Differences in Soil Quality and Trace Elements Across Land Uses in Auckland and Changes in Soil Parameters from 1995-2017

Fiona Curran-Cournane

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Research and Evaluation Unit RIMU

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Executive summary

Te toto o tetangatahe kai, teorangao te tangata, he whenua, he oneone –
"While food provides the blood in our veins, our health is drawn from the land and soils"

Soil is a valuable, natural and non-renewable resource that provides us with food, fibre and timber as well as a wide range of regulating and cultural benefits. Soil quality refers to the ability of the soil to sustain biological production, maintain environmental quality and promote plant, animal and human health. Humans exert an enormous amount of pressure on the soil resource both in rural and urban environments and it is important that the soil is functioning well to ensure that we receive the full benefits of soil natural capital. Amongst other things, poorly managed soil can lead to contamination of surface and groundwater and adjacent water bodies. Section 5 of the Resource Management Act 1991 (RMA) includes the requirement to maintain the life supporting capacity of land and ecosystems. Section 30 of the RMA empowers regional councils to control land for the purposes of soil conservation.

Soil quality monitoring is a science-based soil management tool that is an important component of soil conservation and management. Monitoring soil quality provides a link between nutrient and contaminant source and land management practice and is therefore a useful tool in informing policies to improve land management and associated water quality. Monitoring acts as an early warning system to negative effects of land use on soil quality and can determine where resources may be required to mitigate the risk of land use activity on the soil ecosystem.

Auckland Council's soil quality monitoring programme extends from 1995 to the present. This report is only one of a few that reports on a long-term dataset within Aotearoa New Zealand or globally. The three objectives of this study included:

1. Determining changes in soil quality and selected trace elements for all soil sites, a total of 157 for the region sampled between 2013-2017, across five predominant land use categories namely pasture, horticulture, plantation forestry (hereafter referred to as forestry), native bush (hereafter referred to as native) and urban parkland (hereafter referred to urban) and across eight soil orders.
2. Determining soil quality and trace elements for those soil sites that have been converted to lifestyle blocks and their comparison with specific rural land uses including dairy, drystock, orchards+viticulture and outdoor vegetable production for sampling periods 2013-2015.
3. Reporting on trend analysis for soil sites for the three sampling periods 1995-2000, 2008-2012 and 2013-2017 to determine changes in soil quality and trace elements over the past 20+ years.

Mean concentrations of soil quality parameters were significantly different by land use and soil order. Soil quality indicators of most concern that fell outside recommended guideline ranges on most occurrences were high Olsen P concentrations (an indicator for plant available phosphorus and fertility), particularly for horticulture (outdoor vegetable production and orchards+viticulture) and dairy sites; low soil macroporosity (at -10kPa, an indicator of soil compaction) particularly for all pasture sites (dairy, drystock and lifestyle blocks); and low total carbon (TC) for outdoor vegetable production sites. These results indicate that phosphorus (P) fertiliser in excess of what is needed is being applied to our land and that there are issues with soil compaction and the loss of soil carbon, respectively.

Compacted soils have a reduced volume of air pores which can impact on plant growth and it also reduces their ability to infiltrate water that can result in surface water ponding and subsequent nutrient and suspended sediment loss in runoff. This is exacerbated when a soil is excessively enriched with P fertiliser potentially leading to additional environmental damage to the receiving environment. Soil macroporosity has previously been shown to have a strong annual cycle with values generally better in summer than in late winter. Considering soil monitoring samples were typically collected in late winter-early spring, current assessments correspond with a worst-case scenario when clay-based soils are swollen, minimising pore size, while at the same time having soil pores partially or full of water. Collectively, this makes soil more vulnerable to disturbance such as pugging or vehicle damage.

Similarly, to soil quality parameters, mean concentrations of trace elements were significantly different by land use and soil order. While mean concentrations of trace elements all fell within guideline ranges, exceedances occurred for various analytes across individual sites. Mean concentrations of cadmium (Cd) and copper (Cu) were highest for horticulture sites, with Cd levels also being similar for pasture sites, while arsenic (As), chromium (Cr), nickel (Ni), lead (Pb), zinc (Zn) were highest for sites within the urban environment.

To assess soil environmental quality using concentrations of trace elements a contamination index (CI) was calculated for each analyte at each site. The CI was defined as the mean ratio of an analyte to the mean of the corresponding analyte at native bush sites, the latter acting as an indicator for conservative background conditions. The mean CI (for non-native sites) was classified as high (PI >3) for Cd (mean 6.6) implying that mean concentrations of Cd were more than six times higher than that recorded at native soil sites. Moderate CIs (1< CI ≤3) were calculated for (by decreasing order of CI) Ni>Zn>Pb>Cu>Cr>As. No mean CI was classified as low (i.e. CI ≤1) indicating increased levels of all seven analytes across non-native soil sites in the Auckland region. When the mean CIs for all seven analytes at each site were combined and averaged, an integrated contamination index (ICI) was calculated and deemed moderate measuring at 2.4 (range 0.4-10.1).

Rural land use has changed considerably in Auckland since the commencement of the soil monitoring programme in 1995 which has also been reflected in soil sites that may once have been utilised for traditional commercial farming purposes but are now increasingly being converted and operated as lifestyle blocks. To assess soil parameters by specific land use activities a rural case-study was included which compared dairy, drystock, lifestyle blocks, orchards+viticulture and outdoor vegetable production.

Mean macroporosity was least for dairy sites (6% v/v at -10kPa), followed by drystock (8% v/v), lifestyle blocks (9% v/v), orchards+viticulture (12%v/v) and outdoor vegetable production (22% v/v) sites. Mean Olsen P concentrations were highest, and considerably exceeded recommended guideline ranges, for outdoor vegetable production (206mg/kg) followed by dairy (57mg/kg), orchards+viticulture combined (55mg/kg), drystock (49mg/kg) and lifestyle blocks (36mg/kg).

The conventionally intensive nature of outdoor vegetable production is not only reflected in the large amount of P fertiliser application to the land but also the very low mean concentrations of total carbon (TC), total nitrogen (TN) and anaerobic mineralisable nitrogen (AMN) of 2.7%, 0.25% and 21mg/kg, respectively, for those sites that were all located in Franklin. Outdoor vegetable production requires the soil to be continuously cultivated for rotary hoeing, harvesting and deep ripping purposes. This type of intensive activity reflected in mean concentrations of TC and AMN falling below recommended guideline ranges renders the soil less resilient and more subject to soil erosion and nutrient leaching.

Over the past 20+ years of soil monitoring in Auckland, analysis showed no consistent trends except for significantly declining TC across the three sampling periods. Unlike levels specifically for outdoor vegetable production for the most recent sampling period, mean concentrations of TC were collectively within acceptable guideline values across the three sampling periods. However, trend analysis was only subject to three sampling periods and future resampling will be important to determine longer-term changes in soil TC. For remaining indicators, mean soil parameters were all largely within recommended guideline ranges, except for macroporosity (-5kPa) which was less in the second sampling period and remained below recommended guidelines in the more recent sampling period (2013-2017) for pasture sites compared to when these sites were first sampled in 1995-2000. Across the three soil sampling events, sampling varied by up to three months (August-October), so it is not possible to rule out climatic variability. Additionally, mean concentrations of Olsen P continued to remain above guideline values for all three sampling periods for horticulture sites.

Resources should be targeted towards land management strategies that improve soil ecosystem health. To aid with alleviating soil compaction of pastoral sites (dairy, drystock and lifestyle blocks) practices include restricted grazing, reduced stocking density and removing stock off pasture when bare soil is beginning to be exposed. This is particularly important when grazing soils under wet winter-spring conditions, rendering them more erosion-prone, and even more so for soils that are predominantly clay-based which pose an added environmental risk when lost from land to water. Reducing P fertiliser application largely for horticulture (outdoor vegetable production and orchards+viticulture) and dairy sites is recommended to reduce excessive P-enrichment of soils which would otherwise be at risk of being lost from land to water via surface runoff during rainfall events. The latter is exacerbated if the soil is also subject to compaction. Practices to ameliorate the loss of soil carbon for outdoor vegetable production sites have also been well documented and include the use of cover crops to restore the carbon content of the soil, minimal tillage practices, application of green manures etc.

Soil quality results for the latter specified indicators (macroporosity, Olsen P and TC) for corresponding land uses documented in this evaluation indicate poor uptake of these strategies by farmers which need to be reinforced and encouraged by land management advisors and rural industry. This is particularly important if intentions to improve freshwater ecosystem health are to be realised, the alternative being that these soil quality issues persist for another 20+ years. To help assist land management and rural industry advisors, soil results need to be shared and explained to landowners to help influence good land management practices for all soil parameters that are close to or outside recommended guideline ranges which will complement any additional soil testing that landowners undertake. It will be important to continue to resample and monitor at these soil sites in the future to determine any improvements or deterioration and to ensure the functioning of the soil ecosystem. Future sampling should also consider the incorporation of biological indicators such as soil bacterial communities which have previously been identified as being sensitive indicators of soil quality and trace elements. Future monitoring of soil sites will continue to inform policy and science direction both regionally and nationally, the latter which would be aided by combining regional long-term datasets to gain a comprehensive assessment of soil monitoring state and trends for Aotearoa New Zealand.

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1.0 Introduction

Soil is a valuable, natural and non-renewable resource that provides us with food, fibre and timber as well as a wide range of regulating and cultural benefits. Soil quality refers to the ability of the soil to sustain biological production, maintain environmental quality and promote both plant, animal and human health (Arshad and Martin, 2002, Cotching and Kidd, 2010, Schloter et al., 2003). Soil quality monitoring is a science-based soil management tool and provides evidence for determining the effectiveness of planning and implementation for environmental protection, and acts as an early warning system to aid determining where resources may be required to mitigate the risk of land use activity on the soil ecosystem. Soil quality is therefore an essential link to nutrient and contaminant source and farm practice, as well as a useful tool to assist with informing policies to improve farm management and water quality (Drewry et al., 2018). With the exception of two recent studies that reported on soil quality monitoring for up to 20-year periods in the Waikato (Taylor et al., 2017) and Wellington regions (Drewry et al., 2018), few studies have reported on soil quality and trace element monitoring over the long-term in Aotearoa New Zealand or internationally.

Humans exert an enormous amount of pressure on the soil resource whether it is in relation to rural land use activity, which can significantly impact the receiving environment (Carpenter et al., 1998); or through the development of land for residential and business purposes (Curran-Cournane et al., 2014), which can be a significant source of trace element soil pollution via vehicle and industry emissions (Ajmone-Marsan and Biasioli, 2010). It is therefore important that the soil is functioning well to cope with the pressures we exert and to ensure that we receive the full benefits of soil natural capital (Dominati et al., 2010).

1.1 Rural land use activity in Auckland

Soil supports a wide range of rural land use activities in Auckland which have been subject to various fluctuations over time. For example, changes in livestock numbers in Auckland include a 34% reduction in beef cattle numbers, a 23% decrease in dairy cattle numbers and a 45% decrease in sheep numbers between 2002 and 2018 (Figure 1 and Table 1). Although trends have been steadily declining for sheep and beef stock numbers over the 15-year record in Auckland, fluctuations have been more variable for dairy cattle numbers (Figure 1).

For comparison, New Zealand has seen a 17% reduction in beef cattle numbers, a 24% increase in dairy cattle numbers and a 31% decrease in sheep numbers during the same period (Figure 1 and Table 1).

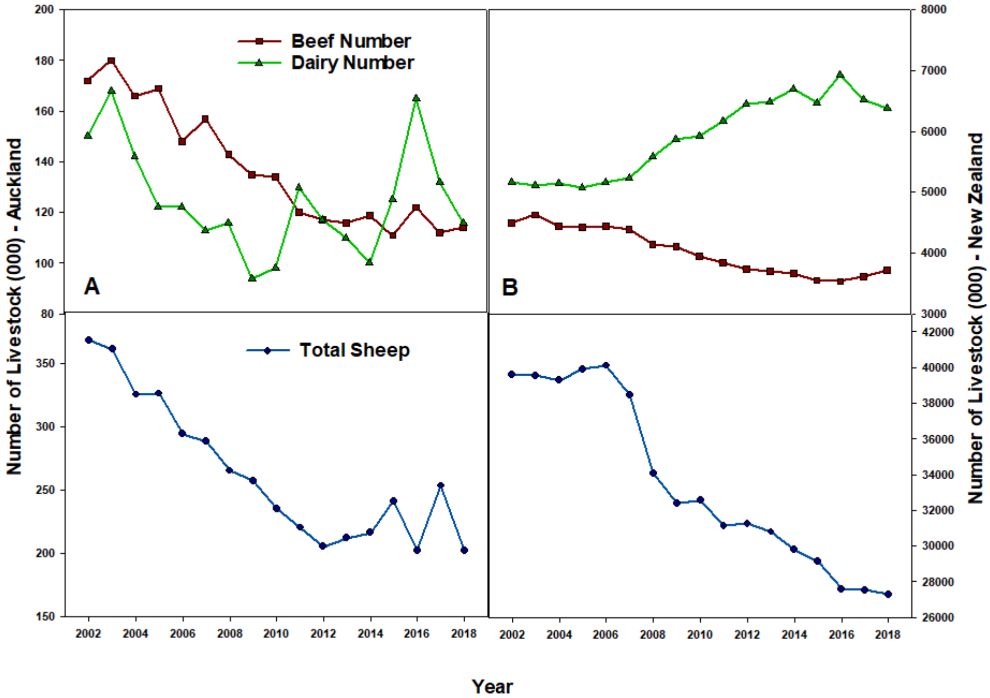

Figure 1. Changes in beef, dairy and sheep numbers 2002-2018 in a) Auckland and b) New Zealand (data sourced from Statistics New Zealand Agricultural Production data).

Table 1. Percentage change in beef cattle, dairy cattle and sheep numbers in Auckland and New Zealand 2002-2018 (with numbers as at 2018 in parentheses) (data sourced from Statistics New Zealand Agricultural Production data).

	Beef cattle	Dairy cattle	Sheep
Auckland	-34% (114,000)	-23% (116,000)	-45% (202,000)
New Zealand	-17% (3,721,000)	24% (6,386,000)	-31% (27,296,000)

Additionally, while there has been a decline in the effective dairy farming area (-29%) in Auckland, the mean herd size has increased by 37.2% resulting in a 3.4% increase in dairy stocking rate (Table 2).

Table 2. Changes in effective dairy farm area, mean herd size and mean stocking rate within the Auckland region, 2001/02-2017/18 (data sourced from Livestock Improvement Corporation).

Period	**Effective farming area (ha)**	**Mean herd size**	**Mean 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	2.40
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	2.40
2010/11	46,947	248	2.36
2011/12	46,282	249	2.37
2012/13	48,655	260	2.30
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	2.40
2017/18	43,619	273	2.42
% change 2002-2018	**-29**	**37.2**	**3.4**

Land used for horticulture in Auckland and New Zealand has also changed over 2002-2017, such as area harvested for outdoor onion and potato production (Figure 2).

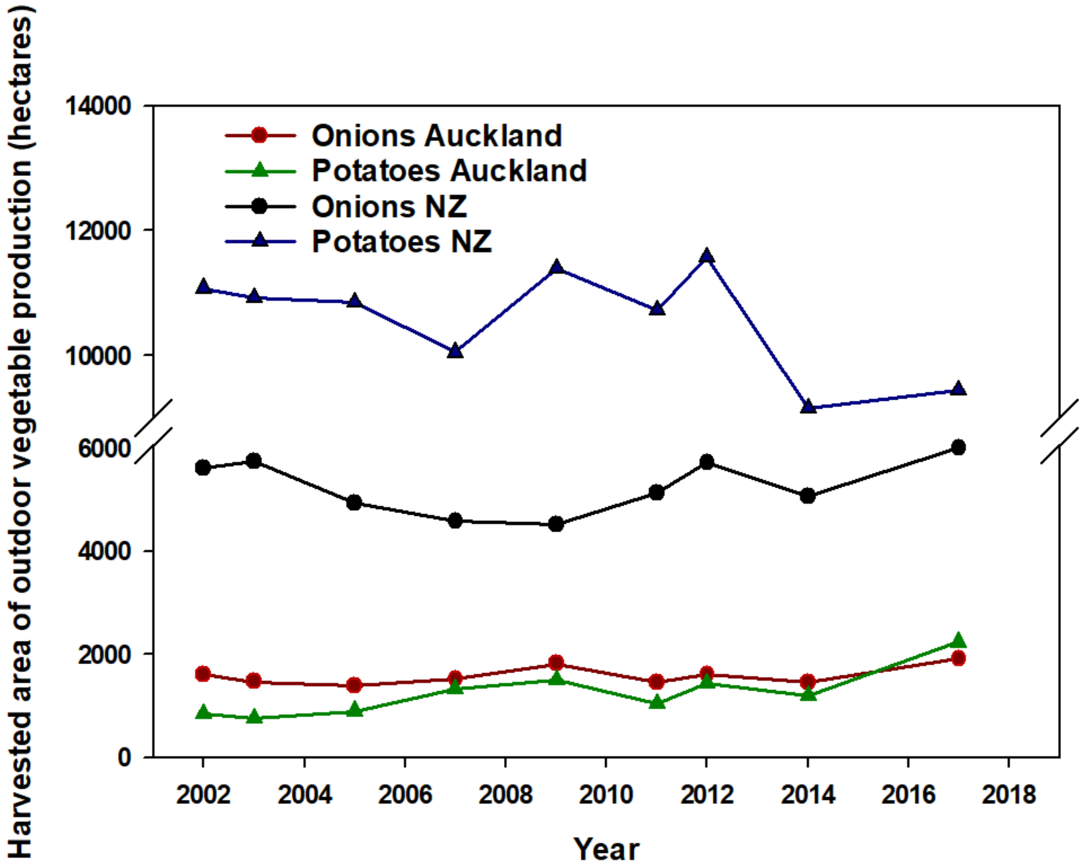

Figure 2. Changes in harvested area of outdoor onion and potato production for Auckland and New Zealand 2002-2017 (data sourced from Statistics New Zealand Agricultural Production data).

The percentage change in harvested area of outdoor onion production increased by 19% and 7%, for Auckland and New Zealand respectively, from 2002 and 2017. In contrast, while harvested area of land used for potato production decreased in New Zealand by 15%, the area of land increased by 164% in Auckland from 2002 to 2017 (Table 3 and Figure 2).

Table 3. Percentage change in harvested area of outdoor onion and potato production for Auckland and New Zealand 2002-2017 (with area in hectares as at 2017[1] in parentheses) (data sourced from Statistics New Zealand Agricultural Production data).

	Onions (ha)	**Potatoes (ha)**
Auckland	19% (1,920 ha)	164% (2,240 ha)
New Zealand	7% (6,010 ha)	-15% (9,450 ha)

Increases in outdoor onion and potato production area are increasing at greater rates in Auckland than nationally, now representing 32% and 24%, respectively, of New Zealand's

[1] Time period differences in Statistics New Zealand Agricultural Production data occur because data for livestock numbers gets collected annually and outdoor harvested area every second year (plus census years). For outdoor harvested area, onion and potato crop types are presented as Auckland is a predominant contributor of yields as well as there being confidentiality restrictions associated with some other crop types.

outdoor production (Table 3). These statistics suggest that rural production continues to be a valuable and important part of the Auckland region and a functioning soil ecosystem is essential to support these land use activities.

There are also a growing number of lifestyle blocks in rural Auckland. Using CoreLogic data, Fairgray (2018) reported that lifestyle blocks increased by 51% from 15,417 to 23,317 properties between 1996-2016 in Auckland. With a mean lifestyle block measuring 4.6ha in size, this land use activity represented a total land area of 107,154ha in 2016. Based on trend data, Fairgray (2018) concluded that demand for lifestyle block properties can be expected to continue. While there has been a substantial amount of literature documenting the state of soil quality across of range of commercially productive rural industries across New Zealand e.g. (Taylor et al., 2010, Ministry for the Environment and Statsistics New Zealand, 2015, Drewry et al., 2017, Taylor et al., 2017, Oliver, 2017) very little is known about the quality of soil under lifestyle blocks (Curran-Cournane et al., 2013).

1.2 Soil monitoring programme background

Preliminary work to develop a soil quality monitoring programme was initiated across several regions in 1995, including Auckland (Hill and Sparling, 2009). Soil quality monitoring has continued to date, although with a break between 2001-2007 in Auckland. Soil quality is assessed based on a suite of seven key soil chemical, physical and biological indicators. Monitoring has been extended to include trace elements since 2008 and the physical archiving of soil samples collected between 1999-2000 permitted the analysis of trace elements for this earlier period. Until 2012, soil quality monitoring has largely focused on rural land, which included dairy and drystock (sheep and beef farming), horticulture (outdoor vegetable growing, orchards, viticulture, nursery), plantation forestry and native bush sites. In 2012, soil quality monitoring was extended into urban Auckland recognising the importance of capturing soil knowledge for this land use. Focus in urban Auckland 2012 was towards selected trace elements (As, Cd, Cr, Cu, Ni, Pb and Zn) as well as bulk density, TC, TN, pH, cation exchange capacity, hot water extractable C and N (Curran-Cournane et al., 2015) but resampling in 2017 included the additional analysis of Olsen P and soil macroporosity.

Land use has changed considerably in Auckland over the past two decades (Figures 1 and 2) some of which has impacted on soil monitoring site representativity (e.g. the conversion of soil sites from dairy and drystock activity increasingly to lifestyle block/residential activity). This makes it difficult to report on trends in soil quality and trace elements for specific land uses. Therefore, between 2011-2014, additional sites were added to the programme, including the introduction of urban parkland sites, to continue to capture representative land uses. At the same time, resampling of all existing soil quality monitoring sites, including those that had been subject to land use change was continued. Land use change and the need for additional sites has increased the complexity of the dataset. Nevertheless, there are three relatively distinct objectives of the current evaluation:

1. Determining differences in soil quality and selected trace elements for the entire number of soil sites, totalling 157 for the region sampled between 2013-2017, across five predominant land use categories namely pasture, horticulture, plantation forestry (hereafter referred to as forestry), native bush (hereafter referred to as native) and urban parkland (hereafter referred to urban) and across eight soil orders. This will

include reporting on the number of sites failing to meet recommended guideline ranges and the establishment of a Contamination Index for trace elements. This will help inform a measure of current 'state' of soil quality and trace elements.

2. Determining soil quality and trace elements for those soil sites that have been converted to lifestyle blocks and their comparison with specific rural land uses including dairy, drystock, orchards and outdoor vegetable production for sampling periods 2013-2015.

3. Conducting and reporting on trend analysis for soil sites for the three sampling periods 1995-2000, 2008-2012 and 2013-2017 to determine changes in soil quality and trace elements over the past 20+ years.

2.0 Materials and methods

2.1 Study area

The Auckland region covers just over 5100km^2 including a number of surrounding islands (ARC, 2010). About 12% of the area is built-up urban land with the majority of the region considered rural land (Figure 3). The mean annual rainfall in the study area is 1200mm/yr. According to the New Zealand Soil Classification soil orders across the Auckland region include (with representation in parenthesis) Allophanic (8.5%), Brown (12.1%), Gley (4.6%), Granular (17%), Melanic (0.6%), Organic (1.5%), Oxidic (0.6%), Podzols (0.1%), Recent (14.6%), Raw (2.9%) and Ultic (37.7%) soils (NZLRI, 2010). Additionally, there are a variety of soils from the Anthropic soil order within urban Auckland that were not mapped in the Fundamental Soils Layer and their representation unknown. Soil sites occupy a variety of these soil types with a greater proportion representing the more representative soil orders (Table 4).

