of sites failed the guideline range for Zn. Only 2% of sites failed the arsenic guideline range. A detailed breakdown of these percentages by land use follows.

Figure 7 shows the percentage of trace elements by land use that fall below, within and above their respective guideline ranges. Under horticulture land use, about 22% of the sites exceeded the upper guideline value for Cu, indicating the widespread use of Cu as a fungicide in this land use. About 17% of the sites have Cd above the upper guideline value while only 6% of the sites exceeded the upper guideline value for Zn. All the other trace elements fell within the guideline range under this land use.

Under pasture land use, 22% of the sites exceeded the upper guideline value for Cd. About 2% of the sites exceeded the upper guideline range for Cu, As and Pb. About 22% of the sites have Zn values below the lower guideline value while about 24% of the sites have Cu levels below the lower guideline value. About 2% of the sites have Ni values below the lower guideline value.

For forestry land use, all trace elements were within their guideline ranges except for Zn, where about 9% of the sites fall below the lower guideline value.

With respect to urban land use, trace element concentrations varied with some falling within, above and below their guideline ranges. For Cd, all the sites fell within the guideline range. For As and Cr, only about 3% of the sites were above their upper guideline values. For Cu, about 8% of the sites were above the upper guideline value. For Pb, about 17% of the sites were above the upper guideline value. About 6% of the sites have Ni levels above the upper guideline value. Chromium (~14% of sites), Zn (~8%) and Cu (~6%) are the trace elements found to have concentrations below their lower guideline ranges. There is some contamination in urban sites particularly for Pb, reflecting the proximity of urban parks to industrial areas,

It should be noted that the guideline ranges for trace elements are based on their total contents (i.e. total recoverable concentrations). However, the behaviour of trace elements in the environment is determined by their specific physicochemical forms rather than their total concentration. In general, only the ionic forms of trace elements are taken up by plants which constitute a small fraction of the total. Also, the availability of trace elements to plants is dependent on many factors (e.g., pH, organic matter, clay content and oxidation-reduction conditions) so that the trace element contents of plants are only poorly related to total elemental concentrations in soil. Soil physical, chemical and biological processes will determine the speciation, redistribution, mobility and ultimately the bioavailability of trace elements (Tack, 2010). Therefore, since total element concentrations are being reported, exceeding an upper guideline value should be viewed as an early warning signal and does not necessarily indicate that toxicities to plants and animals will be observed. It should be noted too that the trace elements Cu, Zn, and Ni are essential plant and animal micronutrients so both deficiency and toxicity of these elements need to be considered in this context.

Figure 7. Percentage of trace elements by land use falling below, within and above guideline ranges, 2018-2022. Abbreviations: As=arsenic, Cd=cadmium, Cr=chromium, Cu=copper, Ni=nickel, Pb=lead, Zn=zinc.

3.3 Number and percentage of sites outside target or guideline ranges for soil quality and trace elements

Table 4 shows the number and percentage of sites outside the target ranges for soil quality indicators and trace elements for each land use. Soil qualities showing 50% or more outside the guideline values have been flagged. Sixty-five per cent of sites under horticulture land use have elevated Olsen P values. About 71% are also compacted, as reflected in their low macroporosity. However, in terms of bulk density, only 24% are compacted, as discussed above, this indicates that it is a less sensitive indicator of soil compaction. Soils under horticulture also have high proportions of total C (41%) and AMN (47%) below their respective guideline values.

Pasture soils are not as enriched in Olsen P compared to horticulture soils, as only 37% have elevated concentrations. However, like the horticulture soils, 70% of samples are compacted. All samples passed the total C and AMN guideline values. However, 30% of samples are outside the total N guideline range.

Table 4. Number and percentage of sites (in parentheses) outside guideline ranges for soil quality indicators and trace elements for each land use in the Auckland region, 2018-2022. Broad guideline ranges are provided with footnotes containing specific guideline ranges by soil order and land use. Percentages in bold highlight the indicators by land use when more than half the soil samples failed to meet targets (n/a = not applicable).

Soil quality indicator and broad target range							
Land Use	Total C[1]: >3%	Total N[2]: 0.35-0.7%	AMN[3]: >40mg/kg	pH[4]: 5.5-7.5	Olsen P[5]: 20-65 mg/kg	Macroporosity[6]: 10-30%	Bulk density[7]: 0.6-1.3 g/cm^3
Forestry (n=11)	3 (27)	4 (36)	4 (36)	0	8 (**73**)	4 (36)	2 (18)
Horticulture (n=17)	7 (41)	n/a	8 (47)	1 (6)	11 (**65**)	12 (**71**)	4 (24)
Pasture (n=46)	0	14 (30)	0	10 (22)	17 (37)	32 (**70**)	2 (4)
Urban (n=36)	1 (3)	5 (14)	0	7 (19)	18 (**50**)	8 (22)	2 (6)
Trace element (mg/kg)							
Land Use	As (0.4-12)	Cd (0.1-0.65)	Cr (2-55)[8]	Cu (1-45)[8]	Ni (0.9-35)	Pb (1-65)	Zn (9-180)[8]
Forestry (n=11)	0	0	0	0	0	0	1 (9)
Horticulture (n=18)	0	3 (17)	0	4 (22)	1 (6)	0	3 (17)
Pasture (n=46)	1 (2)	10 (22)	0	12 (26)	1 (2)	1 (2)	10 (22)
Urban (n=36)	1 (3)	0	6 (17)	5 (14)	2 (6)	6 (17)	3 (8)

[1] Total C: Allophanic >4%; Recent >3%; Brown, Gley, Granular and Ultic >3.5%; Excludes Organic

[2] Total N: Pasture 0.35-0.7%; Forestry 0.2-0.7%; Excludes horticulture

[3] AMN (Anaerobically mineralisable nitrogen): Pasture >60 mg/kg; Horticulture and Forestry >40 mg/kg

[4] pH: Pasture (excludes Organic) 5.5-6.6; Pasture (Organic) 5.0-6.7; Horticulture (excludes Organic) 5.5-7.5; Horticulture (Organic) 5.0-7.5; Forestry (excludes Organic) 4.0-7.5

[5] Olsen P: Pasture and Horticulture (Brown, Gley, Organic, Granular and Ultic) 26-46 mg/kg; Pasture and Horticulture (Allophanic and Granular) 26-65 mg/kg; Forestry 7-39 mg/kg

[6] Macroporosity: Forestry 5-30%; Other 10-30%

[7] Bulk density: Allophanic: 0.6-1.2 g/cm^3; Brown, Gley, Granular and Ultic 0.7-1.3g/cm^3; Organic 0.2-1.0g/cm^3; Recent 0.8-1.3g/cm^3

[8] For volcanic derived soils (Granular and Allophanic) target ranges for Cr are 3-125 mg/kg; Cu are 20-90 mg/kg; Ni 4-320 mg/kg; Zn are 54-1,160 mg/kg

Under urban land use, 50% of samples failed the guideline range for Olsen P suggesting about half of the urban parks are receiving high P application. Under forestry land use, 73% of soil samples have failed the guideline range for Olsen P. However, this is not an environmental concern because the samples that failed were below the lower limit of the guideline value (7 mg/kg) indicating inadequate P fertiliser applied under plantation forestry.

For all trace elements, the percentages of samples that are outside their respective guideline values are 26% or less with fails for Cu, Zn and Cd being most noticeable under pasture and horticulture land uses. For Cu, 26% of pasture sites were outside the guideline range, compared to 22% under horticultural land use. For Zn, 22% are lower under pasture use and 17% are lower under horticultural use. For Cd, about 22% of pasture soils have elevated levels compared to 17% under horticulture.

This suggests that less accumulation of Cd is occurring under horticultural land use. For As and Ni, about 6% or less of the sites were outside their respective guideline ranges under all land uses. In urban parks, about 17% of Cr and Pb fell outside their respective guideline range. In a larger study of soil trace metal analysis in Auckland that included both topsoil and subsurface soils, Martin et al. (2023) indicated that metal pollution in Auckland is not as acute as hypothesised. The findings here are in general agreement with this larger study.

3.4 Soil quality indicators and trace elements by land use, 2018-2022

Table 5 shows the mean topsoil quality indicators and trace elements by land use for the current reporting period, 2018-2022. Horticultural soils have elevated levels of Olsen P (108 mg/kg) well above the upper guideline value of 65 mg/kg. This high level has been attributed to the continuous heavy application of phosphate fertiliser several times a year, particularly on long-term vegetable growing sites (Hicks, 2006). Excessive P fertilisation in soils could lead to elevated P levels in sediment carried by runoff water that leads to eutrophication of surface water bodies. The risk of P loss in runoff, however, depends on the P retention capacity of soils. This risk is high in sedimentary soils with low P retention capacity compared to volcanic soils that have high P retention capacity.

The mean Olsen P level in horticultural soil is significantly higher than the mean Olsen P levels in pasture and urban soils (41 and 37 mg/kg, respectively) where the values did not exceed the upper guideline value (65 mg/kg). As expected, soils under native vegetation have low mean Olsen P. Forestry soils have a mean Olsen P value of 9 mg/kg just above the lower forestry guideline value of 7 mg/kg. This indicates a much lower level of P fertiliser application compared to pasture and horticulture land uses. In fact, this low value suggests forestry soils are under fertilised since a good tree growth response to P fertilisation is expected when the Olsen P level is below 25 mg/kg (Davis et al., 2010).

Both horticulture and pasture soils have mean macroporosity values below the lower macroporosity guideline value of 10% (7% and 9%, respectively) indicating compaction under these two land uses. Native and forestry soils are the most porous (macroporosity of 17% and 28% , respectively) while urban soils have mean macroporosity within the guideline range (13%).

Bulk density was significantly higher in horticulture soils (1.12 g/cm^3) relative to the rest of the soils under other land uses, although the mean value did not exceed the upper guideline value of 1.30 g/cm^3. Although bulk density is also a measure of soil compaction, it appears to be a less sensitive indicator compared to macroporosity. Being less porous, a compacted soil increases the surface runoff of nutrients and suspended sediments that can enter waterways. Compaction of soils under horticulture is associated with frequent tillage operations, particularly in outdoor vegetable sites, while compaction of soils under pasture is due to trampling by livestock and overstocking the paddock, particularly during the wet winter and spring months.

Table 5. Soil quality indicators and trace elements by land use in the Auckland region, 2018-2022[1]

	Indicator						
Land use	Total C (%)	Total N (%)	AMN (mg/kg)	pH	Olsen P (mg/kg)	Macroporosity (%)	Bulk Density (g/cm^3)
Forestry (n=11)	4.71	0.26	71	5.3	9	28	0.94
Horticulture (n=17)	4.43	0.33	68	6.3	108	7	1.12
Native (n=33)	7.13	0.41	137	5.4	6	17	0.91
Pasture (n=46)	7.15	0.63	146	5.9	41	9	0.93
Urban (n=36)	6.55	0.53	176	5.8	37	13	0.89
SED	0.94	0.065	17.0	0.14	12.4	2.0	0.06
LSD (0.05)	1.85	0.128	33.6	0.27	24.4	4.0	0.11
P value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.008

	Trace element (mg/kg)						
Land use	As	Cd	Cr	Cu	Ni	Pb	Zn
Forestry (n=11)	5.67	0.08	13	8	4	8	29
Horticulture (n=18)	5.61	0.50	19	43	7	20	55
Native (n=33)	3.45	0.07	13	14	5	15	32
Pasture (n=46)	4.26	0.51	14	17	5	14	45
Urban (n=36)	4.42	0.16	30	26	38	41	83
SED	0.98	0.067	4.5	6.1	8.0	7.5	12.9
LSD (0.05)	1.94	0.133	8.9	12.0	15.8	14.8	25.4
P value	0.088ns	<0.001	<0.006	<0.001	<0.001	<0.001	<0.001

[1]Significant differences are highlighted in bold and ns denotes 'not significant'. Soil parameters in red and blue bold text are mean values that are above and below recommended guidelines, respectively. The standard error of difference (SED) and least significant difference (LSD) are presented using un-transformed data and the *P* value is presented using log transformed data, except for pH and bulk density.

