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Soil Quality in the Marlborough Region

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Report Prepared by:
Matt Oliver Senior Environmental Scientist – Land Resources
Marlborough District Council

Final Edition approved by
Peter Hamill
Marlborough District Council

Marlborough District Council
Seymour Square
PO Box 443
Blenheim 7240
Phone: 520 7400
Website: www.marlborough.govt.nz

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Executive Summary

Under Section 35 of the Resource Management Act 1991, Councils are required to report on the "life supporting capacity of soil" and to determine whether current practices will meet the "foreseeable needs of future generations". To meet these goals, Marlborough District Council undertakes a Soil Quality Monitoring Programme across a network of sites representing the main land use activities and soil orders within the region. The aim of this report is to update both the current state of, and long-term trends in, soil quality in the Marlborough region including sampling across this network in 2025. This sampling covers a suite of soil physical, biological and chemical properties that have been shown to be robust indicators of soil quality. The sampling takes place under the National Environmental Monitoring Standards for Soil Quality and Trace Element Monitoring. Changes in soil quality often take a long time to become evident. The Soil Quality Monitoring Programme has now been operating for 25 years and has clearly identified persistent issues in some soil quality parameters.

A major change in this reporting round is the adoption of revised national soil quality reference ranges developed by the Ministry for the Environment in 2025. These replace the previous soil quality guidelines and have altered the way some parameters are reported and interpreted. The revised reference ranges have changed how risk is described, especially for nitrogen, bulk density and Olsen P. Readers are cautioned when interpreting results in comparison with previous reports. Despite these changes, the overall findings remain consistent with previous Marlborough soil quality reports. Soil compaction, elevated nutrient levels, low soil carbon and trace element accumulation remain the persistent soil quality concerns for the region.

In 2025, soils were sampled from 19 monitoring sites, comprising three pasture sites, two cropping sites, one native bush site, eight vineyard sites and four exotic forestry sites. These sites represented four soil orders, and six of the sites were new to the programme. As three samples are taken from each vineyard site, in total, 35 sets of samples were taken in 2025.

The 2025 results show that many sites continue to have good soil quality; however, most farmed soils show effects of human land use, with several indicators falling outside reference ranges. Soil compaction remains one of the most widespread concerns. Seventy-four percent of samples had bulk density values outside the relevant reference range, and 37% had air-filled porosity values below the reference range. These results indicate reduced soil pore space and increased risk of poor aeration, impeded drainage, restricted root growth, reduced water infiltration and increased surface runoff.

Soil nutrient status continues to indicate potential risks to water quality. Olsen P concentrations in 2025 ranged from 2 to 70 mg/L, with 17 of 35 samples (49%) above the relevant reference range. Elevated Olsen P increases the potential for phosphorus loss in surface runoff. Long-term trends indicate that phosphorus risk is declining in dairy systems but increasing in viticulture, where regional values are approaching environmental risk levels.

Animal-based systems, particularly dairy and pasture, continue to show higher total nitrogen and anaerobically mineralisable nitrogen values, reflecting greater nitrogen inputs and cycling through organic matter. These values are generally within reference ranges at the regional scale but may still present water quality risks where combined with compaction, wet soils, high stocking rates, effluent disposal, fertiliser inputs or winter grazing practices.

Low soil carbon remains a significant concern for some land uses in Marlborough. Total carbon is an important measure of soil organic matter and is closely related to nutrient retention, water-holding capacity, soil structure and resilience to physical damage. In 2025, four of 35 samples (11%) were below the relevant reference range for total carbon, all from vineyard sites. The long-term dataset shows that native bush has the highest median carbon values, while cropping and under-vine vineyard soils show the clearest signs of organic matter depletion.

Hot water extractable carbon provides additional information on the quality and biological activity of soil carbon. In 2025, 16 of 35 samples (46%) were below the HWEC reference range. These results suggest that some soils have reduced biologically active carbon pools, with potential implications for microbial activity, soil structure, nutrient cycling and water retention. The HWEC dataset is still relatively new, but it is expected to become increasingly useful for understanding soil carbon function and response to management over time.

The vineyard dataset was analysed in more detail to investigate the relationship between organic matter content and the soil's ability to retain water and make it available to plants. Soils with elevated organic matter inputs (such as pasture or grassed interrows) are known to have the ability to retain more water. This analysis showed that under-vine soils had significantly lower organic matter (measured as total carbon) and plant available water than inter-row soils. Plant available water was positively associated with total carbon, indicating that soils with higher carbon content tend to retain more water for plant growth. Cluster analysis identified that the studied soils formed a continuum of water holding capacity ranging from low to high. Under-vine soils tended to a lower capacity to retain water compared to interrow soils. This indicates that vineyard floor management has a clear spatial effect on soil function and provides an understanding that under-vine carbon loss is not just a soil chemistry issue; it appears linked to reduced soil function namely, water availability and potentially drought resilience.

Trace element concentrations were within guideline values in 2025. With baseline fluoride testing now completed across the monitoring network, the relationship between phosphate fertiliser use and the accumulation of cadmium and fluoride was investigated. Farmed soils continue to show higher cadmium concentrations than non-farmed soils. However, long-term regional trends do not show a statistically significant increase in cadmium. Site-specific analysis indicates that cadmium concentrations are generally stable or declining across the region, with the strongest declines occurring in dairy soils reflecting changes in phosphate fertiliser management over time. Fluoride also showed a positive relationship with Olsen P across the full dataset, but relationships by land use were more variable and generally weaker. The analysis supports careful and prudent phosphate fertiliser management.

The trend analysis confirms the key issues for Marlborough soils. Some indicators show evidence of gradual improvement, but these trends are not yet sufficient to remove concern. Cropping soils remain vulnerable to low soil carbon and structural degradation. Pasture and dairy systems require ongoing attention to nitrogen management and compaction from animal treading. Vineyard managers need to address both soil compaction in wheel tracks and declining carbon and plant available water in under-vine areas.

Since 2024, Council has partnered with NZ Landcare Trust to deliver free on-farm soil health workshops. These workshops are intended to support landowners to better understand soil health, identify soil quality issues and apply practical management responses.

A series of soil quality recommendations are included throughout this report. These are intended as practical guidance to landowners and land managers on how to measure, maintain and improve soil quality on their properties.

Table of Contents

1. Introduction 1
2. Materials and Methods 2
   - 2.1. Sampling Sites 2
     - 2.1.1. Changes to sampling sites 2
     - 2.1.2. Viticulture sampling sites 3
   - 2.2. Soil Sampling 4
   - 2.3. Soil Quality Measurements 4
   - 2.4. Soil Analysis 5
     - 2.4.1. Chemical Analysis 5
     - 2.4.2. Biological Analysis 5
     - 2.4.3. Physical Analysis 6
   - 2.5. Data analysis and display 6
     - 2.5.1. Data display 7
   - 2.6. Reference Ranges and Guideline Values 8
3. Results and Discussion 9
   - 3.1. Comparison with Reference Ranges 9
   - 3.2. Soil Chemical results 10
     - 3.2.1. Soil pH 10
     - 3.2.2. Olsen P 12
     - 3.2.3. Trace Elements 14
   - 3.3. Soil Biological Results 17
     - 3.3.1. Anaerobically Mineralisable Nitrogen 17
     - 3.3.2. Total Carbon 19
     - 3.3.3. Hot Water Extractable Carbon 22
     - 3.3.4. Total Nitrogen 24
     - 3.3.5. Carbon: Nitrogen Ratio 26
   - 3.4. Soil Physical Results 29
     - 3.4.1. Bulk Density 29
     - 3.4.2. Air Filled Porosity 31
     - 3.4.3. Aggregate Stability 33
4. Analysis 34
   - 4.1. Relationship of Fluoride and Cadmium to Olsen P 34
   - 4.2. Correlation of Total Carbon to Plant Available Water. 39
5. Changes in Soil Quality through time 44
   - 5.1. Introduction 44
   - 5.2. Nutrient loss to water 45

5.2.1. Phosphorus risk 45
5.2.2. Nitrogen dynamics 47
5.3. Soil compaction risks 50
5.4. Loss of Soil Organic Matter 53
5.5. Trace Element Accumulation 57
6. Discussion and Summary 60
7. References 62
8. Appendix A - 2025 Soil Test Results 66
9. Appendix B - Soil Reference Values 70
10. Appendix C – MEP Environmental Outcome 74
11. Appendix D - Use of Artificial Intelligence Disclosure 75

List of Figures

Figure 1: Basic features of a boxplot 7

Figure 2: The percentage of sites not meeting their reference range 9

Figure 3: Soil pH by landuse for 2025 samples 11

Figure 4:Soil pH by land use for all samples since 2000 11

Figure 5: Olsen P values by land use for 2025 samples 13

Figure 6: Soil Olsen P values for all samples since 2000 13

Figure 7: Trace element results for all sites since 2000 15

Figure 8: Soil cadmium concentrations by land use for all samples since 2000 15

Figure 9: Soil fluoride concentrations by land use for all samples since 2000 16

Figure 10: AMN concentrations for 2025 18

Figure 11: AMN concentrations by land uses for all samples since 2000 18

Figure 12: Total carbon values for 2025 20

Figure 13: Total carbon by land use for all samples since 2000 20

Figure 14: Hot water extractable carbon values for 2025 23

Figure 15: Hot water extractable carbon values since 2019 23

Figure 16: Total nitrogen values for 2025 25

Figure 17: Total nitrogen values all values since 2000 25

Figure 18: The C:N ratio of some organic materials 26

Figure 19: Carbon: nitrogen ratio for 2025 27

Figure 20: Carbon: nitrogen ratio values for all data since 2000 28

Figure 21: Dry bulk density by land use for 2025 samples 30

Figure 22: Soil dry bulk density values for all samples since 2000 30

Figure 23: Air filled porosity by land use for 2025 values 32

Figure 24: Air filled porosity by land use for all samples since 2000 33

Figure 25: Correlation plot of cadmium vs Olsen P across all landuses 35

Figure 26: Correlation plot of fluoride vs Olsen P across all landuses 35

Figure 27: Cadmium vs Olsen P landuse correlation plots 36

Figure 28: Fluoride vs Olsen P landuse correlation plots 37

Figure 29: Cadmium and fluoride correlation and significance across landuses 37

Figure 30: Conceptual relationship between soil carbon, soil structure and plant available water 40

Figure 31: Comparisons of PAW and total carbon for undervine and interrow soils 41

Figure 32: Fuzzy c-means cluster plot showing two separate clusters for PAW soil function 42

Figure 33: Long-term trend in regional Olsen P averages by land use 46

Figure 34: Long-term trend in AMN by land use 48

Figure 35: Long-term trend in total nitrogen by land use 49

Figure 36: Long-term trend in bulk density for all land uses 51

Figure 37: Long-term trend in AFP for all land uses 52

Figure 38: Key differences between particulate and mineral-associated organic matter 54

Figure 39: Long-term trend in total carbon by landuse 55

Figure 40: Long-term trends in cadmium since 2000 57

Figure 41: Site-Specific change in cadmium for all sites 58

List of Tables

Table 1: Soil type, soil classification and landuse of sites sampled in Marlborough in 2025 3

Table 2: Indicators used for soil quality assessment 5

Table 3: Spearman ρ-rho values and interpretation 34

Table 4: Soil Chemical results 66

Table 5: Soil Biological results 68

Table 6: Soil Physical Results 69

Table 7: Reference ranges for soil pH 70

Table 8: Reference range for Olsen P 70

Table 9: Reference range for AMN 71

Table 10: Reference range for total carbon 71

Table 11: Distribution of HWEC results 72

Table 12: Reference ranges for total N (%) in mineral soils 72

Table 13: Reference ranges for C:N ratio 72

Table 14: Reference ranges for bulk density 73

Table 15: Reference ranges for air filled porosity (-10kPa) 73

Table 16: Reference ranges for trace elements 73

List of Plates

Plate 1: Soil Quality sample collection 4

Plate 2: Dried soil cores inside their extraction rings following oven drying. 6

Plate 3: Compacted topsoil at one of the cropping sites 53

Plate 4: Attendees at a soil heath workshop 61

1. Introduction

Regional (and Unitary) Councils have a responsibility for promoting the sustainable management of the natural and physical resources of their region. Under Section 35 of the Resource Management Act (1991), one of the physical resources that we have a duty to monitor and report on is soil. Specifically, to report on the "life supporting capacity of soil" and to determine whether current practices will meet the "foreseeable needs of future generations". Alongside the national regulation, the Marlborough Environment Plan sets in place policies to protect soils against disturbance, erosion and inappropriate use.