Table 4. Breakdown of sites by soil order and land cover (with proportion of sites in parentheses)

Soil order (% of region)[1]	**No. of sites[2]**	**Land cover (% of region)[3]**	**No. of sites[2]**
Allophanic (8.5%)	24 (15%)	Horticulture (2.5%)	19 (12%)
Anthropic (unknown)	10 (6%)	Pasture (48.4%)	49 (31%)
Brown (12.1%)	17 (11%)	Plantation forestry (11.3%)	15 (10%)
Gley (4.6%)	10 (6%)	Indigenous forest and scrub (24.7%)	38 (24%)
Granular (17%)	25 (16%)	Parkland (1.6%)	36 (23%)
Organic (1.5%)	6 (4%)		
Recent (14.6%)	18 (11%)		
Ultic (37.7%)	47 (30%)		

[1] Fundamental Soils Layer

[2] Proportion of sites should match the actual coverage, with the proviso some over-representativeness may be required, for example, for statistical purposes

[3] Land Cover Data Base 2012

2.2 Soil quality sites by land use

During the early establishment of the soil quality monitoring programme in Auckland, soil sites were selected based on representative land uses occupying representative soil types across the region. The breakdown of soil sites by land cover are also presented in Table 4. While the predominant land covers are generally well-represented (albeit recognising a slight short-fall for pasture land) a degree of over-representation occurs for horticulture and parklands. Considering the range of specific land use activities that occur in these general land cover types [e.g. horticulture encompasses outdoor vegetable production (n=7), nursery (n=1), viticulture (n=5) and orchards (n=6) land uses] that need to be captured across representative soil orders necessitates the number of sites.

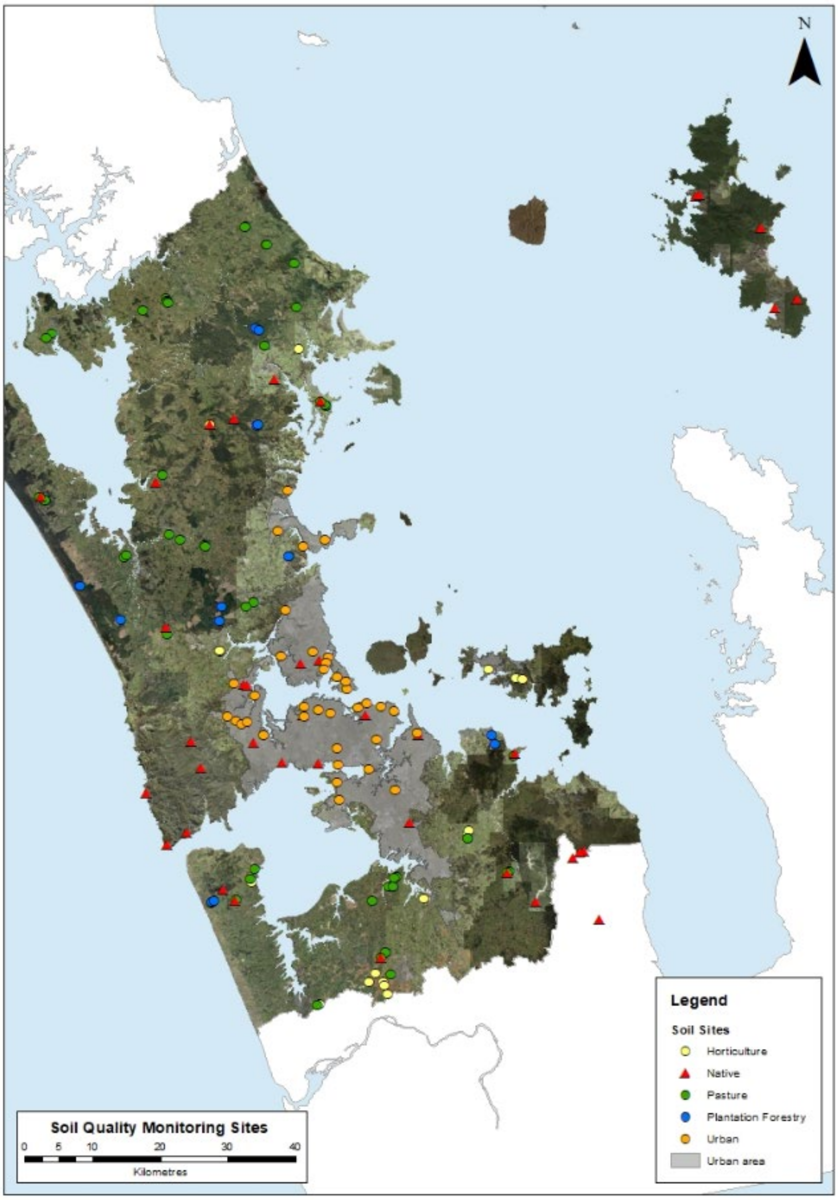

Figure 3. Distribution of State of Environment soil monitoring sites across Auckland

As of 2017, the number of soil monitoring sites totalled 157 (Table 4). A number of sites were added to the network between 2011-2014 for various reasons including accounting for the conversion of sites from commercial farming to lifestyle blocks and the introduction of urban sites in 2012[2].

[2] The additional new sites were added to the Auckland soil monitoring network for the following reasons:
In 2011, eight new plantation forestry sites were added to increase geographic representativeness
In 2012, 36 urban parkland sites considered in this evaluation were added to incorporate this previously absent but important land use
In 2012, 25 native bush sites were added, including 10 urban native bush sites, to increase geographic representativeness which included sampling on Great Barrier Island
In 2013, eight new horticulture sites were added to increase land use and geographic representativeness which included sampling on Waiheke Island
In 2014, five new dairy sites were added to increase land use representativeness

In the early establishment of the soil monitoring programme between 1995-2000, pastoral land was originally separated into dairy and drystock land uses. However, pastoral land now encompasses the following land use activities as a result of land use change over the past 20 years:

- Dairy n=12
- Drystock n=23 (including dairy-drystock n=9, horticulture-drystock n=2, and forestry-drystock n=1 converted sites)
- Lifestyle blocks n=14 (including dairy-lifestyle n=4, drystock-lifestyle n=5, and horticulture-lifestyle n=5 converted sites).

Given the complexities and changes to the soil monitoring programme over the past 20 years, the report will be structured in three parts to address three objectives:

1. Determining differences in soil quality and selected trace elements for the entire number of soil sites, totalling 157 for the region sampled between 2013-2017, across five predominant land use categories namely pasture, horticulture, plantation forestry (hereafter referred to as forestry), native bush (hereafter referred to as native) and urban parkland (hereafter referred to urban) and across eight soil orders. This will include reporting on the number of sites failing to meet recommended guideline ranges and the establishment of a Contamination Index for trace elements. This will help inform a measure of current 'state' of soil quality and trace elements.

2. Determining soil quality and trace elements for those soil sites that have been converted to lifestyle blocks and their comparison with specific rural land uses including dairy, drystock, orchards and outdoor vegetable production for sampling periods 2013-2015.

3. Conducting and reporting on trend analysis for soil sites for the three sampling periods 1995-2000, 2008-2012 and 2013-2017 to determine changes in soil quality and trace elements over the past 20+ years.

2.3 Soil sampling

At each sampling site a 50m transect was used following national guidelines (Hill and Sparling, 2009). A GPS was used at either end of the transect to georeference the site. Soil samples were collected for biological, chemical and physical analysis. For biological and chemical analysis, twenty-five 2.5cm diameter soil samples, 0-10cm depth, were composited (every 2m across the 50m transect). Stainless steel rings (10cm in diameter and 7.5cm depth) were placed at the 15m, 30m and 45m intervals across the transect and intact soil samples were excavated within the 0-7.5cm soil depths for physical analysis.

From 2008-2017, one land use category typically got revisited and sampled in September of each year, thus each site and land use is resampled every five years (Appendix 1). That is, each site is represented once within each sampling period (roughly every five years) for trend analysis purposes.

Recommended guideline ranges
Each soil quality indicator measurement has a range within which the majority of national soil samples fall. From this process it has been possible to assign a range for each measurement

that identifies levels from low, adequate/optimal, and high. For example, Olsen P is expressed as low, optimal/adequate, or high versus bulk density which is expressed as loose, optimal/adequate or compact. Targets levels for each indicator measurement are set considering negative impacts on the environment and agronomic production and these are based on national guidelines which were specifically designed for SoE soil quality monitoring measurements (Sparling et al., 2003), which have been reviewed and updated over time (Hill and Sparling, 2009, Mackay et al., 2013), and summarised in Table 5. The target range for macroporosity (MP) (-10kPa) is based on values reported by Mackay et al., 2006. Guidelines for TC and BD are determined for soil orders while the remaining guidelines are specified for land use (Sparling et al., 2003).

For soil trace elements, background concentrations specific to the Auckland region as reported in ARC (2001), and summarised in Table 5, were applied in the current report. According to these guidelines, background levels were defined as '*concentrations of an element in soils which can not be attributed to any identifiable event or activity other than normal lithological processes and is considered representative of the levels to be found wherever relatively undisturbed soils derived from an identifiable parent rock material exists or near the surface*'. Background guideline concentrations from predominant soils groups developed in the ARC (2001) report for Auckland '*were determined on 91 undisturbed soil samples believed only to be minimally contaminated by human activity and were collected across parks, forests and public lands*'.

Both soil quality and trace element guidelines provide and early warning system indicating that values falling outside recommended ranges can pose a risk to the environment and/or agronomic production.

Figure 4. An intact soil core used to analyse the soil physical quality of the soil

2.4 Laboratory analysis

All chemical analysis were carried out at International Accreditation New Zealand (IANZ) laboratories according to national guidelines (Hill and Sparling, 2009, Kim and Taylor, 2009). Analysis included pH, total carbon (TC), total nitrogen (TN), Olsen P, anaerobic mineralisable nitrogen (AMN an estimation of potentially mineralisable N), bulk density, macroporosity (-5kPa and -10kPa i.e. pore sizes >60 and >30microns, respectively), (hereafter collectively referred to as *soil quality*); arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn) (hereafter collectively referred to as *trace elements*).

Prior to analysis the composite samples were well mixed. Moist sieved (<4mm) soil was used for the AMN test (Keeney and Bremner, 1966), while air-dried and sieved (< 2mm) soil was used for the others. Olsen P was extracted using bicarbonate (Olsen et al., 1954). High temperature (1050 °C) combustion methods were used for TC and TN analysis (Blakemore et al., 1987). Soil pH was measured in deionised water at a 2.5:1 water to soil ratio (Blakemore et al., 1987). Total recoverable As, Cd, Cr, Cu, Pb, Ni and Zn were extracted by digesting soil in nitric/hydrochloric acid and the elements analysed by inductively coupled plasma mass spectrometry (USEPA 200.8). While this method does not fully destroy the silica matrix or fully extract strongly interstitially held elements (Silva et al., 2014), it is an internationally recognised method that represents the total fraction of elements that are likely to be extracted or leached under normal environmental conditions. All chemical soil parameters are presented as concentrations.

For soil physical analysis, smaller rings (5.5cm width and 3cm depth) were used to subsample the samples in the larger rings by pressing into the larger core using a bench mounted drill press. This ensured the measurement of a fully intact soil core and minimised any ‘edge effects’ of core soil loss during sampling and transportation. The smaller cores were saturated and equilibrated at -5kPa and -10kPa (i.e. pore sizes >60 and >30 microns, respectively) on ceramic tension plates to determine macroporosities. Dry bulk densities and total porosities were calculated gravimetrically from oven (105°C) dry weights (Gradwell, 1972, Klute, 1986). After laboratory analysis, soil samples are returned in an air-dried, sieved condition for archiving purposes which allows the retesting of anomalies or the analysis of any new soil parameters.

2.5 Statistical analysis

The soil biological, chemical and physical results were tested for normality and log transformed before being subjected to analysis of variance (ANOVA) fitting terms for land use and soil order. For trend analysis, 78 repeat sites were included to determine soil quality changes [(including pH, TC, TN, Olsen P, AMN, bulk density and macroporosity -5kPa (macroporosity -10kPa data is not available for all sites sampled between 1995-2000 see Appendix 2)] across sampling periods (i.e. 1995-2000, 2008-2012 and 2013-2017); whilst 48 repeat sites were included in the ANOVA to determine changes in trace elements for As, Cd, Cr, Cu, Ni, Pb and Zn. Non-detects were given a value of half the detection limit. Soil analytical data for each site is provided in Appendix 2[3]. The factorial interaction between sampling period and rural land use (forestry, horticulture, native and pasture) was investigated for soil quality indicators and trace elements for both the 78 and 48 sites, respectively. The latter was repeated again for those soil sites on land uses that had remained unconverted and while this analysis had the ability to split out dairy and drystock sites the sampling size was reduced (47 and 30 repeat soil sites for soil quality and trace elements, respectively) which needs to be considered when interpreting results (Appendix 3).

Blocking was used to compare the three sampling periods and site number used as the blocking factor. Mean replicate data (i.e. x3 cores per site) were used when comparing soil physical quality (bulk density and macroporosity -5 kPa and -10kPa). Where used, standard

[3] Reassessing the classification of some of the soil types by a pedologist is recommended in the future particularly for those soil sites belonging to the Organic soil order and any other site where a ‘full’ soil description has not been completed (i.e. those new soil sites introduced to the programme listed in footnote 2)

error of difference (SED- using un-transformed[4] data), least significant difference at the 5% significance level (LSD- using untransformed data) and *P*-value (using log transformed data) are presented. All analysis were carried out using the statistical package Genstat 19th edition and graphical package Sigmaplot 14.0 edition.

To determine whether soil quality indicators 'met or failed' recommended guideline ranges, with the exclusion of native bush sites, all chemical results are presented on a gravimetric basis (Table 5) according to the guidelines presented in Sparling et al., (2003), Hill and Sparling (2009), and Mackay et al., (2013). While target ranges for Olsen P have been developing over time both numerically and on a gravimetric to volumetric basis (the latter by multiplying gravimetric laboratory data by undisturbed field bulk density or direct from a volumetric laboratory value utilizing a 2mL scoop method (Drewry et al., 2014)), gravimetric values have been considered in the current analysis which can apply interchangeably to a gravimetric or volumetric unit (Drewry et al., 2017) by soil order and land use (Table 5)[5]. For soil trace elements, guidelines were according to background concentrations of trace elements in soils from the Auckland region (ARC, 2001) (Table 5).

Additionally, a contamination index (CI) was calculated for each trace element at each site to assess the soil environmental quality, an approach adopted from previous international studies (Biasiolia et al., (2006) and Chen et al., (2005)) and for urban Auckland in 2015 (Curran-Cournane et al., 2015). The references cited above referred to the index as a 'Pollution Index', a term that has now been revisited in the current report on consideration that contamination regards the presence of a substance that should not be present naturally versus pollution which is the introduction of a contaminant that can cause harm to organisms or infrastructure (pers comm Taylor, M). It is therefore considered more appropriate to refer to this approach as a 'Contamination Index'. The CI was defined as the mean ratio of an analyte to the mean of the corresponding analyte at *native bush sites*, the latter acting as an indicator of conservative natural background conditions. While native bush sites may also be exposed to diffuse contamination from surrounding land use activity, as per background concentrations outlined in ARC (2001), these sites additionally have forest canopy cover which has been reported to be an effective buffer for capturing trace elements and protecting against their aerial deposition onto soils (Trammell et al., 2011, Weathers et al., 2001). This was also observed for soil sites in Auckland in 2015 with mean concentrations of trace elements being least for native forest sites when compared to non-native sites within an urban setting (Curran-Cournane et al., 2015). It is therefore considered that the CI approach is a more conservative approach at comparing trace elements of native sites with non-native sites then what would otherwise be the case if the guideline values reported in ARC (2001) were applied to the CI. Additionally, the native soil sites occupy the most representative soil orders for the region, namely Allophanic, Brown, Granular, Ultic and Recent soil orders thereby the CI approach largely considers the influence of soil type variation [recognising native sites would not be considered 'native' if occupying Anthropic soil and have limited opportunity of occupying the lesser representative Organic (1.5% regional coverage) and Gley (4.6% regional coverage) soil orders].

The CI and ICI approach have previously been considered useful techniques for interpreting data against native sites and they complement traditional ways of reporting concentrations of trace elements but do not necessarily imply as having any potential degradational effect on

[4] Untransformed SED and LSD values were reported to allow the reader to easily determine differences across land use, soil order and sampling period against untransformed soil parameter data

[5] Note National Environmental Monitoring Standards (NEMS) for soil quality and trace elements are currently under development and soil quality monitoring targets will be addressed in the new version of the Land Monitoring Forum (LMF) guidelines

soil ecological receptors, the latter which would need to refer to an approach set out by Cavanagh and Munir (2019) which was outside the scope of this current evaluation.

The CI was calculated for each site and classified as either low (CI ≤ 1), moderate (1 < CI ≤ 3) or high (CI > 3) for comparison against background native conditions. When CIs were combined and averaged an integrated contamination index (ICI) was calculated and classified as low (ICI ≤ 1), moderate (1 < ICI ≤ 3) or high (ICI > 3).

3.0 Results and discussion

3.1 Soil parameters failing to meet recommended guideline ranges

A total of 157 soil sites, between 2013-2017 across a variety of land uses, were considered in the determination of meeting recommended soil guidelines. Most of the non-native sites failed at least meeting one soil quality indicator as follows:

- 16% of sites met all 7 recommended soil quality guideline recommendations
- 38% of sites met 6 soil quality indicators
- 36% of sites met 5 soil quality indicators
- 32% of sites met 4 indicators
- 22% of sites met 3 indicators
- 3% of sites met 2 indicators
- 6% of sites met 1 indicator.

The indicators that most frequently fell outside recommended guideline ranges on most occurrences were Olsen P (66% of non-native sites) followed by soil macroporosity (46% of non-native sites) with the breakdown for all soil quality parameters as follows:

- 66% of sites fell outside Olsen P recommended guideline ranges
- 46% of sites fell outside macroporosity targets
- 27% of sites fell outside total nitrogen (TN) targets
- 13% of sites fell outside total carbon (TC) targets
- 12% of sites fell outside anaerobic mineralisable nitrogen (AMN) targets
- 11% of sites fell outside bulk density (BD) targets
- 8% of sites fell outside pH recommended guideline ranges.

The breakdown of sites by land use falling outside guideline ranges are presented in Table 5. For TC, AMN and soil pH sites that fell outside guideline ranges, concentrations were all below targets as no upper limits exist for these parameters. For the remaining indicators the percentage of sites falling above or below the targets by land use are presented in Figure 5.

Figure 5 illustrates that for most of the horticulture and pasture sites concentrations of Olsen P exceeded recommended guideline ranges. A predominant source of phosphorus (P) available to surface runoff in a farming system is the application of fertiliser (Curran Cournane et al., 2011b), other sources include the plant, soil and manure (Nash and Halliwell, 1999). Olsen P, plant available P, is a standard measurement of soil fertility to help determine P fertiliser requirements of plants (Hill and Sparling, 2009). Olsen P values exceeding guideline ranges in this evaluation indicate that an excess of P fertiliser is being applied to the majority of pastoral, and in particular, horticultural land. Not only is there no agronomic benefit in applying P fertiliser in excess of plant requirements as uptake is naturally limited in plants, anything in excess risks being lost in surface runoff, interflow or groundwater accumulating in receiving environments and risking eutrophication (Carpenter et al., 1998, Curran Cournane et al., 2011b). While Olsen P targets are more relevant in rural areas, when applied to urban parks 44% of sites had concentrations of Olsen P below recommended guideline ranges. The urban sites were not being used for agronomic commercial purposes therefore do not pose either as risks to environmental and/or agronomic production. That said, 22% of urban sites had Olsen P concentrations exceeding guidelines and considering the sites are largely intended for recreational use, versus primary production, would suggest an ill use of P fertiliser notwithstanding the environmental risk it can pose (Figure 5). Concentrations of Olsen P by specific rural land use will be discussed further in section 3.3.

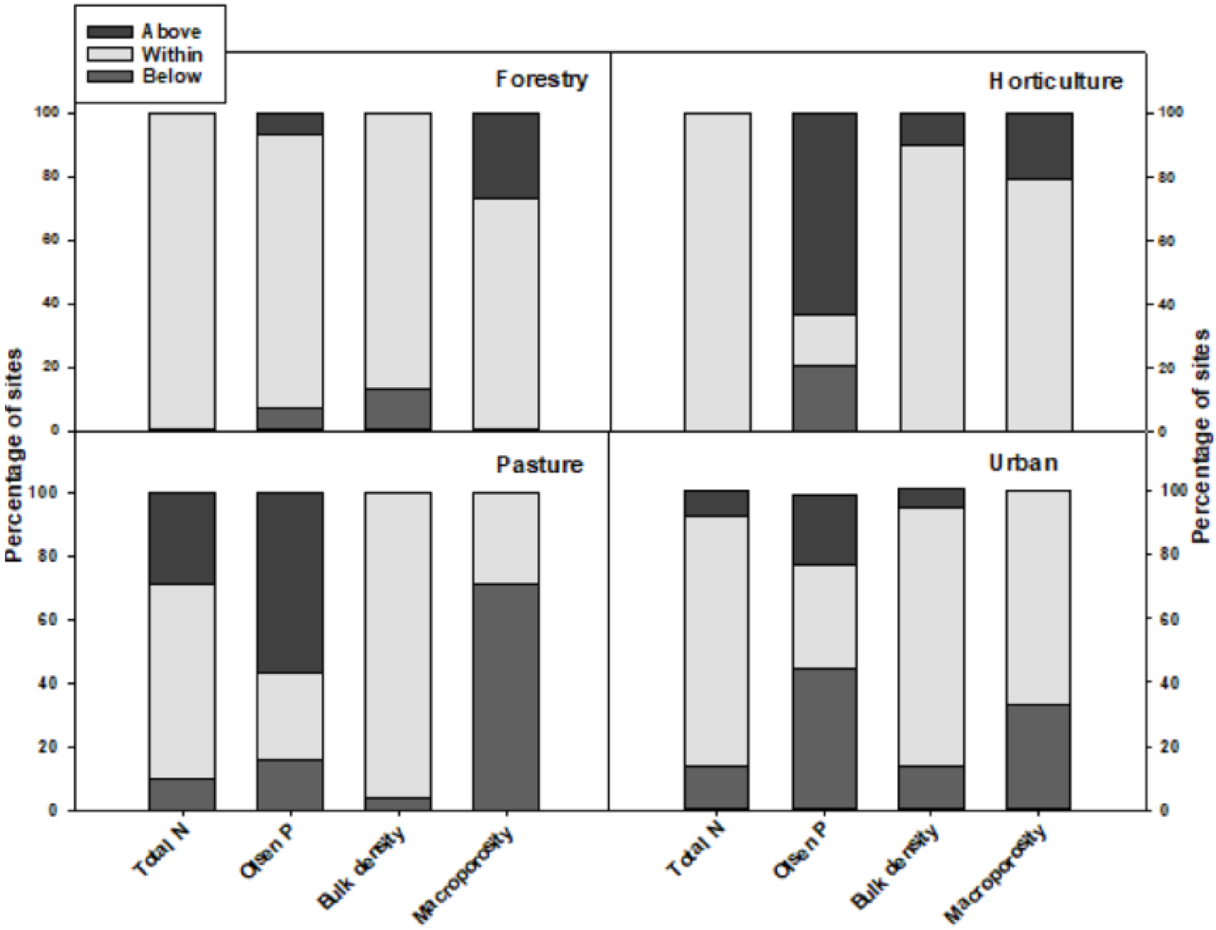

Figure 5. Percentage of soil quality indicators by land use falling above, below or within recommended guideline ranges.