Soils under horticultural land use have significantly lower mean total C and AMN than those in pasture, native and urban land uses, but have comparable values with forestry soils. Total N is also low in horticulture soils and only slightly higher than in forestry soils. Urban soils have high mean total C, total N and AMN comparable to pasture soils. Since urban park soils are practically grassland soils that are regularly mown, this probably reflects a significant input of organic matter in these soils, particularly if the cut grass or clippings are left on the soil surface and allowed to decompose rather than transported off-site.

In terms of acidity, horticulture soils are less acidic (mean pH of 6.3) compared with soils from the other land uses (pH less than 6.0). This is a consequence of applying lime to reduce soil acidity, making it more suitable for growing a range of fruit and vegetable crops, whose optimum pH requirements are generally in the range of 6.0 to 6.5.

In general, the mean concentrations of trace elements are within their guideline values. They also differed with land use type, except for As (Table 5) where levels did not significantly differ among land uses. Soils under horticulture and pasture have significantly higher Cd levels than the other land uses and this is attributed to the long-term regular application of phosphate fertilisers. Since Cd is an impurity in phosphate fertiliser manufacture that is not easy to remove, it tends to accumulate in phosphate-fertilised soils and becomes an inherent contaminant.

Horticulture and urban sites had the highest mean concentrations of Cu. Copper is widely used in horticulture sites as a fungicide on both orchard and outdoor vegetable sites. In urban areas, brake pad wear has been identified as a significant source Cu, while garden products such as roof and pathway cleaners have the greatest potential to contribute additional (Kennedy and Sutherland, 2008).

Martin et al. (2023) indicated that, in general, soil pollution by trace elements in urban environments is a function of the duration of urbanisation and dwelling quality (e.g., Pb paint still being present on disproportionately high number of pre-1970s timber clad dwellings). In addition, trace element concentrations can be high in cities built on volcanic rocks like Auckland. Urban sites had the highest concentrations of Pb, Zn, Cr, and Ni, reflecting their proximity to industrial areas. For Pb, historic vehicle emissions could have contributed to this increase. The Pb present in older paints can also be a significant contributor to Pb loading, while Zn is common in urban soils due to it being a constituent of some paints. Runoff coming from Zn roof surfaces can be a significant contributor to the Zn load in stormwater (Kennedy and Sutherland, 2008). Chromium and Ni were high in a few urban sites classified as Anthropic soils which are disturbed soils. The original source of these could be volcanic soils or they could already be contaminated with these two elements when soils were placed on these sites. Chromium is used in making steel, chrome plating, dyes and pigments, while Ni is used in the manufacture of stainless steel and metal alloys, plating and the production of some batteries and some chemicals (Appendix 2). The mean Ni concentration of 38 mg/kg under urban land use is higher than the upper guideline value of 35 mg/kg.

3.5 Soil parameters under various rural land use activity

As pointed out by Curran-Cournane (2020), rural land use in Auckland has changed considerably since the inception of regional soil quality monitoring 30 years ago. This has effectively led to a reduction in traditional commercial farming sites and an increase in the number of lifestyle blocks. Changes in land ownership, the decision of new landowners not to pursue further commercial farming activities, and the subdivision of rural land into residential properties are expected to further alter the picture of land utilisation in the foreseeable future. In order to compare soil quality indicators and trace elements for specific pasture and horticulture land uses, the approach used by Curran-Cournane (2020) was followed whereby the sites sampled between 2018-2020 were further classified into dairy, drystock, lifestyle block, orchard+viticulture and outdoor vegetable production categories (Table 6).

Table 6 shows that outdoor vegetable sites are the most degraded among the various rural land uses. Total C, total N and AMN are significantly lower in outer vegetable sites compared to most of the other rural land uses. Orchard + viticulture sites also have low levels of total C, total N and AMN while dairy, drystock and lifestyle blocks have comparable values of these indicators. The low values of these parameters in horticultural sites indicate organic matter is being lost in the soil. This has been documented in the Pukekohe area by Haynes and Tregurtha (1999) and is likely to negatively affect soil function if it continues. Olsen P of 228 mg/kg in outdoor vegetable sites is more than three times its upper guideline value. Outdoor vegetable sites are also compacted, having a high bulk

Table 6. Mean values of soil quality indicators and trace elements by rural land use activity in the Auckland region, 2018-2020[1].

Rural land use	Total C (%)	Total N (%)	AMN (mg/kg)	pH	Olsen P (mg/kg)	Macroporosity (%)	Bulk Density (g/cm³)
Dairy (n=11)	7.77	0.66	134	6.06	**52**	**6**	0.90
Drystock (n=22)	7.42	0.67	159	5.73	44	**9**	0.92
Lifestyle block (n=12)	6.29	0.55	135	5.99	28	10	0.95
Orchard+Vitic.[2] (n=11)	5.61	0.35	97	6.20	43	10	1.09
Outdoor vegetable (n=6)	**2.27**	**0.22**	**16**	6.38	**228**	**3**	1.28
SED	1.40	0.11	22.3	0.18	15.4	2.0	0.07
LSD (0.05)	2.80	0.22	44.6	0.37	30.8	4.0	0.15
P value	<0.001	<0.001	<0.001	0.006	<0.001	<0.001	<0.001
Trace element (mg/kg)							
	As	Cd	Cr	Cu	Ni	Pb	Zn
Dairy (n=11)	2.91	0.55	11	13	5	9	41
Drystock (n=22)	4.11	0.55	15	14	6	11	46
Lifestyle block (n=12)	5.58	0.40	17	27	5	23	47
Orchard+Vitic.[2] (n=11)	3.36	0.47	13	39	4	13	54
Outdoor vegetable (n=6)	10.17	0.53	30	**51**	12	36	62
SED	1.37	0.15	2.9	9.5	1.3	6.7	15.2
LSD (0.05)	2.74	0.29	5.9	19.0	2.6	13.4	30.4
P value	<0.001	0.264ns	<0.002	<0.001	<0.001	<0.001	0.266ns

[1]Within a column, significant differences are highlighted in bold and ns denotes 'not significant'. Soil parameters in red and blue bold text are mean values that are above and below recommended guidelines, respectively. The standard error of difference (SED) and least significant difference (LSD) are presented using un-transformed data and the *P*-value is presented using log transformed data, except for pH and bulk density.
[2]Orchard and viticulture include both orchard (n=6) and viticulture sites (n=5). The broader horticulture land use category also included one nursery site which was removed from the analysis since it does not truly belong to the orchard+ viticulture category.

density (1.3 g/cm³) while macroporosity is 3% and far below the lower guideline value. The only soil indicator that shows good condition is pH which is around 6.4.

Dairy, drystock, lifestyle blocks and orchard + viticulture sites have Olsen P values within the guideline range. They also experience some compaction in terms of low macroporosity but not to the same degree as the outdoor vegetable sites.

Significant differences in As, Cr, Cu, Ni, Pb and Zn exist among the rural land uses, with outdoor vegetable sites having the highest values. There were no statistically significant differences in Cd and Zn among the various rural land uses.

3.6 Changes in values of soil quality indicators and trace elements across all land uses: 2018-2022 vs. 2013-2017

The mean values of the soil quality indicators and trace elements across all land uses sampled during the period 2018-2022 were compared with the mean values from the previous sampling period 2013-2017 (five-year trend). For reference, the mean values of the soil quality indicators and trace elements with the more complete data set from all the 157 sites (compared with 143 sites) were also included (Curran-Cournane, 2020) (Table 7).

Table 7. Changes in soil quality indicators and trace elements: 2013-2017 vs 2018-2022 (all land uses)[1].

Soil parameter	Sampling period			Difference	*P* value	Guideline range
	2013-2017 (n=157)	2013-2017 (n=143)	2018-2022 (n=143)			
Indicator						
Soil pH	5.87	5.73	5.76	0.03	0.680ns	5.5-7.5
Total C (%)	6.4	6.2	6.5	0.3	0.438ns	>3
Total N (%)	0.52	0.47	0.49	0.02	0.626ns	0.35-0.70
Olsen P (mg/kg)	42	38	38	0	0.902ns	20-65
AMN (mg/kg)	132	133	136	3	0.652ns	>40
Macroporosity (%)	12	12	13	1	0.237ns	10-30
Bulk density (g/cm^3)	0.94	0.90	0.94	0.04	0.142ns	0.6-1.3
Trace element (mg/kg)	Sampling period			Difference	*P* value	Guideline range
	2013-2017 (n=157)	2013-2017 (n=144)	2018-2022 (n=144)			
As	4.2	4.3	4.4	0.1	0.820ns	0.4-12
Cd	0.39	0.27	0.29	0.02	0.574ns	0.10-0.65
Cr	12	17	18	1	0.357ns	2-55
Cu	16	21	21	0	0.994ns	1-45
Ni	4.2	12	14	2	0.663ns	0.9-35
Pb	12	23	21	-2	0.657ns	1-65
Zn	34	45	52	7	0.210ns	9-180

[1]Broad guideline ranges appear in the last column. ns = not significant.

Mean values across all land uses were within the guideline ranges for both time periods. The results showed that for both soil quality indicators and trace elements, there were no statistically significant differences between the two sampling periods. However, the following observations were made:

- There were slight improvements in pH, total C, total N, AMN and macroporosity.
- Olsen P remained the same, but bulk density increased by 0.04 g/cm^3.
- Increases in As, Cd, Cr, Ni and Zn were not significant.
- Copper concentration remained the same while a slight insignificant decrease in Pb was noted.

While not statistically comparable (due to differences in sample size), mean values for soil quality indicators in the 2013-2017 data set were similar to the 2018-2022 data set (which excluded a number of sites) for some parameters like total C, macroporosity and bulk density. However, noticeable differences were observed for some trace elements like Ni, Pb and Zn, which were much lower in the 2013-2017 data set that included native and forestry sites (Table 7). As stated in the methods section, some forestry and native sites were unable to be sampled in 2021 and 2022, respectively. They notably have lower levels of the trace elements because little or no disturbance or trace element additions occur at these sites.

In summary, no statistically significant changes in soil quality indicators and trace element concentrations were detected over current and previous sampling periods. This shows that the soil parameters observed during these time periods are being maintained, and the same soil issues identified five years ago and even earlier as discussed in Curran-Cournane (2020) remain.