The collection of detailed soil monitoring data is therefore vital because it provides information on what effect current land use activities are having on soil quality and whether we need to change or prioritise the way we manage the land environment. This is becoming increasingly important as land use activities are intensifying across New Zealand and putting pressure on our soils.

Furthermore, the way soils respond to different land use activities can affect other parts of the environment, for example water quality. This is because soils act as buffers to; capture and store nutrients such as nitrogen, phosphorous and microbes, treat a range of waste products as well as to store and filter water.

To help determine what effect land use practices are having on soil quality, in 2000 the Marlborough District Council (MDC) became a participant in a national soil quality project known as "The 500 Soils Project". At the completion of this project MDC implemented its own Soil Quality Monitoring Programme (SQMP) commencing in 2007 to continue assessing the quality of soils throughout the Marlborough region. This programme is based on the National Environmental Monitoring Standard for Soil Quality and Trace Elements (Hill, 2022) as part of the national programme and is in line with soil quality monitoring currently undertaken in other regions in New Zealand.

The Marlborough Environment Plan identifies issues and objectives related to the management of soils in Marlborough. To inform management of these the goals of the Soil Quality Monitoring Programme are:

- Provide information on the physical, chemical and biological properties of soils to assess overall soil health.
- Provide an early-warning system to identify the effects of primary land uses on long-term soil productivity and the environment.
- Track specific, identified issues relating to the effects of land use on long term soil productivity.
- Assist in the detection of spatial and temporal changes in soil quality; and
- Provide a mechanism to determine the effectiveness of regional policies and plans.

A network of 111 soil quality monitoring sites has now been established in Marlborough. This report discusses if they meet their reference ranges for soil quality and presents results for 19 sites last sampled in 2000 and six new sites sampled for the first time.

2. Materials and Methods

The Soil Quality Monitoring Programme samples a range of different soils in a representative manner depending on the soil order and land use. The aim is to have a representative combination of all soil orders and all land uses found in the region. Soil orders are the broadest classification of soils under the New Zealand Soil Classification (Hewitt, 2010). As examples, soils from the Recent soil order come from areas where soil development has commenced on relatively young parent material such as on flat alluvial floodplains. In contrast, Pallic soils are more developed, mature soils that can be form often in uniform silt-dominated loess material blown from river floodplains. Pallic soils typically form in locations where summers are dry and can form dense subsoil pans.

In 2022 the SQMP was reviewed in light of the extensive land use change that has occurred in Marlborough since its inception. This analysis (Hill & Dunn, 2022) made a number of recommendations and these have been adopted. These include:

- Continuing to monitor soil quality in the Marlborough district, resampling between 20-30 sites annually to maintain sufficient data for assessing long term soil quality trends in the region.
- Increase the minimum number of sites in the monitoring programme to an adequate minimum of 20-25 per land use (excluding indigenous vegetation) depending on the intensity of land use types.
- Increase the number of sites for indigenous vegetation to eight sites to provide 'reference' sites for the main soil orders across all land use types.
- Additional sites should be prioritised towards the underrepresented soil orders for each land use to improve the representation of the main soil orders within each land use type.

Council has undertaken to follow these recommendations, and this will increase site numbers from 96 to 123 across the region. Starting in 2023, additional sites have been added to each sampling round. The programme now stands at 111 sites and the full 123 sites should be in place for the publication of the 2027 monitoring report.

2.1. Sampling Sites

Soils were sampled from 19 sites previously sampled in 2020 as well as 6 new sites. These include four pasture sites, two cropping sites, one native bush site, eight vineyard sites and four exotic forestry sites. These sites represented four soil orders (Table 1). In total 35 samples were taken.

2.1.1. Changes to sampling sites

Ideally, the location of sampling sites should not change to maintain the representativeness of the programme. However, a key objective of this project is to monitor land use and landscape changes to these sites. The land use of several of the sites sampled in this round have changed markedly from the original. Field notes and GPS coordinates from past sampling rounds help staff to locate the original transects so samples can be replicated as closely as possible. However, it has not been possible to replicate exactly the location of the original transect on some sites. Reasons for this include large changes in vegetation (especially in forested areas and where land use has changed), errors in GPS location markers and unclear field notes. Where transects could not be located accurately, a new transect was established as closely as possible to the original using the original site photographs. New transects were documented with explicit notes and photographs to ensure location in the future. In 2025, four sites needed to be relocated due to landuse change from pasture to viticulture.

Table 1: Soil type, soil classification and landuse of sites sampled in Marlborough in 2025.

Site Code	Sampling Years	Soil Order	Initial Landuse	Current Landuse	Site changes since last visit
Soil Site 61	2010, 2015, 2020, 2025	Pallic	Cropping	Vineyard	Realigned for vineyard
Soil Site 62	2010, 2015, 2020, 2025	Recent	Cropping	Vineyard	Realigned for vineyard
Soil Site 63	2010, 2015, 2020, 2025	Pallic	Cropping	Vineyard	Realigned for vineyard
Soil Site 64	2010, 2015, 2020, 2025	Pallic	Cropping	Vineyard	Realigned for vineyard
Soil Site 65	2010, 2015, 2020, 2025	Pallic	Vineyard	Vineyard	
Soil Site 66	2010, 2015, 2020, 2025	Brown	Vineyard	Vineyard	
Soil Site 69	2010, 2015, 2020, 2025	Pallic	Vineyard	Vineyard	
Soil Site 70	2010, 2015, 2020, 2025	Recent	Vineyard	Vineyard	
Soil Site 71	2010, 2015, 2020, 2025	Brown	Cropping	Cropping	
Soil Site 72	2010, 2015, 2020, 2025	Pallic	Cropping	Cropping	
Soil Site 73	2010, 2015, 2020, 2025	Brown	Pasture	Pasture	
Soil Site 74	2010, 2015, 2020, 2025	Brown	Pasture	Pasture	
Soil Site 75	2010, 2015, 2020, 2025	Recent	Pasture	Pasture	
Soil Site 104	2025	Pallic	Exotic Forest	Exotic Forest	New
Soil Site 107	2025	Ultic	Exotic Forest	Exotic Forest	New
Soil Site 108	2025	Ultic	Exotic Forest	Exotic Forest	New
Soil Site 109	2025	Brown	Exotic Forest	Exotic Forest	New
Soil Site 110	2025	Brown	Native Bush	Native Bush	New
Soil Site 111	2025	Brown	Pasture	Pasture	New

2.1.2. Viticulture sampling sites

Because of the economic importance and scale of viticulture in Marlborough, it was decided in 2012 that more detailed understanding of soil quality at vineyard sites would be useful. As such, three samples– under the vines, in the wheel tracks and in the inter-row - per vineyard site are collected to allow the impact of various management practices to be evaluated. Management practices include:

- Under vine
  - banding of fertiliser
  - herbicide applications
  - maintenance of bare ground
  - absence of traffic
  - irrigation
  - transfer of inter-row mowing's
- Wheel tracks
  - Repeated vehicle trafficking
- Inter-row
  - inputs of organic matter including pruning's
  - lower rates of fertiliser
  - rainfall inputs only

2.2. Soil Sampling

Two types of soil samples are collected from each site. Firstly, a composite sample comprising 25 individual cores taken at 2 m intervals along a 50 m transect at a depth of 100 mm (Plate 1). These samples are combined into one large sample and used for chemical and biological analysis. In addition, three undisturbed soil cores (100 mm diameter by 75 mm depth) are sampled at 15-, 30- and 45-m positions along the transect (Plate 1). These soil cores were removed as one unit by excavation around the liner, bagged and loaded into padded crates for transport to the laboratory for analysis. These soil samples are used for soil physical analysis. Samples are collected from mid-October to early November. In 2025, all sites had moist soil moisture conditions.



Plate 1: Soil Quality sample collection. Left: Collecting a composite of core samples along a transect using a soil corer. **Right**: One of three intact core samples taken at each site, to establish the physical properties of the soil.

2.3. Soil Quality Measurements

The National Environmental Monitoring Standards for Soil Quality and Trace Element Monitoring (NEMS) outlines the parameters and methods for soil quality monitoring (Hill, 2022). Several different soil properties are measured to assess soil quality. Soil chemical characteristics are assessed by soil pH, Olsen P and trace element concentrations. Soil biological characteristics are determined by measuring anaerobically mineralisable nitrogen, total carbon, total nitrogen, carbon: nitrogen ratio and hot water carbon.

Soil physical conditions are assessed using bulk density, particle density and water release characteristics which in turn were used to calculate total soil porosity, air filled porosity and macroporosity (Table 2).

Table 2: Indicators used for soil quality assessment.

Indicators	Soil Quality Information	Method
Chemical properties		
Soil pH	Acidity or alkalinity	Glass electrode pH meter
Olsen P	Plant available phosphate	Bicarbonate extraction, molybdenum blue method
Trace elements	Deficiency or toxicity of trace elements in soil	Acid digestion, ICP-OES Spectroscopy
Biological properties		
Anaerobically mineralisable N	Readily mineralisable nitrogen reserves, indicator of microbiological activity	Waterlogged incubation at 40 ºC for 7 days
Total Carbon	Organic matter status	Dry combustion, CNS analyser
Total Nitrogen	Organic N reserves	Dry combustion, CNS analyser
Carbon: Nitrogen Ratio	Indicator for ability of organic matter to supply nitrogen	Calculated from above
Hot Water Carbon	Measure of labile soil carbon, indicator of soil microbiological abundance	Hot water extraction at 80°C for 16 hours followed by IR detection
Physical properties		
Dry bulk density	Compaction, volumetric conversions	Soil cores
Air filled porosity and macroporosity	Soil compaction, aeration, drainage	Air-filled porosity- percentage of soil pores measured at -10 kPa matric potential. Macroporosity- percentage of soil pores measured at -5 kPa matric potential

2.4. Soil Analysis

Descriptions of the different soil analysis process are detailed below. Analysis follows the processes described in the NEMS (Hill, 2022).

2.4.1. Chemical Analysis

All chemical analysis was undertaken by Hills Laboratory, Hamilton. Soil pH was measured in a 1:2 (v/v) soil water slurry followed by potentiometric determination of pH (Blakemore, 1987). Soil phosphorus is determined using a volumetric method with Olsen extraction followed by Molybdenum Blue colorimetry (Olsen et al., 1954). Trace element determination made by Nitric/hydrochloric digestion followed by ICP-OES (Hills Laboratories, 2018).