Most pasture sites also had soil macroporosities falling below recommended guidelines indicating issues with soil compaction- as did a third of urban sites. Compacted soils have a reduced volume of air pores which can impact on plant growth (Drewry et al., 2004). It also reduces their ability to infiltrate water that can result in surface water ponding and increases the risk of transferring nutrients and suspended sediment from land to water via surface runoff e.g. Figure 6 (McDowell et al., 2008, Curran Cournane et al., 2011a). This is exacerbated when a soil is excessively enriched with a contaminant, for example, excessive P fertiliser applications, potentially causing additional environmental damage to the receiving environment (Figure 6). Effects on water quality are marked from any eroded sediment alone but exacerbated further when an eroded soil is enriched with P (e.g., erosional effects can lead to lesser water clarity, reduced macrophyte growth, excessive sedimentation in lacustrine and inter-tidal environments, sediment anoxia, internal nutrient release and greater algal biomass). In urban environments, the lesser availability of pervious surfaces means changes in soil macroporosity have disproportionate effects on runoff generation; compaction resulting in greater peaks of stormwater discharged to streams and piped networks, increasing risks of bankside erosion, loss of aquatic habitat (by excessive flow and associated secondary effects on erosion), flooding and reduced efficacy of stormwater management devices (by reduced residence time in stormwater detention ponds and wetlands).

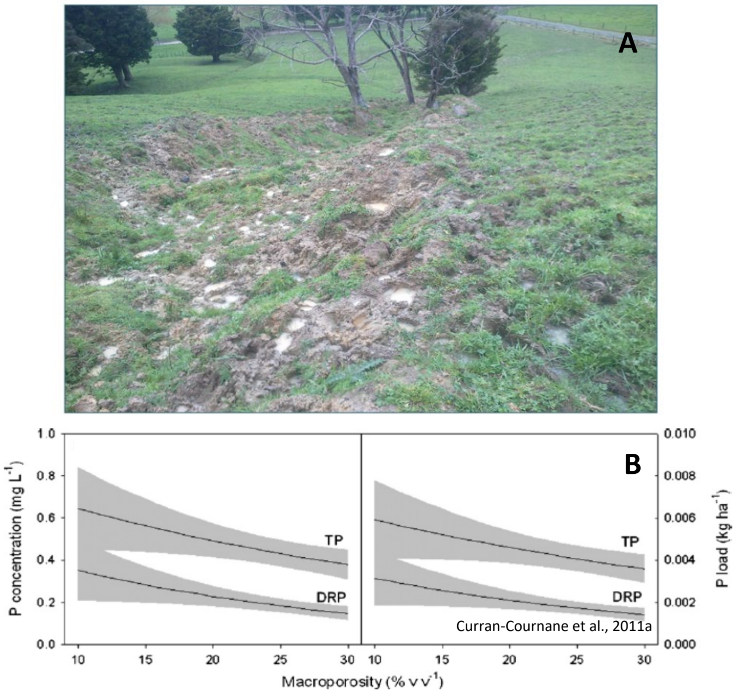

Figure 6. Schematic illustrating a) surface water ponding and pugging damage of grazed pasture in Rodney, Auckland and b) the correlation of soil macroporosity (-10kPa) and losses of concentrations and loads of P in surface runoff of a Pallic soil order.

While 67% of pasture and 33% of urban sites had low soil macroporosities, 27% of forestry sites had soil macroporosities above target ranges. This proportion consisted of four sites, three of which were located on Pinaki soils and one on a Red Hill soil. These soil types are Typic Sandy Recent and Typic Sandy Brown soils, respectively, according to the NZ Soil Classification. Soil with high macroporosities are typically excessively draining, susceptible to climate extremes, particularly drought but also erosion (Mackay et al., 2006), and can become hydrophobic. The risk of wind and water erosion increases as the soil becomes more loose. This risk should be considered at harvest.

For concentrations of soil trace elements, the percentage of sites falling outside recommended guideline ranges by land use are also presented in Table 5. All analytes that failed to meet targets fell above recommended guideline ranges. Of the seven trace elements, Pb most frequently exceeded guidance (predominantly in urban sites), followed by Cd (predominantly in pastoral sites) and Cu (predominantly in horticulture sites). This will be discussed in a later section with respect to differences in trace elements by land use and soil order and in regard to a Contamination Index (Tables 6-8) but briefly:

- 81% of sites met all trace element target ranges
- 16% of sites met 6 trace element target ranges
- 1% of sites met 5 trace element target ranges
- 2% of sites met 4 trace element target ranges.

The trace element most frequently above target ranges (by decreasing order) was Pb> Cd> Cu> Ni> As with the breakdown as follows:

- 8.4% of sites fell above Pb recommended guideline ranges
- 8% of sites fell above Cd targets
- 5% of sites fell above Cu targets
- 2% of sites fell above Ni targets
- 1% of sites fell above As targets.

Table 5. Number (percentage in parentheses) of soil sites outside target ranges for soil indicators for each land use sampled 2013-2017. Broad target ranges are provided with footnotes containing specific target ranges by soil order and land use. Percentages in **bold** highlight the indicators by land use whereby more than half the soil samples failed to meet targets.

Land use	Indicator and broad target ranges						
	Total C[1]: >3%	**Total N**[2]: 0.35-0.7%	**AMN**[3]: >40mg/kg	**pH**[4]: 5.5-7.5	**Olsen P**[5]: 5-50 mg/kg	**Macroporosity (-10kPa)**[6]: 10-30% v/v	**Bulk density**[7]: 0.6-1.3g/cm^3
Forestry (n=15)	4 (27%)	5 (33%)	5 (33%)	0	2 (13%)	4 (27%)	2 (13%)
Horticulture (n=19)	8 (42%)	0	7 (37%)	0	16 **(84%)**	4 (21%)	2 (11%)
Native (n=38)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Pasture (n=49)	1 (2%)	19 (39%)	1 (2%)	1 (2%)	36 **(73%)**	35 **(71%)**	2 (4%)
Urban (n=36)	2 (6%)	8 (22%)	1 (3%)	9 (25%)	24 **(66%)**	12 (33%)	7 (19%)
				mg/kg			
	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=15)	0	0	0	0	0	0	0
Horticulture (n=19)	0	1 (5%)	0	2 (11%)	0	0	0
Native (n=38)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Pasture (n=49)	0	8 (16%)	0	1 (2%)	0	1 (2%)	0
Urban (n=36)	1 (3%)	0	0	3 (8%)	2 (6%)	9 (25%)	0

[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:** Pasture >60mg/kg; Horticulture and Forestry >40mg/kg

[4] **pH:** 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

[5] **Olsen P:** Pasture and Horticulture (Brown, Gley, Organic, Granular and Ultic) 20-35mg/kg; Pasture and Horticulture (Allophanic and Granular) 20-50mg/kg; Hill country 15-20mg/kg; Forestry 5-30mg/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 target ranges for **Cr** are 3-125 mg/kg; **Cu** are 20-90 mg/kg; **Ni** 4-320 mg/kg; **Zn** are 54-1160 mg/kg

3.2 Concentrations of soil parameters by land use and soil order 2013-2017

3.2.1 Soil quality

For the period 2013-2017, there were significant differences (P<0.001) for nearly all soil parameters by land use (Table 6) and soil order (Table 7), excluding arsenic. There were significant correlations between various soil parameters including log Olsen P and log Cd, TC and TN (Figure 7a and b) as well between log TC and log AMN (R^2=0.57 data not displayed) and TC and bulk density (R^2=0.45 data not displayed). These relationships have been reported elsewhere e.g. (Hermans et al., 2017, Curran-Cournane et al., 2013) where several soil parameters are usually correlated with each other (either negative or positive). Therefore, instead of discussing results for each individual parameter in depth, representative soil parameters will be considered.

Mean concentrations of Olsen P were highest for horticulture (109 mg/kg) and pasture (47 mg/kg) sites (Table 6). Concentrations of Olsen P at horticultural sites ranged from 11-361 mg/kg (Appendix 2). Similarly, mean concentrations of cadmium were highest for horticulture and pasture sites (0.46mg/kg for both) (Table 6). There was a significant positive correlation between concentrations of Olsen P and cadmium (Figure 7a) suggesting a shared origin in fertiliser use (Canty et al., 2014). This relationship is an example of the importance of analysing and reporting basic soil parameters in conjunction with trace elements to identify potential contamination sources and inform options for mitigation. Management options to address excessive fertility includes the reduction of excessive P fertiliser application.

Mean soil macroporosity was significantly different across land uses and was least for pasture sites (Table 6), particularly for dairy sites followed by drystock, lifestyle block, orchard+viticulture combined and outdoor vegetable production sites (Table 10). Reduced macroporosity indicates soil compaction and can have both negative environmental and agronomic effects. For example, Drewry et al., (2004) associated a 1.6% increase in spring relative pasture yield with a unit increase in macroporosity (-10 kPa) at the 0-5cm soil depths across four New Zealand soil orders. Land management also plays an important role on soil quality with good management practices often effective at the mitigation of soil compaction (Drewry, 2006). Macroporosity improvements include restricted grazing, reduced stocking density and removing stock off pasture when bare soil is beginning to be exposed. However, soil macroporosity results for pasture sites in particular indicate poor uptake of these strategies by farmers.

Additionally, sampling was undertaken in September of each year so likely capturing a worst-case scenario as soil macroporosity has been shown to have a strong annual cycle with values generally better in summer than in late winter (Curran Cournane et al., 2011a). Sampling during late winter-early spring means clay-based soils are fully swollen and soil moisture is near or close to field capacity rendering the soil more vulnerable to pugging and vehicle damage.

Macroporosity can also be strongly influenced by soil order (Taylor et al., 2017) which was also observed in the current evaluation (Table 7). Macroporosity was least for the Gley and Organic soil orders, but these had small sample sizes given their sparse representativeness in Auckland. Additionally, most sites in these soil orders were located under pasture and hence reflected the lower values of this land use (albeit noting that there were no significant differences between soil macroporosity and soil order when only pasture sites were compared – Appendix 4).

It has previously been reported that some soil orders would struggle to meet recommended guideline ranges even under ungrazed conditions and this was especially the case for the clay-rich Ultic soils that are the predominant soil order in Auckland representing nearly 50% of the region (Curran-Cournane et al., 2013). The Ultic soils are some of the oldest soils in Aotearoa and it raises the question whether the guideline ranges should be revisited for this soil order. However, a mean macroporosity of 14% was observed for the fifteen native Ultic soil sites that were sampled in 2017 arguably suggesting the appropriateness of the guidelines for this soil order. Additionally, when disturbed and the structure disrupted, the high clay content of the Ultic soils can cause relatively high amounts of fine sediment to be generated by surface erosion (Phillips et al., 2007) and being lost from land to water via surface runoff. Their high-clay content can pose an additional environmental risk when compared to silt and sand fractions being lost from land to water via surface runoff hence disturbance of these clay-rich soils needs to be minimised.

The soil quality issues associated with high concentrations of Olsen P and low macroporosities for dairy, drystock, cropping and orchards were also observed at the national level (Ministry for the Environment and Statistics New Zealand, 2018). Significant differences across land uses observed for some of the remaining soil quality parameters, including TC, TN and AMN, will be discussed in a later section in relation to specific rural land use activities.

Table 6. Mean concentrations of soil parameters by land use in Auckland 2013-2017. 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. Significant differences are highlighted in bold and ns denotes 'not significant'. Soil parameters in **red** and **blue** bold figures are mean values that are above and below recommended guidelines, respectively.

	Soil parameters						
Land use	**Total C %**	**Total N %**	**AMN mg/kg**	**pH**	**Olsen P mg/kg**	**Macroporosity -10kPa %**	**Bulk density g/cm^3**
Forestry (n=15)	4.40	0.22	59	5.3	12	21	1.12
Horticulture (n=19)	4.78	0.38	65	6.3	**109**	16	1.02
Native (n=38)	6.54	0.38	121	5.2	6	14	0.87
Pasture (n=49)	7.22	0.63	165	6.0	47	**8**	0.90
Urban (n=36)	6.19	0.52	163	5.7	29	11	0.78
SED	0.912	0.068	17.8	0.13	12.7	1.8	0.055
LSD	1.801	0.134	35.1	0.252	25.2	3.5	0.110
P value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	mg/kg						
	As	**Cd**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Forestry (n=15)	3.71	0.10	8	6	3	6	18
Horticulture (n=19)	5.03	0.46	17	37	6	20	42
Native (n=38)	3.36	0.05	13	15	5	15	26
Pasture (n=49)	4.07	0.46	12	15	5	14	36
Urban (n=36)	5.11	0.18	29	30	34	47	84
SED	0.89	0.056	3.8	6.7	5.8	7.6	10.2
LSD	1.76	0.111	7.6	13.3	11.5	15.0	20.8
P value	ns	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

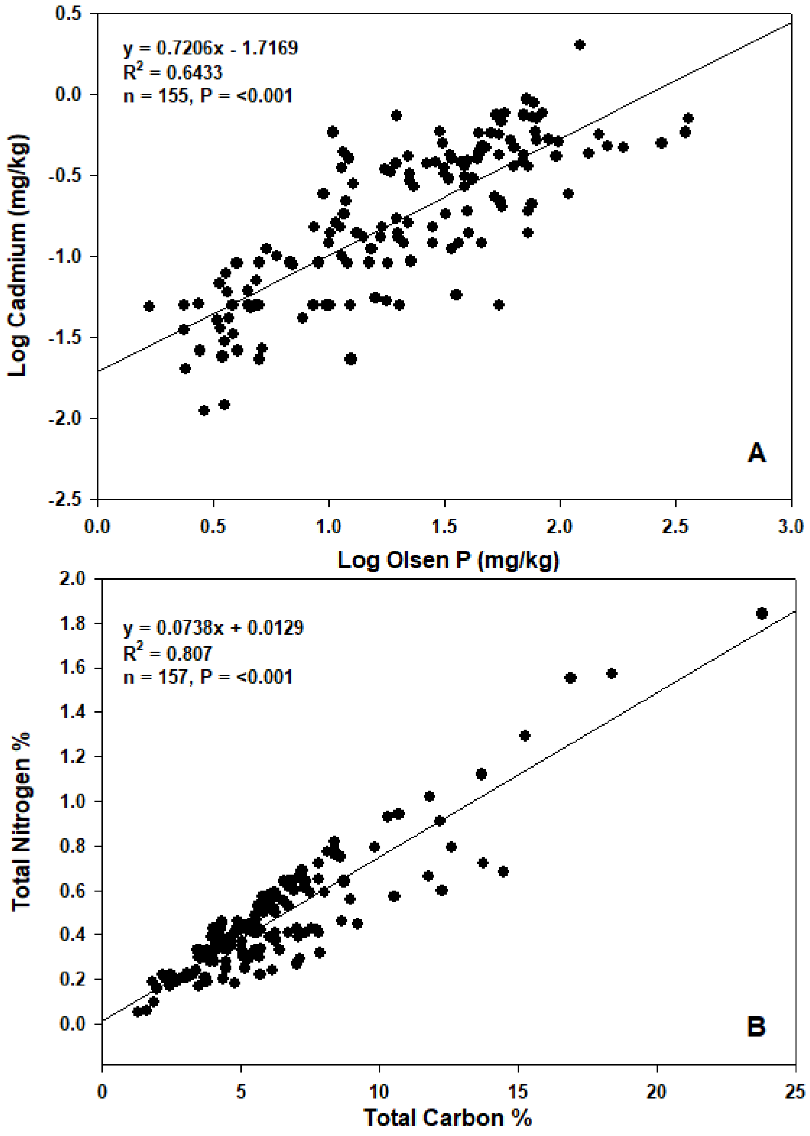

Figure 7. Correlations between concentrations of a) Log Olsen P and Log cadmium (mg/kg) and b) total carbon and total nitrogen (%).
(note two native sites with Olsen P values <0.1 were removed from the correlation analysis in Graph A).

Table 7. Mean concentrations of soil parameters by soil order in Auckland 2013-2017. The standard error of difference (SED) and least difference (LSD) are highlighted in bold and ns denotes 'not significant'. Soil parameters in **red** and **blue** bold figures are mean values that are above and below recommended guidelines, respectively.

Land use	Soil parameters							
	Total C %	**Total N %**	**AMN mg/kg**	**pH**	**Olsen P mg/kg**	**Olsen P g/m^3**	**Macroporosity -10kPa %**	**Bulk density g/cm^3**
Allophanic (n=24)	6.7	0.58	143	5.92	45	41	10	0.91
Anthropic (n=10)	5.8	0.49	170	5.77	29	21	12	0.74
Brown (n=17)	5.4	0.41	142	5.80	23	22	12	0.95
Gley (n=10)	5.3	0.44	137	5.88	55	**55**	**8**	0.94
Granular (n=25)	6.1	0.46	119	5.81	72	**74**	15	0.87
Organic (n=6)	16.3	1.23	241	6.18	79	47	**9**	0.61
Recent (n=18)	5.1	0.36	107	5.52	19	18	16	1.00
Ultic (n=47)	5.9	0.40	115	5.50	20	17	12	0.92
SED	1.08	0.09	29.5	0.238	21.5	22.3	3.0	0.086
LSD	2.14	0.18	58.3	0.469	42.4	44.0	5.9	0.170
P value	**<0.001**	**<0.001**	**<0.01**	**<0.01**	**<0.001**	**<0.01**	**<0.01**	**<0.001**
				mg/kg				
	As	**Cd**	**Cd g/m^3**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Allophanic (n=24)	5.3	0.38	0.35	31	24	35	34	81
Anthropic (n=10)	6.3	0.17	0.12	25	38	23	63	77
Brown (n=17)	3.9	0.19	0.19	12	13	4	10	34
Gley (n=10)	2.4	0.33	0.30	7	26	3	10	28
Granular (n=25)	5.3	0.33	0.31	19	23	8	32	41
Organic (n=6)	2.9	0.90	0.53	17	29	6	12	66
Recent (n=18)	5.2	0.12	0.12	12	17	6	13	31
Ultic (n=47)	2.9	0.17	0.14	11	15	5	14	26
SED	1.24	0.092	0.078	5.6	10.4	9.0	11.2	15.7
LSD	2.45	0.182	0.153	11.2	20.6	17.7	22.1	31.0
P value	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

3.2.2 Trace elements

Trace elements are naturally present in soils but are significantly altered by anthropogenic activity which can pose both environmental and human health risks (Longhurst et al., 2004, Chen et al., 2005, Elless et al., 2007, Godt et al., 2006). While mean concentrations of all trace elements were within guideline ranges, the analytes for individual sites that exceeded targets on most occurrences were Pb (predominantly for urban sites), Cd (predominantly for pasture sites), Cu (predominantly for horticulture and urban sites), and Ni (predominantly for urban sites) (Table 5).

Mean concentrations of all soil trace elements were significantly different ($P<0.001$) across land use (except for As) and soil order (Tables 6 and 7). Mean concentrations of Cd were significantly higher for pasture and horticulture sites which is largely attributed to the application of P fertiliser for these land uses (section 3.2.1). Mean concentrations of Cu were significantly higher for horticulture sites, which is likely due to copper-based fungicides that typically get applied to orchard and viticulture crops (Gaw et al., 2006). Copper is also used in roofing, guttering, electronics and in car brake linings.

Urban land use was associated most frequently with the greatest mean trace element concentrations [As (although insignificant), Cr, Ni, Pb and Zn] (Table 6) compared to other land uses. High concentrations of Cr, Ni and Zn have been related to transportation; these elements can be added to gasoline or contained in engines and galvanised parts, tyres and lubricating oils (Ajmone-Marsan and Biasioli, 2010, Falahi-Ardakani, 1984). There are multiple sources of Zn in the New Zealand environment including mineral and organic fertilisers, 369 veterinary medicines, 35 registered pesticides, galvanised (Zn coated) iron, Zn paint, tyre rubber and human sewage discharges (Taylor, 2016). Concentrations of Zn tend to be greater in urban areas than for rural areas in most parts of the world and sources include zinc-coated metal and car tyres (Councell et al., 2004). In New Zealand, Zn is extensively used to prevent facial eczema. It is estimated that 5-8000 tonnes of zinc is now being applied (with animal waste) to Waikato pasturelands each year (Kim and Taylor, 2017).

Urban state of environment monitoring sites were chosen to be sufficiently distant from recreational sports fields, passive turf or flower gardens that receive routine maintenance such as fertiliser, pesticide, re-seeding, etc., to ensure that all sampling sites were representative of minimally disturbed conditions. Hence concentrations of trace elements for urban monitoring sites would be mainly influenced by surrounding activities typical of an urban environment, e.g. high levels of trace elements also originate from vehicle emissions, coal and fuel combustion, paint, local industry (Elless et al., 2007, Chen et al., 2005).

As well as being significantly influenced by anthropogenic activity, trace elements are naturally present in soils and are predominantly inherited from the soil's parent material (Longhurst et al., 2004). The mean spacing between each volcanic center in the Auckland region is only 3km (Molloy, 1993). Volcanically derived soils are therefore prevalent in the Auckland region and have naturally higher concentrations of cadmium (Cd) (Godt et al., 2006, McDowell et al., 2013), chromium (Cr), copper (Cu), nickel (Ni) and zinc (Zn) (Chen et al., 2005, Godt et al., 2006, Ward et al., 1977). Over 60% of the urban sites belonged to the Allophanic and Anthropic soil orders[6] which would have been exposed to multiple sources of trace elements within an urban environment. These two soil orders had the highest mean concentrations of As (although not significant), Cr, Ni, Pb and Zn (Table 7). As well as being

[6] The Anthropic soil order was only occupied by urban sites (n=10)

the most predominant soil order occupying urban sites (n=11), the Allophanic soil order is also a volcanically derived soil and this was reflected in the higher concentrations of Cr and Ni observed for this soil, consistent with Curran-Cournane et al., 2015. Urban sites will be analysed for trends when they are resampled in 2022 for the third time.

3.2.3 Contamination Index

To assess the soil environmental quality by using concentrations of trace elements, a contamination index (CI) was calculated for each analyte at each site [(adapted by (Chen et al., 2005, Biasiolia et al., 2006)] (defined as the mean ratio of an analyte to the mean of the corresponding analyte at native sites)[7]. The CI was calculated for each site and classified as low (CI > 1), moderate (1≤ CI > 3) or high (CI ≥3) (Table 8). When CIs were combined and averaged, an integrated pollution index (ICI) was calculated and classified as low (ICI >1), moderate (1 ≤ICI >3) or high (ICI ≥3).

The regional mean CI was classified as high (CI >3) for Cd only (mean 6.6) indicating that soil concentrations of Cd were more than six time higher within non-native sites than concentrations recorded at native soil sites. Moderate regional mean CIs (1< CI ≤3) were calculated for (by decreasing CI order) Ni>Zn>Pb>Cu>Cr>As. No regional mean CI was classified as low (i.e. CI ≤1) indicating elevated levels for all seven trace elements for non-native sites (Table 8).

When the mean CIs for each trace element at each site were combined and averaged across all sites (unweighted by analyte), a whole-of-region-and-all-of-trace-element ICI was calculated and deemed moderate measuring at 2.4 (range 0.4-10.1) (Table 8). Eighteen sites were classified as having a low ICI, 70 sites as having a moderate ICI, and 31 sites as having a high ICI. Most sites with a low ICI were forestry sites (n=10) albeit noting that there were no significant differences between native and forestry sites for all seven trace elements (Table 6). Most sites with a high ICI were urban sites (n=14), followed by horticulture (n=9) and pasture sites (n=8). The site with the highest ICI of 10.1 was an urban site occupying an Allophanic soil in a high traffic location. The ICI of this site was recorded as 9.25 when it was first sampled in 2012. It is likely the change is less influenced by a specific land use activity and more a case of a larger sample size of native soil sites and a more recent analysis of urban sites in the current evaluation. Continuing future soil sampling will be important to monitor any changes over time. The CI and ICI are considered useful techniques for interpreting data and they complement traditional ways of reporting concentrations of trace elements.