4 Discussion

4.1 Addressing issues identified in soil quality monitoring

Auckland's soil quality issues identified in long-term monitoring also reflect those observed at the national level. Cavanagh et al. (2025) note that nationally, the key soil quality issues today are the same as identified in the early 2000s, namely low soil carbon in cropping soils, elevated Olsen P in some agricultural soils, and soil compaction, particularly in pastoral and cropping systems (MfE and Stats NZ, 2021). They suggested that the objective of the SoE monitoring programme being an early warning system, as currently stated in the NEMS-Soil Quality, should be revisited with a potential focus on more robustly linking soil quality targets to environmental outcomes and encouraging the adoption of sustainable land management practices at property level.

Reduction in the use of phosphate fertiliser should be encouraged particularly on horticultural sites since the soils are already over-fertilised. Such practice would also save on fertiliser input cost. There is also a need to evaluate and/or promote the use of slow-release P fertiliser on crops to increase P use efficiency and minimise P losses via sediment in runoff (Guinto, 2022; Fertiliser Technology Centre, undated). For example, a P fertiliser called struvite which is a magnesium ammonium phosphate hexahydrate [$(NH_4)MgPO_4{\cdot}6H2O$], can also supply the essential elements N and magnesium for crop growth. Its slow-release nature suggests that it could be effective on crops with long growing cycles such as orchard crops, but less so on crops with short growing cycles like some leafy vegetables. However, it is also showing some potential for use as a P fertiliser for acidic pasture soils in New Zealand (De Luca Agrelo et al., 2025).

To minimise compaction, timing of cultivation should occur in late spring or early summer, so soil is close to optimum moisture for tillage operations on horticultural sites. On pasture sites, heavy stocking in winter and spring should be avoided so that pugging does not occur. Where possible, stock needs to be moved to lighter-textured soils. Keeping the grazing rotation short should also be practised.

It is acknowledged that improving and maintaining soil quality in intensive farming such as outdoor vegetable production is challenging, due to a combination of inherent agricultural practices and environmental factors like frequent tillage to prepare seedbeds, control weeds and incorporate soil amendments. These practices disrupt soil structure, expose organic matter to decomposition, compact the soil, and negatively impact beneficial soil organisms. Despite these challenges, many sustainable and regenerative agricultural practices can be adopted to improve soil health in vegetable production, such as cover cropping, crop rotation, reduced tillage, composting, and promoting biodiversity. However, their widespread implementation requires a shift in mindset, investment, and often, adaptation to specific farm conditions.

4.2 Programmes and initiatives that link to improving soil quality in Auckland

Given the long-standing soil quality issues identified nationally since the early 2000s, Cavanagh et al. (2025) raised the question of how best to balance investment between research aimed at developing soil quality targets and thresholds more robustly linked to environmental outcomes, and direct investment in actions to improve soil quality. The latter includes investment in both land management practices that can improve soil quality indicators, as well as encouraging adoption of those practices on-farm through extension activities like field days, trainings, technical advice, etc. The degraded state of soil quality under outdoor vegetable and dairy land uses in Auckland, characterised by excessive P fertility and compaction, point to the lack of widespread adoption of good soil management practices (Curran-Cournane, 2020). However, there is recognition of the soil issues mentioned in previous sections of this report by the agricultural industry, farmers and Auckland Council. The following programmes and initiatives that link to improving soil quality in the region are briefly discussed below.

With funding from Auckland Council, a resource guide entitled 'Empowering Farmer Compliance for Auckland' (Perrin Ag Consultants, 2024) has been developed. The guide aims to assist farmers in understanding their compliance requirements, self-assess their own businesses, identify any gaps or areas for prioritisation, and provide links to further information and support. It is targeted at drystock, dairy, and horticultural farm businesses. Guidance topics covered that relate to freshwater and soil quality include farm planning, critical source areas, intensive winter grazing, fertiliser use, effluent application, stocking including stock exclusion from waterways, agrichemical use and cultivation. Similar guides have also been developed for use by other regional councils.

In the Pukekohe vegetable growing area, the Te Tautara o Pukekohe Trust, a partnership between the Crown, industry groups, and mana whenua, is currently administering a $5.65 million grant from the Essential Freshwater Fund to oversee 11 priority projects from the Te Ora o te Wai Pukekohe Action Plan (About — Te Tautara o Pukekohe).The vision of the trust is: "*A healthy freshwater environment flowing within and from Pukekohe where its wellbeing is protected and enhanced while supplying fresh vegetables for the health and wellbeing of the people of Aotearoa New Zealand*". One project still in its early stages, the freshwater and soil health monitoring project, aims to improve the soil quality of Pukekohe soils through a planned expansion of their soil quality monitoring programme. Other projects that link to soil quality improvement include:

- Crop stacking: This is a project that is exploring and validating the planting of a grass cover crop alongside cash crops, to improve soil health and prevent nutrient and sediment loss.
- Installation of retention ponds: Sediment management is being addressed by reducing sediment runoff through the use of ponds to settle out sediment following run-off from land.
- Sustainable Vegetable Systems (SVS) tool: Farmers are being trained in the adoption of the SVS tool which is an N budgeting tool to help optimise their N fertiliser management practices to reduce N leaching and improve crop N uptake in vegetable crop production.

The "crop stacking" pilot trial in Kingseat and Patumāhoe was funded by Auckland Council's Healthy Waters and Jobs for Nature. The trial involved planting an annual ryegrass cover crop, followed by a commercial broccolini crop. It showed that this approach does not significantly reduce crop yield or gross margin relative to conventional cropping. In terms of soil quality, the trial improved the topsoil structure and the uniformity of N mineralisation. Also, the trial area planted with ryegrass experienced a 31% reduction in potential environmental N loss during the broccolini crop cycle (Martin et al., 2024). There is a plan to further expand this project to other vegetable crops if funding can be obtained (Bryan Hart, General Manager – Growing, AS Wilcox, personal communication).

Te Ahikawariki, the Vegetable Industry Centre of Excellence (VICE) based in Pukekohe, have a range of applied research and extension projects to support the entire vegetable industry (Leanne Roberts, Senior Environmental Policy Advisor, Horticulture New Zealand, personal communication). Te Ahikawariki/VICE is a government-funded project that has set up a vegetable research farm in collaboration between mana whenua and vegetable growers that aims to create a central location for research to support the entire vegetable industry and protect the land.

Finally, the regional soil quality monitoring programme has influenced the fertiliser industry to look into the health of soils. The fertiliser cooperative Ballance Agri-nutrients (in cooperation with Landcare Research), for example, is now offering a Soil Health Check for their customers which includes pH, total N, total C, Olsen P and AMN in addition to their standard soil fertility tests. The Soil Health Check also includes the analysis of hot water-soluble carbon and anion storage capacity (Anonymous, 2022). It is hoped that current and future efforts to stem the decline in soil quality will prove effective in achieving high-quality soils that support both productive and environmental outcomes.

4.3 Future directions for soil quality monitoring

With increasing interest in more sustainable farming methods such as organic farming and regenerative agriculture, developing biological indicators of soil health should be a key focus area in soil quality monitoring. Soil biology is an important aspect of soil health and is the largest indicator gap (Stevenson, 2022). The different organisms in the soil create a food web that cycles organic material and nutrients through the soil. Unfortunately, the biological component of the soil is generally more costly and labour intensive to measure, and it is also more difficult to interpret the results and determine what constitutes 'healthy' levels of organisms in different land uses. Therefore, research on identifying suitable biological indicators that are less expensive, easier to analyse and interpret is continuing. Pollutants can obviously have a negative impact on soil biology (including soil fauna such worms, as well as soil microbes), but the number and diversity of these organisms can vary depending on soil pH, land use, vegetation type and diversity, soil carbon (and carbon inputs into the soil), and a host of other properties.

Hot water extractable carbon (HWEC) or hot water carbon (HWC), an indicator of the labile or readily mineralisable soil carbon pool, has been proposed as a replacement for AMN (Mackay et al., 2013; Taylor et al., 2017; 2022) due to its correlation with microbial biomass and rapidity of analysis (16-hour extraction with HWEC vs 7-day incubation for AMN). Hill Laboratories (undated a) has already offered this as a routine test and some regional councils (e.g. Waikato, Marlborough and Tasman) have used it in addition to AMN.

There is an opportunity to trial the use of other methods of assessing biological indicators of soil health for future routine use. This is an area of soil health research that needs more attention. Initial work in Otago by Button et al. (2024) utilised three levels of assessment that included visual assessment (identifying and counting broad invertebrates in the field); extraction and identification of macrofauna; and extraction and sequencing of environmental DNA (eDNA) of fauna, fungi and bacteria.

The presence of earthworms is generally considered an indicator of a healthy soil in pasture and cropping land uses (Stevenson, 2022). Different groups of earthworms perform different soil functions such as carbon storage, creation of macropores, improving water infiltration and the formation of stable soil aggregates. Thus, it is important to quantify both their abundance and diversity (Schon et al., 2022). On pastoral soils, Hill Laboratories (undated b) and AgResearch (Schon et al., 2022) have developed a commercially available eDNA test for earthworms that does not rely on counting earthworms in the field (Hsu et al., 2023). The test detects traces of genetic material left behind as earthworms pass through the soil. Currently, however, it can only reliably identify one species of earthworm – the grey earthworm (*Aporrectodea caliginosa*) which is abundant in New Zealand's pastoral topsoils. Hopefully, the method improves in due course to accurately identify and quantify other earthworm groups.

Overseas, there are several recommended methods of soil health analysis that include a suite of biological measures ranging from soil respiration, soil enzyme assays, permanganate oxidisable carbon, through to eDNA techniques (Lapis-Gaza and Pattison, 2021; Karlen et al., 2021). Some of these tests are not expensive to perform and can potentially provide insight into the biological functioning of soils and could serve as routine indicators of biological soil quality/health. Important considerations for candidate biological indicators of soil quality include their ability to measure soil functions that are sensitive to changes in soil management, affordability, ease of interpretation for farmers and land managers, relatively simple equipment, substrates that are readily available to purchase, and safety for analysts (Lapis-Gaza and Pattison, 2021).

Currently, the focus of soil quality monitoring is the topsoil layer (0-10 cm) but in the future, it is also important to include the assessment of soil conditions occurring in subsoils which may present constraints for primary production (De Oliveira and Bell, 2022) and may also have negative environmental impacts. For example, subsoil compaction limits the ability of water to penetrate the soil, increasing surface runoff leading to the transport of sediments, nutrients and other pollutants into waterways. Leaching of nitrate is not captured in the soil quality monitoring but is known to be a significant problem in the Pukekohe vegetable growing area (Rogers and Buckthought, 2022). Pesticide residues in the soil and other emerging contaminants in soils (e.g. microplastics) may also need to be quantified in the future.

5 Conclusion

The current monitoring data show that some soil quality indicators fell outside the recommended guideline values. When broad land use types are considered, excessive P fertility and compaction remain the most important soil quality issues under horticultural land use. Under pasture land use, soils are less enriched in P compared to horticulture soils, but like the latter, most of them were also compacted. When rural land use activities are considered, excessive P fertility and low macroporosity were observed in both dairy and outdoor vegetable land uses. In addition, low organic matter and biological activity appear under outdoor vegetable land use.

Averaged across all land uses, there were no significant changes in soil quality indicators and trace elements for the current monitoring period (2018-2022) and the previous period (2013-2017). This shows that the soil parameters monitored over this time period are similar and the same soil quality issues identified in the past persist.