2.4.2. Biological Analysis

Biological analysis was carried out by Hills Laboratory, Hamilton. Anaerobically mineralisable nitrogen was estimated anaerobic incubation followed by extraction using 2M KCl followed by Berthelot colorimetry (Keeney & Bremner, 1966). Total carbon and nitrogen were determined by dry combustion of air-dry soil

(Hills Laboratories, 2018). Hot water carbon extraction carried out on a dried and sieved (<2mm) 1-20 soil sample at 80°C for 16 hours followed by IR detection for Non Purgeable Organic Carbon (NPOC) (Hills Laboratories, 2019).

2.4.3. Physical Analysis

Soil physical analysis was undertaken by Landcare Research in Hamilton. Dry bulk density was measured on soil samples extruded from cores and dried in an oven at 105°C until the weight remained constant and the sample was then weighed (Gradwell & Birrell, 1979). Particle density was measured by the pipette method. Air filled porosity (-10 kPa) and total porosity were calculated as described by Klute (1986). An example of cores being processed is shown in Plate 2.

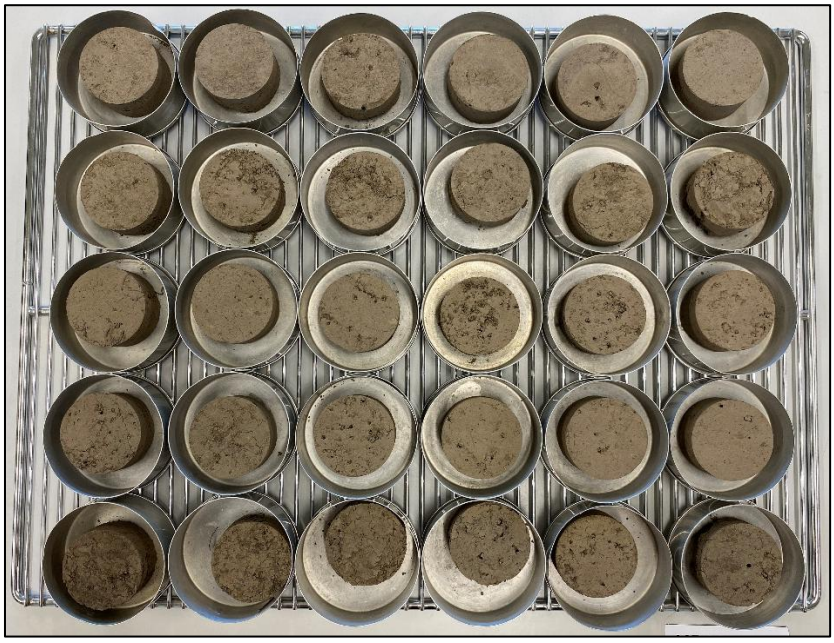


Plate 2: Dried soil cores inside their extraction rings following oven drying. Credit: J. Guthrie, Manaaki Whenua Landcare Research.

This report uses the - 10kPa measurement (defined in this report as air filled porosity), with the - 5kPa data (macroporosity) included for reference because this has been used and reported by MDC and others in the past. Section 4.2 utilises matric potential data collected as part of the soil physical parameters. These are measured as part of the process to calculate air-filled porosity but are not usually reported in the annual reporting.

2.5. Data analysis and display

All data handling is automated using Council Hilltop environmental data management software. Analysis of the data and preparation of graphs is also automated using R statistical software (version: 4.5.3 (2026-03-11 ucrt) -- "Reassured Reassurer"). Graphing used the the 'ggplot2' package. Statistical analysis utilised the base R 'stats' package This ensures improved data security, reductions in errors and in the time needed to create reports. An artificial intelligence agent has been used to develop the graph plotting code, statistical analysis and two illustrations for this report. Further details of the use of AI are included in Appendix D - Use of Artificial Intelligence Disclosure.

For two parameters (pH and total carbon) differences between land uses were evaluated using non-parametric statistical methods within R statistical software. To determine the statistical differences between landuse, an overall Kruskal-Wallis test (kruskal.test function from the base R stats package) was. Where significant differences were detected ($p < 0.05$), pairwise Wilcoxon rank-sum tests with Holm-adjusted p-values (also from base-R stats package) were used to identify which land-use groups

differed. Results were summarised using compact letter displays, whereby groups sharing one or more letters were not significantly different, while groups with no letters in common were considered significantly different. Section 4 utilises several statistical analyses also derived from R. These are documented in a specific method section for the relevant analysis. The long-term data trend uses a linear regression model. This is done to smooth data outliers and to help illustrate long-term trends in the data while utilising all the data. See Section 5 for further details.

2.5.1. Data display

This report displays data several ways. Table 4 and Table 5show the raw chemical and biological data from the bulked transect sample. Table 6 shows the physical data for each sample as a single averaged value for the three 100mm diameter soil cores extracted from each site. Where appropriate, data are expressed on a weight/volume or volume/volume basis to allow comparison between soils with differing bulk density.

Box and whisker plots are used extensively in this report to illustrate the data in a simple, standard format. They are used to compare the distributions of different datasets and can provide an indication of how skewed or dispersed the data is.

Box and whisker plots describe the centre and spread of a data set using five summary values: the minimum, first quartile, median, third quartile, and maximum. The central line represents the median of the data; the box shows the inter-quartile range (IQR) or the zone where 50% of the data lies. The whiskers show the range where 99.3% of the data should be found. They are set as 1.5 times the IQR. Data points outside the whiskers represent outliers and are marked as dots (Figure 1). Where appropriate, in this report, all datapoints are displayed on plots as "jittered" points. This enables the reader to get an impression of the spread of the data.

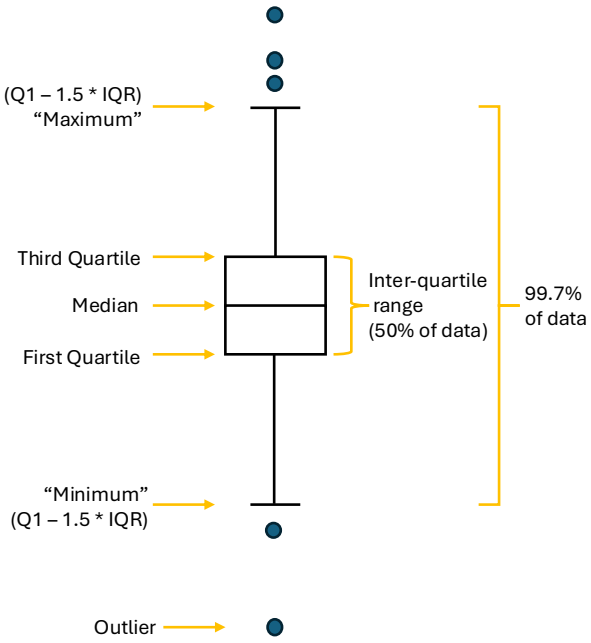


Figure 1: Basic features of a boxplot.

The land uses sampled in this current year are displayed in the first plot in each section. Where a landuse was not sampled, the landuse is included in the plot but a 'no data' notation is included. To provide a more complete view, the second plot in each section shows all data for all land uses since the inception of the programme.

2.6. Reference Ranges and Guideline Values

In 2025, a new set of reference ranges for soil quality monitoring were developed by the Ministry for the Environment (Cavanagh, Drewry, et al., 2025). All reporting on the nine main soil quality parameters is assessed against these new reference ranges. This document has replaced the previous guidelines (Hill & Sparling, 2009; Mackay et al., 2013). The reference ranges from Cavanagh, Drewry, et al. (2025) used in this report are presented in Appendix B - Soil Reference Values.

The revised reference ranges now differ between landuses and soil orders. The revised reference ranges were based on similar approaches used for the original target ranges, but utilising more extensive and/or recent data. In summary, these approaches were:

- pH and Olsen P: a fixed range based on agronomic recommendations for agricultural land uses, and distribution-based 'typical values' for non-agricultural land uses.
- For C, N, AMN, and HWEC: distribution-based 'typical values' (10th to 90th percentile of monitoring data set) for different land uses and soil order groupings, with a function-based (crop yield) minimum value of 2%C for non-Allophanic mineral soils under cropping.
- For air filled porosity and bulk density: reference distributions based on a currently small data set of soils from unimpacted controls for pastoral and forestry sites (Cavanagh, Drewry, et al., 2025; Cavanagh et al., 2026).

In the graphs that follow, these ranges are depicted in two main ways. Where falling outside the reference range represents an environmental hazard, the graph has been shaded pink. Where reference ranges are set for agronomic reasons or from analysis of the national soil quality dataset, they are depicted as a solid red line for upper values and a dashed red line for lower values. Where the reference range is neither environmentally nor agronomically undesirable, the ranges are depicted as green dotted lines (Appendix B - Soil Reference Values).

The guideline value for cadmium results is sourced from the Tiered Fertiliser Management System (TFMS) from the New Zealand Cadmium Management Group. The value for Tier 1 soil quality trigger value is 0.6mg/kg, which is considered to represent the 99th percentile of background soil concentrations. Soil guideline values for the protection of soil biota for soil cadmium is set at 1.5 mg/kg by Cavanagh and Harmsworth (2023); (FANZ, 2019).

Fluoride results are reported again this year. Fluoride is strongly bound to soil and is not readily taken up by plants. To exhibit toxicity, stock must ingest soil particles (or other sources of fluoride such as volcanic ash or fertiliser). (Loganathan et al., 2003; McDowell, 2012). This means a soil guideline value cannot be set for fluoride. Attempts to set ecological guideline values have been made but these are not currently supported by sufficient data to be adopted (Cavanagh & Harmsworth, 2023). The reference ranges used in this report are the median value for soil fluoride (316 mg/kg) previously surveyed in Marlborough (Gray, 2011) and the nationally surveyed baseline for sedimentary soils (43- 166 mg/kg) (Loganathan et al., 2003).

The trace element results (except for cadmium and fluoride) have been compared against the Ecological Soil Guideline Values (Eco-SGVs) described in Cavanagh and Harmsworth (2023) (Appendix B - Soil Reference Values). These guidelines identify reference ranges suitable to protect soil biota. These levels replace the NZWWA guidelines formerly used in this report. There are no Eco-SGVs currently identified by Cavanagh and Harmsworth (2023) for mercury and nickel due to insufficient data and understanding around these elements in NZ. A reference range for mercury is set at 0.7mg/kg as the minimal risk guideline from the Auckland region by Cavanagh (2006). The nickel reference range is set at 45mg/kg using the Canadian Soil Quality Guidelines (Canadian Council of Ministers of the Environment, 2015). Both nickel and chromium have been noted as co-occurring at elevated levels in Marlborough and Otago based on the presence of elevated content of these in some of the ultramafic parent rocks in these regions (Cavanagh, Thompson-Morrison, McNeill, et al., 2025). Soils with elevated levels of these do appear some in sites in the Soil Quality Monitoring program (see section 3.2.3).

3. Results and Discussion

3.1. Comparison with Reference Ranges

Figure 2 shows the percentage of samples not meeting their target for a specific soil quality indicator. All parameters had samples falling outside their references ranges in 2025. The results of soil chemical, biological and physical analyses from soils sampled at each site are given in Table 1, Table 5 and Table 6 (Appendix A - 2025 Soil Test Results) respectively and are discussed separately below.