[7] Mean concentrations of trace elements by land use category in the current study (Table 6) confirmed the conservative nature of the CI approach identifying that mean concentrations of trace elements at native sites were at the lower end of the corresponding analyte guideline range presented in Table 5 that was sourced from ARC (2001)

Table 8. Statistical results of the contamination index (CI) and integrated contamination index (ICI) for concentrations of selected trace elements sampled across 119 pasture, urban, forestry and horticulture sites 2013-2017.

(a)	**Contamination index**			**Number of sites** (n=119)		
	Mean	**Min**	**Max**	**Low** (CI≤1)	**Moderate** (1<CI≤3)	**High** (CI>3)
As	1.3	0.1	5.7	51	64	4
Cd	6.6	1.0	40	0	38	81
Cr	1.4	0.1	7.8	54	55	10
Cu	1.5	0.1	8.6	61	46	12
Pb	1.6	0.13	14.0	62	42	15
Ni	2.8	0.1	39.8	57	39	23
Zn	1.9	0.2	13.3	33	68	18

(b)

Integrated CI	**Mean**	**Minimum**	**Maximum**
Low (ICI≤1)	0.7 (n=18)	0.4	0.9
Moderate (1<ICI≤3)	1.9 (n=70)	1.0	2.9
High (ICI>3)	4.6 (n=31)	3.0	10.1

3.3 Soil parameters by rural land use activity

Rural land use has changed considerably in Auckland since the commencement of the soil monitoring programme in 1995, that has resulted in the reduction of sites from traditional commercial farming and an increase in the number of sites for lifestyle block living purposes. Lifestyle blocks are a rapidly expanding land use activity in rural Auckland that is expected to continue into the future (Fairgray, 2018). However, little is known about the soil quality of this land use. The breakdown of farm land use by property size, as recorded by Auckland Council's rates assessment, are provided for the soil sites included in this programme (Table 9, Appendix 5).

Table 9. Property size of farmland uses for soil sites

Land use	Mean (ha)	Range (ha)
Dairy	62	8-106[1]
Drystock	78	10-216
Lifestyle	11	0.3-31
Orchards+viticulture	10	4.1-20
Outdoor vegetable production	13	6-19

[1] The smaller 8ha dairy property is that of a goat dairy operation. Other dairy properties are cow operations.

The extent of land use change within rural Auckland has required the broad generalisation of land use classification particularly when trend analysis are being conducted (e.g. pasture land encompasses dairy, drystock and lifestyle block converted sites) otherwise it would require removing a number of sites which would ultimately reduce the sample size of a land use category (Appendix 3). While this approach is suitable for such trend analysis circumstances it can neglect reporting on specific rural land use activities. In order to compare soil quality and trace elements for specific pasture and horticulture land uses, sites that were sampled between 2013-2015 were broken into dairy, drystock, lifestyle block, orchards+viticulture combined and outdoor vegetable production categories (Tables 9 and 10).

Specifically, for pastoral sites, mean macroporosity were significantly different ($P < 0.05$ using log transformed data) and were least for dairy sites (6% v/v; Table 10) but similar for drystock and lifestyle blocks. There were no significant differences for the remaining six key soil quality indicators across these three specific pastoral land uses (Appendix 6).

Mean concentrations of Olsen P, pH, TC, TN, AMN and macroporosity were significantly different across rural land uses with Olsen P, pH and macroporosity being highest and TC, TN and AMN least for outdoor vegetable production (Table 10). The mean concentrations of Olsen P at these sites was 206 mg/kg, while the range was 48-361 mg/kg (Appendix 2), well in excess of soil quality guidelines of 20-50mg/kg (Table 5). Additionally, outdoor vegetable production is a very intensive land use activity where the soil is continuously being rearranged by cultivation, e.g. ploughing, hoeing, harrowing, deep ripping. It can therefore be less subject to activities that would result in soil compaction which can be further influenced by the sampling design of the x3 averaged in-situ soil cores that could be collected across differing soil surfaces ranging from the row, inter-row, wheel tracks or permanent traffic tracks. Establishing permanent traffic tracks have been reported to provide an opportunity for growers to limit compaction and reduce the amount of cultivation necessary between crop seasons (Johnstone et al., 2011).

Soil organic matter (SOM) plays a significant role in the structural stability of soils as well as provision of nitrogen and carbon for use by soil microbes and plants. The indicator for organic matter status is total carbon (TC). The very low mean concentrations of TC, TN and AMN of 2.7%, 0.25% and 21mg/kg, respectively (Table 10), observed for outdoor vegetable production sites are consistent with losses of SOM. Constant soil disturbance associated with outdoor vegetable production activity, previously described above, results in the loss of soil carbon (Haynes and Tregurtha, 1999). Mean TC and AMN concentrations below recommended guideline ranges (Table 10) indicate the soil may be less resilient with poorer functioning due to reduced structure. Soils with poorer structure are more subject to erosion and nutrient leaching (Basher et al., 1997). All the outdoor vegetable production sites were located in Franklin where high levels of fertiliser application are common. Declines in soil carbon in this area indicate an increased risk of contaminant leaching losses, particularly N (Cathcart, 1996, Crush et al., 1997, Francis et al., 2003, Ledgard et al., 1997, Williams et al., 2000). Issues with elevated nitrate concentrations in Franklin surface and groundwater continue (Meijer et al., 2016) despite that strategies to improve these issues have been well documented (Basher et al., 1997). Strategies, such as the use of cover crops to restore the carbon content of the soil, minimal tillage practices, application of green manures, including at least four years pasture in the crop rotation, etc, can result in both environmental and agronomic benefits (Komatsuzaki and Wagger, 2015, Myers and Watts, 2015). However, soil quality results indicate poor uptake of these strategies by farmers or there are other factors not mitigated by the strategies.

There were significant differences between rural land uses for As, Cr, Cu, Ni, and Pb with mean concentrations being highest for outdoor vegetable production sites for all these analytes (Table 10). All the outdoor vegetable production sites were located on Patumahoe clay loam soil which belong to the volcanically derived Granular soil order as a result of an eruption in the central plateau 250,000 years ago (Lowe, 2010) which can explain the inherently high mean concentrations of Cr and Ni. Mean concentrations of trace elements at outdoor vegetable production sites were within guideline ranges but mean concentrations of Cu are close to exceeding guidelines. Not only will future sampling be important to determine any additional increases but soil results need to be shared and explained to landowners to assist and help influence good land management practices for all soil parameters that are close to or outside recommended guideline ranges.

Table 10. Mean concentrations of soil parameters by rural land use activities in Auckland 2013-2015. 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. Significant differences are highlighted in bold and ns denotes 'not significant'. Soil parameters in **red** and **blue** bold figures are mean values that are above and below recommended guidelines, respectively.

Land use	Soil parameters						
	Total C %	**Total N %**	**AMN mg/kg**	**pH**	**Olsen P mg/kg**	**Macroporosity -10kPa %**	**Bulk density g/cm^3**
Dairy (n=12)	7.8	0.66	170	6.1	**57**	**6**	0.89
Drystock (n=23)	7.3	0.66	177	5.9	49	**8**	0.88
Lifestyle block (n=14)	6.5	0.56	140	6.0	36	**9**	0.94
Orchard+viticulture (n=11)	5.2	0.43	84	6.2	**55**	12	1.04
Outdoor vegetable (n=7)	**2.7**	0.25	**21**	6.6	**206**	22	1.04
SED	1.57	0.125	28.0	0.15	21.3	1.8	0.079
LSD	3.14	0.250	56.3	0.30	42.6	3.53	0.158
P value	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**<0.001**	ns
	mg/kg						
	As	**Cd**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Dairy (n=12)	2.9	0.50	10	14	3.6	9	31
Drystock (n=23)	4.1	0.47	11	12	5.0	12	37
Lifestyle block (n=14)	4.9	0.40	15	22	4.5	22	38
Orchard+viticulture (n=11)	3.2	0.43	13	34	4.2	12	38
Outdoor vegetable (n=7)	8.0	0.52	24	44	8.9	33	49
SED	1.04	0.121	2.2	8.7	0.99	7.0	10.5
LSD	2.09	0.243	4.4	17.4	1.97	13.9	21.0
P value	**<0.01**	ns	**<0.001**	**<0.001**	**<0.001**	**<0.001**	ns

[1] In order to increase the sample size, 'orchard+viticulture' encompassed both orchard (n=6) and viticulture sites (n=5). The broader horticulture land use category also encompassed one nursery site which was excluded from the analysis as it was not considered appropriate to identify it as either an orchard+viticulture or outdoor vegetable site

3.4 Soil quality and trace element trend analysis for rural sites from 1995-2017

There were significant differences in mean concentrations of soil pH, TC, Olsen P, AMN, macroporosity (-5kPa), bulk density and As across the three sampling periods 1995-2000, 2008-2012 and 2013-2017 (Table 11). There were also significant differences in soil pH, TN, Olsen P, macroporosity, bulk density, Cd, Cr and Ni for the factorial interaction of sampling period and land use (Figure 8 and Table 12). That is, soil parameter changes over time varied significantly by land use. Trend analysis across sampling period for soil sites on land uses that remained unconverted are reported in Appendix 3 and while this analysis had the ability to split out dairy and drystock sites the sampling size was reduced (47 and 30 repeat soil sites for soil quality and trace elements, respectively) which needs to be considered when interpreting results.

Trend analysis showed no consistent trends except for significantly declining TC across the three sampling periods (Table 11). Unlike levels specifically for outdoor vegetable production for the most recent sampling period (Table 10), mean concentrations of TC were collectively within acceptable guideline values across the three sampling periods (Table 11). However, trend analysis were only subject to three sampling periods and future resampling will be important to determine longer-term changes in soil TC.

For remaining indicators, mean soil parameters were all largely within recommended guideline ranges, except for macroporosity (-5kPa) which was less in the second sampling period and remained below recommended guidelines in the more recent sampling period (2013-2017) for pasture sites compared to when these sites were first sampled in 1995-2000 (Table 12). Changes in soil macroporosity could be attributed to some extent to sampling time as climatic conditions may have significant seasonal effects on these measurements. Values for macroporosity are, generally, higher in summer than in late winter (Curran Cournane et al., 2011a). Across the three soil sampling events, sampling varied by up to three months (August-October), so it is not possible to rule out climatic variability. Additionally, mean concentrations of Olsen P continued to remain above guidelines for all three sampling periods for horticulture sites (Table 12).

Table 11. Mean results of soil parameters across three sampling periods 1995-2000, 2008-2012 and 2013-2017. The standard error of difference (SED) and least significant difference (LSD) are presented using un-transformed and the *P*-value is presented using log transformed data. Significant differences are highlighted in bold and ns denotes 'not significant'.

Soil parameter[1]	**1995-2000**	**2008-2012**	**2013-2017**	**SED**	**LSD**	***P* value**
Soil pH	5.86	5.96	5.87	0.046	0.090	**<0.05**
Total C (%)	7.3	6.9	6.4	0.22	0.43	**<0.001**
Total N (%)	0.54	0.54	0.52	0.016	0.032	ns
Olsen P (mg/kg)	37	44	42	3.3	6.6	**<0.01**
AMN (mg/kg)	145	151	132	6.8	13.3	**<0.05**
Macroporosity (-5kPa%)[2]	12	8	9	0.7	1.3	**<0.001**
Bulk density (g/cm^3)	0.92	0.98	0.94	0.019	0.038	**<0.001**
Arsenic (mg/kg)	3.7	3.6	4.2	0.32	0.63	**<0.001**
Cadmium (mg/kg)	0.38	0.40	0.39	0.017	0.035	ns
Chromium (mg/kg)	12	12	12	0.6	1.2	ns
Copper (mg/kg)	15	16	16	1.5	3.0	ns
Nickel (mg/kg)	3.8	4.0	4.2	0.24	0.47	ns
Lead (mg/kg)	11.9	11.4	12.4	0.86	1.71	ns
Zinc (mg/kg)	31	34	34	2.5	5.0	ns

[1] 78 and 48 repeat sites were included in the soil quality and trace element analysis, respectively; the 30 remaining sites sampled between 1995-1998 did not have corresponding trace element data

[2] Macroporosities are presented as -5kPa% (soil pores >60 microns) because -10kPa data was not available for all sites sampled between 1995-2000 (Appendix 2). Macroporosity guideline range for -5kPa% is 8-30% for horticulture and pastoral land uses

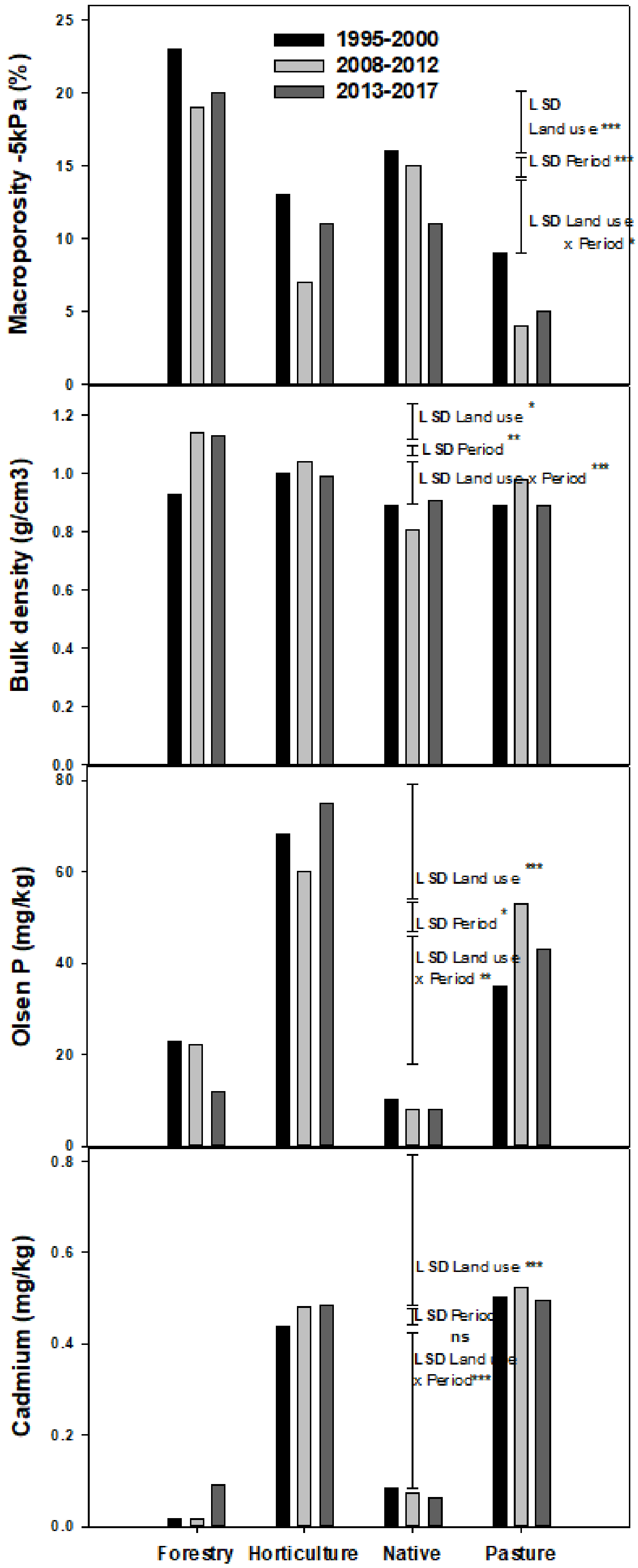

Figure 8. Changes in mean macroporosity (-5kPa), bulk density, concentrations of Olsen P and cadmium for three soil sampling periods by land use and sampling period. The least significant difference (LSD_{05} using untransformed data) is given for land use, period and the interaction of land use x period with ***, **, * indicating significance at the *P*<0.001, *P*<0.01 and *P*<0.0.05 level (using log-transformed data), respectively.

Table 12. Mean concentrations of soil parameters by land use and sampling period. The *P*-value is presented using log transformed data. Significant differences are highlighted in bold and ns denotes 'not significant'. Soil parameters in **red** and **blue** bold figures are mean values that are above and below recommended guidelines, respectively.

Land use[1]	Period	pH	TC	TN	Olsen P	AMN	MP-5kPa[2]	BD	As	Cd	Cr	Cu	Ni	Pb	Zn
Forestry	1995-00	5.21	5.2	0.33	23	57	23	0.93	5.7	0.02	6	5	2.7	6.8	19
	2008-12	5.38	3.9	0.24	22	79	19	1.14	7.0	0.02	12	7	5.4	9.2	22
	2013-17	5.61	3.8	0.22	12	63	20	1.13	6.6	0.09	6	5	2.7	8.2	18
Horticulture	1995-00	6.20	6.3	0.45	**68**	111	13	1.00	2.4	0.44	12	26	3.1	10.1	28
	2008-12	6.36	6.2	0.45	**60**	88	**7**	1.04	3.0	0.48	13	26	3.4	12.0	35
	2013-17	6.19	6.1	0.47	**75**	88	11	0.99	3.9	0.48	16	30	5.0	12.6	44
Native	1995-00	5.39	7.5	0.40	10	122	16	0.89	3.6	0.08	13	9	4.8	14.2	38
	2008-12	5.58	7.1	0.40	8	134	15	0.81	3.2	0.07	11	10	3.9	10.8	30
	2013-17	5.39	5.7	0.34	8	106	11	0.91	4.0	0.06	11	8	4.3	10.8	29
Pasture	1995-00	5.99	8.1	0.67	35	186	9	0.89	4.2	0.50	12	12	3.9	12.6	32
	2008-12	6.01	7.7	0.68	**53**	202	**4**	0.98	3.6	0.52	11	13	4.3	11.5	36
	2013-17	5.93	7.4	0.66	43	175	**5**	0.89	4.2	0.50	11	12	3.9	13.4	32
P value land use		**<0.001**	**<0.01**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.05**	ns	**<0.001**	ns	**<0.001**	ns	ns	ns
P value period		**<0.05**	**<0.001**	ns	**<0.05**	**<0.05**	**<0.001**	**<0.01**	**<0.001**	ns	ns	ns	**<0.05**	ns	ns
P value land use x period		**<0.05**	ns	**<0.05**	**<0.01**	ns	**<0.05**	**<0.001**	ns	**<0.001**	**<0.001**	ns	**<0.001**	ns	ns

[1] The breakdown of land use sites for soil quality analysis are as follows: forestry n=7, horticulture n=18, native n=13 and pasture n=37
The breakdown of land use sites for trace element analysis are as follows: forestry n=3, horticulture n=13, native n=9 and pasture n=23
[2] The guideline range for soil macroporosity -5kPa is 8-30% for horticulture and pastoral land uses

4.0 Conclusion

Soil quality indicators of most concern that fell outside recommended guideline ranges on most occurrences were high Olsen P concentrations (an indicator for plant available phosphorus and fertility) particularly for horticulture (outdoor vegetable production and orchards) and dairy sites; low soil macroporosity (at -10kPa, an indicator of soil compaction) particularly for all pasture sites (dairy, drystock and lifestyle blocks); and low total carbon (TC) for outdoor vegetable production sites. These results indicate that phosphorus (P) fertiliser in excess of what is needed is being applied to our land and that there are issues with soil compaction and losses of soil carbon, respectively.

Compacted soils have a reduced volume of air pores which can impair plant growth and productivity, as well as reduce the ability for water to infiltrate thereby causing greater surface water ponding. Altered hydrology and plant uptake mean greater soil compaction is also associated with greater surface runoff of nutrients and suspended sediment. Pastoral sites exhibited elevated Olsen-P (relative to other land uses barring horticulture) and during the period 2008-2012 exceeded guideline ranges. Consequently, compacted pastoral soils appear to be of higher risk to water quality from erosion of soil also already (excessively) P-enriched.

Soil macroporosity has been shown to have a strong annual cycle with values generally better in summer than in late winter (Curran Cournane et al., 2011a). In Auckland, State of Environment soil sampling is generally carried out in late-winter/early-spring, representing a worst-case scenario (i.e., when the soil pores are water-filled and therefore more vulnerable to compaction and pugging damage).

Similarly, to soil quality parameters, mean concentrations of trace elements were significantly different by land use and soil order, but means fell within guideline ranges. Mean concentrations of Cd and Cu for sampling period 2013-2017 were highest for horticulture sites; and pasture sites for Cd. Mean concentrations of As, Cr, Ni, Pb, Zn were highest for sites within the urban environment over the equivalent period.

To assess the soil environmental quality using concentrations of trace elements a contamination index (CI) was calculated for each analyte at each site i.e. it pools concentrations of trace elements for sites across all land uses and soil orders together. The CI was defined as the mean ratio of an analyte to the mean of the corresponding analyte at *native bush sites*, the latter acting as an indicator for conservative natural background conditions. The mean CI was classified as high (CI >3) for Cd only (mean 6.6) indicating that concentrations of Cd were more than six times higher than concentrations recorded at native soil sites. Moderate CIs ($1 < CI \leq 3$) were calculated for (by decreasing order) Ni>Zn>Pb>Cu>Cr>As. No mean CI was classified as low (i.e. $CI \leq 1$) indicating increased levels for all trace elements for non-native sites. The mean CIs for each analyte were combined and averaged at each site, to create an integrated contamination index (ICI). The region-wide combined mean ICI across all sites was calculated as being moderate measuring at 2.4 (ranging from 0.4-10.1). The CI and ICI are considered useful techniques for interpreting data and they complement traditional ways of reporting concentrations of trace elements for non-native sites.

Rural land use change was assessed by specifically comparing dairy (n=12), drystock (n=23), lifestyle blocks (n=14), orchards+viticulture (n=11) and outdoor vegetable production (n=7) sites for sampling years 2013-2015. Compaction, indicated by mean macroporosity, was greatest for dairy operations (6% v/v at -10kPa), followed by drystock (8% v/v), lifestyle blocks (9% v/v), orchards+viticulture (12%v/v) and outdoor vegetable production (22% v/v) sites. Excessive phosphorous, indicated by mean concentrations of Olsen P, were highest, and considerably exceeded recommended guideline ranges for outdoor vegetable production (206mg/kg) followed by dairy (57mg/kg), orchards+viticulture (55mg/kg), drystock (49mg/kg) and lifestyle blocks (36mg/kg).

The intensive conventional nature of outdoor vegetable production is not only reflected in considerably enriched Olsen-P (consequence of the large amount of P fertiliser applied) but the very low mean concentrations of TC, TN and AMN of 2.7%, 0.25% and 21mg/kg, respectively. Loss of soil carbon is most likely from continuous cultivation. Strategies to improve these issues have been well documented which include, but not limited to the use of cover crops to restore the carbon content of the soil, minimal tillage practices, application of green manures etc. that can result in both environmental and agronomic benefits (Komatsuzaki and Wagger, 2015, Myers and Watts, 2015, Basher et al., 1997).

Trend analysis showed no consistent trends except for significantly declining soil total carbon (TC) across the three sampling periods albeit with mean concentrations collectively remaining within acceptable recommended guidelines. While other mean soil parameters were also largely within recommended guideline ranges across sampling periods, mean macroporosity (-5kPa) was less in the second sampling period and remained below recommended guidelines in the more recent sampling period (2013-2017) for pasture sites when compared with sites first sampled in 1995-2000. Across the three soil sampling events, sampling varied by up to three months (August-October), so it is not possible to rule out climatic variability. Additionally, mean concentrations of Olsen P continued to remain above guidelines for all three sampling periods for horticulture sites.