Reduction in use of phosphate fertiliser in high P soils should be encouraged since the soils are already over-fertilised as well as the promotion of slow-release phosphate fertiliser to increase phosphorus use efficiency and minimise losses to the environment (Fertiliser Technology Research Centre, undated). Building up soil organic matter by minimising cultivation, growing cover crops, maintaining ground cover, etc. will address organic matter and structural declines (Magdoff and Van Es, 2021).

On horticultural sites, timing of cultivation should occur in late spring or early summer so soil is close to optimum moisture for tillage operations. On pasture sites, avoiding heavy stocking in winter and spring, moving stock into lighter-textured soils, and keeping the grazing rotation short, will help reduce compaction issues.

There is a need to balance investment in research for developing soil quality targets with investment in improving soil quality through good land management practices and encouraging their adoption. In Auckland, various programmes and initiatives that have links to improving soil and water quality are currently underway. This involves empowering environmental compliance on farms, soil health monitoring, crop stacking, sediment management and nutrient budgeting.

6 Acknowledgements

Many thanks to all environmental specialists at Auckland Council's Environmental Evaluation and Monitoring Unit (EEMU) for assistance during the soil sample collection particularly to Jonathan de Villiers for organising logistics.

Thanks to landowners for allowing soil samples to be collected on their properties without which the monitoring would not be possible. Grant Lawrence is thanked for preparing the map of soil sample locations. Tony Edhouse, chair of the Peer Review Panel, for overseeing the peer review process. Hamish Allen (EEMU) and Dr Tony Asis (Department of Agriculture and Fisheries, Northern Territory, Australia) are thanked for their insightful comments and suggestions to improve this report.

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Appendix 1: Soil quality and trace element data used in this report

(**Note:** In column 1, the first number is the year of sampling, the second number is the site number and third number is the number of times the site has been sampled. Asterisks in the data columns indicate missing data)

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2018-01-04	1	2018	Current	Granular	Outdoor vegetable	Horticulture	5.05	2	0.21	308	17	1.29	3	10	0.59	33	56	12	36	78
2013-01-03	1	2013	Previous	Granular	Outdoor vegetable	Horticulture	6.02	2.2	0.22	276	13	1.04	24	5.6	0.5	29	47	10	29	47
2020-02-05	2	2020	Current	Granular	Drystock-Lifestyle	Pasture	5.39	5.1	0.48	13	163	0.92	8	21	0.42	38	48	12	122	112
2015-02-04	2	2015	Previous	Granular	Drystock-Lifestyle	Pasture	6.13	6.9	0.64	34	172	0.81	9	11	0.42	20	41	6	120	88
2021-03-04	3	2021	Current	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2016-03-03	3	2016	Previous	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2021-05-04	5	2021	Current	Ultic	Forestry	Forestry	5.67	4.3	0.2	2	76	1.12	14	4.7	0.05	26	16	8	12	35
2016-05-03	5	2016	Previous	Ultic	Forestry	Forestry	5.69	5.2	0.25	5	81	1.16	7	1.8	0.09	10	5	3	6	11
2022-06-08	6	2022	Current	Ultic	Native	Native	4.78	8.6	0.46	5	143	0.72	25	3	0.05	29	13	7	8	24
2017-06-07	6	2017	Previous	Ultic	Native	Native	5.14	5.7	0.34	3	132	0.9	10	1.7	0.024	32	21	12	5	44
2019-07-05	7	2019	Current	Organic	Dairy	Pasture	5.9	12	0.95	57	179	0.79	8	1	0.56	19	23	7	6	62
2014-07-04	7	2014	Previous	Organic	Dairy	Pasture	6.53	13.7	1.12	98	244	0.64	3	1	0.51	16	23	6	6	45
2019-08-05	8	2019	Current	Organic	Dairy	Pasture	5.97	11.8	0.97	90	200	0.8	1	1	0.61	22	26	7	7	107
2014-08-04	8	2014	Previous	Organic	Dairy	Pasture	6.19	12.2	0.91	76	265	0.66	8	1.1	0.72	17	31	6	8	54
2019-09-05	9	2019	Current	Allophanic	Dairy	Pasture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2014-09-04	9	2014	Previous	Allophanic	Dairy	Pasture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2018-10-04	10	2018	Current	Allophanic	Veg-Drystock	Pasture	5.81	4.7	0.41	25	93	1.07	8	7	0.44	17	20	9	22	49
2013-10-03	10	2013	Previous	Allophanic	Veg-Drystock	Pasture	6.41	3.6	0.3	70	51	1.09	12	6.1	0.42	15	16	8	19	44
2022-11-08	11	2022	Current	Granular	Native	Native	5.87	6.8	0.5	4	170	0.93	15	6.2	0.05	18	12	5	24	43
2017-11-07	11	2017	Previous	Granular	Native	Native	5.58	5.7	0.42	5	127	0.9	11	9.5	0.07	21	15	3	47	35
2019-12-05	12	2019	Current	Granular	Dairy-Lifestyle	Pasture	5.71	6.9	0.59	14	132	0.84	22	7	0.42	21	17	8	20	42

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2014-12-04	12	2014	Previous	Granular	Dairy-Lifestyle	Pasture	5.9	7.3	0.61	11	189	0.99	10	5.4	0.35	16	13	5	18	27
2018-14-04	14	2018	Current	Allophanic	Orchard-Lifestyle	Pasture	6.15	6	0.54	101	123	0.99	6	6	0.4	14	14	6	37	61
2013-14-03	14	2013	Previous	Allophanic	Orchard-Lifestyle	Pasture	6.09	6	0.52	161	92	1.08	11	6.9	0.48	17	13	7	27	69
2022-17-04	17	2022	Current	Ultic	Native	Native	5.65	6.5	0.38	7	173	0.93	6	2.2	0.11	14	14	6	9	29
2017-17-03	17	2017	Previous	Ultic	Native	Native	5.34	5.1	0.3	5	111	1	4	1.6	0.048	13	8	2	8	16
2020-18-05	18	2020	Current	Ultic	Drystock	Pasture	5.65	5.8	0.51	25	156	0.94	15	1	0.45	11	12	2	3	31
2015-18-04	18	2015	Previous	Ultic	Drystock	Pasture	5.87	5.6	0.5	22	133	0.83	9	1.3	0.32	7	8	2	3	15
2022-19-08	19	2022	Current	Ultic	Native	Native	4.97	4.6	0.29	3	88	1.02	5	1.5	0.05	20	8	4	10	16
2017-19-07	19	2017	Previous	Ultic	Native	Native	4.76	5.7	0.3	2	108	0.9	8	1.6	0.02	27	13	4	6	19
2018-20-04	20	2018	Current	Recent	Orchard-Lifestyle	Pasture	6.07	10.8	0.79	52	142	0.59	10	1	0.53	7	129	3	10	50
2013-20-03	20	2013	Previous	Recent	Orchard-Lifestyle	Pasture	6.2	12.6	0.79	64	140	0.76	12	2.2	0.47	9	120	4	14	61
2020-21-05	21	2020	Current	Brown	Drystock	Pasture	5.25	4.9	0.51	40	110	1.04	9	6	0.3	20	9	8	11	70
2015-21-04	21	2015	Previous	Brown	Drystock	Pasture	5.32	4.3	0.45	39	155	1.02	7	6.7	0.31	16	10	7	9	51
2021-22-04	22	2021	Current	Brown	Forestry	Forestry	6.08	7.8	0.55	39	131	0.64	48	6.6	0.17	18	7	8	8	93
2016-22-03	22	2016	Previous	Brown	Forestry	Forestry	6.37	4.1	0.36	32	83	0.91	37	6.2	0.18	16	7	6	9	66
2021-23-04	23	2021	Current	Brown	Forestry	Forestry	5.68	5.8	0.42	11	100	0.89	21	6.9	0.21	19	7	8	6	48
2016-23-03	23	2016	Previous	Brown	Forestry	Forestry	5.89	3.9	0.28	10	68	1	29	6.3	0.12	14	6	4	5	28
2021-24-04	24	2021	Current	Brown	Drystock	Pasture	5.55	4.5	0.45	14	104	1.1	22	6.3	0.34	19	10	9	7	56
2016-24-03	24	2016	Previous	Brown	Drystock	Pasture	5.52	4.3	0.46	44	130	1.11	10	5.4	0.4	14	9	6	6	43
2019-25-04	25	2019	Current	Brown	Dairy-Drystock	Pasture	5.56	4.7	0.49	55	149	1.19	12	6	0.53	17	10	7	6	56
2014-25-04	25	2014	Previous	Brown	Dairy-Drystock	Pasture	5.45	4	0.43	55	160	1.07	5	5.4	0.42	14	9	5	6	43
2020-27-05	27	2020	Current	Ultic	Drystock	Pasture	6.05	8.3	0.81	32	224	0.81	6	2	0.4	6	15	6	13	27
2015-27-04	27	2015	Previous	Ultic	Drystock	Pasture	6.06	8.1	0.77	40	218	0.7	10	7.6	0.39	5	20	15	35	32
2019-28-05	28	2019	Current	Ultic	Dairy	Pasture	6.02	4.5	0.37	10	87	1.12	8	1	0.22	2	3	1	1	2
2014-28-04	28	2014	Previous	Ultic	Dairy	Pasture	6.39	4.6	0.37	9	71	0.99	9	0.5	0.24	3	3	2	3	5
2020-30-05	30	2020	Current	Recent	Drystock	Pasture	6	4.7	0.44	80	143	1	8	1	0.45	21	16	7	7	45
2015-30-04	30	2015	Previous	Recent	Drystock	Pasture	5.97	3.5	0.33	52	134	0.98	5	1.2	0.23	11	9	4	4	24
2019-33-05	33	2019	Current	Ultic	Dairy-Drystock	Pasture	5.96	6.1	0.61	76	164	0.91	2	2	0.58	20	25	11	8	109
2014-33-04	33	2014	Previous	Ultic	Dairy-Drystock	Pasture	6.25	5.8	0.57	79	198	0.74	8	2.4	0.52	13	19	7	8	68