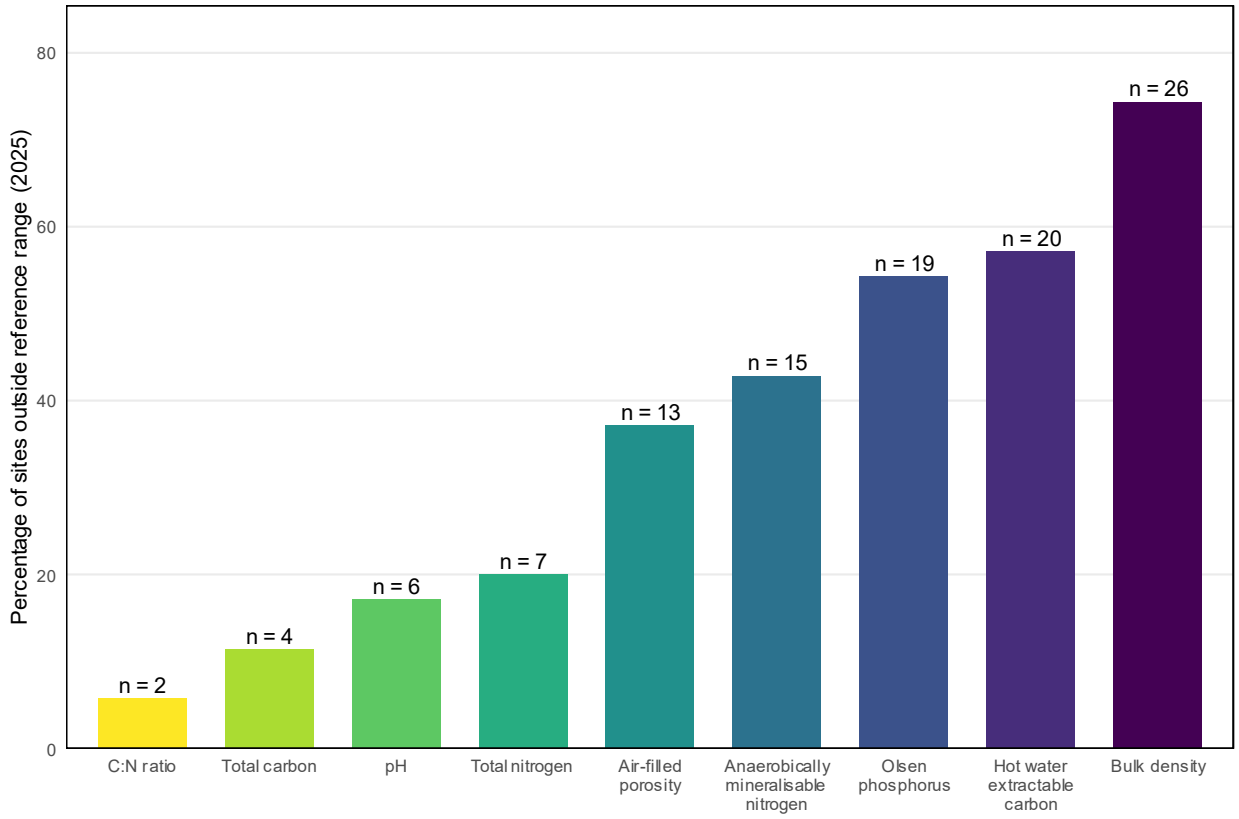


Figure 2: The percentage of sites not meeting their reference range for a specific soil quality indicator.

3.2. Soil Chemical results

Results of soil chemical analysis (pH, Olsen P and Trace elements) are reported in Table 4 (Appendix A - 2025 Soil Test Results). Each of the chemical properties is discussed individually. The reference ranges appropriate to the relevant landuse and soil order can be found in Appendix B - Soil Reference Values.

3.2.1. Soil pH

Soil pH is a measure of the acidity and alkalinity in soil. It is an important soil indicator because it affects nutrient and contaminant availability in plants and the functioning of beneficial soil macro- and micro-organisms. Most plants and soil organisms will have an optimum pH range for growth, and the pH of the soil affects which species will grow best. For vineyards, exotic forestry and native bush, reference ranges are now based on the typical range of values from the national data set. For pasture, dairy and cropping, reference values reflect the pH range for optimal plant growth (Cavanagh, Drewry, et al., 2025).

As indicated in Figure 3 and Table 4, six sites had soil pH values outside the acceptable target for their respective land use in 2025 (17%). Differences are also evident between land uses (Figure 4). Vineyards have slightly higher pH than other land uses with exotic forestry having the lowest pH (most acidic) readings.

Analysis of pH by soil order shows significant differences in pH between soil order. Differences between landuses seen in Figure 3 and Figure 4 are probably due to land management, with vineyard sites, pastoral farming, forested land and cropping each forming their own groupings. This is most likely a reflection of fertiliser practice depending on the crop grown. Land uses that receive lower inputs of lime will tend to lower pH due to the natural acidifying effects of plant growth. Land that can produce higher returns often receive larger or more regular inputs of lime and fertiliser. This can have an impact on pH. The lower returns and larger scale of some forms of farming often restrict fertiliser applications to correction of limiting nutrients only. This seems to have led to an overall lower pH for pastoral and forested land.

While most values fall within the reference ranges for the respective landuses (Figure 4), the higher medians for viticulture are noticeable. The reasonably even distribution of values indicates that some sites (while falling within the reference ranges) may have a higher pH than is agronomically desirable. Given the increased emphasis on sound nutrient management (and the financial costs of fertiliser), it is suggested that vineyard managers may wish to examine fertiliser practice more closely.

Soil Quality recommendation.

- Soil pH should be monitored by soil testing periodically. At a minimum, high intensity land use should be soil tested three yearly, low intensity land use, five yearly.
- The areas to be tested should reflect on-farm management practice. Only areas that can be effectively managed as a single Land Management Unit[i] should be tested.
- Soil pH can range widely while soils remain productive. Crop guides are available to help landowners decide on an optimal pH range for their enterprise.
- Landowners should be aware that pH can be altered by additions of fertilisers and other substances other than lime. Heavy additions nitrogen or sulphur containing fertilisers can lower pH. Additions of wastewater or soil amendments can supply large amounts of elements that can raise or lower pH depending on the element and quantity added. Landowners should test more frequently where additions of this nature are made.

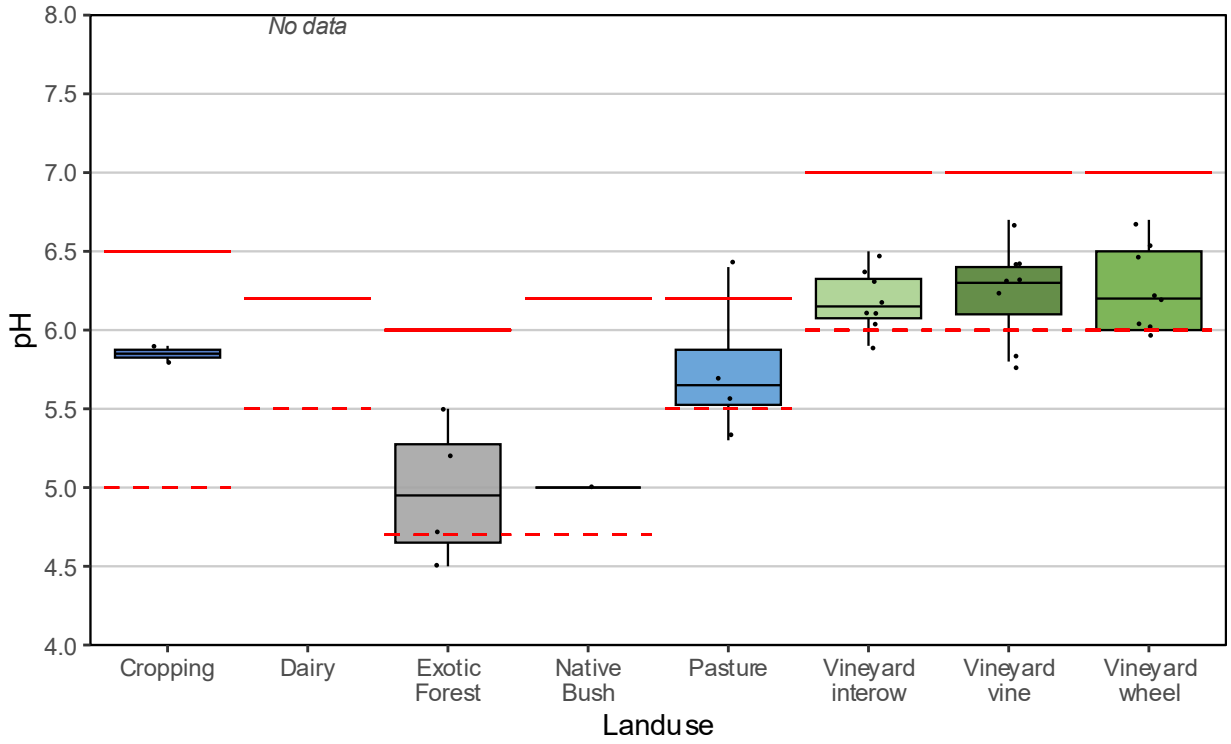


Figure 3: Soil pH by landuse for 2025 samples. Upper Reference ranges denoted by solid red lines, lower ranges by dashed lines. Refer Appendix B - Soil Reference Values.

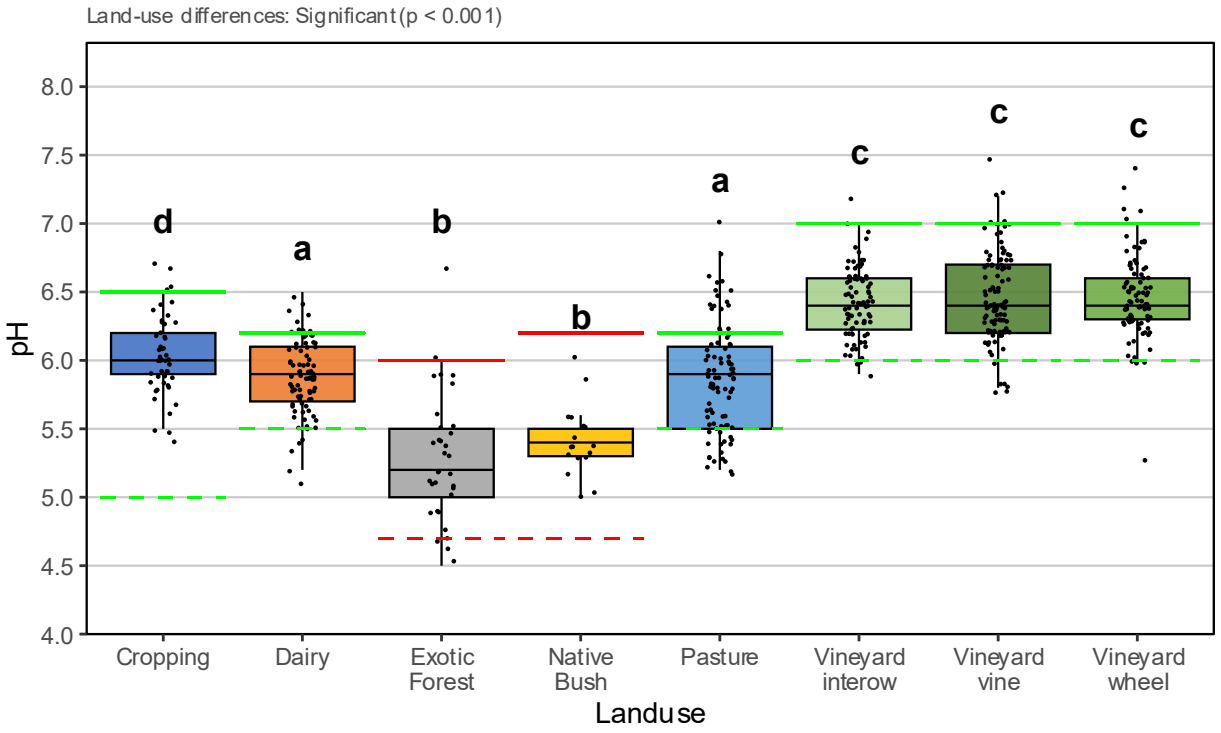


Figure 4:Soil pH by land use for all samples since 2000. Landuses with different letters are statistically different. Upper Reference ranges denoted by solid red lines, lower ranges by dashed lines. Refer Appendix B - Soil Reference Values

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[i] For fertiliser recommendations, an LMU is a distinct area which is managed in a similar way due to soil type, capability and function, and is of strategic importance to the farm in relation to fertiliser application.