Resources should be targeted towards land management strategies that improve soil ecosystem health. To aid with alleviating soil compaction of pastoral sites (dairy, drystock and lifestyle blocks) practices include restricted grazing, reduced stocking density and removing stock off pasture when bare soil is beginning to be exposed (Drewry, 2006). This is particularly important when grazing soils under wet winter-spring conditions (peak risk-period), rendering them more erosion-prone, and even more so for soils that are predominantly clay-based which pose an added environmental risk when lost from land to water [i.e. being a vector of other contaminants including phosphorus and trace elements (Haygarth et al., 2006) and can present greater habitat degradation from sedimentation (Bilotta and Brazier, 2008)].

Reducing P fertiliser application largely for horticulture (outdoor vegetable production and orchards+viticulture) and dairy sites is recommended to reduce excessive P-enrichment of soils which would otherwise be at risk of being lost from land to water via surface runoff during rainfall events. The latter is exacerbated if the soil is also subject to compaction. Practices to ameliorate the loss of soil carbon have also been well documented and include the use of cover crops to restore the carbon content of the soil, minimal tillage practices, application of green manures etc.

Soil quality results for the latter specified indicators (macroporosity, Olsen P and TC) for corresponding land uses documented in this evaluation indicate poor uptake of these strategies by farmers which need to be reinforced and encouraged by land management advisors and rural industry. This is particularly important if intentions to improve freshwater ecosystem health are to be realised, the alternative being that these soil quality issues persist for another 20+ years. To help assist land management and rural industry advisors, soil results need to be shared and explained to landowners to help influence good land management practices for all soil parameters that are close to or outside recommended guideline ranges which will complement any additional soil testing that landowners undertake.

As only three sampling periods were subject to trend analysis in the current report, it will be important to continue to resample and monitor these soil sites to increase the size of the dataset and improve the robustness of the trend analysis. Future sampling will also help determine any improvements or deterioration and to ensure the functioning of the soil ecosystem. Additionally, future sampling should consider the incorporation of biological indicators such as soil bacterial communities which have previously been identified as being sensitive indicators of soil quality and trace elements (Hermans et al., 2017). Future monitoring of soil sites will continue to inform policy and science direction both regionally and nationally, the latter which would be aided by combining regional long-term datasets to gain a comprehensive assessment of soil monitoring state and trends for Aotearoa New Zealand. Continued monitoring and reporting will also fulfill legal requirements under the Resource Management Act 1991 and its amendments.

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6.0 References

Ajmone-Marsan, F. and Biasioli, M. 2010. Trace elements in soils of urban areas. *Water, Air and Soil Pollution,* 213**,** 121-143.

ARC 2001. Background concentrations of inorganic elements in soils from the Auckland region. Technical Publication No. 153. Auckland Regional Council, New Zealand.

ARC 2010. State of the Auckland Region. Auckland Regional Council ISBN 978-1-877540-45-5 pg 301.

Arshad, M. A. and Martin, S. 2002. Identifying critical limits for soil quality indicators in agro-ecosystems. *Agriculture, Ecosystems and Environment,* 88**,** 153-160.

Basher, L. R., Cathcart, S. N., Crush, J. R., Hart, B., Clark, S., Ross, C. W. and Williams, P. H. Soil and water management for sustainable vegetable production in a peri-urban area, Pukekohe, New Zealand. 24th Hydrology and Water Resources Symposium: proceedings : water/land : wai-whenua p321-326. Auckland, New Zealand. 1997.

Biasiolia, M., Barberisb, R. and F, A.-M. 2006. The influence of a large city on some soil properties and metals content. *Science of the Total Environment,* 356**,** 154-164.

Bilotta, G. S. and Brazier, R. E. 2008. Understanding the influence of suspended solids on water quality and aquatic biota. *Water Research,* 42**,** 2849-2861.

Blakemore, L. C., Searle, P. L. and Daly, B. K. 1987. Methods for chemical analysis of soils. NZ Soil Bureau Scientific Report 80, Lower Hutt, DSIR Soil Bureau.

Canty, M. J., Scanlon, A., Collins, D. M., Mcgrath, G., Clegg, T. A., Lane, E., Sheridan, M. K. and More, S. J. 2014. Cadmium and other heavy metal concentrations in bovine kidneys in the Republic of Ireland. *Science of the Total Environment,* 485-486**,** 223-231.

Carpenter, S. R., Caraco, N. F., Corell, D. L., Howarth, R. W., Sharpley, A. N. and Smith, V. H. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications,* 8**,** 559-568.

Cathcart, S. N. 1996. An investigation of the nitrate contamination of an unconfined, shallow, fractured, basaltic aquifer at Pukekohe, South Auckland, New Zealand. *In* Currie, L. D and Loganathan, P. Recent developments in understanding chemical movement in soils: significance in relation to water quality and efficiency of fertiliser use: Proceedings of the workshop held by the Fertilizer and Lime Research Centre at Massey University, Palmerston North, New Zealand, 14-15 February 1996.

Cavanagh, J. and Munir, K. 2019. Updated Development of soil guideline values for the protection of ecological receptors (Eco -SGVs): Technical document. Envirolink Tools Grant C09X1402 Prepared for: Regional Waste and Contaminated Land Forum, Land Monitoring Forum and Land Managers Group Envirolink Grant: 1935 -GSDC156. Update prepared for: Gisborne District Council June 2019.

Chen, T. B., Zheng, Y. M., Lei, M., Huang, Z. C., Wu, H. T., Chen, H., Fan, K. K., Yu, K., Wu, X. and Tian, Q. Z. 2005. Assessment of heavy metal pollution in surface soils of urban parks in Beijing, China. *Chemosphere,* 60**,** 542-551.

Cotching, W. E. and Kidd, D. B. 2010. Soil quality evaluation and the interaction with land use and soil order in Tasmania, Australia. *Agriculture, Ecosystems and Environment,* 137**,** 358-366.

Councell, T. B., Duckenfield, K. U., Landa, E. R. and Callender, E. 2004. Tire-wear particles as a source of zinc to the environment. *Environmental Science and Technology,* 38**,** 4206-4214.

Crush, J. R., Cathcart, S. N., Singleton, P. and Longhurst, R. D. 1997. Potential for nitrate leaching from different land uses in the Pukekohe area. *Proceedings of the New Zealand Grassland Association,* 59**,** 55-58.

Curran-Cournane, F., Fraser, S., Hicks, D. L., Houlbrooke, D. J. and Cox, N. 2013. Changes in soil quality and land use in grazed pasture within rural Auckland. *New Zealand Journal of Agricultural Research,* 56**,** 102-116.

Curran-Cournane, F., Lear, G., Schwendenmann, L. and Khin, J. 2015. Heavy metal soil pollution is influenced by the location of green spaces within urban settings. *Soil Research* 53**,** 306-315.
Curran-Cournane, F., Vaughan, M., Memon, A. and Fredrickson, C. 2014. Trade-offs between high class land and development: recent and future pressures on Auckland's valuable soil resources. *Land Use Policy* 39**,** 146-154.
Curran Cournane, F., Mcdowell, R. W., Littlejohn, R. P. and Condron, L. M. 2011a. Effects of cattle, sheep and deer grazing on soil physical quality and phosphorus and suspended sediment losses in surface runoff. *Agriculture Ecosystems & Environment,* 140**,** 264-272.
Curran Cournane, F., Mcdowell, R. W., Littlejohn, R. P., Houlbrooke, D. J. and Condron, L. M. 2011b. Is mechanical soil aeration a strategy to alleviate soil compaction and decrease phosphorus and suspended sediment losses from irrigated and rain-fed cattle-grazed pastures? *Soil Use and Management* 27**,** 376-384.
Dominati, E., Patterson, M. and Mackay, A. 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics,* 69**,** 1858-1868.
Drewry, J., Littlejohn, R., Paton, R., Singleton, P., Monaghan, R. and Smith, L. 2004. Dairy pasture responses to soil physical properties. *Australian Journal of Soil Research,* 42**,** 99-105.
Drewry, J., Taylor, M., Curran-Cournane, F., Gray, C. and Mcdowell, R. 2014. Olsen P methods and soil quality monitoring: Are we comparing "apples with apples?". *In: Accurate and efficient use of nutrients on farms. (Eds L.D. Currie and C L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 26. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. February 2013.*
Drewry, J. J. 2006. Natural recovery of soil physical properties from treading damage of pastoral soils in New Zealand and Australia: A review. *Agriculture, Ecosystems & Environment,* 114**,** 159-169.
Drewry, J. J., Cavanagh, J. E., Mcneill, S. and Taylor, M. D. 2018. Long term monitoring of soil quality including trace elements in the Wellington region. In: Farm environmental planning – Science, policy and practice. (Eds L. D. Currie and C. L. Christensen). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 31. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 11 Pages.
Drewry, J. J., Parkes, R. and Taylor, M. D. 2017. Soil quality and trace elements for land uses in the Wellington region and implications for farm management. In: Science and policy: nutrient management challenges for the next generation. (Eds L. D. Currie and M. J. Hedley). http://flrc.massey.ac.nz/publications.html. Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 12 p.
Elless, M. P., Bray, C. A. and Blaylock, M. J. 2007. Chemical behavior of residential lead in urban yards in the United States. *Environmental Pollution,* 148**,** 291-300.
Fairgray, D. 2018. Statement of rebuttal evidence of Dr Doug Fairgray on behalf of Auckland Council before the Environment Court at Auckland ENV-2016-304-000111. 02 March 2018.
Falahi-Ardakani, A. 1984. Contamination of environment with heavy metals emitted from automotives. *Ecotoxicology and Environmental Safety,* 8**,** 152-161.
Francis, G. S., Trimmer, L. A., Tregurtha, C. S., Williams, P. H. and Butler, R. C. 2003. Winter nitrate leaching losses from three land uses in the Pukekohe area of New Zealand. *New Zealand Journal of Agricultural Research,* 46**,** 215-224.
Gaw, S., Wilkins, A., Kim, N., Palmer, G. and Robinson, P. 2006. Trace element and DDT concentrations in horticultural soils from the Tasman, Waikato and Auckland regions of New Zealand. *Science of the Total Environment,* 355**,** 31-47.
Godt, J., Scheidig, F., Grosse-Siestrup, C., Esche, V., Brandenburg, P., Reich, A. and Groneberg, D. 2006. The toxicity of cadmium and resulting hazards for human health. *Journal of Occupational Medicine and Toxicology,* **1**:22.
Gradwell, M. W. 1972. Methods for Physical Analysis of Soils in "New Zealand Soil Bureau Scientific Report 10C". Department of Scientific and Industrial Research, New Zealand.

Haygarth, P. M., Bilotta, G. S., Bol, R., Brazier, R. E., Butler, P. J., Freer, J., Gimbert, L. J., Granger, S. J., Krueger, T., Macleod, C. J. A., Naden, P., Old, G., Quinton, J. N., Smith, B., Worsfold, P. and 2006. Processes affecting transfer of sediment and colloids, with associated phosphorus, from intensively farmed grasslands: an overview of key issues. *Hydrological Processes,* 20**,** 4407-4413.

Haynes, R. and Tregurtha, R. 1999. Effects of increasing periods under intensive arable vegetable production on biological, chemical and physical indices of soil quality. *Biological Fertility of Soils,* 28**,** 259-266.

Hermans, S. M., Buckely, H. L., Case, B. S., Curran-Cournane, F., Taylor. M. and Lear, G. 2017. Bacteria as emerging indicators of soil condition. *Applied and Environmental Microbiology* 83**,** e02826-16.

Hill, R. B. and Sparling, G. P. 2009. Soil quality monitoring. In: *Land Monitoring Forum. Land and soil monitoring: a guide for SoE and regional council reporting*, pp.27-88. Land Monitoring Forum, Hamilton.

Johnstone, P. R., Wallace, D. R., Arnold, N. and Bloomer, D. 2011. Holding it together – soils for sustainable vegetable production July 2011. Prepared by Plant and Food and LandWISE for Hortciulture New Zealand. SPTS No. 5756.

Keeney, D. R. and Bremner, J. M. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal,* 58**,** 498-503.

Kim, N. D. and Taylor, M. D. 2009. Trace element monitoring. Chapter 5 in Land and Soil Monitoring: A guide for SoE and Regional Council Reporting; New Zealand *In:* Land Monitoring Forum, N. Z. (ed.).

Kim, N. D. and Taylor, M. D. 2017. Cadmium and zinc – a tale of two metals. In: The New Zealand Land & Food Annual 2017, Edited by Claire Massey, Massey University Press, Massey University, Palmerston North.

Klute, A. 1986. Water Retention: Laboratory methods Pp 635 - 662 "Methods of Soil Analysis Part 1" Agronomy, No 9, American Society of Agronomy, Madison, Wisconsin.

Komatsuzaki, M. and Wagger, M. G. 2015. Nitrogen recovery by cover crops in relation to time of planting and growth termination. *Journal of Soil and Water Conservation,* 70**,** 385-398.

Ledgard, S. F., Crush, J. R., Ouyang, L., Sprosen, M. and Rajendram, G. S. 1997. Nitrate leaching under spinach, onion and potato crops in the Pukekohe region during 1996. Report for BOP Fertiliser Ltd. www.fertresearch.org.nz.

Longhurst, R. D., Roberts, A. H. C. and Waller, J. E. 2004. Concentrations of arsenic, cadmium, copper, lead and zinc in New Zealand pastoral topsoils and herbage. *New Zealand Journal of Agricultural Research,* 47**,** 23-32.

Lowe, D. J. Pukekohe silt loam, Pukekohe Hill. In: Guidebook for pre-conference North Island, New Zealand 'Volcanoes to Ocean' field tour (27-30 July, 2010). . *In:* Lowe, D. J., Neall, V. E., Hedley, M., Clothier, B. and Mackay, A., eds. 19th World Soils Congress, International Union of Soil Sciences, Brisbane. Soil and Earth Sciences Occasional Publication No. 3, Massey University, Palmerston North, pp. 1.12-1.23., 2010.

MacKay, A., Dominati, E. and Taylor, M. 2013. Soil Quality Indicators: The Next Generation. Report prepared for Land Monitoring Forum of Regional Councils. Client report number: RE500/2012/025.

MacKay, A., Simcock, R., Sparling, G., Vogler, I. and Francis, G. 2006. Macroporosity. Internal SLURI report. AgResearch, Hamilton. *Internal SLURI report. AgResearch, Hamilton.*

Mcdowell, R. W., Houlbrooke, D. J., Muirhead, R. W., Muller, K., Sheperd, M. and Cuttle, S. P. (Eds.) 2008. *Grazed pastures and surface water quality. Nova Science Publishers, Inc., New York*

Mcdowell, R. W., Taylor, M. D. and Stevenson, B. A. 2013. Natural background and anthropogenic contributions of cadmium to New Zealand soils. *Agriculture, Ecosystems and Environment,* 165**,** 80-87.

Meijer, K., Buckthought, L., Curran-Cournane, F., Martindale, M., Prebble, N. and Long, L. 2016. Elevated nitrate concentrations in Franklin surface and groundwater: A Review. Auckland Council Technical Report 2016/015.

Ministry For The Environment and Statistics New Zealand 2018. Our Land 2018. Data to 2017 At a Glance. New Zealand's Environmental Reporting Series. New Zealand Government.
Ministry For The Environment AND Statsistics New Zealand 2015. New Zealand's Environmental Reporting Series: Environment Aotearoa 2015. Available from www.mfe.govt.nz and www.stats.govt.nz. Ministry for the Environment and Statistics New Zealand.
Molloy, L. (Ed.) 1993. *Soils in the New Zealand Landscapes: The Living Mantle, New Zealand Society of Soil Science*: New Zealand Society of Soil Science, Lincoln University, Canterbury, New Zealand.
Myers, R. and Watts, C. 2015. Progress and perspectives with cover crops: Interpreting three years of farmer surveys on cover crops. *Journal of Soil and Water Conservation,* 70**,** 125A-133A.
Nash, D. M. and Halliwell, D. J. 1999. Fertilizers and phosphorus loss from productive grazing systems. *Australian Journal of Soil Research,* 37**,** 403-429.
NZLRI 2010. New Zealand Land Resource Inventory NZLRI. Landcare Research http://lris.scinfo.org.nz/#/layer/79-fsl-new-zealand-soil-classification/
Oliver, M. 2017. Soil Quality In The Marlborough Region In 2016.Technical Report No: 17-003 July 2017.
Olsen, S. R., Cole, C. V., Watanabe, F. S. and Dean, L. A. (Eds.) 1954. *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*: United States Department of Agriculture Circular No. 939. Washington, D.C. USA
Phillips, C., Marden, M. and Basher, L. 2007. Review of sediment generation processes in exotic forestry and the applicability of using compound-specific isotopes to understand sediment movement. *In:* Prepared By Landcare Research For Rayonier Nz Ltd For Matariki Forests. Po Box 12 285, T. C. R. L. (ed.).
Schloter, M., Dilly, O. and Munch, J. C. 2003. Indicators for evaluating soil quality. *Agriculture, Ecosystems and Environment,* 98**,** 255-262.
Silva , Y. J. A. B., Nascimento, C. W. A. and Biondi, C. M. 2014. Comparison of USEPA digestion methods to heavy metals in soil samples. *Environmental Monitoring and Assessment,* 186**,** 47-53.
Sparling, G., Lilburne, L. and Vojvodic-Vucovic, M. 2003. Provisional targets for soil quality indicators in New Zealand. Landcare Research Science Series No. 34. Manaaki Whenua Press. Lincoln Canterbury, New Zealand.
Taylor, M., Cox, N., Littler, R. and Drewry, J. 2017. Trends in soil quality monitoring data in the Waikato region 1995-2015. Waikato Regional Council Technical Report 2017/26.
Taylor, M. D. 2016. The fate and impact of fertiliser derived contaminants in New Zealand soils – development of a priority assessment model. PhD dissertation, Von der Fakultät Architektur, Bauingenieurwesen und Umweltwissenschaften der Technischen Universität Carolo-Wilhelmina zu Braunschweig zur Erlangung des Grades eines Doktors der Naturwissenschaften (Dr. rer. nat.) genehmigte. Technischen Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig, Germany.
Taylor, M. D., Kim, N. D., Hill, R. B. and Chapman, R. 2010. A review of soil quality indicators and five key issues after 12 yr soil quality monitoring in the Waikato Region. *Soil Use and Management,* 26**,** 212-224.
Trammell, T. L. E., Schneid, B. P. and Carreiro, M. M. 2011. Forest soils adjacent to urban interstates: soil physical and chemical properties, heavy metals, disturbance legacies, and relationships with woody vegetation. *Urban Ecosystems,* 14**,** 525-552.
Ward, N., Brooks, E. R., Robert, E. and Boswell, C. R. 1977. Heavy-metal pollution from automotive emissions and its effect on roadside soils and pasture species in New Zealand. *Environmental Science & Technology,* 11**,** 917-920.
Weathers, K. C., Cadenasso, M. L. and Pickett, S. T. A. 2001. Forest edges as nutrient and pollutant concentrators: potential synergisms between fragmentation, forest canopies, and the atmosphere. *Conservation Biology,* 15**,** 1506-1514.

Williams, P. H., Tregurtha, C. S. and Francis, G. S. 2000. Strategies for reducing nitrate leaching from vegetable crops grown in Pukekohe. New Zealand Fertiliser Manufacturers' Research Association Technical Conference (26th, 2000 Lincoln NZ) p70-76.

7.0 Appendices

Appendix 1: Soil sampling design by land uses from 1995-2017

Sampling year	Land use category	Sampling round
1995	subset of 78[1] sites across a variety of land uses	1
1996	subset of 78 sites across a variety of land uses	1
1997	subset of 78 sites across a variety of land uses	1
1998	subset of 78 sites across a variety of land uses	1
1999	subset of 78 sites across a variety of land uses	1
2000	subset of 78 sites across a variety of land uses	1
2001-2007	no-sampling	
2008	Horticulture	2
2009	Pastoral[2] (Dairy)	2
2010	Pastoral (Drystock)	2
2011	Forestry	2
2012	Native+Urban	2+1
2013	Horticulture	3
2014	Pastoral (Dairy + dairy converted sites)	3
2015	Pastoral (Drystock + drystock converted sites)	3
2016	Forestry	3
2017	Native+Urban	3+2

[1] 78 repeat sites for soil quality (48 for trace elements) were considered in the current trend analysis as a few of the original sites were dropped from the monitoring programme for various reasons including physical development obstructions, site access difficulties etc.

[2] Pastoral land was specifically split and reported by dairy and drystock land uses up until 2011-2013 when the extent of land use change, in particular the conversion to lifestyle blocks, became apparent.