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2019-35-05	35	2019	Current	Ultic	Dairy-Drystock	Pasture	5.92	5.7	0.46	33	109	1.06	5	3	0.51	22	15	5	5	33
2014-35-04	35	2014	Previous	Ultic	Dairy-Drystock	Pasture	6	6.7	0.53	37	139	1.04	3	2	0.38	12	8	3	3	26
2018-37-04	37	2018	Current	Recent	Veg-Lifestyle	Pasture	6.7	5.1	0.41	33	81	1.17	4	10	0.46	14	27	5	19	47
2013-37-03	37	2013	Previous	Recent	Veg-Lifestyle	Pasture	6.22	5	0.37	32	93	1.21	3	8.9	0.35	17	26	7	21	28
2019-38-05	38	2019	Current	Allophanic	Dairy	Pasture	6.21	5.8	0.51	27	107	1.03	3	7	0.63	23	18	10	28	52
2014-38-04	38	2014	Previous	Allophanic	Dairy	Pasture	5.84	5.9	0.54	31	128	1.15	1	6.7	0.5	21	13	6	21	38
2022-39-08	39	2022	Current	Allophanic	Native	Native	5.9	4.3	0.21	2	92	1.19	17	3	0.05	8	3	3	7	33
2017-39-07	39	2017	Previous	Allophanic	Native	Native	5.75	7.6	0.43	3	122	0.9	20	4.5	0.07	9	5	3	10	32
2022-40-04	40	2022	Current	Brown	Native	Native	5.72	9.8	0.48	3	154	0.77	23	4.5	0.05	12	7	5	12	46
2017-40-03	40	2017	Previous	Brown	Native	Native	5.52	8.7	0.46	3	161	0.7	20	4.8	0.05	13	7	4	11	29
2018-41-04	41	2018	Current	Organic	Orchard	Horticulture	*	*	*	*	*	*	*	5	2.1	29	56	15	18	240
2013-41-03	41	2013	Previous	Organic	Orchard	Horticulture	*	*	*	*	*	*	*	5	2	28	38	10	16	160
2019-42-05	42	2019	Current	Organic	Dairy-Horse Stud	Pasture	5.41	22.5	1.77	58	242	0.6	5	2.5	1	16	40	7	16	60
2014-42-04	42	2014	Previous	Organic	Dairy-Horse Stud	Pasture	5.65	23.8	1.84	77	309	0.59	3	2.6	0.89	11	30	4	12	49
2019-43-05	43	2019	Current	Organic	Dairy-Horse stud	Pasture	5.69	17.9	1.5	48	212	0.59	9	3	0.97	17	26	6	20	71
2014-43-04	43	2014	Previous	Organic	Dairy-Horse stud	Pasture	5.72	18.4	1.57	72	301	0.58	10	3	0.93	13	22	4	15	48
2022-45-08	45	2022	Current	Granular	Native	Native	4.3	9.1	0.49	3	91	0.75	26	4.5	0.05	7	5	3	16	18
2017-45-07	45	2017	Previous	Granular	Native	Native	4.18	7.8	0.41	4	51	0.8	20	5	0.03	5	4	1	17	13
2020-46-05	46	2020	Current	Granular	Drystock	Pasture	5.37	8.1	0.73	81	160	0.84	16	5	0.42	10	15	4	30	69
2015-46-04	46	2015	Previous	Granular	Drystock	Pasture	5.59	8.4	0.77	89	163	0.91	8	6.4	0.53	10	20	3	63	95
2019-47-05	47	2019	Current	Granular	Dairy-Drystock	Pasture	5.64	7.1	0.67	46	154	0.92	6	5	1.16	13	8	6	19	43
2014-47-04	47	2014	Previous	Granular	Dairy-Drystock	Pasture	5.79	7.8	0.72	58	212	0.98	8	3.1	0.77	8	6	3	15	28
2020-48-05	48	2020	Current	Brown	Drystock	Pasture	5.29	4.5	0.38	16	118	1.03	12	2	0.31	7	6	1	9	21
2015-48-04	48	2015	Previous	Brown	Drystock	Pasture	5.51	4.5	0.37	20	105	1.04	9	2.1	0.37	6	5	2	5	16
2022-49-08	49	2022	Current	Brown	Native	Native	6.28	4.4	0.33	14	115	1.13	11	4.9	0.21	11	18	5	20	64
2017-49-07	49	2017	Previous	Brown	Native	Native	6.33	4.5	0.33	11	110	0.9	11	6	0.16	10	20	6	20	57
2020-50-05	50	2020	Current	Recent	Drystock	Pasture	5.59	3.8	0.35	23	70	1.21	18	5	0.12	10	4	6	3	28
2015-50-04	50	2015	Previous	Recent	Drystock	Pasture	5.82	3.5	0.33	17	79	1.27	10	5.4	0.13	8	5	4	3	24
2020-51-05	51	2020	Current	Recent	Drystock	Pasture	5.12	3.9	0.31	26	71	1.09	24	5	0.05	9	4	4	5	35

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2015-51-04	51	2015	Previous	Recent	Drystock	Pasture	5.55	3.7	0.32	18	73	1.02	19	5.6	0.05	8	5	4	10	26
2022-52-08	52	2022	Current	Recent	Native	Native	5.56	3.2	0.2	14	50	1.15	32	6.4	0.05	10	3	5	3	27
2017-52-07	52	2017	Previous	Recent	Native	Native	5.5	2.4	0.17	12	56	1.2	31	6.9	0.02	8	3	4	3	23
2019-53-05	53	2019	Current	Ultic	Dairy-Drystock	Pasture	6.07	10.2	0.92	53	316	0.69	5	6	0.48	15	18	7	12	41
2014-53-04	53	2014	Previous	Ultic	Dairy-Drystock	Pasture	6.46	10.7	0.94	55	344	0.53	7	2.6	0.56	8	15	6	6	28
2019-55-05	55	2019	Current	Ultic	Dairy-Drystock	Pasture	6.41	9.8	0.88	37	320	0.66	6	3	1.16	11	14	7	10	30
2014-55-04	55	2014	Previous	Ultic	Dairy-Drystock	Pasture	6.45	10.3	0.93	30	362	0.58	6	2.5	0.59	8	12	5	9	19
2022-56-08	56	2022	Current	Granular	Native	Native	6.32	10.6	0.55	11	189	0.64	27	3.5	0.18	25	12	6	11	32
2017-56-07	56	2017	Previous	Granular	Native	Native	5.88	6.3	0.41	7	130	0.8	13	4.4	0.09	10	11	6	10	34
2022-57-04	57	2022	Current	Granular	Native	Native	6.01	8.6	0.44	5	182	0.81	14	2.9	0.05	33	14	12	13	52
2017-57-03	57	2017	Previous	Granular	Native	Native	5.54	5.5	0.33	4	118	0.9	11	1.3	0.06	25	12	11	10	42
2021-58-04	58	2021	Current	Recent	Forestry	Forestry	5.59	2.5	0.13	6	32	1.19	45	9.9	0.05	6	4	3	2	20
2016-58-03	58	2016	Previous	Recent	Forestry	Forestry	5.58	1.3	0.05	9	18	1.29	38	9.1	0.09	5	2	3	2	15
2021-60-04	60	2021	Current	Recent	Forestry	Forestry	4.89	2.9	0.09	15	20	0.51	52	8.1	0.05	9	3	5	3	24
2016-60-03	60	2016	Previous	Recent	Forestry	Forestry	4.96	1.6	0.06	15	10	1.56	36	6.8	0.09	6	2	4	3	20
2020-61-05	61	2020	Current	Granular	Drystock-Lifestyle	Pasture	5.49	5.9	0.53	15	153	1.01	11	2	0.38	13	6	2	5	23
2015-61-04	61	2015	Previous	Granular	Drystock-Lifestyle	Pasture	5.69	6.1	0.55	12	186	0.88	6	2.4	0.4	10	6	2	6	15
2019-62-05	62	2019	Current	Allophanic	Dairy	Pasture	6.34	5.9	0.48	47	97	1.11	8	5	0.51	10	8	5	13	40
2014-62-04	62	2014	Previous	Allophanic	Dairy	Pasture	5.97	5.3	0.45	39	111	1.08	6	4.4	0.36	8	5	3	11	26
2020-63-05	63	2020	Current	Allophanic	Drystock-Lifestyle	Pasture	5.59	8.6	0.8	21	159	0.83	16	6	0.8	17	13	10	21	42
2015-63-04	63	2015	Previous	Allophanic	Drystock-Lifestyle	Pasture	5.83	8.4	0.76	20	130	0.76	7	5.6	0.73	13	13	7	18	34
2019-64-05	64	2019	Current	Allophanic	Dairy	Pasture	6.15	6.7	0.64	69	130	1.04	5	5	0.69	15	18	6	17	64
2014-64-04	64	2014	Previous	Allophanic	Dairy	Pasture	6.37	7.2	0.69	79	155	1	2	5.1	0.59	12	13	5	17	43
2018-65-04	65	2018	Current	Allophanic	Orchard	Horticulture	6.79	6	0.49	86	98	0.98	13	8	0.85	21	20	8	23	65
2013-65-03	65	2013	Previous	Allophanic	Orchard	Horticulture	6.53	5.3	0.43	84	50	0.97	23	7	0.77	21	17	8	20	46
2019-66-05	66	2019	Current	Allophanic	Dairy-Lifestyle	Pasture	5.99	8.7	0.78	8	172	0.86	16	6	0.62	17	24	6	13	57
2014-66-04	66	2014	Previous	Allophanic	Dairy-Lifestyle	Pasture	5.96	8.4	0.78	10	210	0.91	12	5.7	0.58	14	22	5	13	44

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2018-67-04	67	2018	Current	Allophanic	Orchard	Horticulture	6.01	4.7	0.41	51	119	1.09	17	5	0.31	13	20	3	14	56
2013-67-03	67	2013	Previous	Allophanic	Orchard	Horticulture	5.45	4.9	0.42	13	124	0.92	22	6.1	0.28	16	8	5	18	29
2018-68-04	68	2018	Current	Allophanic	Veg-Drystock	Pasture	5.76	7.3	0.69	44	114	0.78	6	8	1	24	17	7	14	76
2013-68-03	68	2013	Previous	Allophanic	Veg-Drystock	Pasture	5.95	7.1	0.66	53	127	0.93	8	7.2	0.74	22	15	7	12	72
2020-69-05	69	2020	Current	Granular	Drystock-Lifestyle	Pasture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2015-69-04	69	2015	Previous	Granular	Drystock-Lifestyle	Pasture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2018-70-04	70	2018	Current	Granular	Outdoor vegetable	Horticulture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2013-70-03	70	2013	Previous	Granular	Outdoor vegetable	Horticulture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2018-71-04	71	2018	Current	Organic	Nursery	Horticulture	6.15	19.3	0.83	47	94	0.61	5	3	0.63	20	34	5	15	39
2013-71-03	71	2013	Previous	Organic	Nursery	Horticulture	6.2	14.5	0.68	27	165	0.65	18	4.6	0.37	18	27	5	14	37
2021-72-04	72	2021	Current	Brown	Forestry	Forestry	5.62	4.3	0.27	5	115	1.14	10	4.9	0.05	9	12	4	24	35
2016-72-03	72	2016	Previous	Brown	Forestry	Forestry	5.51	3.3	0.22	5	91	1.03	10	4	0.09	7	11	2	20	20
2019-73-05	73	2019	Current	Gley	Dairy-Drystock	Pasture	5.54	6.2	0.6	45	140	0.85	7	9	0.38	16	12	6	9	43
2014-73-04	73	2014	Previous	Gley	Dairy-Drystock	Pasture	5.88	6.7	0.64	63	215	0.86	10	7.1	0.36	10	11	4	7	31
2020-74-05	74	2020	Current	Gley	Drystock	Pasture	5.16	6.5	0.62	38	182	0.76	7	6	0.27	16	14	6	8	40
2015-74-04	74	2015	Previous	Gley	Drystock	Pasture	5.62	6.8	0.64	29	191	0.67	9	7	0.38	11	13	6	8	38
2019-75-05	75	2019	Current	Granular	Dairy-Lifestyle	Pasture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2014-75-04	75	2014	Previous	Granular	Dairy-Lifestyle	Pasture	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2020-76-05	76	2020	Current	Gley	Drystock	Pasture	6.01	4.8	0.45	58	107	1.09	6	1	0.69	5	4	2	4	12
2015-76-04	76	2015	Previous	Gley	Drystock	Pasture	5.72	4.9	0.46	70	116	0.91	6	0.7	0.74	5	3	2	4	11
2019-77-05	77	2019	Current	Gley	Dairy-Lifestyle	Pasture	5.74	4.8	0.45	10	111	1.16	3	1	0.21	4	13	1	4	13
2014-77-04	77	2014	Previous	Gley	Dairy-Lifestyle	Pasture	5.84	5.5	0.49	12	163	0.93	9	0.7	0.22	3	12	2	4	11
2020-78-05	78	2020	Current	Ultic	Drystock-Lifestyle	Pasture	6.43	3.9	0.39	18	97	1.13	2	1	0.26	20	11	4	10	33
2015-78-04	78	2015	Previous	Ultic	Drystock-Lifestyle	Pasture	5.95	4	0.39	22	102	1.07	4	1.8	0.29	19	10	4	11	32
2018-79-04	79	2018	Current	Ultic	Veg-Lifestyle	Pasture	6.44	4.3	0.38	18	106	0.92	9	3	0.16	20	7	3	9	25
2013-79-03	79	2013	Previous	Ultic	Veg-Lifestyle	Pasture	6.34	3.5	0.3	40	73	1.08	7	3.1	0.19	22	7	4	10	30
2018-80-04	80	2018	Current	Ultic	Viticulture	Horticulture	5.84	5.2	0.46	12	154	0.96	7	2	0.46	20	59	2	4	34