3.2.2. Olsen P

Phosphorus is an essential nutrient for both plants and animals. Only a small amount of the total phosphorus in soil is in forms able to be taken up by plants (plant-available P). The Olsen P soil test method uses a chemical extractant that provides a reasonable estimate of the amount of plant-available phosphorus by measuring phosphate from soil solution and exchange surfaces (Olsen et al, 1954). Olsen-P can also provide an indicator for the risk of phosphorous loss to water. Phosphorus in run-off water is known to increase with increased Olsen-P values (McDowell et al., 2003; McDowell et al., 2004; McDowell et al., 2015). The revised reference ranges for Olsen P encompass agronomic levels as lower ranges and environmental risk for upper levels. (Cavanagh, Drewry, et al., 2025).

From the 35 Olsen P samples taken in 2025, concentrations varied from 2 mg/L to 70 mg/L. 19 of 35 values were outside the reference ranges for the relevant landuses (54%). This year, the lowest values are found in exotic forest and native bush (Figure 5). The highest values were found in pasture and vineyard samples. The maximum Olsen P reference range for all soils is now set at 26 mg/L for pasture, 10 mg/L for native bush and 30 mg/L for other landuses. The reference range is set for exotic forestry at below 25 mg/L (Cavanagh, Drewry, et al., 2025).

The revisions to the reference ranges appear to significantly elevate the environmental risk profile of Olsen P compared to the previous situation (50mg/L for all landuses). Farmed sites generally reflect higher Olsen P concentrations compared to unfarmed sites (Figure 6). It must be noted that while elevated Olsen P levels have been shown to increase risk to surface water quality, this can be influenced by many other factors such as soil disturbance, rainfall and transport distance to waterways (McDowell et al., 2004; McDowell et al., 2015). Note the skewed nature of Olsen P in some landuses. The medians for exotic forest, native bush and pasture tend lower within their boxes, indicating the data tends toward lower values overall.

Soil Quality recommendations:

- Olsen P or other phosphate measurements should be included in regular soil testing. Phosphate fertiliser should only be applied following soil testing to ensure the application is necessary.
- Olsen P Values higher than 30 mg/L represent a risk to water quality. Do not apply phosphate fertilisers when Olsen P is above the reference range for your landuse.
- Low Olsen P values may indicate reduced plant productivity. Depending on the crop grown, phosphate fertiliser should be applied to increase productivity in accordance with the relevant crop guide.
- Phosphorus attaches to soil particles. When these are eroded into waterways, the phosphorus can degrade water quality by fertilising unwanted algal and plant growth in the waterway.
- Soil erosion should be controlled. Controls can include installation of wide well-grassed buffer strips around cultivated areas, fencing of critical source areas (low-lying wet areas that drain to waterways) and planting of trees to reduce hillside erosion.
- Phosphate fertiliser contains cadmium as a contaminant. Check cadmium levels prior to applying phosphate especially where there is a long history of phosphate fertiliser use.

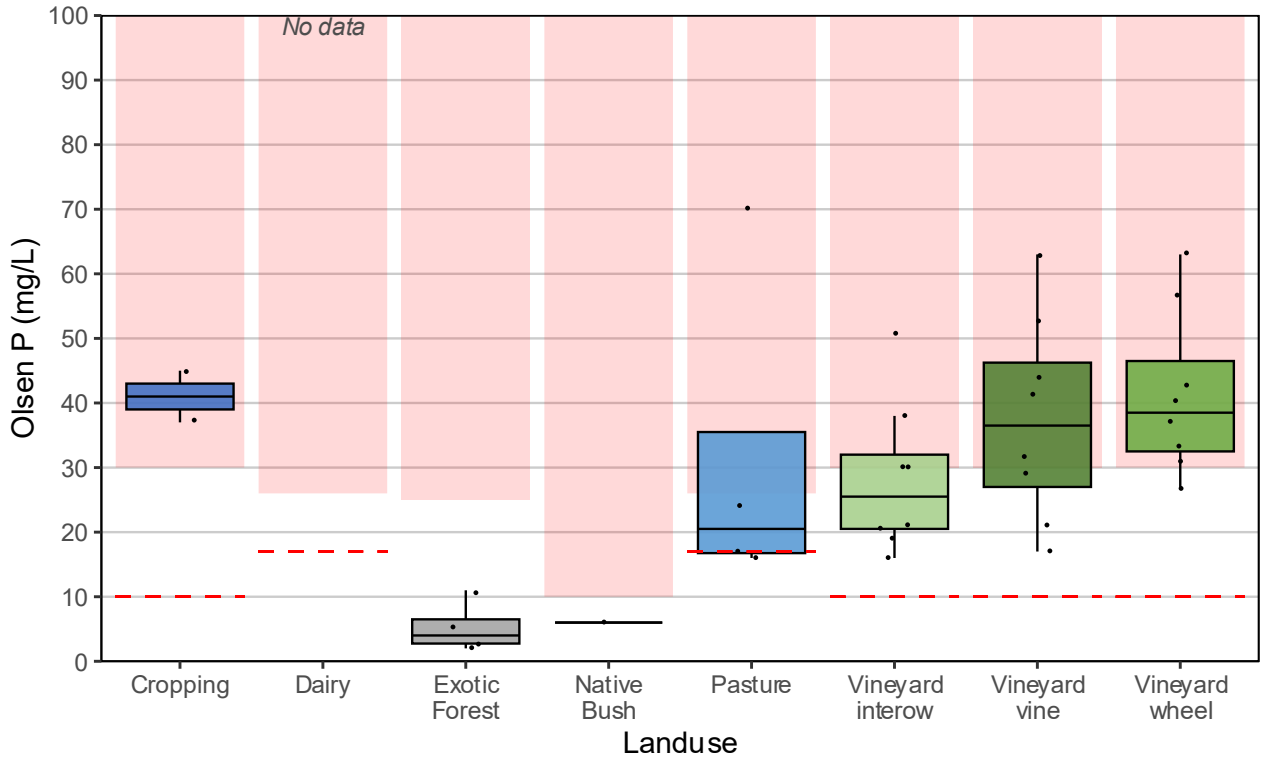


Figure 5: Olsen P values by land use for 2025 samples. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (agronomic minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

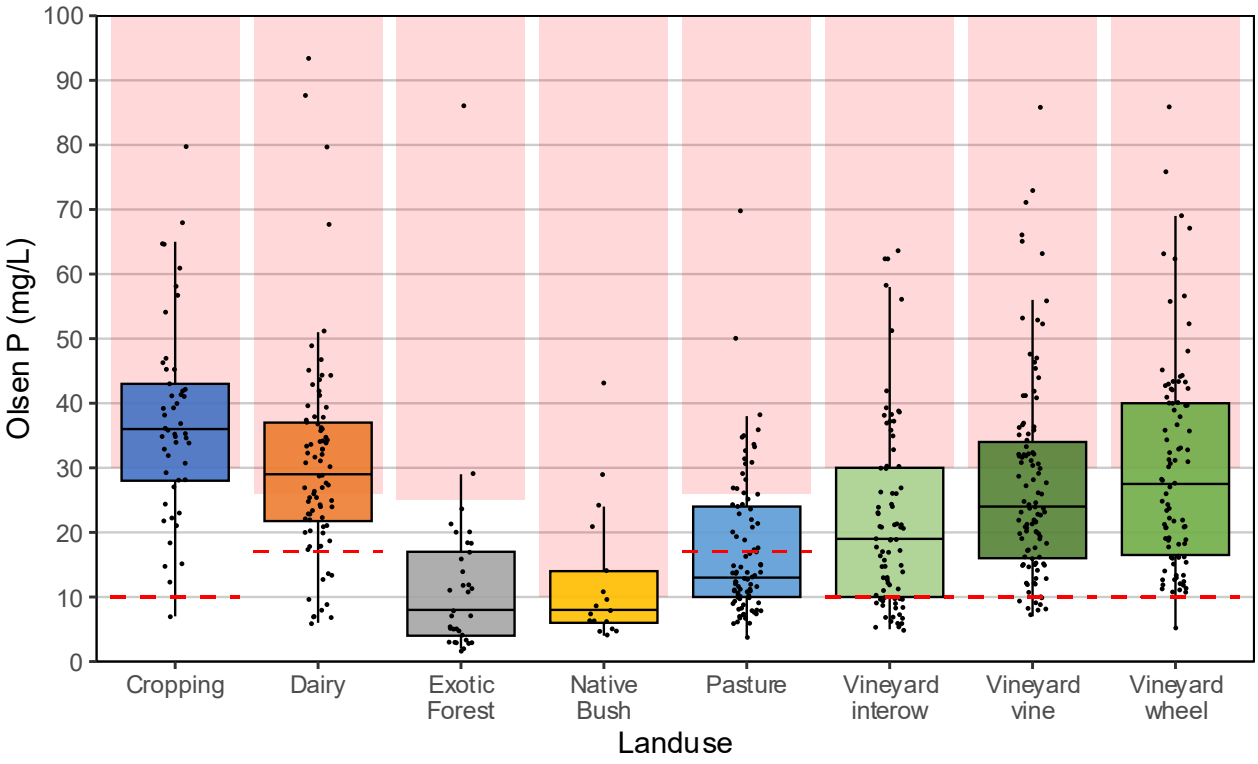


Figure 6: Soil Olsen P values for all samples since 2000. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (agronomic minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

3.2.3. Trace Elements

Trace elements accumulate in soils either naturally through weathering of minerals contained in the soil parent material or from anthropogenic sources. While many trace elements such as copper and zinc are essential for healthy plant and animal growth, at high concentrations in soils, these can have a negative impact on soil fertility and plant, animal and soil microorganism health. Furthermore, some trace elements such as cadmium, arsenic and fluoride are not essential in soil and their accumulation can be toxic to soil life, plants and animals. In some cases, there is potential for them to accumulate in the human food chain.