Appendix 2. Soil results for individual sites utilised in the state and trends report

Site No.[1]	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1995-**01**-01	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	7.17	2.1	0.20	200	9	0.96	30								
2008-**01**-02	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	6.41	2.0	0.19	181	13	1.16	12	13	7.3	0.57	28	48	11	28	59
2013-**01**-03	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	6.02	2.2	0.22	276	13	1.04	23	24	5.6	0.5	29	47	10	29	47
1995-**02**-01	Patumahoe clay loam	Allophanic Oxidic Granular	Drystock	6.3	6.1	0.57	14	130	0.87	9								
2010-**02**-02	Patumahoe clay loam	Allophanic Oxidic Granular	Drystock-Lifestyle	6.19	7.1	0.63	39	221	0.98	2	5	11.0	0.46	22	34	6	54	78
2015-**02**-04.	Patumahoe clay loam	Allophanic Oxidic Granular	Drystock-Lifestyle	6.13	6.9	0.64	34	172	0.81	6	9	11.0	0.42	20	41	6	120	88
1996-**03**-01	Whangaripo clay loam	Typic Yellow Ultic	Forestry	4.67	4.6	0.30	34	40	1.05	13	14							
2011-**03**-02	Whangaripo clay loam	Typic Yellow Ultic	Forestry	4.75	6.7	0.39	68	94	0.95	12	15	1.7	0.17	16	20	4	5	21
2016-**03**-03.	Whangaripo clay loam	Typic Yellow Ultic	Forestry	5.3	7.1	0.29	7	87	0.99	17	19	1.1	0.088	16	10	4	12	17
1996-**05**-01	Whangaripo clay loam	Typic Yellow Ultic	Forestry	4.93	5.6	0.30	13	65	0.84	7	8							
2011-**05**-02	Whangaripo clay loam	Typic Yellow Ultic	Forestry	4.73	7.2	0.44	6	133	0.83	11	13	2.1	0.12	21	40	2	4	12
2016-**05**-03.	Whangaripo clay loam	Typic Yellow Ultic	Forestry	5.69	5.2	0.25	5	81	1.16	5	7	1.8	0.09	10	5	3	6	11

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1996-**06**-01	Whangaripo clay loam	Typic Yellow Ultic	Native	5.32	6.8	0.40	5	142	0.78	10	11							
2012-**06**-02.	Whangaripo clay loam	Typic Yellow Ultic	Native	5.1	6.1	0.30	2	122	0.62	8	11	1.7	0.032	28	17	9	5	35
2017-**06**-07.	Whangaripo clay loam	Typic Yellow Ultic	Native	5.14	5.7	0.34	3	132	0.9	8	10	1.7	0.024	32	21	12	5	44
1996-**07**-01	Ruakaka loamy peat	Organic soil	Dairy	5.93	11.6	0.87	20	206	0.75	3	5							
2009-**07**-02	Ruakaka loamy peat	Organic soil	Dairy	6.06	10.2	0.81	62	180	0.94	3	3	1.0	0.56	24	21	7	8	38
2014-**07**-04	Ruakaka loamy peat	Organic soil	Dairy	6.53	13.7	1.12	98	244	0.64	2	3	1.0	0.51	16	23	6	6	45
1996-**08**-01	Ruakaka loamy peat	Organic soil	Dairy	6.07	13.2	1.09	33	245	0.62	3	6							
2009-**08**-02	Ruakaka loamy peat	Organic soil	Dairy	5.72	9.8	0.76	75	176	1.02	1	2	1.0	0.63	25	27	10	8	32
2014-**08**-04	Ruakaka loamy peat	Organic soil	Dairy	6.19	12.2	0.91	76	265	0.66	5	8	1.1	0.72	17	31	6	8	54
1997-**09**-01	Karaka silt loam	Typic Orthic Allophanic	Dairy	6.19	7.1	0.64	46	162	0.95	14	16							
2009-**09**-02	Karaka silt loam	Typic Orthic Allophanic	Dairy	6.54	7.3	0.65	91	185	1.10	5	7	4.9	0.53	18	25	7	21	59
2014-**09**-04	Karaka silt loam	Typic Orthic Allophanic	Dairy	6.35	6.7	0.62	61	138	1.12	7	8	4.9	0.52	14	24	5	19	44
1997-**10**-01	Karaka silt loam	Typic Orthic Allophanic	Outdoor vegetable	6.58	6.5	0.56	22	85	0.86	15	20							
2008-**10**-02	Karaka silt loam	Typic Orthic Allophanic	Outdoor vegetable	6.88	4.4	0.35	44	26	0.9	20	24	5.9	0.47	14	18	8	21	44
2013-**10**-03	Karaka silt loam	Typic Orthic Allophanic	Veg-Drystock	6.41	3.6	0.30	70	51	1.09	9	12	6.1	0.42	15	16	8	19	44

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1997-**11**-01	Patumahoe clay loam	Typic Oxidic Granular	Native	5.35	7.6	0.49	4	137	0.82	19	21							
2012-**11**-02.	Patumahoe clay loam	Typic Oxidic Granular	Native	6.0	7.0	0.50	4	169	0.87	9	11	4.2	0.065	14	13	3	23	34
2017-**11**-07.	Patumahoe clay loam	Typic Oxidic Granular	Native	5.58	5.7	0.42	5	127	0.9	8	11	9.5	0.07	21	15	3	47	35
1997-**12**-01	Patumahoe clay loam	Typic Oxidic Granular	Dairy	6.91	6.9	0.65	58	267	0.96	8	10							
2009-**12**-02	Patumahoe clay loam	Typic Oxidic Granular	Dairy-Lifestyle	6.33	7.2	0.66	130	256	0.93	6	9	7.7	0.42	23	39	10	130	150
2014-**12**-04	Patumahoe clay loam	Typic Oxidic Granular	Dairy-Lifestyle	5.9	7.3	0.61	11	189	0.99	7	10	5.4	0.35	16	13	5	18	27
1998-**14**-01	Karaka silt loam	Typic Orthic Allophanic	Orchard	6.17	6.5	0.59	53	109	0.91	16								
2008-**14**-02	Karaka silt loam	Typic Orthic Allophanic	Orchard	6.31	5.7	0.49	150	108	1.03	6	8	5.5	0.39	13	13	5	25	67
2013-**14**-03	Karaka silt loam	Typic Orthic Allophanic	Orchard-Lifestyle	6.09	6.0	0.52	161	92	1.08	9	11	6.9	0.48	17	13	7	27	69
1998-**17**-01	Warkworth clay loam	Typic Yellow Ultic	Native	4.83	4.8	0.24	4	96	1.18	7								
2012-**17**-02	Warkworth clay loam	Typic Yellow Ultic	Native	5.5	4.5	0.29	4	99	1.05	4	5	1.9	0.03	22	21	5	6	23
2017-**17**-03.	Warkworth clay loam	Typic Yellow Ultic	Native	5.34	5.1	0.30	5	111	1.0	3	4	1.6	0.048	13	8	2	8	16
1998-**18**-01	Warkworth clay loam	Typic Yellow Ultic	Drystock	5.86	5.1	0.40	9	98	1.09	14								
2010-**18**-02	Warkworth clay loam	Typic Yellow Ultic	Drystock	5.94	5.5	0.50	20	156	1.04	5	7	0.8	0.24	4	7	2	2	14
2015-**18**-04	Warkworth clay loam	Typic Yellow Ultic	Drystock	5.87	5.6	0.50	22	133	0.83	6	9	1.3	0.32	7	8	2	3	15

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1998-**19**-01	Warkworth clay loam	Typic Yellow Ultic	Native	5.17	5.9	0.34	4	117	0.86	13								
2012-**19**-02	Warkworth clay loam	Typic Yellow Ultic	Native	4.9	6.2	0.37	2	161	0.84	9	10	1.2	0.02	21	10	3	5	16
2017-**19**-07.	Warkworth clay loam	Typic Yellow Ultic	Native	4.76	5.7	0.30	2	108	0.9	7	8	1.6	0.02	27	13	4	6	19
1998-**20**-01	Waitemata silt loam	Weathered Fluvial Recent	Orchard	6.38	6.1	0.42	97	65	1.03	8								
2008-**20**-02	Waitemata silt loam	Weathered Fluvial Recent	Orchard	5.97	4.7	0.31	86	82	1.21	2	4	0.4	0.25	3	63	1	4	28
2013-**20**-03	Waitemata silt loam	Weathered Fluvial Recent	Orchard-Lifestyle	6.2	12.6	0.79	64	140	0.76	11	12	2.2	0.47	9	120	4	14	61
1998-**21**-01	Red Hill sand	Typic Sandy Brown	Drystock	5.55	6.6	0.67	21	175	1.01	6								
2010-**21**-02	Red Hill sand	Typic Sandy Brown	Drystock	5.78	4.3	0.43	47	118	1.23	1	4	5.5	0.26	14	8	6	16	79
2015-**21**-04	Red Hill sand	Typic Sandy Brown	Drystock	5.32	4.3	0.45	39	155	1.02	3	7	6.7	0.31	16	10	7	9	51
1998-**22**-01	Red Hill sand	Typic Sandy Brown	Forestry	5.27	5.3	0.49	22	79	0.76	35								
2011-**22**-02	Red Hill sand	Typic Sandy Brown	Forestry	6.3	4.0	0.35	32	141	1.18	16	22	5.9	0.17	16	7	6	8	78
2016-**22**-03	Red Hill sand	Typic Sandy Brown	Forestry	6.37	4.1	0.36	32	83	0.91	28	37	6.2	0.18	16	7	6	9	66
1998-**23**-01	Red Hill sand	Typic Sandy Brown	Forestry	4.9	11.0	0.76	76	89	0.91	18								
2011-**23**-02	Red Hill sand	Typic Sandy Brown	Forestry	5.69	3.2	0.24	25	59	0.95	25	32	6.6	0.1	11	6	5	7	29
2016-**23**-03	Red Hill sand	Typic Sandy Brown	Forestry	5.89	3.9	0.28	10	68	1.00	21	29	6.3	0.12	14	6	4	5	28
1998-**24**-01	Red Hill sand	Typic Sandy Brown	Forestry	5.53	9.4	0.86	14	170	0.64	23								
2011-**24**-02	Red Hill sand	Typic Sandy Brown	Drystock	5.81	3.8	0.40	35	86	1.10	4	9	7.2	0.22	16	10	7	7	51
2016-**24**-03	Red Hill sand	Typic Sandy Brown	Drystock	5.52	4.3	0.46	44	130	1.11	7	10	5.4	0.4	14	9	6	6	43

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1998-**25**-01	Red Hill sand	Typic Sandy Brown	Dairy	5.46	7.1	0.65	15	106	1	7								
2009-**25**-02	Red Hill sand	Typic Sandy Brown	Dairy-Drystock	5.71	4.5	0.45	72	113	1.15	4	9	5.9	0.46	17	11	7	7	53
2014-**25**-04	Red Hill sand	Typic Sandy Brown	Dairy-Drystock	5.45	4.0	0.43	55	160	1.07	2	5	5.4	0.42	14	9	5	6	43
1998-**27**-01	Waikare clay	Perch-gley Albic Ultic	Drystock	5.64	8.5	0.77	14	214	0.64	11								
2010-**27**-02	Waikare clay	Perch-gley Albic Ultic	Drystock	6.3	9.2	0.90	34	271	0.73	6	9	1.8	0.51	5	15	5	7	32
2015-**27**-04	Waikare clay	Perch-gley Albic Ultic	Drystock	6.06	8.1	0.77	40	218	0.70	6	10	7.6	0.39	5	20	15	35	32
1998-**28**-01	Waikare clay	Perch-gley Albic Ultic	Dairy	6.13	7.6	0.65	21	185	0.94	12								
2009-**28**-02	Waikare clay	Perch-gley Albic Ultic	Dairy	6.28	7.1	0.62	40	153	1.04	4	6	0.9	0.45	5	5	2	4	12
2014-**28**-04	Waikare clay	Perch-gley Albic Ultic	Dairy	6.39	4.6	0.37	9	71	0.99	5	9	0.5	0.24	3	3	2	3	5
1998-**30**-01	Whakapara silt loam	Weathered Fluvial Recent	Drystock	5.67	6.6	0.60	36	150	0.92	12								
2010-**30**-02	Whakapara silt loam	Weathered Fluvial Recent	Drystock	5.88	3.9	0.37	36	145	1.12	4	6	1.1	0.23	12	9	4	4	<66
2015-**30**-04	Whakapara silt loam	Weathered Fluvial Recent	Drystock	5.97	3.5	0.33	52	134	0.98	3	5	1.2	0.23	11	9	4	4	24
1998-**33**-01	Warkworth clay loam	Typic Yellow Ultic	Dairy	6.73	6.4	0.58	113	137	1.01	7								
2009-**33**-02	Warkworth clay loam	Typic Yellow Ultic	Dairy-Drystock	5.89	6.3	0.58	66	219	0.95	5	7	1.9	0.37	14	13	5	9	54
2014-**33**-04	Warkworth clay loam	Typic Yellow Ultic	Dairy-Drystock	6.25	5.8	0.57	79	198	0.74	4	8	2.4	0.52	13	19	7	8	68
1998-**35**-01	Whangaripo clay loam	Typic Yellow Ultic	Dairy	6.07	5.3	0.50	60	134	0.95	14								
2009-**35**-02	Whangaripo clay loam	Typic Yellow Ultic	Dairy-Drystock	6.16	6.5	0.60	52	180	0.98	4	6	1.8	0.46	13	8	3	4	31
2014-**35**-04	Whangaripo clay loam	Typic Yellow Ultic	Dairy-Drystock	6	6.7	0.53	37	139	1.04	2	3	2.0	0.38	12	8	3	3	26

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1998-**37**-01	Waitemata silt loam	Weathered Fluvial Recent	Outdoor vegetable	5.34	3.8	0.31	112	40	1	22								
2008-**37**-02	Waitemata silt loam	Weathered Fluvial Recent	Outdoor vegetable	7.2	5.2	0.36	44	72	1.21	2	4	3.1	0.35	11	20	3	15	21
2013-**37**-03	Waitemata silt loam	Weathered Fluvial Recent	Veg-Lifestyle	6.22	5.0	0.37	32	93	1.21	2	3	8.9	0.35	17	26	7	21	28
1999-**38**-01	Matekawau clay loam	Typic Orthic Allophanic	Dairy	6.33	7.4	0.67	32	135	0.92	3		4.8	0.74	19	11	6	14	40
2009-**38**-02	Matekawau clay loam	Typic Orthic Allophanic	Dairy	6.37	6.2	0.54	44	135	1.13	2	4	5.3	0.91	22	14	8	22	44
2014-**38**-04	Matekawau clay loam	Typic Orthic Allophanic	Dairy	5.84	5.9	0.54	31	128	1.15	<1	1	6.7	0.50	21	13	6	21	38
1999-**39**-01	Matekawau hills soils	Typic Orthic Allophanic	Native	5.93	8.3	0.48	3	138	0.68	31		7.9	0.11	16	11	8	26	75
2012-**39**-02	Matekawau hills soils	Typic Orthic Allophanic	Native	5.9	6.3	0.35	3	151	0.76	18	22	3.3	0.09	7	4	3	10	43
2017-**39**-07	Matekawau hills soils	Typic Orthic Allophanic	Native	5.75	7.6	0.43	3	122	0.9	18	20	4.5	0.07	9	5	3	10	32
1999-**40**-01	Red Hill sandy loam	Typic Orthic Brown Soil	Native	5.56	9.4	0.45	3	165	0.65	31		4.8	0.11	16	7	6	13	36
2012-**40**-02	Red Hill sandy loam	Typic Orthic Brown Soil	Native	5.8	9.6	0.49	2	141	0.56	26	29	3.2	0.06	10	7	4	11	25
2017-**40**-03	Red Hill sandy loam	Typic Orthic Brown Soil	Native	5.52	8.7	0.46	3	161	0.7	17	20	4.8	0.05	13	7	4	11	29
1999-**41**-01	Ardmore peaty loam	Mellow Humic Organic	Orchard	6.82	16.1	1.34	78	171	0.45	8		4.5	1.30	23	21	6	14	49
2008-**41**-02	Ardmore peaty loam	Mellow Humic Organic	Orchard	6.51	15.4	1.21	52	139	0.62	6	3	4.3	1.60	20	25	7	18	88
2013-**41**-03	Ardmore peaty loam	Mellow Humic Organic	Orchard	6.79	15.3	1.29	122	165	0.54	9	11	5.0	2.00	28	38	10	16	160
1999-**42**-01	Ardmore peaty loam	Mellow Humic Organic	Dairy	5.75	24.1	1.57	66	197	0.64	6		2.8	0.63	11	22	4	13	57
2009-**42**-02	Ardmore peaty loam	Mellow Humic Organic	Dairy-Horse stud	6	23.0	1.81	87	381	0.60	3	7	2.2	0.96	13	32	6	13	60
2014-**42**-04	Ardmore peaty loam	Mellow Humic Organic	Dairy-Horse Stud	5.65	23.8	1.84	77	309	0.59	1	3	2.6	0.89	11	30	4	12	49

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1999-**43**-01	Ardmore loamy peat	Mellow Humic Organic	Dairy	5.91	23.8	1.70	60	245	0.58	4		2.2	1.10	14	27	4	10	40
2009-**43**-02	Ardmore loamy peat	Mellow Humic Organic	Dairy-Horse stud	5.91	18.1	1.57	76	313	0.66	2	5	3.0	1.00	14	29	5	19	64
2014-**43**-04	Ardmore loamy peat	Mellow Humic Organic	Dairy-Horse stud	5.72	18.4	1.57	72	301	0.58	8	10	3.0	0.93	13	22	4	15	48
1999-**45**-01	Ararimu clay	Typic Orthic Granular	Native	4.13	13.0	0.64	40	97	0.88	12		3.4	0.05	5	7	2	18	18
2012-**45**-02	Ararimu clay	Typic Orthic Granular	Native	4.4	10.4	0.55	3	84	0.64	25	27	3.9	0.04	5	5	1	16	13
2017-**45**-07	Ararimu clay	Typic Orthic Granular	Native	4.18	7.8	0.41	4	51	0.8	18	20	5.0	0.03	5	4	1	17	13
1999-**46**-01	Ararimu clay	Typic Orthic Granular	Drystock	5.76	7.5	0.62	53	167	0.95	6		4.4	0.34	9	12	3	62	39
2010-**46**-02	Ararimu clay	Typic Orthic Granular	Dairy	5.74	8.2	0.73	87	243	0.95	5	7	6.1	0.53	10	18	3	28	76
2015-**46**-04	Ararimu clay	Typic Orthic Granular	Drystock	5.59	8.4	0.77	89	163	0.91	5	8	6.4	0.53	10	20	3	63	95
1999-**47**-01	Ararimu clay loam	Typic Orthic Granular	Dairy	6.12	7.0	0.59	16	165	0.92	6		3.2	0.61	6	5	3	15	21
2009-**47**-02	Ararimu clay loam	Typic Orthic Granular	Dairy-Drystock	5.85	6.0	0.56	75	205	1.02	1	3	2.2	0.69	7	5	3	13	27
2014-**47**-04	Ararimu clay loam	Typic Orthic Granular	Dairy-Drystock	5.79	7.8	0.72	58	212	0.98	6	8	3.1	0.77	8	6	3	15	28
1999-**48**-01	Marua clay loam	Typic Orthic Brown	Drystock	5.52	4.5	0.33	50	108	1.06	6		1.7	0.44	6	7	2	5	18
2010-**48**-02	Marua clay loam	Typic Orthic Brown	Drystock	5.5	4.8	0.39	18	128	1.13	6	9	1.3	0.36	5	6	2	5	13
2015-**48**-04	Marua clay loam	Typic Orthic Brown	Drystock	5.51	4.5	0.37	20	105	1.04	6	9	2.1	0.37	6	5	2	5	16

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1999-**49**-01	Marua clay loam	Typic Orthic Brown	Native	6.26	5.9	0.41	12	109	1.06	13		4.4	0.17	7	14	8	27	70
2012-**49**-02	Marua clay loam	Typic Orthic Brown	Native	6.5	4.7	0.33	25	116	0.97	11	13	4.6	0.19	11	19	4	20	51
2017-**49**-07	Marua clay loam	Typic Orthic Brown	Native	6.33	4.5	0.33	11	110	0.9	9	11	6.0	0.16	10	20	6	20	57
1999-**50**-01	Pinaki sand	Typic Sandy Recent	Drystock	6.1	4.3	0.35	18	91	0.88	22		5.1	0.12	7	5	3	2	23
2010-**50**-02	Pinaki sand	Typic Sandy Recent	Drystock	6.01	4.7	0.42	15	115	1.08	12	23	4.6	0.10	8	4	4	3	<68
2015-**50**-04	Pinaki sand	Typic Sandy Recent	Drystock	5.82	3.5	0.33	17	79	1.27	3	10	5.4	0.13	8	5	4	3	24
1999-**51**-01	Pinaki sand	Typic Sandy Recent	Drystock	5.49	2.9	0.21	15	44	1.17	15		5.3	0.03	7	3	4	2	20
2010-**51**-02	Pinaki sand	Typic Sandy Recent	Drystock	5.46	4.3	0.35	35	97	0.99	16	27	5.5	<0.091	8	5	4	4	<68
2015-**51**-04	Pinaki sand	Typic Sandy Recent	Drystock	5.55	3.7	0.32	18	73	1.02	12	19	5.6	0.05	8	5	4	10	26
1999-**52**-01	Pinaki sand	Typic Sandy Recent	Native	5.31	3.9	0.20	5	64	0.99	27		5.0	0.02	8	3	4	2	20
2012-**52**-02	Pinaki sand	Typic Sandy Recent	Native	5.8	2.9	0.19	12	57	0.98	29	38	5.8	0.02	8	2	4	2	20
2017-**52**-07	Pinaki sand	Typic Sandy Recent	Native	5.50	2.4	0.17	12	56	1.2	21	31	6.9	0.02	8	3	4	3	23
1999-**53**-01	Aponga clay	Mottled Yellow Ultic	Dairy	6.02	8.7	0.68	17	204	0.84	13		2.0	0.42	5	11	3	8	25
2009-**53**-02	Aponga clay	Mottled Yellow Ultic	Dairy-Drystock	6.35	13.9	1.21	119	529	0.53	9	11	3.0	0.42	8	17	5	6	51
2014-**53**-04	Aponga clay	Mottled Yellow Ultic	Dairy-Drystock	6.46	10.7	0.94	55	344	0.53	3	7	2.6	0.56	8	15	6	6	28
1999-**55**-01	Aponga clay	Mottled Yellow Ultic	Dairy	5.55	10.6	0.88	12	350	0.62	6		2.2	0.49	8	12	5	7	31
2009-**55**-02	Aponga clay	Mottled Yellow Ultic	Dairy-Drystock	6.28	8.2	0.71	24	226	0.90	3	5	2.2	0.42	7	12	5	8	17
2014-**55**-04	Aponga clay	Mottled Yellow Ultic	Dairy-Drystock	6.45	10.3	0.93	30	362	0.58	3	6	2.5	0.59	8	12	5	9	19

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
1999-**56**-01	Cornwallis clay	Typic Orthic Granular	Native	6.55	11.7	0.66	10	235	0.71	15		2.7	0.18	24	14	6	15	43
2012-**56**-02	Cornwallis clay	Typic Orthic Granular	Native	6.2	9.2	0.54	12	198	0.68	19	21	3.0	0.15	13	29	6	9	45
2017-**56**-07	Cornwallis clay	Typic Orthic Granular	Native	5.88	6.3	0.41	7	130	0.8	10	13	4.4	0.09	10	11	6	10	34
1999-**57**-01	Parau clay loam	Typic Orthic Granular	Native	5.44	9.3	0.40	1	110	0.83	5		2.6	0.06	32	17	9	11	47
2012-**57**-02	Parau clay loam	Typic Orthic Granular	Native	5.7	11.5	0.57	7	234	0.74	12	10	2.5	0.07	31	13	11	13	48
2017-**57**-03	Parau clay loam	Typic Orthic Granular	Native	5.54	5.5	0.33	4	118	0.9	8	11	1.3	0.06	25	12	11	10	42
1999-**58**-01	Pinaki sand	Typic Sandy Recent	Forestry	5.72	4.2	0.26	5	62	0.89	28		5.8	0.02	7	3	3	3	22
2011-**58**-02	Pinaki sand	Typic Sandy Recent	Forestry	5.66	1.8	0.06	5	19	1.48	30	39	8.6	0.01	7	3	4	2	19
2016-**58**-03	Pinaki sand	Typic Sandy Recent	Forestry	5.58	1.3	0.05	9	18	1.29	31	38	9.1	0.09	5	2	3	2	15
1999-**60**-01	Pinaki sand	Typic Sandy Recent	Forestry	5.89	0.9	0.04	6	9	1.02	43		7.5	<0.01	6	2	3	2	16
2011-**60**-02	Pinaki sand	Typic Sandy Recent	Forestry	5.18	1.6	0.05	15	12	1.52	30	37	7.3	0.01	9	3	5	2	23
2016-**60**-03	Pinaki sand	Typic Sandy Recent	Forestry	4.96	1.6	0.06	15	10	1.56	29	36	6.8	0.09	6	2	4	3	20
1999-**61**-01	Parau clay	Typic Orthic Granular	Drystock	5.46	7.4	0.60	9	171	1	3		2.2	0.29	16	7	3	6	17
2010-**61**-02	Parau clay	Typic Orthic Granular	Drystock-Lifestyle	5.96	9.2	0.82	19	266	0.98	4	6	2.4	0.45	12	8	2	6	22
2015-**61**-04	Parau clay	Typic Orthic Granular	Drystock-Lifestyle	5.69	6.1	0.55	12	186	0.88	3	6	2.4	0.40	10	6	2	6	15
1999-**62**-01	Otao silt loam	Typic Orthic Allophanic	Dairy	5.68	6.1	0.54	22	56	1.08	2		4.9	0.55	10	7	3	13	26
2009-**62**-02	Otao silt loam	Typic Orthic Allophanic	Dairy	6.14	4.5	0.39	58	107	1.26	2	2	0.9	0.42	5	4	2	5	16
2014-**62**-04	Otao silt loam	Typic Orthic Allophanic	Dairy	5.97	5.3	0.45	39	111	1.08	4	6	4.4	0.36	8	5	3	11	26