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2013-80-03	80	2013	Previous	Ultic	Viticulture	Horticulture	5.64	4.4	0.38	19	79	1.02	11	1.6	0.33	17	18	2	4	18
2018-81-04	81	2018	Current	Ultic	Orchard-Lifestyle	Pasture	6.16	5.4	0.44	28	183	0.98	9	3	0.14	15	13	4	11	64
2013-81-03	81	2013	Previous	Ultic	Orchard-Lifestyle	Pasture	5.99	4.8	0.4	23	98	0.89	12	2.1	0.09	12	6	3	9	27
2018-82-04	82	2018	Current	Brown	Orchard	Horticulture	5.95	5.5	0.52	34	141	0.9	10	2	0.32	16	21	2	12	24
2013-82-03	82	2013	Previous	Brown	Orchard	Horticulture	6.05	5.7	0.53	55	126	0.94	10	2.2	0.22	11	35	2	7	17
2022-83-04	83	2022	Current	Brown	Native	Native	5.69	7.6	0.43	15	139	0.81	15	1.4	0.05	12	4	2	7	18
2017-83-03	83	2017	Previous	Brown	Native	Native	5.56	5.1	0.31	36	97	1	10	1.5	0.06	7	3	1	9	19
2020-84-05	84	2020	Current	Granular	Drystock	Pasture	6.83	5.7	0.54	31	147	1.05	8	2	0.37	19	9	4	10	18
2015-84-04	84	2015	Previous	Granular	Drystock	Pasture	6.56	6.2	0.58	45	165	0.8	10	1.8	0.44	14	9	4	9	17
2022-85-08	85	2022	Current	Brown	Native	Native	4.9	5.1	0.27	4	46	1.11	7	0.9	0.05	4	2	1	7	7
2017-85-07	85	2017	Previous	Brown	Native	Native	5.01	3.7	0.21	4	59	1	8	1.6	0.01	11	7	3	8	15
2018-86-04	86	2018	Current	Gley	Viticulture	Horticulture	6.15	4	0.34	96	99	1.03	9	1	0.39	6	127	4	12	32
2013-86-03	86	2013	Previous	Gley	Viticulture	Horticulture	5.97	4.1	0.34	133	86	0.95	18	1.1	0.43	7	120	5	8	31
2018-87-04	87	2018	Current	Gley	Orchard	Horticulture	6.27	2.8	0.18	47	13	1.45	4	1	0.18	3	55	1	5	12
2013-87-03	87	2013	Previous	Gley	Orchard	Horticulture	6.05	3.1	0.21	56	30	1.41	1	0.8	0.2	5	61	3	5	10
2018-88-04	88	2018	Current	Gley	Orchard	Horticulture	6.53	2.9	0.2	48	18	1.35	10	3	0.26	6	13	2	20	63
2013-88-03	88	2013	Previous	Gley	Orchard	Horticulture	6.36	3	0.21	73	22	1.35	3	1.9	0.19	6	9	3	14	46
2021-89-03	89	2021	Current	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2016-89-02	89	2016	Previous	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2021-90-03	90	2021	Current	Ultic	Forestry	Forestry	4.71	6.8	0.39	4	111	0.67	22	1.9	0.1	16	9	2	5	9
2016-90-02	90	2016	Previous	Ultic	Forestry	Forestry	4.95	7.1	0.39	7	132	0.71	26	1.2	0.09	12	7	2	6	8
2021-91-03	91	2021	Current	Recent	Forestry	Forestry	5.75	1.7	0.07	5	17	0.99	50	9.4	0.05	7	4	4	2	21
2016-91-02	91	2016	Previous	Recent	Forestry	Forestry	5.77	1.9	0.1	12	38	1.49	38	9.8	0.09	5	3	3	2	17
2021-92-03	92	2021	Current	Ultic	Forestry	Forestry	4.87	4.7	0.2	4	56	0.79	21	4.7	0.05	21	7	1	7	7
2016-92-02	92	2016	Previous	Ultic	Forestry	Forestry	5.06	7	0.27	7	69	1.07	14	2.2	0.09	8	3	1	9	7
2021-93-03	93	2021	Current	Ultic	Forestry	Forestry	4.69	5.3	0.19	3	21	1.32	14	1.3	0.05	3	7	1	3	9
2016-93-02	93	2016	Previous	Ultic	Forestry	Forestry	4.85	4.8	0.18	4	27	1.17	22	1.3	0.09	3	3	1	3	7
2021-94-03	94	2021	Current	Ultic	Forestry	Forestry	5.03	5.7	0.3	3	97	1.06	14	4	0.05	7	14	2	11	18

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2016-94-02	94	2016	Previous	Ultic	Forestry	Forestry	4.96	3.5	0.17	5	57	1.28	7	1.1	0.09	4	4	1	5	7
2021-95-03	95	2021	Current	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2016-95-02	95	2016	Previous	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2021-96-03	96	2021	Current	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2016-96-02	96	2016	Previous	Ultic	Forestry	Forestry	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2022-97-03	97	2022	Current	Ultic	Native	Native	5.24	4.5	0.28	6	163	1.08	18	12.3	0.05	5	115	11	25	38
2017-97-02	97	2017	Previous	Ultic	Native	Native	5.05	2.8	0.2	4	68	1.4	16	16	0.08	3	180	18	26	29
2022-98-03	98	2022	Current	Ultic	Native	Native	4.87	5.8	0.36	22	89	1.07	9	6.9	0.05	9	11	3	18	42
2017-98-02	98	2017	Previous	Ultic	Native	Native	4.99	4.5	0.28	5	117	1	13	5	0.03	8	11	3	17	33
2022-99-03	99	2022	Current	Ultic	Native	Native	4.93	14	0.77	3	225	0.56	22	5.2	0.05	13	12	4	15	29
2017-99-02	99	2017	Previous	Ultic	Native	Native	4.53	13.7	0.72	3	122	0.6	18	7.4	0.04	12	15	5	17	28
2022-100-07	100	2022	Current	Ultic	Native	Native	5.19	3.3	0.2	3	85	0.95	17	6.4	0.05	12	26	7	20	50
2017-100-06	100	2017	Previous	Ultic	Native	Native	4.6	7.8	0.42	4	105	0.7	18	5.8	0.03	8	14	3	13	29
2022-101-03	101	2022	Current	Ultic	Native	Native	4.91	10.5	0.6	4	194	0.6	28	6.2	0.05	11	10	3	14	30
2017-101-02	101	2017	Previous	Ultic	Native	Native	4.68	8.9	0.56	5	192	0.6	10	4.3	0.02	5	6	2	12	19
2022-102-03	102	2022	Current	Granular	Native	Native	5.03	12.9	0.68	3	283	0.61	16	1.5	0.05	15	39	4	11	30
2017-102-02	102	2017	Previous	Granular	Native	Native	4.75	11.8	0.66	2	223	0.4	20	1.4	0.05	10	35	2	10	23
2022-103-07	103	2022	Current	Granular	Native	Native	4.66	12.9	0.57	2	199	0.65	16	1.7	0.15	11	14	2.5	12	17
2017-103-06	103	2017	Previous	Granular	Native	Native	4.55	12.3	0.6	2	180	0.5	16	1.8	0.04	10	12	3	15	14
2022-104-03	104	2022	Current	Brown	Native	Native	6.33	9.6	0.63	7	249	0.76	17	2.6	0.12	8	38	5	28	88
2017-104-02	104	2017	Previous	Brown	Native	Native	5.51	7	0.43	4	173	0.7	7	1.2	0.04	9	43	3	15	42
2022-105-07	105	2022	Current	Brown	Native	Native	6.78	2.9	0.23	4	157	1.17	20	3.8	0.05	15	4	6	6	84
2017-105-06	105	2017	Previous	Brown	Native	Native	6.71	3	0.23	3	106	1.2	11	3.3	0.04	18	6	6	7	51
2022-107-07	107	2022	Current	Granular	Native	Native	5.26	7.9	0.45	3	204	0.83	15	1.4	0.05	12	13	1	9	24
2017-107-06	107	2017	Previous	Granular	Native	Native	5	7.3	0.41	3	163	0.7	14	1.6	0.03	8	16	2	12	16
2022-108-03	108	2022	Current	Recent	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2017-108-02	108	2017	Previous	Recent	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2022-109-03	109	2022	Current	Recent	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2017-109-02	109	2017	Previous	Recent	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2022-110-03	110	2022	Current	Brown	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2017-110-02	110	2017	Previous	Brown	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2022-111-03	111	2022	Current	Brown	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2017-111-02	111	2017	Previous	Brown	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2022-112-03	112	2022	Current	Recent	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2017-112-02	112	2017	Previous	Recent	Native	Native	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2018-113-02	113	2018	Current	Granular	Outdoor vegetable	Horticulture	6.95	1.8	0.19	316	12	1.2	7	10	0.61	28	66	12	34	70
2013-113-01	113	2013	Previous	Granular	Outdoor vegetable	Horticulture	6.43	1.8	0.19	348	7	1.06	22	9.2	0.58	23	61	9	30	48
2018-114-02	114	2018	Current	Granular	Outdoor vegetable	Horticulture	6.14	1.9	0.18	198	8	1.36	2	10	0.62	29	53	14	35	50
2013-114-01	114	2013	Previous	Granular	Outdoor vegetable	Horticulture	6.13	2.5	0.22	148	9	1.16	16	8.4	0.56	24	49	10	31	40
2018-115-02	115	2018	Current	Granular	Outdoor vegetable	Horticulture	6.19	3.9	0.37	74	30	1.21	1	9	0.24	28	35	11	39	60
2013-115-01	115	2013	Previous	Granular	Outdoor vegetable	Horticulture	6.22	4.3	0.42	73	45	1	17	8.7	0.36	22	43	7	56	66
2018-116-02	116	2018	Current	Granular	Outdoor vegetable	Horticulture	7.03	2	0.17	199	10	1.33	1	12	0.46	33	49	14	34	50
2013-116-01	116	2013	Previous	Granular	Outdoor vegetable	Horticulture	7.07	2	0.16	187	7	0.98	29	9.2	0.47	26	43	10	31	36
2018-117-02	117	2018	Current	Granular	Outdoor vegetable	Horticulture	6.93	2	0.19	275	17	1.26	3	10	0.68	28	46	11	36	61
2013-117-01	117	2013	Previous	Granular	Outdoor vegetable	Horticulture	6.89	2.4	0.21	361	18	1.06	23	7.6	0.7	22	40	7	30	51
2018-118-02	118	2018	Current	Ultic	Viticulture	Horticulture	6.66	4	0.33	11	126	1.01	6	4	0.19	9	17	2	15	26
2013-118-01	118	2013	Previous	Ultic	Viticulture	Horticulture	6.62	4.2	0.34	11	78	1.04	14	3.3	0.15	8	12	3	13	18
2018-119-02	119	2018	Current	Ultic	Viticulture	Horticulture	5.89	3.4	0.27	17	84	1.15	9	3	0.05	6	10	1	7	17
2013-119-01	119	2013	Previous	Ultic	Viticulture	Horticulture	6.24	3.4	0.24	16	70	1.17	9	1.7	0.06	9	8	3	7	11
2018-120-02	120	2018	Current	Ultic	Viticulture	Horticulture	5.94	3.9	0.33	24	117	0.94	10	3	0.1	10	30	1	9	21
2013-120-01	120	2013	Previous	Ultic	Viticulture	Horticulture	6.28	4	0.32	28	96	1.15	6	4	0.15	13	44	4	18	33
2019-121-02	121	2019	Current	Gley	Dairy	Pasture	5.64	5.7	0.48	42	118	0.86	10	1	0.4	4	4	1	3	10
2014-121-01	121	2014	Previous	Gley	Dairy	Pasture	5.55	5.4	0.45	69	139	0.79	7	0.3	0.38	3	3	1	2	5
2019-122-02	122	2019	Current	Gley	Dairy	Pasture	5.77	5.2	0.41	60	83	0.99	7	1	0.32	4	3	1	2	6