Table 4 and Figure 7 summarise trace element concentrations in soils from the monitoring sites. No sites showed trace elements in excess of the reference ranges in 2025. Only nickel has shown values above the reference ranges since 2000. Chromium has also displayed elevated levels in some samples but not over the reference ranges during this time. All the elevated nickel and chromium levels are associated with a small set of sites in the Pelorus area downstream of the Rai and Pelorus River confluence. The parent material for these soils is derived from ultramafic rocks with elevated nickel and chromium levels in the headwaters of the Pelorus River and so these values are viewed as natural.

For cadmium, a 2011 survey identified the background median level for all soils to be 0.12 mg/kg in Marlborough (Gray, 2011). This compares to a median for all farmed soils of 0.15 mg/kg and 0.09 mg/kg from the SQMP (Figure 8). The source of cadmium is most likely phosphate fertiliser which has long been shown to contain cadmium as an incidental impurity (Gray & Cavanagh, 2023; Longhurst et al., 2004; McDowell, 2012). Typically, farmed land uses have a higher cadmium concentration than non-farmed (i.e. forestry or native bush). Within the farmed land uses, the concentration of cadmium is likely to reflect the duration and nature of the application of phosphate fertilisers. Different phosphate fertilisers are also noted to have differing cadmium content depending on source and type (Gray & Cavanagh, 2023) (Figure 8). While there is a wide spread of values, Dairy continues to have the highest cadmium concentrations indicative of that industry's historic reliance on phosphate fertilisers to boost pasture (and clover) growth. Cadmium can be taken up by grazing animals and accumulate in internal organs, sale of these for consumption is restricted by law. Transfer of cadmium into milk and muscle meat is considered to make only a minimal contribution to human dietary uptake (Gray & Cavanagh, 2023). It should be noted that even at soil levels below 0.6 mg/kg, cadmium has been documented to exceed food safety thresholds in vegetable produce (Cavanagh et al., 2019). Further detail regarding cadmium dynamics in relation to fertiliser use and trends over time are presented in Sections 4.1 & 5.5.

Fluoride has been included in the SQMP since 2019 to provide a baseline measurement for all of the sites. The source of fluoride in farming systems is likely a combination of soil parent material and phosphate fertilisers (Loganathan et al., 2003). Fluoride is strongly bound to soil and is not taken up by plants. To exhibit toxicity, stock must ingest soil particles or other sources of fluoride such as volcanic ash or phosphate fertiliser (Gray, 2018; Loganathan et al., 2003). This means a soil reference value cannot be set for fluoride. The main risk for land users to consider is the low grazing of forage when animals can ingest large amounts of soil such as during winter crop grazing. The background levels of fluoride for the soil quality monitoring sites are shown in Figure 9. All monitoring sites now have a fluoride baseline measurement. In this report, fluoride is compared to the regional median level (316mg/kg-Gray (2011) and national background levels (43-166 mg/kg-Loganathan et al. (2003). The data would indicate that similar to cadmium, fluoride levels are strongly influenced by addition of phosphate fertilisers. The main risk for land users to consider is the low grazing of forage when animals can ingest large amounts of soil such as during winter crop grazing or grazing of low forage in vineyards over winter (Cronin et al., 2000). Management practice such as grazing immediately after fertiliser application should also consider fluoride ingestion risks.

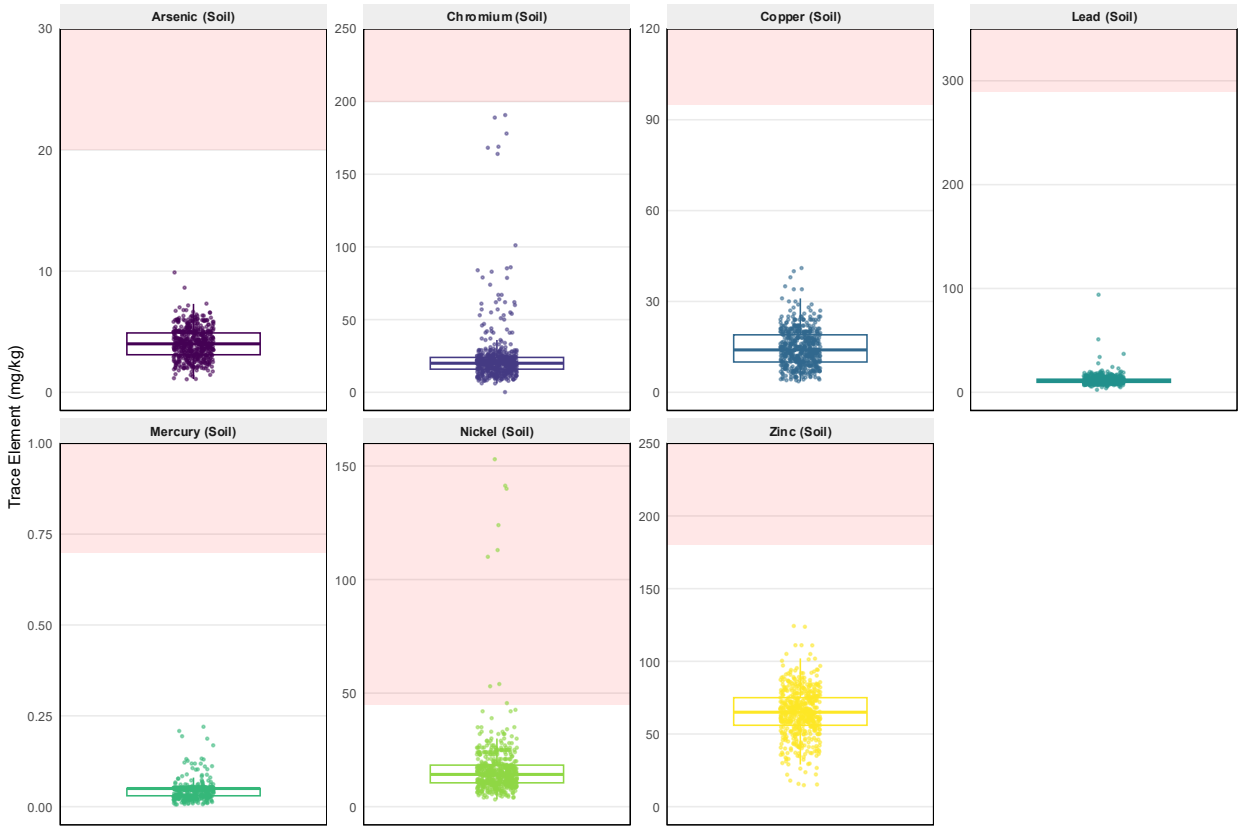


Figure 7: Trace element results for all sites since 2000. Upper reference ranges denoted by pink shading (environmental or health risk). Refer Appendix B - Soil Reference Values.

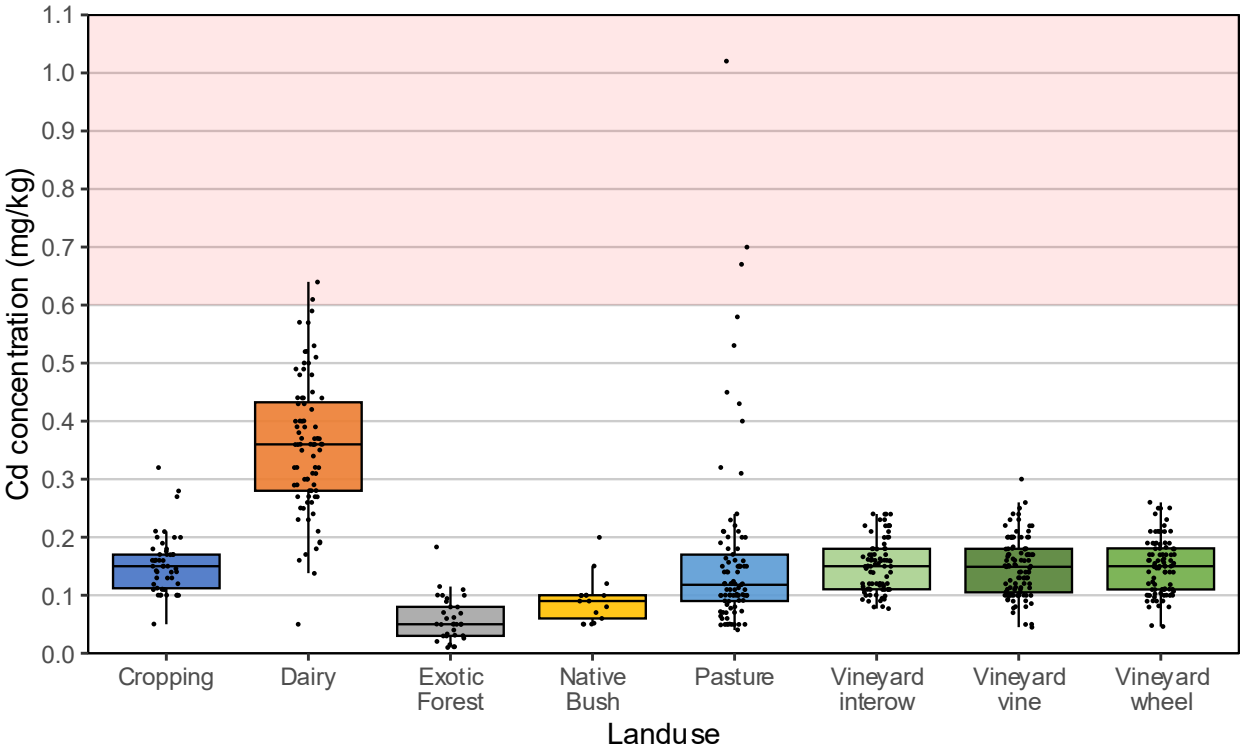


Figure 8: Soil cadmium concentrations by land use for all samples since 2000. Guidance set at 0.6 mg/kg. Refer Appendix B - Soil Reference Values.

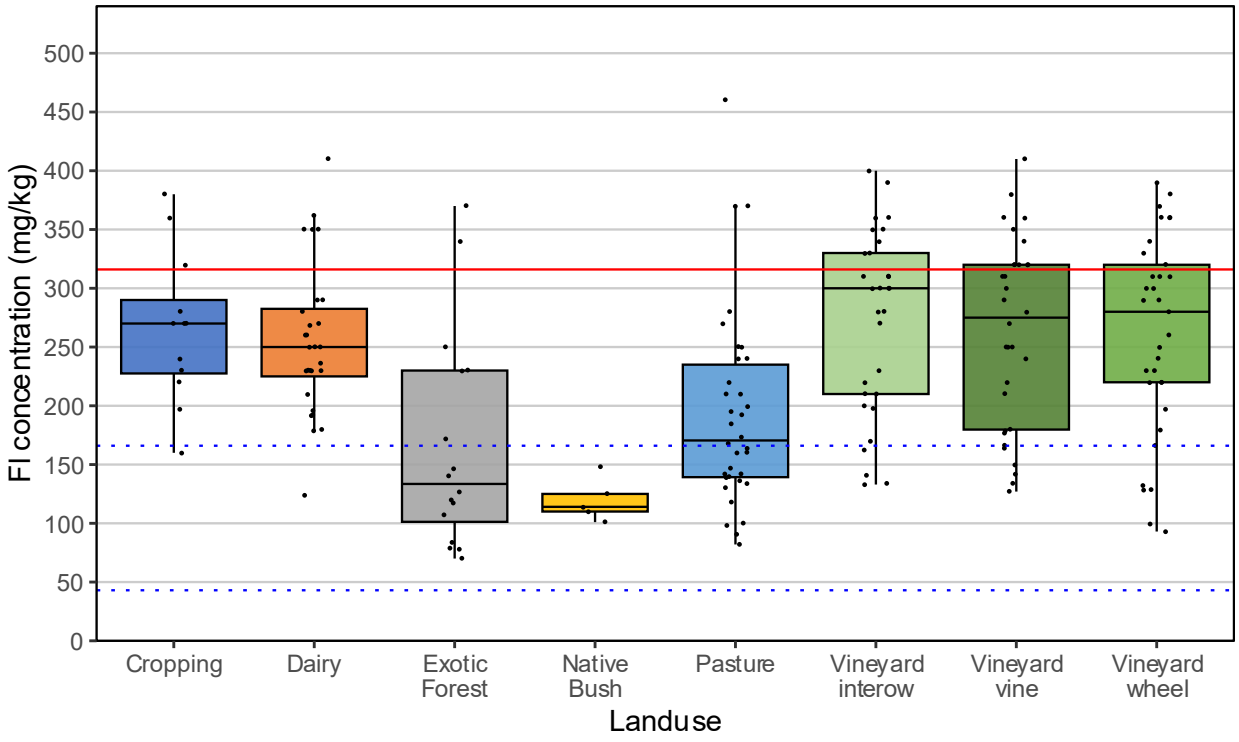


Figure 9: Soil fluoride concentrations by land use for all samples since 2000. Guidance set at 316 mg/kg as median background level. Blue dotted lines indicate high and low national guidance levels (43 - 166 mg/kg). Refer Appendix B - Soil Reference Values.