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2000-**63**-01	Karaka silt loam	Typic Orthic Allophanic	Drystock	6.59	7.5	0.64	30	204	0.77	14	18	21.0	0.60	22	24	7	36	59
2010-**63**-02	Karaka silt loam	Typic Orthic Allophanic	Drystock-Lifestyle	5.85	8.9	0.82	23	206	0.81	9	13	5.4	0.74	13	13	8	18	33
2015-**63**-04	Karaka silt loam	Typic Orthic Allophanic	Drystock-Lifestyle	5.83	8.4	0.76	20	130	0.76	4	7	5.6	0.73	13	13	7	18	34
2000-**64**-01	Karaka silt loam	Typic Orthic Allophanic	Dairy	6.85	7.9	0.72	86	246	0.86	12	10	4.9	0.67	13	12	6	16	54
2009-**64**-02	Karaka silt loam	Typic Orthic Allophanic	Dairy	6.28	7.9	0.75	96	200	0.96	3	6	4.8	0.69	13	18	5	18	54
2014-**64**-04	Karaka silt loam	Typic Orthic Allophanic	Dairy	6.37	7.2	0.69	79	155	1.00	<1	2	5.1	0.59	12	13	5	17	43
2000-**65**-01	Karaka silt loam	Typic Orthic Allophanic	Orchard	6.57	6.1	0.47	63	139	0.96	18	19	4.4	0.67	14	13	4	19	28
2008-**65**-02	Karaka silt loam	Typic Orthic Allophanic	Orchard	6.81	5.8	0.47	61	72	1.07	7	9	5.4	0.75	15	16	6	20	37
2013-**65**-03	Karaka silt loam	Typic Orthic Allophanic	Orchard	6.53	5.3	0.43	84	50	0.97	21	23	7.0	0.77	21	17	8	20	46
2000-**66**-01	Matakawau sandy loam	Typic Orthic Allophanic	Dairy	6	8.1	0.71	7	203	0.86	8	13	4.7	0.77	14	12	5	12	51
2009-**66**-02	Matakawau sandy loam	Typic Orthic Allophanic	Dairy-Lifestyle	5.95	8.5	0.77	12	218	0.93	4	7	5.1	0.66	17	28	5	14	58
2014-**66**-04	Matakawau sandy loam	Typic Orthic Allophanic	Dairy-Lifestyle	5.96	8.4	0.78	10	210	0.91	8	12	5.7	0.58	14	22	5	13	44
2000-**67**-01	Matakawau sandy clay loam	Typic Orthic Allophanic	Orchard	6.24	4.8	0.38	14	162	1.16	14	16	2.6	0.23	9	20	2	10	21
2008-**67**-02	Matakawau sandy clay loam	Typic Orthic Allophanic	Orchard	6.68	4.8	0.41	42	115	1.07	15	18	4.4	0.38	13	23	3	19	55
2013-**67**-03	Matakawau sandy clay loam	Typic Orthic Allophanic	Orchard	5.45	4.9	0.42	13	124	0.92	20	22	6.1	0.28	16	8	5	18	29

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2000-**68**-01	Matakawau sandy loam	Typic Orthic Allophanic	Outdoor vegetable	5.76	5.8	0.46	72	78	1.16	0	1	5.1	0.67	19	12	5	13	51
2008-**68**-02	Matakawau sandy loam	Typic Orthic Allophanic	Outdoor vegetable	6.09	7.6	0.65	29	135	0.98	4	8	6.3	0.66	18	10	5	11	47
2013-**68**-03	Matakawau sandy loam	Typic Orthic Allophanic	Veg-Drystock	5.95	7.1	0.66	53	127	0.93	5	8	7.2	0.74	22	15	7	12	72
2000-**69**-01	Patumahoe silt loam	Typic Orthic Granular	Drystock	6.05	8.1	0.73	12	271	0.84	12	14	5.1	0.47	16	13	6	17	38
2010-**69**-02	Patumahoe silt loam	Typic Orthic Granular	Drystock-Lifestyle	6.04	8.7	0.80	12	266	0.86	8	11	6.4	0.45	18	13	6	21	43
2015-**69**-04	Patumahoe silt loam	Typic Orthic Granular	Drystock-Lifestyle	5.84	6.5	0.64	12	157	0.80	9	12	8.0	0.44	21	12	4	26	37
2000-**70**-01	Patumahoe silt loam	Typic Orthic Granular	Outdoor vegetable	6.36	5.6	0.46	18	145	0.83	25	26	4.2	0.47	16	14	4	23	30
2008-**70**-02	Patumahoe silt loam	Typic Orthic Granular	Outdoor vegetable	7.02	5.1	0.45	21	91	1.06	13	15	6.1	0.55	18	18	6	31	45
2013-**70**-03	Patumahoe silt loam	Typic Orthic Granular	Outdoor vegetable	7.2	4.1	0.38	48	48	0.98	21	22	7.5	0.47	24	25	10	27	53
2000-**71**-01	Ardmore humic loam	Mellow Humic Organic	Nursery	6.4	19.9	0.80	30	59	0.74	11	5	2.9	0.5	14	21	3	11	25
2008-**71**-02	Ardmore humic loam	Mellow Humic Organic	Nursery	6.41	20.0	0.82	27	63	0.63	7	8	2.5	0.53	16	22	4	12	27
2013-**71**-03	Ardmore humic loam	Mellow Humic Organic	Nursery	6.2	14.5	0.68	27	165	0.65	14	18	4.6	0.37	18	27	5	14	37
2000-**72**-01	Marua clay	Acidic Orthic Brown	Forestry	5.08	4.7	0.19	5	56	1.05	18	19	3.8	0.03	6	11	1	15	19
2011-**72**-02	Marua clay	Acidic Orthic Brown	Forestry	5.32	3.0	0.18	4	97	1.10	6	8	5.2	0.03	20	15	8	23	23
2016-**72**-03	Marua clay	Acidic Orthic Brown	Forestry	5.51	3.3	0.22	5	91	1.03	8	10	4.0	0.09	7	11	2	20	20

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2000-**73**-01	Kaipara clay	Typic Orthic Gley	Dairy	5.9	6.7	0.54	71	240	1.02	4	4	5.6	0.38	11	11	5	8	36
2009-**73**-02	Kaipara clay	Typic Orthic Gley	Dairy-Drystock	6.25	7.1	0.66	75	195	0.95	4	6	7.0	0.39	11	12	5	8	34
2014-**73**-04	Kaipara clay	Typic Orthic Gley	Dairy-Drystock	5.88	6.7	0.64	63	215	0.86	8	10	7.1	0.36	10	11	4	7	31
2000-**74**-01	Kaipara clay	Typic Orthic Gley	Drystock	5.5	6.6	0.56	42	251	0.84	10	12	7.6	0.36	10	13	5	8	32
2010-**74**-02	Kaipara clay	Typic Orthic Gley	Drystock	5.55	8.0	0.75	34	333	0.93	1	5	5.9	0.35	11	14	5	8	36
2015-**74**-04	Kaipara clay	Typic Orthic Gley	Drystock	5.62	6.8	0.64	29	191	0.67	5	9	7.0	0.38	11	13	6	8	38
2000-**75**-01	Waitemata complex	Typic Orthic Granular	Dairy	6.03	7.0	0.58	72	194	1.03	7	8	3.8	0.65	13	11	4	12	41
2009-**75**-02	Waitemata complex	Typic Orthic Granular	Dairy-Drystock	5.83	7.3	0.66	90	200	1.06	4	6	4.6	0.7	15	12	4	17	58
2014-**75**-04	Waitemata complex	Typic Orthic Granular	Dairy-Lifestyle	5.83	6.7	0.63	50	156	1.03	2	4	5.2	0.57	14	12	3	15	26
2000-**76**-01	Waitemata complex	Typic Orthic Gley	Drystock	5.99	6.2	0.49	86	231	1.00	9	12	0.8	0.84	6	6	3	4	27
2010-**76**-02	Waitemata complex	Typic Orthic Gley	Drystock	5.83	7.0	0.63	82	173	1.03	3	5	1.3	0.89	6	4	3	6	13
2015-**76**-04	Waitemata complex	Typic Orthic Gley	Drystock	5.72	4.9	0.46	70	116	0.91	4	6	0.7	0.74	5	3	2	4	11
2000-**77**-01	Waitemata complex	Typic Orthic Gley	Dairy	6.02	5.8	0.47	7	226	0.98	7	10	0.9	0.33	6	22	3	5	14
2009-**77**-02	Waitemata complex	Typic Orthic Gley	Dairy-Lifestyle	5.85	5.9	0.53	15	172	1.00	5	8	0.7	0.25	4	18	2	10	17
2014-**77**-04	Waitemata complex	Typic Orthic Gley	Dairy-Lifestyle	5.84	5.5	0.49	12	163	0.93	4	9	0.7	0.22	3	12	2	4	11
2000-**78**-01	Warkworth clay loam	Typic Yellow Ultic	Drystock	6.38	5.4	0.45	16	244	0.85	10	13	1.0	0.43	16	12	2	5	20
2010-**78**-02	Warkworth clay loam	Typic Yellow Ultic	Drystock-Lifestyle	6.08	5.0	0.36	21	130	1.16	4	11	1.4	0.19	11	7	2	7	14
2015-**78**-04	Warkworth clay loam	Typic Yellow Ultic	Drystock-Lifestyle	5.95	4.0	0.39	22	102	1.07	2	4	1.8	0.29	19	10	4	11	32

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2000-**79**-01	Warkworth clay loam	Typic Yellow Ultic	Outdoor vegetable	6.33	3.9	0.28	17	153	0.99	2	4	1.3	0.2	22	11	3	7	38
2008-**79**-02	Warkworth clay loam	Typic Yellow Ultic	Outdoor vegetable	6.2	4.6	0.32	15	102	1.02	3	5	1.2	0.17	23	10	4	7	34
2013-**79**-03	Warkworth clay loam	Typic Yellow Ultic	Veg-Lifestyle	6.34	3.5	0.30	40	73	1.08	6	7	3.1	0.19	22	7	4	10	30
2000-**80**-01	Warkworth clay loam	Typic Yellow Ultic	Viticulture	5.84	4.9	0.40	16	158	0.97	17	19	0.8	0.37	13	9	1	3	12
2008-**80**-02	Warkworth clay loam	Typic Yellow Ultic	Viticulture	5.57	5.3	0.45	19	105	1.07	7	7	0.9	0.35	16	14	1	3	18
2013-**80**-03	Warkworth clay loam	Typic Yellow Ultic	Viticulture	5.64	4.4	0.38	19	79	1.02	10	11	1.6	0.33	17	18	2	4	18
2000-**81**-01	Warkworth clay loam	Typic Yellow Ultic	Orchard	5.77	5.1	0.37	17	155	0.93	10	12	1.4	0.10	9	9	2	8	26
2008-**81**-02	Warkworth clay loam	Typic Yellow Ultic	Orchard	6.11	5.0	0.39	15	150	1.01	5	8	1.6	0.07	8	6	2	6	22
2013-**81**-03	Warkworth clay loam	Typic Yellow Ultic	Orchard-Lifestyle	5.99	4.8	0.40	23	98	0.89	9	12	2.1	0.09	12	6	3	9	27
2000-**82**-01	Waitemata complex	Mottled Orthic Brown	Orchard	5.94	5.8	0.48	44	228	1.05	9	11	1.1	0.18	9	40	1	6	18
2008-**82**-02	Waitemata complex	Mottled Orthic Brown	Orchard	5.89	5.5	0.48	37	126	1.01	6	9	1.4	0.22	13	28	1	8	19
2013-**82**-03	Warkworth clay loam	Mottled Orthic Brown	Orchard	6.05	5.7	0.53	55	126	0.94	8	10	2.2	0.22	11	35	2	7	17
2000-**83**-01	Waitemata complex	Mottled Orthic Brown	Native	5.72	5.5	0.28	36	124	1.05	10	12	1.1	<0.09	7	4	1	7	27
2012-**83**-02	Waitemata complex	Mottled Orthic Brown	Native	5.8	7.0	0.40	21	150	0.85	13	16	1.0	0.03	7	5	1	7	20
2017-83-03	Waitemata complex	Mottled Orthic Brown	Native	5.56	5.1	0.31	36	97	1.0	7	10	1.5	0.06	7	3	1	9	19
2000-**84**-01	Cornwallis clay	Typic Orthic Granular	Drystock	6.5	7.7	0.59	12	270	0.95	5	5	1.0	0.30	24	10	3	10	11
2010-**84**-02	Cornwallis clay	Typic Orthic Granular	Drystock	6.59	6.2	0.56	47	190	1.07	1	3	1.5	0.40	11	7	3	7	13
2015-**84**-04	Cornwallis clay	Typic Orthic Granular	Drystock	6.56	6.2	0.58	45	165	0.80	7	10	1.8	0.44	14	9	4	9	17

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2000-**85**-01	Waitemata complex	Mottled Orthic Brown	Native	4.54	5.8	0.27	2	57	1.07	10	14	0.9	0.01	3	5	1	9	6
2012-**85**-02	Waitemata complex	Mottled Orthic Brown	Native	4.9	6.9	0.36	3	60	1.01	9	10	1.1	0.01	3	4	1	9	6
2017-**85**-07	Waitemata complex	Mottled Orthic Brown	Native	5.01	3.7	0.21	4	59	1.0	5	8	1.6	0.01	11	7	3	8	15
2000-**86**-01	Waitemata complex	Typic Orthic Gley	Viticulture	5.8	3.5	0.24	144	91	1.40	8	8	1.0	0.42	5	84	5	7	29
2008-**86**-02	Waitemata complex	Typic Orthic Gley	Viticulture	6.19	4.3	0.33	115	81	1.28	3	5	0.9	0.42	4	47	3	7	24
2013-**86**-03	Waitemata complex	Typic Orthic Gley	Viticulture	5.97	4.1	0.34	133	86	0.95	16	18	1.1	0.43	7	120	5	8	31
2000-**87**-01	Waitemata complex	Typic Orthic Gley	Orchard	5.87	3.4	0.20	107	115	1.23	13	16	0.9	0.36	3	72	2	5	21
2008-**87**-02	Waitemata complex	Typic Orthic Gley	Orchard	6.29	3.9	0.26	79	72	1.25	5	7	1.2	0.35	3	110	2	8	26
2013-**87**-03	Waitemata complex	Typic Orthic Gley	Orchard	6.05	3.1	0.21	56	30	1.41	1	1	0.8	0.20	5	61	3	5	10
2000-**88**-01	Waitemata complex	Typic Orthic Gley	Outdoor vegetable	6.18	2.7	0.16	119	34	1.35	4	6	1.2	0.23	4	18	2	7	13
2008-**88**-02	Waitemata complex	Typic Orthic Gley	Outdoor vegetable	5.97	3.1	0.18	57	25	1.18	9	11	2.2	0.22	4	11	2	7	15
2013-**88**-03	Waitemata complex	Typic Orthic Gley	Orchard	6.36	3.0	0.21	73	22	1.35	2	3	1.9	0.19	6	9	3	14	46
2016-**89**-02	Whangaripo clay loam	Typic Yellow Ultic	Forestry	4.56	5.2	0.31	20	47	0.86	6	9	1.4	0.14	14	15	4	6	19
2016-**90**-02	Whangaripo clay loam	Typic Yellow Ultic	Forestry	4.95	7.1	0.39	7	132	0.71	24	26	1.2	0.09	12	7	2	6	8
2016-**91**-02	Pinaki sand	Typic Sandy Recent	Forestry	5.77	1.9	0.1	12	38	1.49	32	38	9.8	0.09	5	3	3	2	17
2016-**92**-02	Hukerenui	Albic Ultic	Forestry	5.06	7.0	0.27	7	69	1.07	13	14	2.2	0.09	8	3	1	9	7
2016-**93**-02	Hukerenui	Albic Ultic	Forestry	4.85	4.8	0.18	4	27	1.17	20	22	1.3	0.09	3	3	1	3	7
2016-**94**-02	Rangiora	Mottled Ultic	Forestry	4.96	3.5	0.17	5	57	1.28	6	7	1.1	0.09	4	4	1	5	7
2016-**95**-02	Mahurangi	Albic Ultic	Forestry	5.04	4.4	0.2	18	41	1.19	11	13	1.1	0.09	2	1	1	3	7

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2016-**96**-02	Mahurangi	Albic Ultic	Forestry	5.08	5.7	0.22	21	34	1.11	6	6	2.3	0.12	4	5	3	4	18
2017-**97**-02	Marua brown clay loam	Mafic Ultic	Native	5.05	2.8	0.20	4	68	1.4	14	16	16.0	0.08	3	180	18	26	29
2017-**98**-02	Marua clay loam	Typic Yellow Ultic	Native	4.99	4.5	0.28	5	117	1.0	11	13	5.0	0.03	8	11	3	17	33
2017-**99**-02	Marua clay loam	Typic Yellow Ultic	Native	4.53	13.7	0.72	3	122	0.6	16	18	7.4	0.04	12	15	5	17	28
2017-**100**-06	Marua clay loam	Typic Yellow Ultic	Native	4.60	7.8	0.42	4	105	0.7	15	18	5.8	0.03	8	14	3	13	29
2017-**101**-02	Te Ranga steepland	Typic Yellow Ultic	Native	4.68	8.9	0.56	5	192	0.6	7	10	4.3	0.02	5	6	2	12	19
2017-**102**-02	Waitakere clay	Typic Orthic Granular	Native	4.75	11.8	0.66	2	223	0.4	16	20	1.4	0.05	10	35	2	10	23
2017-**103**-06	Waitakere clay	Typic Orthic Granular	Native	4.55	12.3	0.60	2	180	0.5	12	16	1.8	0.04	10	12	3	15	14
2017-**104**-02	Huia steepland soil	Mafic Brown	Native	5.51	7.0	0.43	4	173	0.7	4	7	1.2	0.04	9	43	3	15	42
2017-**105**-06	Huia steepland soil	Mafic Brown	Native	6.71	3.0	0.23	3	106	1.2	8	11	3.3	0.04	18	6	6	7	51
2017-**107**-06	Mottled Waitakere clay	Mottled Orthic Granular	Native	5.00	7.3	0.41	3	163	0.7	11	14	1.6	0.03	8	16	2	12	16
2017-**108**-02	Te Kie	Weathered Orthic Recent	Native	5.07	6.0	0.39	4	146	0.9	6	7	1.3	0.03	21	10	3	14	21
2017-**109**-02	Te Kie	Weathered Orthic Recent	Native	4.70	5.3	0.29	3	115	0.9	9	11	1.7	0.01	11	5	1	7	9
2017-**110**-02	Parau clay loam	Typic Mafic Brown	Native	6.24	10.5	0.57	8	256	0.8	10	12	4.6	0.04	23	11	1	7	18

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2017-**111**-02	Awapuku	Mottled Mafic Brown	Native	5.45	6.3	0.50	4	207	0.7	6	8	1.9	0.06	10	18	4	9	38
2017-**112**-02	Te Kie	Weathered Orthic Recent	Native	4.69	7.9	0.32	0	107	0.8	10	12	1.1	0.02	20	3	2	7	11
2013-**113**-01	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	6.43	1.8	0.19	348	7	1.06	20	22	9.2	0.58	23	61	9	30	48
2013-**114**-01	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	6.13	2.5	0.22	148	9	1.16	15	16	8.4	0.56	24	49	10	31	40
2013-**115**-01	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	6.22	4.3	0.42	73	45	1.00	16	17	8.7	0.36	22	43	7	56	66
2013-**116**-01	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	7.07	2.0	0.16	187	7	0.98	27	29	9.2	0.47	26	43	10	31	36
2013-**117**-01	Patumahoe clay loam	Typic Orthic Granular	Outdoor vegetable	6.89	2.4	0.21	361	18	1.06	22	23	7.6	0.70	22	40	7	30	51
2013-**118**-01		Mottled Albic Ultic	Viticulture	6.62	4.2	0.34	11	78	1.04	12	14	3.3	0.15	8	12	3	13	18
2013-**119**-01		Mottled Albic Ultic	Viticulture	6.24	3.4	0.24	16	70	1.17	7	9	1.7	0.06	9	8	3	7	11
2013-**120**-01		Yellow Albic Ultic	Viticulture	6.28	4.0	0.32	28	96	1.15	4	6	4.0	0.15	13	44	4	18	33
2014-**121**-01	Kara Sandy Clay	Gley	Dairy	5.55	5.4	0.45	69	139	0.79	3	7	0.3	0.38	3	3	1	2	5
2014-**122**-01	Kara Sandy Loam	Gley	Dairy	5.78	4.7	0.35	39	86	0.92	4	7	0.2	0.27	4	3	1	2	8

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2014-**123**-01	Tangitiki Sandy Clay	Ultic	Dairy	6.2	11.8	1.02	44	187	0.69	2	6	<1.8	0.57	7	15	<5	4	<68
2014-**124**-01	Tawharanui Sandy Clay	Ultic	Dairy	5.85	7.5	0.59	80	193	0.77	2	7	6.8	0.70	11	12	5	2	<69
2014-**125**-01	Whareora clay loam and Waipuna clay	Brown	Dairy	6.63	8.4	0.82	56	326	0.90	4	6	3.5	0.68	8	17	<4	11	<66
2017-**201**-02		Anthropic	Urban	5.32	5.1	0.44	11	147	0.6	10	16	3.0	0.10	7	10	5	15	49
2017-**202**-02	Whareora clay loam	Recent	Urban	6.23	5.8	0.50	10	158	0.7	9	13	9.0	<0.10	11	23	15	28	58
2017-**203**-02	Whakapara	Recent	Urban	5.63	6.7	0.41	20	102	0.9	4	8	6.0	0.17	13	9	8	10	41
2017-**204**-02	Whananaki Sand	Recent	Urban	5.51	3.8	0.33	15	72	1.0	5	9	8.0	0.11	7	3	4	4	22
2017-**205**-02	Albany Clay	Ultic	Urban	6.19	5.6	0.47	109	154	0.7	8	12	4.0	0.24	15	29	7	27	49
2017-**206**-02	Albany Clay	Ultic	Urban	5.18	2.3	0.20	55	72	1.3	16	23	<2	<0.10	6	2	2	3	33
2017-**207**-02	Hukerenui	Ultic	Urban	5.29	2.7	0.19	5	59	1.0	7	12	<2	<0.10	6	4	3	8	14
2017-**208**-02	Whakapai clay loam	Granular	Urban	5.94	6.2	0.52	9	155	0.7	8	12	2.0	0.15	84	23	77	86	96
2017-**209**-02	Anthropic	Anthropic	Urban	5.77	6.5	0.55	28	202	0.7	7	12	4.0	0.12	31	22	36	82	79

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2017-**210-**02	Anthropic	Anthropic	Urban	5.55	4.4	0.34	9	106	0.9	7	11	<2	<0.10	6	6	4	9	16
2017-**213-**02	Coatesville silt loam	Allophanic	Urban	5.88	4.6	0.39	20	118	1.3	3	4	10.0	0.13	10	12	7	17	38
2017-**214-**02	Coatesville silt loam	Allophanic	Native	5.06	3.8	0.19	0	63	1.1	7	10	2.0	<0.10	9	4	3	12	12
2017-**215-**02	Mahurangi fine sandy loam	Ultic	Native	4.67	6.1	0.24	2	48	1.0	17	20	<2	<0.10	28	6	27	19	11
2017-**216-**02	Coatesville silt loam	Ultic	Native	5.12	5.0	0.33	20	87	1.0	9	12	<2	<0.10	9	5	6	23	18
2017-**217-**02	Kapu	Allophanic	Urban	5.63	5.0	0.42	10	73	0.6	13	17	2.0	<0.10	33	16	43	29	39
2017-**218-**02	Ohaeawai	Allophanic	Urban	6.12	9.8	0.79	18	231	0.8	8	12	5.0	0.34	101	50	193	75	173
2017-**219-**02	Anthropic	Anthropic	Urban	6.76	8.0	0.59	23	204	0.7	6	10	8.0	0.27	40	69	57	210	170
2017-**220-**02	Whangaripo Clay	Ultic	Urban	6.09	4.1	0.28	5	98	0.9	10	14	2.0	<0.10	13	13	17	31	44
2017-**221-**02	Albany Clay	Ultic	Urban	5.5	6.6	0.55	12	191	0.6	10	16	10.0	0.18	10	25	7	21	123
2017-**222-**02	Albany Clay	Ultic	Urban	5.27	5.5	0.42	14	158	0.6	12	17	4.0	0.13	8	19	6	21	28
2017-**223-**02	Whakapara clay/sandy clay	Gley	Urban	6.04	8.7	0.64	10	325	0.7	6	9	4.0	0.14	15	28	8	41	92