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2014-122-01	122	2014	Previous	Gley	Dairy	Pasture	5.78	4.7	0.35	39	86	0.92	7	0.2	0.27	4	3	1	2	8
2019-123-02	123	2019	Current	Ultic	Dairy	Pasture	6.16	10.7	0.93	43	144	0.74	3	1	0.69	8	13	3	6	36
2014-123-01	123	2014	Previous	Ultic	Dairy	Pasture	6.2	11.8	1.02	44	187	0.69	6	0.45	0.57	7	15	2.5	4	34
2019-124-02	124	2019	Current	Ultic	Dairy	Pasture	6.22	8.6	0.69	70	157	0.67	10	5	0.6	9	9	5	3	25
2014-124-01	124	2014	Previous	Ultic	Dairy	Pasture	5.85	7.5	0.59	80	193	0.77	7	6.8	0.7	11	12	5	2	34
2019-125-02	125	2019	Current	Brown	Dairy	Pasture	6.25	8.6	0.84	58	176	0.8	5	4	0.82	10	17	4	12	51
2014-125-01	125	2014	Previous	Brown	Dairy	Pasture	6.63	8.4	0.82	56	326	0.9	6	3.5	0.68	8	17	2	11	33
2022-201-03	201	2022	Current	Anthropic	Urban	Urban	5.35	6	0.45	12	136	0.97	11	2.5	0.05	5	3	1	9	13
2017-201-02	201	2017	Previous	Anthropic	Urban	Urban	5.32	5.1	0.44	11	147	0.6	16	3	0.1	7	10	5	15	49
2022-202-03	202	2022	Current	Recent	Urban	Urban	5.41	6.3	0.49	12	173	0.92	11	2.9	0.16	5	22	3	29	67
2017-202-02	202	2017	Previous	Recent	Urban	Urban	6.23	5.8	0.5	10	158	0.7	13	9	0.05	11	23	15	28	58
2022-203-03	203	2022	Current	Recent	Urban	Urban	5.74	7.9	0.48	28	120	1.05	11	8.1	0.19	15	13	8	12	41
2017-203-02	203	2017	Previous	Recent	Urban	Urban	5.63	6.7	0.41	20	102	0.9	8	6	0.17	13	9	8	10	41
2022-204-03	204	2022	Current	Recent	Urban	Urban	5.55	3.8	0.33	23	80	1.09	13	7.7	0.1	6	3	4	4	21
2017-204-02	204	2017	Previous	Recent	Urban	Urban	5.51	3.8	0.33	15	72	1	9	8	0.11	7	3	4	4	22
2022-205-03	205	2022	Current	Ultic	Urban	Urban	6.28	6.1	0.53	85	157	0.91	9	3.8	0.2	13	24	7	31	60
2017-205-02	205	2017	Previous	Ultic	Urban	Urban	6.19	5.6	0.47	109	154	0.7	12	4	0.24	15	29	7	27	49
2022-206-03	206	2022	Current	Ultic	Urban	Urban	5.53	2.7	0.24	64	127	1.34	24	3.2	0.05	6	4	3	4	29
2017-206-02	206	2017	Previous	Ultic	Urban	Urban	5.18	2.3	0.2	55	72	1.3	23	1	0.05	6	2	2	3	33
2022-207-03	207	2022	Current	Ultic	Urban	Urban	5.43	3.7	0.26	9	87	1.09	9	1.5	0.05	5	4	1	8	16
2017-207-02	207	2017	Previous	Ultic	Urban	Urban	5.29	2.7	0.19	5	59	1	12	1	0.05	6	4	3	8	14
2022-208-03	208	2022	Current	Granular	Urban	Urban	5.86	6.9	0.54	9	154	0.75	11	1.9	0.05	73	23	120	220	136
2017-208-02	208	2017	Previous	Granular	Urban	Urban	5.94	6.2	0.52	9	155	0.7	12	2	0.15	84	23	77	86	96
2022-209-03	209	2022	Current	Anthropic	Urban	Urban	6.12	6.4	0.56	56	237	0.88	14	4.2	0.15	23	30	30	62	81
2017-209-02	209	2017	Previous	Anthropic	Urban	Urban	5.77	6.5	0.55	28	202	0.7	12	4	0.12	31	22	36	82	79
2022-210-03	210	2022	Current	Anthropic	Urban	Urban	5.62	5.8	0.44	13	149	0.84	12	2.6	0.11	7	8	4	11	20
2017-210-02	210	2017	Previous	Anthropic	Urban	Urban	5.55	4.4	0.34	9	106	0.9	11	1	0.05	6	6	4	9	16
2022-213-03	213	2022	Current	Allophanic	Urban	Urban	5.98	3.3	0.3	58	99	1.27	14	6.3	0.05	8	6	4	7	35
2017-213-02	213	2017	Previous	Allophanic	Urban	Urban	5.88	4.6	0.39	20	118	1.3	4	10	0.13	10	12	7	17	38

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2022-214-03	214	2022	Current	Allophanic	Native	Native	5.11	6.2	0.3	3	110	1.02	23	2.2	0.05	6	4	1	8	11
2017-214-02	214	2017	Previous	Allophanic	Native	Native	5.06	3.8	0.19	0	63	1.1	10	2	0.05	9	4	3	12	12
2022-215-03	215	2022	Current	Ultic	Native	Native	4.52	4.9	0.19	2	42	1.07	25	1	0.05	11	3	6	10	5
2017-215-02	215	2017	Previous	Ultic	Native	Native	4.67	6.1	0.24	2	48	1	20	1	0.05	28	6	27	19	11
2022-216-03	216	2022	Current	Ultic	Native	Native	5.56	4.5	0.29	12	89	1.06	14	0.8	0.05	8	4	5	21	12
2017-216-02	216	2017	Previous	Ultic	Native	Native	5.12	5	0.33	20	87	1	12	1	0.05	9	5	6	23	18
2022-217-03	217	2022	Current	Allophanic	Urban	Urban	5.93	5	0.37	11	141	1.06	10	2.2	0.05	22	14	27	26	36
2017-217-02	217	2017	Previous	Allophanic	Urban	Urban	5.63	5	0.42	10	73	0.6	17	2	0.05	33	16	43	29	39
2022-218-03	218	2022	Current	Allophanic	Urban	Urban	6.24	8.2	0.7	14	353	0.77	19	3.9	0.21	101	26	200	49	138
2017-218-02	218	2017	Previous	Allophanic	Urban	Urban	6.12	9.8	0.79	18	231	0.8	12	5	0.34	101	50	193	75	173
2022-219-03	219	2022	Current	Anthropic	Urban	Urban	6.1	7.8	0.53	14	162	0.84	19	2.5	0.13	106	46	210	62	111
2017-219-02	219	2017	Previous	Anthropic	Urban	Urban	6.76	8	0.59	23	204	0.7	10	8	0.27	40	69	57	210	170
2022-220-03	220	2022	Current	Ultic	Urban	Urban	6.1	4.8	0.38	8	121	0.94	9	2.8	0.05	45	20	50	24	51
2017-220-02	220	2017	Previous	Ultic	Urban	Urban	6.09	4.1	0.28	5	98	0.9	14	2	0.05	13	13	17	31	44
2022-221-03	221	2022	Current	Ultic	Urban	Urban	5.23	7.3	0.57	13	203	0.77	13	1.4	0.25	7	11	3	16	38
2017-221-02	221	2017	Previous	Ultic	Urban	Urban	5.5	6.6	0.55	12	191	0.6	16	10	0.18	10	25	7	21	123
2022-222-03	222	2022	Current	Ultic	Urban	Urban	5.38	6.8	0.55	32	251	0.86	10	3.2	0.1	6	16	2	16	36
2017-222-02	222	2017	Previous	Ultic	Urban	Urban	5.27	5.5	0.42	14	158	0.6	17	4	0.13	8	19	6	21	28
2022-223-03	223	2022	Current	Gley	Urban	Urban	6.49	9.8	0.64	20	336	0.64	14	8.7	0.11	17	28	7	17	82
2017-223-02	223	2017	Previous	Gley	Urban	Urban	6.04	8.7	0.64	10	325	0.7	9	4	0.14	15	28	8	41	92
2022-224-03	224	2022	Current	Anthropic	Urban	Urban	5.51	6.6	0.61	34	193	0.84	15	22	0.27	16	114	7	79	75
2017-224-02	224	2017	Previous	Anthropic	Urban	Urban	5.47	7	0.65	33	198	0.7	12	19	0.3	19	129	9	75	81
2022-225-03	225	2022	Current	Anthropic	Urban	Urban	5.72	6.5	0.52	25	162	0.96	11	2.1	0.05	9	19	18	18	74
2017-225-02	225	2017	Previous	Anthropic	Urban	Urban	5.43	6.5	0.55	46	221	0.7	14	4	0.12	9	35	5	26	55
2022-226-03	226	2022	Current	Anthropic	Urban	Urban	5.95	6.5	0.57	63	183	0.83	11	6	0.14	21	21	18	42	77
2017-226-02	226	2017	Previous	Anthropic	Urban	Urban	5.94	5.9	0.52	41	178	0.8	9	5	0.14	25	23	21	47	73
2022-227-03	227	2022	Current	Ultic	Urban	Urban	6.11	8	0.52	10	158	0.89	7	4.1	0.11	11	20	8	75	68
2017-227-02	227	2017	Previous	Ultic	Urban	Urban	5.77	5.5	0.41	5	124	0.8	8	4	0.11	14	24	16	99	69
2022-228-03	228	2022	Current	Granular	Native	Native	4.96	8.5	0.46	5	105	0.84	27	3.5	0.05	8	9	2	45	43