Soil Quality Recommendations:

- Farms should test soil cadmium at least once every five years where phosphate fertiliser has been applied. Cadmium is managed using the Tiered fertiliser Management System. Details can be found at https://www.fertiliser.org.nz/news/articles/updated-tiered-fertiliser-management-system. Factsheets on the management of cadmium can be found here: https://www.fertiliser.org.nz/news/articles/managing-cadmium-in-new-zealand-fact-sheets.
- Where Olsen P levels are high due to historic fertiliser use, volcanic parent material is present and grazing practice includes low grazing, consider assessing fluoride levels in either soil or animals. Seek further veterinarian advice should testing indicate high levels of fluoride are present.

3.3. Soil Biological Results

Results of soil biological analysis (anaerobically mineralisable nitrogen, total nitrogen, total carbon and C:N ratio) are reported in Table 5 (Appendix A - 2025 Soil Test Results). A new analysis was introduced in 2019, hot water carbon. Each of these organic matter properties is discussed individually. The reference ranges appropriate to the relevant landuse and soil order can be found in Appendix B - Soil Reference Values.

3.3.1. Anaerobically Mineralisable Nitrogen

Anaerobically mineralisable nitrogen (AMN) is a measure of the amount of nitrogen that can be supplied to plants through the decomposition of soil organic matter by soil microbes. It is a measure of the extent to which nitrogen stored in organic matter can be made available to plants. The amount of AMN has also been found to correspond with the amount of soil microbial biomass – hence it is also a useful indicator of microbial activity in soils (Cavanagh, Thompson-Morrison, Drewry, et al., 2025; Curtin et al., 2017).

AMN can provide an indication of N loading in soil as organic matter and plant residues are mineralised (converted by microbes to mineral N). In past Soil Quality reporting, this test has been used to represent the risk of nitrogen leaching. However, during the revisions to the reference ranges it has become clear that AMN does not accurately reflect the real risk of nitrate-N leaching (Cavanagh, Drewry, et al., 2025). Mineralisation rates are strongly influenced by many factors such as temperature, moisture and C: N ratio. If the rate of mineralisation exceeds the rate of plant uptake, this will increase the amount of soil solution N (NO_3—N) (Havlin et al., 2017). Increased soil solution N may increase the risk of nitrate leaching. However, NO_3^--N losses are also controlled by other factors such as plant uptake, rainfall, infiltration, soil porosity and pore connectivity which affect the rate of N assimilation and water movement (drainage) in the soil and therefore the rate of NO_3^--N loss. Cavanagh, Drewry, et al. (2025); Cavanagh, Thompson-Morrison, Drewry, et al. (2025) and Curtin et al. (2017) all note that while AMN can be broadly correlated to Total C and N across the different landuses, this relationship can be variable within and between landuses.

The revision of reference ranges has identified differences in the national data set for Organic and Allophanic soils. None of these soil types exist in the Marlborough Soil Quality Monitoring dataset so the new reference ranges for AMN have been set to represent the tenth and ninetieth percentile from the national dataset. The medians for all landuses since 2000 fall between the reference ranges which is reassuring but exceedances of the upper reference ranges are noticeable in vineyards and dairy (Figure 11).

Typically, anaerobically mineralisable nitrogen concentrations vary widely between sites with the lowest values found on unfarmed sites. Fifteen samples had values higher than their reference range in 2025 (43%) (Table 5 and Figure 10)

This year, three samples from two sites showed values under the agronomic reference range indicating N metabolism may be below optimal productive levels. Sites with lower organic matter inputs or with a high level of soil disturbance report lower levels of AMN. Increased soil disturbance increases oxidation of soil organic matter. Fewer sites have fallen below the minimum AMN target level for their land use, but clear differences are seen between land uses (Figure 11). Particularly striking is the lower AMN values within vineyards. Vineyard wheel tracks and inter-rows show similar AMN values but the area under the vines has noticeably lower AMN values. The regular use of herbicide in this area is probably limiting organic matter input. The long-term effect of this will be to limit nitrogen availability in this area potentially leading to increased fertiliser use or declining crop growth. Cropping sites show very low AMN values due to the combination of regular cultivation and low organic matter inputs. As exotic forestry sites retain a reasonable level of total carbon (Figure 13), it is likely that the low AMN levels are related the elevated carbon: nitrogen ratio on these sites.

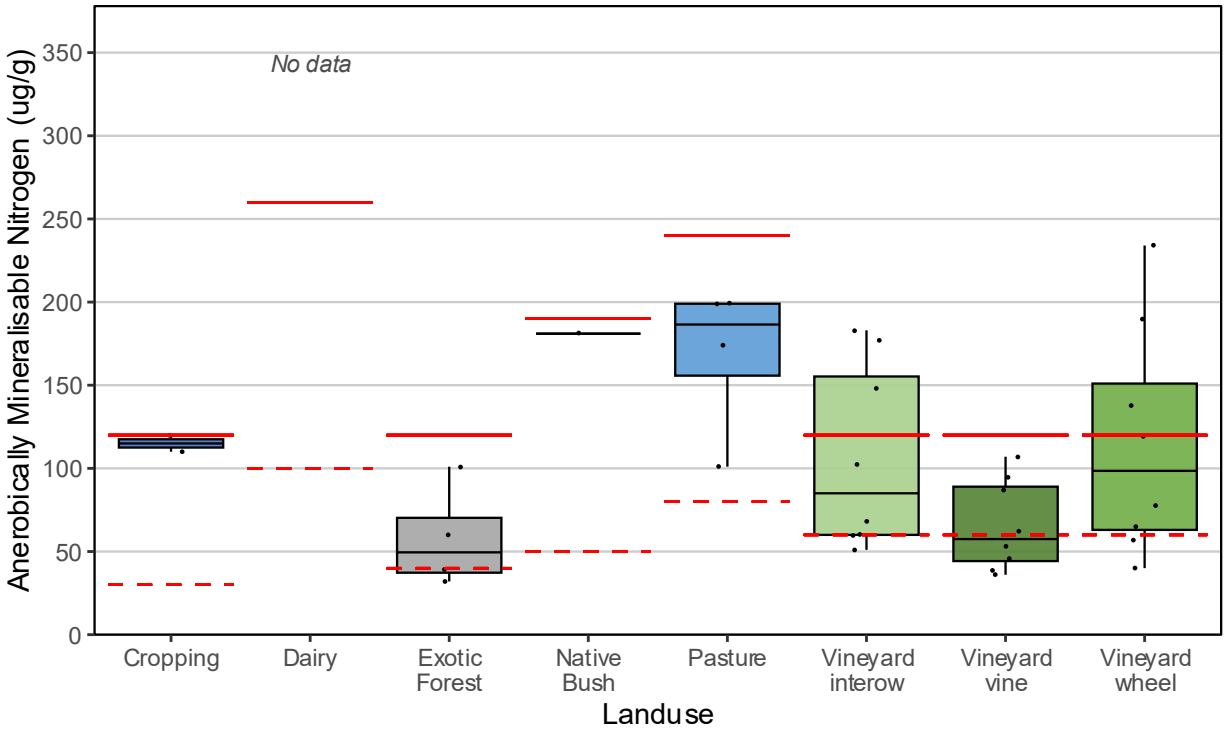


Figure 10: AMN concentrations for 2025. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (agronomic minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

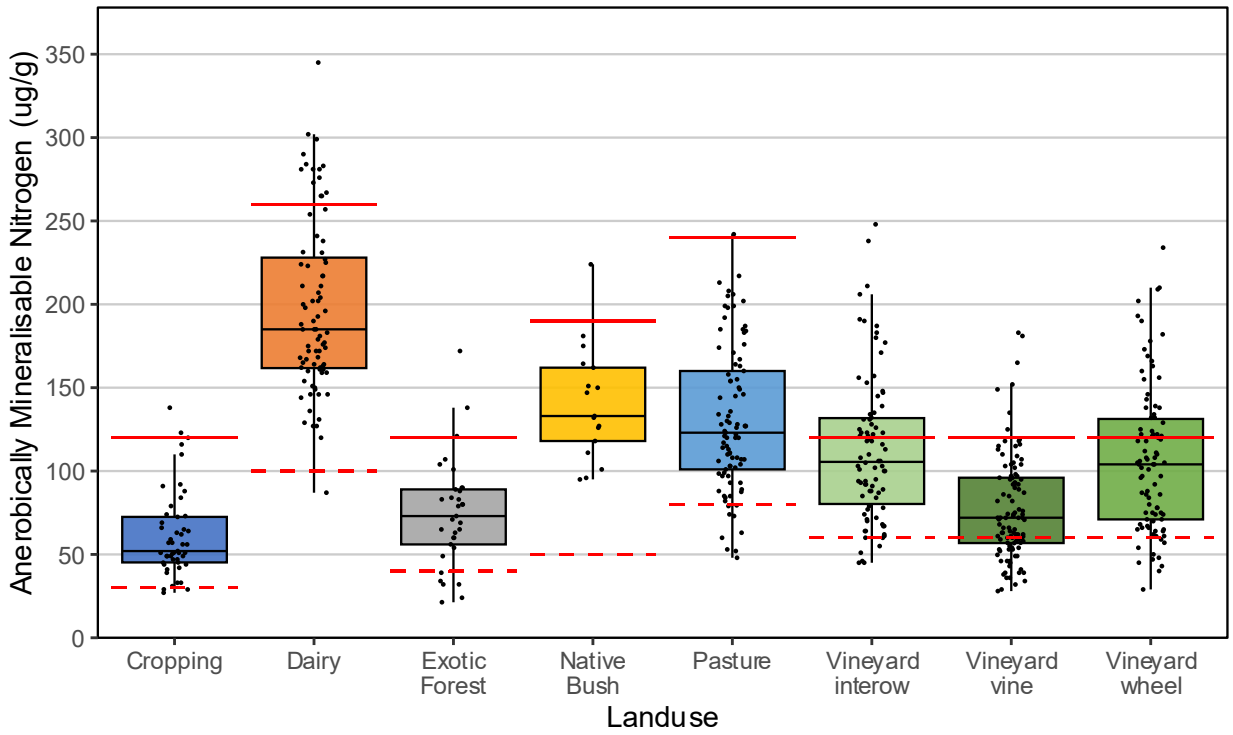


Figure 11: AMN concentrations by land uses for all samples since 2000. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (agronomic minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

Soil Quality Recommendations

- Dairy farmers should incorporate AMN (or similar) measurements in their soil testing regime to account for the release of N from organic matter decomposition when considering application rates of N fertilisers.
- Where AMN is low, reduced supply of nitrogen from organic matter decomposition may be limiting plant growth. Consider methods to lift organic matter levels (see total carbon section 3.3.2).
- Cropping farmers and vineyard managers must consider the impact of repeated cultivations and bare earth under-vine practices respectively on soil organic matter. Increased frequency of fallowing of cropping land and reductions in herbicide use in vineyards may be necessary to lift organic matter levels and improve nitrogen cycling in these land uses.