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2017-**224**-02	Anthropic	Anthropic	Urban	5.47	7.0	0.65	33	198	0.7	8	12	19.0	0.30	19	129	9	75	81
2017-**225**-02	Anthropic	Anthropic	Urban	5.43	6.5	0.55	46	221	0.7	10	14	4.0	0.12	9	35	5	26	55
2017-**226**-02	Anthropic	Anthropic	Urban	5.94	5.9	0.52	41	178	0.8	5	9	5.0	0.14	25	23	21	47	73
2017-**227**-02	Whangaripo clay loam	Ultic	Urban	5.77	5.5	0.41	5	124	0.8	5	8	4.0	0.11	14	24	16	99	69
2017-**228**-02	Ohaewai/ Whakapai	Granular	Native	4.66	9.2	0.45	9	92	0.6	20	25	3.0	<0.10	5	10	6	59	44
2017-**229**-02	Kiripaka	Allophanic	Urban	6.24	5.7	0.42	46	128	0.9	8	11	8.0	0.48	36	77	39	198	340
2017-**233**-02	Papakauri silt loam	Allophanic	Urban	5.94	6.2	0.51	22	167	0.9	1	4	8.0	0.16	56	38	67	78	108
2017-**234**-02	Papakauri silt loam	Allophanic	Urban	5.9	6.9	0.60	75	217	0.6	5	10	5.0	0.21	30	23	26	62	152
2017-**235**-06	Whakapai	Granular	Native	5.85	6.3	0.50	12	191	0.9	7	10	3.0	<0.10	19	10	9	24	40
2017-**236**-02	Anthropic	Anthropic	Urban	6.03	4.0	0.39	36	113	1.0	7	11	8.0	0.12	19	24	21	53	68
2017-**237**-02	Whananaki sand	Recent	Urban	5.24	7.3	0.64	10	143	0.8	7	11	6.0	<0.10	13	14	18	22	44
2017-**238**-02	Kiripaka	Allophanic	Urban	5.65	5.6	0.53	32	179	0.7	9	13	5.0	0.32	42	37	27	21	62

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2017-**239**-02	Ohaeawai	Allophanic	Urban	5.4	16.9	1.55	22	243	0.6	5	8	3.0	0.41	46	49	108	38	158
2017-**241**-02	Whangamarie clay	Recent	Urban	5.53	8.6	0.75	34	319	0.6	8	12	3.0	0.11	31	55	17	41	70
2017-**242**-02	Brookby clay	Ultic	Native	5.78	4.5	0.25	5	77	1.1	10	13	3.0	<0.10	16	4	5	21	18
2017-**243**-02	Hukerenui	Ultic	Native	4.94	6.3	0.38	5	77	0.9	10	14	<2	<0.10	5	4	<2	9	8
2017-**245**-02	Warkworth clay loam	Ultic	Native	4.69	6.4	0.33	4	61	0.8	15	19	<2	<0.10	7	4	3	20	16
2017-**249**-02	Mahurangi fine sandy loam	Ultic	Native	5.24	6.2	0.37	4	108	1.0	12	14	<2	<0.10	10	5	2	17	18
2017-**251**-02	Kiripaka	Allophanic	Urban	5.86	6.0	0.58	34	123	1.0	0	1	4.0	0.4	68	37	111	32	112
2017-**252**-02	Anthropic	Anthropic	Urban	6.05	5.3	0.43	42	184	0.8	5	7	7.0	0.3	54	44	55	83	124
2017-**256**-02	Papakauri stonyloam	Allophanic	Urban	5.97	7.8	0.65	73	240	0.7	5	8	3.0	0.14	53	36	68	22	102
2017-**257**-02	Ohaeawai stony loam	Allophanic	Urban	6.02	6.2	0.59	96	201	0.7	5	7	2.0	0.41	76	31	85	16	133
2017-**258**-02	Anthropic	Anthropic	Urban	5.34	5.2	0.42	17	146	0.6	10	15	4.0	0.15	37	14	17	32	58
2017-**259**-02	Whangamarie clay	Recent	Urban	5.12	4.8	0.40	13	121	0.7	6	10	2.0	0.14	15	11	10	32	49

Site No.	Soil series	NZ Soil Classification	Land use	pH	TC %	TN %	Olsen P	AMN	BD	MP-5	MP-10	As	Cd	Cr	Cu	Ni	Pb	Zn
2017-**262**-06	Brookby clay	Ultic	Native	5.72	5.6	0.41	6	135	0.9	10	14	3.0	0.10	20	8	7	16	30

Note: Shaded cells are aimed to help distinguish between individual sites.

[1] Individual site number is indicated as the second number and highlighted in **bold** e.g. 0X as per the following 2018-**0X**-01. The number/year on the left-hand-side of the site number indicates the year the site was sampled and the number on the right-hand-side indicates the number of times the site has been resampled which can range from 01-07 for data incorporated in this evaluation (some native sites may have been resampled x7 times for previous research purposes e.g. Hermans et al., 2017 but only their most recent values are utilised).

Appendix 3. Trend analysis for soil sites on land uses that remained unconverted

Mean results of soil parameters across three sampling periods 1995-2000, 2008-2012 and 2013-2017 for soil sites on land uses that had remained **unconverted**. The standard error of difference (SED) and least significant difference (LSD) are presented using un-transformed and the *P*-value is presented using log transformed data. Significant differences are highlighted in bold and ns denotes 'not significant'.

Soil parameter[1]	1995-2000	2008-2012	2013-2017	SED	LSD	*P* value
Soil pH	5.76	5.88	5.81	0.057	0.114	ns
Total C (%)	6.9	6.4	5.8	0.25	0.50	***P*<0.001**
Total N (%)	0.48	0.46	0.43	0.018	0.035	***P*<0.05**
Olsen P (mg/kg)	33	37	37	3.5	6.9	ns
AMN (mg/kg)	131	128	110	6.9	13.7	***P*<0.01**
Macroporosity (-5kPa%)[2]	14	10	11	0.9	1.7	***P*<0.001**
Bulk density (g/cm^3)	0.93	0.99	0.96	0.025	0.05	***P*<0.05**
Arsenic (mg/kg)	3.6	3.6	4.4	0.24	0.48	***P*<0.01**
Cadmium (mg/kg)	0.31	0.33	0.32	0.022	0.045	ns
Chromium (mg/kg)	11	11	12	0.9	1.7	ns
Copper (mg/kg)	16	16	17	2.3	4.7	ns
Nickel (mg/kg)	3.8	4.0	4.3	0.35	0.69	ns
Lead (mg/kg)	10.6	10.9	11.0	0.75	1.49	ns
Zinc (mg/kg)	29	31	32	3.3	6.7	ns

[1] 47 and 30 repeat sites were included in the soil quality and trace element analysis, respectively; the 17 remaining sites sampled between 1995-1998 did not have corresponding trace element data

[2] Macroporosities are presented as -5kPa% (soil pores >60 microns) because -10kPa data was not available for all sites sampled between 1995-2000 (Appendix 2). Macroporosity guideline range for -5kPa% is 8-30% for horticulture and pastoral land uses

Mean concentrations of soil parameters by sampling period and land use for **unconverted** sites. The *P*-value is presented using log transformed data. Significant differences are highlighted in bold and ns denotes 'not significant'. Soil parameters in **red** and **blue** bold figures are mean values that are above and below recommended guidelines, respectively.

Land use[1]	Period	pH	TC	TN	Olsen P	AMN	MP-5kPa[2]	BD	As	Cd	Cr	Cu	Ni	Pb	Zn
Forestry	1995-00	5.21	5.2	0.33	23	57	23	0.93	5.7	0.02	6	5	2.7	6.8	19.0
	2008-12	5.38	3.9	0.24	22	79	19	1.14	7.0	0.02	12	7	5.4	9.2	21.7
	2013-17	5.61	3.8	0.22	12	63	20	1.13	6.6	0.09	6	5	2.7	8.2	18.3
Horticulture	1995-00	6.30	7.2	0.50	**71**	128	15	0.97	2.5	0.50	12	32	3.1	10.8	25.9
	2008-12	6.38	7.2	0.51	**63**	88	8	1.02	3.0	0.57	13	34	3.5	14.0	37.7
	2013-17	6.19	6.3	0.49	**83**	89	14	0.94	4.0	0.56	16	39	5.4	13.2	44.6
Native	1995-00	5.39	7.5	0.40	10	122	16	0.89	3.6	0.08	14	9	4.8	14.2	38.0
	2008-12	5.58	7.1	0.40	8	134	15	0.81	3.2	0.07	11	10	3.9	10.8	30.1
	2013-17	5.39	5.7	0.34	8	106	11	0.91	4.0	0.06	11	8	4.3	10.8	29.3
Dairy	1995-00	6.17	8.7	0.74	37	177	7	0.87	4.9	0.65	14	10	5.0	14.3	40.0
	2008-12	6.20	7.6	0.65	**67**	162	**3**	1.07	3.7	0.67	13	12	5.2	15.1	38.0
	2013-17	6.23	7.9	0.67	**56**	159	**3**	0.95	5.4	0.48	14	10	4.3	16.3	35.7
Drystock	1995-00	5.78	5.9	0.50	30	163	11	0.96	3.6	0.35	10	7	3.1	5.1	21.8
	2008-12	5.88	5.8	0.53	37	173	**5**	1.03	3.4	0.36	8	7	3.4	5.3	23.8
	2013-17	5.80	5.1	0.47	35	137	**6**	0.92	3.8	0.35	9	7	3.6	6.5	22.0
P value landuse		**<0.001**	**<0.05**	**<0.001**	**<0.001**	**<0.01**	**<0.001**	ns	ns	**<0.01**	ns	**<0.01**	ns	ns	ns
P value period		ns	**<0.001**	ns	ns	**<0.01**	**<0.001**	**<0.05**	**<0.01**	ns	ns	ns	ns	ns	ns
P value landuse x period		ns	ns	ns	ns	ns	**<0.05**	**<0.001**	ns	ns	**<0.01**	ns	**<0.01**	**<0.05**	ns

[1] The breakdown of land use sites for soil quality analysis are as follows: forestry n=7, horticulture n=10, native n=13, dairy n=7, drystock n=10
The breakdown of land use sites for trace element analysis are as follows: forestry n=3, horticulture n=9, native n=9, dairy n=3, drystock n=6
[2] The guideline range for soil macroporosity -5kPa is 8-30% for horticulture and pastoral land uses

Appendix 4. Statistical outputs for soil macroporosity -10kPa by soil order only for pasture sites (n=49) that were sampled 2013-2015

Analysis of variance

Variate: Air_filled_MP_10kPa

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
NZSC_Order	6	41.61	6.93	0.64	0.701
Residual	42	457.99	10.90		
Total	48	499.59			

Message: the following units have large residuals.

units 41 10. approx. s.e. 3.

Tables of means

Variate: Air_filled_MP_10kPa

Grand mean 8.

NZSC_Order	Allophanic	Brown	Gley	Granular	Organic	Recent
	7.	8.	8.	8.	6.	10.
rep.	9	5	6	8	4	5

NZSC_Order	Ultic
	7.
rep.	12

Standard errors of differences of means

Table	NZSC_Order	
rep.	unequal	
d.f.	42	
s.e.d.	2.3X	min.rep
	1.9	max-min
	1.3X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	NZSC_Order	
rep.	unequal	
d.f.	42	
l.s.d.	4.7X	min.rep
	3.8	max-min
	2.7X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(Air_filled_MP_10kPa)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
NZSC_Order	6	0.9118	0.1520	0.54	0.772
Residual	42	11.7315	0.2793		
Total	48	12.6433			

Message: the following units have large residuals.

units 16	-1.772 approx. s.e.	0.489
units 23	-1.130 approx. s.e.	0.489

Tables of means

Variate: LOG(Air_filled_MP_10kPa)

Grand mean 1.951

NZSC_Order	Allophanic	Brown	Gley	Granular	Organic	Recent
	1.772	1.993	2.064	2.092	1.692	2.099
rep.	9	5	6	8	4	5

NZSC_Order	Ultic
	1.942
rep.	12

Standard errors of differences of means

Table	NZSC_Order	
rep.	unequal	
d.f.	42	
s.e.d.	0.3737X	min.rep
	0.3051	max-min
	0.2158X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	NZSC_Order	
rep.	unequal	
d.f.	42	
l.s.d.	0.7542X	min.rep
	0.6158	max-min
	0.4354X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Appendix 5. Property size (ha) by pastoral and horticulture land use activity for soil sites according to Auckland Council's rates assessment.

Site number	Land use/conversion	Area (ha)
7	Dairy	51
8	Dairy	51
9	Dairy- Goat dairy	7.75[1]
28	Dairy	61.3
38	Dairy	76.9
62	Dairy	51.9
64	Dairy	40.6
121	Dairy	105.5
122	Dairy	105.5
123	Dairy	45.5
124	Dairy	45.5
125	Dairy	100
10	Vegetable production-Drystock	88
18	Drystock	87
21	Drystock	215.9
24	Drystock	215.9
25	Dairy-Drystock	215.9
27	Drystock	31.9
30	Drystock	69.6
33	Dairy-Drystock	104
35	Dairy-Drystock	104
42	Dairy-Horse stud	49
43	Dairy-Horse stud	49
46	Drystock	17.7
47	Dairy-Drystock	49.4
48	Drystock	149.5
50	Drystock	65
51	Drystock	65
53	Dairy-Drystock	31.9
55	Dairy-Drystock	31.9
68	Vegetable production-Drystock	53.5
73	Dairy-Drystock	40.4
74	Drystock	13.1
76	Drystock	9.5
84	Drystock	46.8
1	Vegetable production (outdoor)	14.5
41	Orchard	9.5
65	Orchard	4.1
67	Orchard	6.2
70	Vegetable production (outdoor)	19.3
71	Nursery	12.6
80	Viticulture	5.9
82	Orchard	20.3
86	Viticulture	10.4
87	Orchard	10.4
88	Orchard	10.4
113	Vegetable production (outdoor)	16.5

Site number	Land use/conversion	Area (ha)
114	Vegetable production (outdoor)	8.1
115	Vegetable production (outdoor)	5.7
116	Vegetable production (outdoor)	14.9
117	Vegetable production (outdoor)	14.9
118	Viticulture	12.8
119	Viticulture	8.5
120	Viticulture	9.1
2	Drystock-Lifestyle block	1.4
12	Dairy-Lifestyle block	30.7
14	Orchard-Lifestyle block	2.8
20	Orchard-Lifestyle block	1.5
37	Vegetable production-Lifestyle block	5
61	Drystock-Lifestyle block	2.6
63	Drystock-Lifestyle block	2.6
66	Dairy-Lifestyle block	11.4
69	Drystock-Lifestyle block	19.3
75	Dairy-Lifestyle block	0.2518[2]
77	Dairy-Lifestyle block	25.8
78	Drystock-Lifestyle block	15.8
79	Vegetable production-Lifestyle block	15.8
81	Orchard-Lifestyle block	15.6

[1] Converted to goat dairy

[2] Lot size of property prior to rural subdivision cannot be sourced

Appendix 6. Statistical outputs for soil quality parameters by dairy, drystock and lifestyle block pastoral sites sampled 2014-2015 according to untransformed and log-transformed data

Analysis of variance

Variate: Air_filled_MP_10kPa

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	55.642	27.821	2.88	0.066
Residual	46	443.951	9.651		
Total	48	499.594			

Message: the following units have large residuals.

units 41	11.	approx. s.e.	3.

Tables of means

Variate: Air_filled_MP_10kPa

Grand mean 8.

Current_land_use	Dairy	Drystock	Lifestyle
	6.	9.	8.
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	1.3X	min.rep
	1.1	max-min
	1.0X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	2.6X	min.rep
	2.3	max-min
	2.0X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: AMN_mg_kg_w_w

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	998.	499.	0.09	0.914
Residual	46	255006.	5544.		
Total	48	256004.			

Message: the following units have large residuals.

units 20	177.	approx. s.e.	72.
units 21	195.	approx. s.e.	72.

Tables of means

Variate: AMN_mg_kg_w_w

Grand mean 165.

Current_land_use	Dairy	Drystock	Lifestyle
	170.	167.	159.
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	30.4X	min.rep
	27.2	max-min
	23.5X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	61.2X	min.rep
	54.7	max-min
	47.4X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: BD_t_m3_Mg_m3

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.00410	0.00205	0.06	0.940
Residual	46	1.53263	0.03332		
Total	48	1.53674			

Tables of means

Variate: BD_t_m3_Mg_m3

Grand mean 0.90

Current_land_use	Dairy	Drystock	Lifestyle
	0.89	0.91	0.89
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.075X	min.rep
	0.067	max-min
	0.058X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.150X	min.rep
	0.134	max-min
	0.116X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: Olsen_P_mg_kg

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	2100.7	1050.3	1.27	0.290
Residual	46	37958.5	825.2		
Total	48	40059.2			

Message: the following units have large residuals.

units 2	122. approx. s.e.	28.

Tables of means

Variate: Olsen_P_mg_kg

Grand mean 47.

Current_land_use	Dairy	Drystock	Lifestyle
	57.	48.	40.
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	11.7X	min.rep
	10.5	max-min
	9.1X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	23.6X	min.rep
	21.1	max-min
	18.3X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: pH

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.46353	0.23177	2.36	0.105
Residual	46	4.51172	0.09808		
Total	48	4.97525			

Tables of means

Variate: pH

Grand mean 5.971

Current_land_use	Dairy	Drystock	Lifestyle
	6.138	5.894	5.944
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.1279X	min.rep
	0.1144	max-min
	0.0990X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.2574X	min.rep
	0.2302	max-min
	0.1993X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: TC%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	47.34	23.67	1.65	0.204
Residual	46	661.07	14.37		
Total	48	708.40			

Message: the following units have large residuals.

units 17	15.6	approx. s.e.	3.7
units 18	10.2	approx. s.e.	3.7

Tables of means

Variate: TC%

Grand mean 7.2

Current_land_use	Dairy	Drystock	Lifestyle
	7.8	6.1	8.2
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	1.55X	min.rep
	1.38	max-min
	1.20X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	3.12X	min.rep
	2.79	max-min
	2.41X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: TN%

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.17918	0.08959	0.99	0.378
Residual	46	4.14450	0.09010		
Total	48	4.32369			

Message: the following units have large residuals.

units 17	1.15	approx. s.e.	0.29
units 18	0.88	approx. s.e.	0.29

Tables of means

Variate: TN%

Grand mean 0.63

Current_land_use	Dairy	Drystock	Lifestyle
	0.66	0.56	0.69
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.123X	min.rep
	0.110	max-min
	0.095X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.247X	min.rep
	0.221	max-min
	0.191X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(Air_filled_MP_10kPa)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	1.6008	0.8004	3.33	0.044
Residual	46	11.0425	0.2401		
Total	48	12.6433			

Message: the following units have large residuals.

units 16 -1.635 approx. s.e. 0.475

Tables of means

Variate: LOG(Air_filled_MP_10kPa)

Grand mean 1.951

Current_land_use	Dairy	Drystock	Lifestyle
	1.635	2.073	2.030
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.2000X	min.rep
	0.1789	max-min
	0.1549X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.4026X	min.rep
	0.3601	max-min
	0.3119X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(AMN_mg_kg_w_w)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.0201	0.0100	0.05	0.951
Residual	46	9.1942	0.1999		
Total	48	9.2143			

Message: the following units have large residuals.

units 1	-1.074	approx. s.e.	0.433

Tables of means

Variate: LOG(AMN_mg_kg_w_w)

Grand mean 5.013

Current_land_use	Dairy	Drystock	Lifestyle
	5.045	5.012	4.991
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.1825X	min.rep
	0.1632	max-min
	0.1414X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.3674X	min.rep
	0.3286	max-min
	0.2846X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(BD_t_m3_Mg_m3)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.00315	0.00157	0.03	0.967
Residual	46	2.13516	0.04642		
Total	48	2.13831			

Message: the following units have large residuals.

units 20 -0.519 approx. s.e. 0.209

Tables of means

Variate: LOG(BD_t_m3_Mg_m3)

Grand mean -0.125

Current_land_use	Dairy	Drystock	Lifestyle
	-0.133	-0.116	-0.130
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.0880X	min.rep
	0.0787	max-min
	0.0681X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.1770X	min.rep
	0.1584	max-min
	0.1371X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(Olsen_P_mg_kg)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	2.6169	1.3084	3.14	0.053
Residual	46	19.1835	0.4170		
Total	48	21.8004			

Message: the following units have large residuals.

units 2	1.734	approx. s.e.	0.626
units 13	-1.653	approx. s.e.	0.626

Tables of means

Variate: LOG(Olsen_P_mg_kg)

Grand mean 3.658

Current_land_use	Dairy	Drystock	Lifestyle
	3.902	3.775	3.349
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.2636X	min.rep
	0.2358	max-min
	0.2042X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.5307X	min.rep
	0.4747	max-min
	0.4111X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(pH)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.012940	0.006470	2.37	0.105
Residual	46	0.125807	0.002735		
Total	48	0.138747			

Tables of means

Variate: LOG(pH)

Grand mean 1.7855

Current_land_use	Dairy	Drystock	Lifestyle
	1.8130	1.7720	1.7819
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.02135X	min.rep
	0.01910	max-min
	0.01654X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.04298X	min.rep
	0.03844	max-min
	0.03329X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(TC%)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.6585	0.3293	1.86	0.167
Residual	46	8.1254	0.1766		
Total	48	8.7839			

Message: the following units have large residuals.

units 17	1.206	approx. s.e.	0.407
units 18	0.949	approx. s.e.	0.407

Tables of means

Variate: LOG(TC%)

Grand mean 1.876

Current_land_use	Dairy	Drystock	Lifestyle
	1.984	1.737	1.964
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.1716X	min.rep
	0.1535	max-min
	0.1329X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.3454X	min.rep
	0.3089	max-min
	0.2675X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Analysis of variance

Variate: LOG(TN%)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Current_land_use	2	0.2900	0.1450	0.88	0.422
Residual	46	7.5924	0.1651		
Total	48	7.8824			

Message: the following units have large residuals.

units 17	1.096	approx. s.e.	0.394
units 18	0.935	approx. s.e.	0.394

Tables of means

Variate: LOG(TN%)

Grand mean -0.547

Current_land_use	Dairy	Drystock	Lifestyle
	-0.482	-0.640	-0.484
rep.	12	20	17

Standard errors of differences of means

Table	Current_land_use	
rep.	unequal	
d.f.	46	
s.e.d.	0.1659X	min.rep
	0.1483	max-min
	0.1285X	max.rep

(No comparisons in categories where s.e.d. marked with an X)

Least significant differences of means (5% level)

Table	Current_land_use	
rep.	unequal	
d.f.	46	
l.s.d.	0.3339X	min.rep
	0.2986	max-min
	0.2586X	max.rep

(No comparisons in categories where l.s.d. marked with an X)

Find out more: phone 09 301 0101, email
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