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2017-228-02	228	2017	Previous	Granular	Native	Native	4.66	9.2	0.45	9	92	0.6	25	3	0.05	5	10	6	59	44
2022-229-03	229	2022	Current	Allophanic	Urban	Urban	6.16	6.7	0.47	65	137	0.89	13	7.9	0.45	45	107	34	163	410
2017-229-02	229	2017	Previous	Allophanic	Urban	Urban	6.24	5.7	0.42	46	128	0.9	11	8	0.48	36	77	39	198	340
2022-233-03	233	2022	Current	Allophanic	Urban	Urban	6	6.9	0.55	30	192	0.8	9	4.7	0.14	69	32	56	78	114
2017-233-02	233	2017	Previous	Allophanic	Urban	Urban	5.94	6.2	0.51	22	167	0.9	4	8	0.16	56	38	67	78	108
2022-234-03	234	2022	Current	Allophanic	Urban	Urban	5.61	7.9	0.67	74	232	0.78	16	5.4	0.16	26	21	22	55	119
2017-234-02	234	2017	Previous	Allophanic	Urban	Urban	5.9	6.9	0.6	75	217	0.6	10	5	0.21	30	23	26	62	152
2022-235-07	235	2022	Current	Granular	Native	Native	6.02	6.7	0.52	7	164	0.87	15	2.7	0.05	14	10	8	19	41
2017-235-06	235	2017	Previous	Granular	Native	Native	5.85	6.3	0.5	12	191	0.9	10	3	0.05	19	10	9	24	40
2022-236-03	236	2022	Current	Anthropic	Urban	Urban	6.6	4.2	0.39	51	97	1.06	9	7.9	0.13	17	31	19	84	104
2017-236-02	236	2017	Previous	Anthropic	Urban	Urban	6.03	4	0.39	36	113	1	11	8	0.12	19	24	21	53	68
2022-237-03	237	2022	Current	Recent	Urban	Urban	5.52	6.1	0.53	12	121	0.89	17	4.1	0.05	12	11	16	11	33
2017-237-02	237	2017	Previous	Recent	Urban	Urban	5.24	7.3	0.64	10	143	0.8	11	6	0.05	13	14	18	22	44
2022-238-03	238	2022	Current	Allophanic	Urban	Urban	5.57	6.4	0.58	34	199	0.61	14	2.5	0.22	31	21	17	13	48
2017-238-02	238	2017	Previous	Allophanic	Urban	Urban	5.65	5.6	0.53	32	179	0.7	13	5	0.32	42	37	27	21	62
2022-239-03	239	2022	Current	Allophanic	Urban	Urban	5.69	17.7	1.52	53	280	0.51	21	3.2	0.41	41	52	114	43	173
2017-239-02	239	2017	Previous	Allophanic	Urban	Urban	5.4	16.9	1.55	22	243	0.6	8	3	0.41	46	49	108	38	158
2022-241-03	241	2022	Current	Recent	Urban	Urban	5.69	4.8	0.46	54	148	0.81	9	2.1	0.11	29	21	18	20	64
2017-241-02	241	2017	Previous	Recent	Urban	Urban	5.53	8.6	0.75	34	319	0.6	12	3	0.11	31	55	17	41	70
2022-242-03	242	2022	Current	Ultic	Native	Native	5.77	4.1	0.24	6	87	1.09	17	2.6	0.05	14	4	4	18	20
2017-242-02	242	2017	Previous	Ultic	Native	Native	5.78	4.5	0.25	5	77	1.1	13	3	0.05	16	4	5	21	18
2022-243-03	243	2022	Current	Ultic	Native	Native	4.83	5.2	0.3	6	70	1.13	11	1	0.05	3	1	1	5	5
2017-243-02	243	2017	Previous	Ultic	Native	Native	4.94	6.3	0.38	5	77	0.9	14	1	0.05	5	4	1	9	8
2022-245-03	245	2022	Current	Ultic	Native	Native	4.93	9.1	0.52	4	107	0.88	19	2.7	0.05	13	6	6	27	22
2017-245-02	245	2017	Previous	Ultic	Native	Native	4.69	6.4	0.33	4	61	0.8	19	1	0.05	7	4	3	20	16
2022-249-03	249	2022	Current	Ultic	Native	Native	5.52	6	0.36	4	116	0.95	12	2	0.05	13	7	4	15	23
2017-249-02	249	2017	Previous	Ultic	Native	Native	5.24	6.2	0.37	4	108	1	14	1	0.05	10	5	2	17	18
2022-251-03	251	2022	Current	Allophanic	Urban	Urban	6.31	6.6	0.64	47	149	0.94	13	3.6	0.43	67	38	121	45	114
2017-251-02	251	2017	Previous	Allophanic	Urban	Urban	5.86	6	0.58	34	123	1	1	4	0.4	68	37	111	32	112

Site No	Site No.	Year	Period	Soil Order	Land Use	Broad Land Use	pH	TC	TN	Olsen P	AMN	BD	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2022-252-03	252	2022	Current	Anthropic	Urban	Urban	5.94	5	0.44	53	179	0.92	11	3.8	0.22	38	31	33	41	96
2017-252-02	252	2017	Previous	Anthropic	Urban	Urban	6.05	5.3	0.43	42	184	0.8	7	7	0.3	54	44	55	83	124
2022-256-03	256	2022	Current	Allophanic	Urban	Urban	6.14	7.4	0.62	84	201	0.78	13	2.7	0.14	47	35	69	21	107
2017-256-02	256	2017	Previous	Allophanic	Urban	Urban	5.97	7.8	0.65	73	240	0.7	8	3	0.14	53	36	68	22	102
2022-257-03	257	2022	Current	Allophanic	Urban	Urban	5.98	7.4	0.62	129	202	0.79	7	2	0.43	77	36	90	15	173
2017-257-02	257	2017	Previous	Allophanic	Urban	Urban	6.02	6.2	0.59	96	201	0.7	7	2	0.41	76	31	85	16	133
2022-258-03	258	2022	Current	Anthropic	Urban	Urban	5.33	6.2	0.5	19	170	0.84	10	3.3	0.16	28	12	13	28	55
2017-258-02	258	2017	Previous	Anthropic	Urban	Urban	5.34	5.2	0.42	17	146	0.6	15	4	0.15	37	14	17	32	58
2022-259-03	259	2022	Current	Recent	Urban	Urban	5.31	6.3	0.52	17	248	0.9	15	2.5	0.14	18	13	11	36	60
2017-259-02	259	2017	Previous	Recent	Urban	Urban	5.12	4.8	0.4	13	121	0.7	10	2	0.14	15	11	10	32	49
2022-262-07	262	2022	Current	Ultic	Native	Native	6.02	6.7	0.47	6	161	0.94	12	2.6	0.11	22	8	10	27	41
2017-262-06	262	2017	Previous	Ultic	Native	Native	5.72	5.6	0.41	6	135	0.9	14	3	0.1	20	8	7	16	30

Appendix 2: Background information on trace elements reported in soil quality monitoring regarded as contaminants or potential contaminants in the soil*

Element	Occurrence	Uses	Exposure Pathways and Effects on Human Health
Arsenic (As)	A naturally occurring element in the earth's crust. Also found in plants and animals	Timber preservation and manufacture of pesticides	Exposure can occur through breathing sawdust or smoke from wood treated with As and ingesting contaminated food or water. Inorganic As compounds are more toxic than organic compounds. Breathing high levels of As can irritate the lungs while ingestion can cause death. Inorganic As is a human carcinogen.
Cadmium (Cd)	A naturally occurring element in soils and rocks. It is found in coal and mineral (phosphate) fertilisers.	It is used in batteries, pigments, metal coatings and plastics.	Exposure to Cd is mostly an occupational nature and associated with the Cd manufacturing industry. Breathing Cd in cigarette smoke doubles the average daily intake. Breathing high levels of Cd can damage the lungs. Ingestion of contaminated food or water can irritate the stomach. Long-term exposure can lead to a build-up of Cd in kidneys and cause kidney disease.
Chromium (Cr)	A naturally occurring element found in rocks, soils, volcanic dusts and gases, and plants and animals. The form of Cr known as Cr (III) is the most stable and most Cr in the environment is in this form	Metallic Cr is used in making steel. Cr compounds are used in chrome plating, dyes and pigments, leather tanning and wood preserving.	Exposure can occur through breathing in contaminated air associated with industries that use Cr. Exposure may also occur through ingesting contaminated food or water. Possible health effects depend on the type of Cr one is exposed to. No health effects are associated with exposure to Cr (III). Breathing high levels of Cr (VI) can damage the nose while ingesting it can cause stomach ulcers, convulsions, and kidney and liver damage. Cr is classified as a human carcinogen.

Element	Occurrence	Uses	Exposure Pathways and Effects on Human Health
Copper (Cu)	Cu occurs naturally in rocks, soil, water, and air as well as in plants and animals. An essential plant and animal micronutrient.	Present in coins, electrical wiring, water pipes and some metal alloys. Copper compounds are used in plant fungicides, for water treatment and as preservatives for wood, leather and fabrics	Exposure can occur through breathing air, drinking water, eating food, and by skin contact with air, soil, water and substances enriched in Cu. Inhalation or skin contact with Cu containing dust can occur in the copper mining industry and the welding of Cu metal. Exposure can occur using garden or farm products to control plant diseases. Low levels are essential for maintaining good health. High levels can cause irritation of the nose, mouth and eyes, and nausea and stomach upsets.
Lead (Pb)	Naturally occurring metal. Distributed in the environment from the burning of fossil fuels, mining and manufacturing	Production of batteries, ammunition and metal products. Can be present in fuels, paints and ceramic products.	Exposure can occur through breathing workplace air or dust, eating contaminated food or drinking contaminated water. Exposure may also occur through ingesting Pb-based paint chips and ingesting or contacting contaminated soil. Pb affects the central nervous system, the kidneys and blood cells. It can lead to hypertension, reproductive toxicity and developmental defects. It is classified as a possible human carcinogen based on animal studies.
Nickel (Ni)	An abundant naturally occurring element found in soils and is emitted from volcanoes. An essential plant and animal micronutrient.	Used in the manufacture of stainless steel and metal alloys. Ni compounds are used for Ni plating, the manufacture of some batteries and some chemicals.	Exposure can occur through eating food or drinking water containing Ni and by skin contact with soil or metals containing Ni. Exposure may also occur through breathing contaminated air and smoking tobacco containing Ni. The most common harmful effect is allergic skin reactions due to direct contact with Ni-containing items such as some jewellery. Breathing large amounts of Ni compounds in Ni refineries can cause chronic bronchitis and lung and nasal sinus cancers. Ni

Element	Occurrence	Uses	Exposure Pathways and Effects on Human Health
			compounds are classified as carcinogens.
Zinc (Zn)	One of the most common substances in the earth's crust. It is found in air, soil and water, and is present in all foods. An essential plant and animal micronutrient.	Used in coatings to prevent rust, in batteries and in metal alloys. Zn compounds are widely used in industry to make paint, rubber, dyes, wood preservatives and ointments.	Exposure to high levels can occur through eating contaminated food, drinking contaminated water and breathing air contaminated by industries such as smelting, galvanising and car repair garages. Low levels of Zn are essential for good health. Exposure to large amounts can be harmful and can cause stomach cramps, anaemia, and changes in cholesterol levels.

*Modified from Guinto (2011).

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