3.3.2. Total Carbon

Total carbon in soil includes carbonates and soil organic matter carbon. Typically, New Zealand soils contain only small amounts of carbonate[ii]; hence total carbon is generally considered a good measure of and proxy for, organic matter in soil. Organic matter is important for soil health because it aids in the retention of moisture and nutrients, contributes to a stable soil structure, provides a source of energy for soil microbes and is a source of nutrients e.g. nitrogen, phosphorus and sulphur (Cotrufo & Lavallee, 2022). In contrast, low soil carbon increases the risk of structural degradation in soils e.g. low aggregate stability, high bulk density, low air-filled porosity, formation of surface crusts and compaction (Houlbrooke et al., 2021). Low total carbon will lead to reduced productivity through reductions in nutrient and water availability.

In 2025, four samples from 35 (11%) were below their reference range for total carbon. Two samples returned values exactly on the lower reference value (Figure 13). All of these are vineyard sites, some are recent conversions from former cropping land and thus display the carried-over impact of repeated cultivation from the cropping regime. Others are longer-term vineyard sites but show declining organic matter levels likely due to management practices.

A single native bush site sampled for the first time in 2025 has returned the highest total carbon value (13%) seen in the SQMP. This new site is paired with an exotic forest site on the same soil type. The exotic forest site returned a value of 6.7% total carbon.

It is clear from Figure 13 that organic matter accumulation is greatest under native bush. This represents the carbon accumulation from deposition of organic matter over many thousands of years in some cases. The median figure for native bush of 5.6% could be taken as a guide to the pre-European level of soil carbon through much of lowland Marlborough. Land uses with high inputs of organic matter (dairy, exotic forest, pasture) also have higher levels of total carbon. Land uses that involve the disturbance of soil (cultivation) have reduced total carbon. Vineyard establishment can involve a large amount of soil disturbance. Readers are referred to previous soil quality reports (2018 & 2019) for analysis of the effect of vineyard establishment on soil carbon. Analysis of the relationship between total carbon and soil water-holding capacity in vineyards is presented in section 4.2.

Cropping reports consistently low organic matter levels and this may have serious implications for soil and water quality. Cropping sites have the lowest carbon contents of the measured land uses and this is statistically different to other landuses. Note also the statistical difference between vineyard undervine areas compared to wheel and interrow areas (Figure 13).

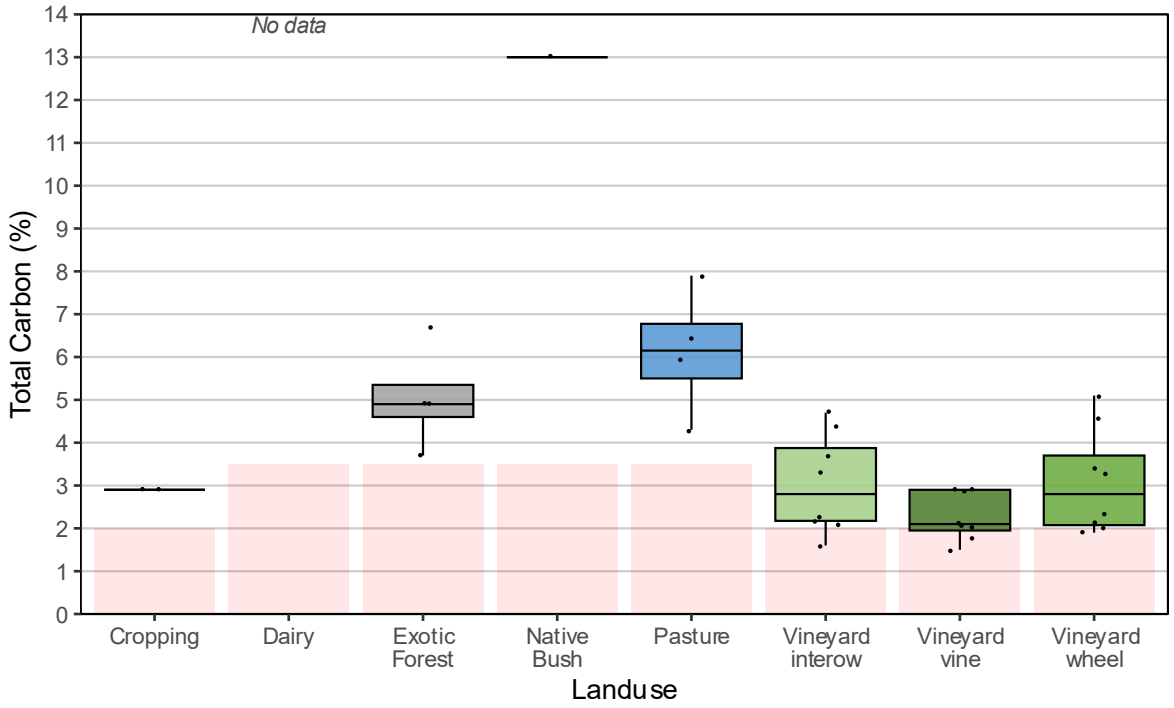


Figure 12: Total carbon values for 2025. Lower reference ranges denoted by pink shading (environmental risk), no upper reference range set. Refer Appendix B - Soil Reference Values.

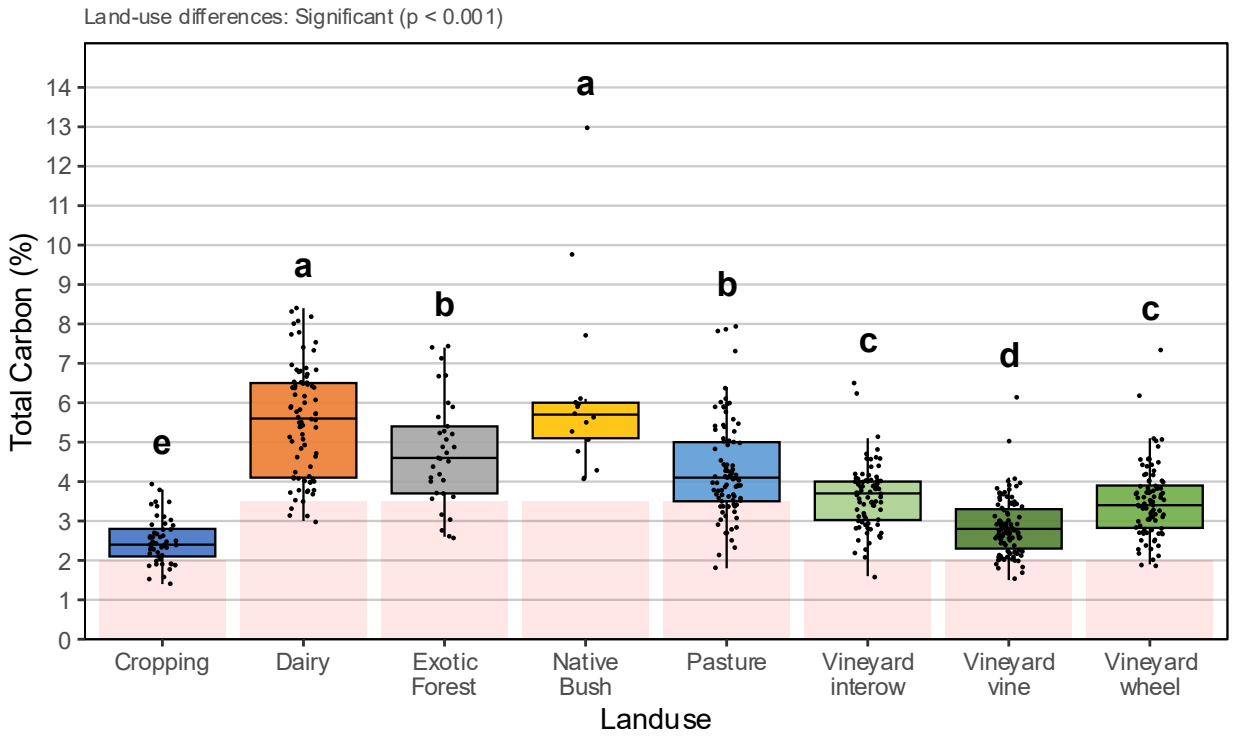


Figure 13: Total carbon by land use for all samples since 2000 Landuses with different letters are statistically different. Lower reference ranges denoted by pink shading (environmental risk), no upper reference range set. Refer Appendix B - Soil Reference Values.

Soil Quality Recommendations

- The factors that influence organic matter, and hence total carbon levels are:

Increased total carbon	Decreased total carbon
Grass/clover pasture	Bare soil
Moist summer growing conditions	Summer drought
Controlled Grazing	Overgrazing
Direct drill/no tillage	Intensive cultivation
Friable soil structure, good root density	Compacted soil, shallow root zone
Moderate N fertiliser application	Excessive N fertiliser applications
Incorporation of crop residues	Removal or burning crop residues
Green manure/cover crops	Erosion

Cropping shows clear signs of soil degradation caused by declining organic matter levels. To lift these levels to the reference ranges (ideally to 4% or greater), the following steps are recommended:

- Increased use of pasture fallow and catch crops in crop rotations.
- Ensure all soils are vegetated over winter (in crop or fallow).
- Reduced cultivation especially rotary hoe use and increased use of direct drilling.

Vineyard under-vine areas show soil degradation from reduced organic matter levels. The following options are suggested:

- Reduce use of herbicide; consider integrating herbicide use with minimal under-vine cultivation and mowing.
- Allow weeds to grow over winter, use grazing to manage excessive growth.
- Add carbon sources (fish, seaweed, humates) to herbicide applications
- Apply compost to under-vine area.

[ii] Recent evidence from soil mapping work in Marlborough has shown soils with carbonates do exist in South Marlborough. They are likely to be limited in extent and will be researched in more detail in coming years.

3.3.3. Hot Water Extractable Carbon

Recent work by Taylor et al. (2022) and Lawrence-Smith et al. (2018) has shown that hot water carbon extractions could provide a better soil quality indicator than the current set of organic matter indicators. In 2019, MDC undertook the first set of Hot Water Extractable Carbon (HWEC) analysis. The reference ranges for HWEC have been updated in similar fashion to AMN with ranges set at the 10th to 90th percentile in the national dataset. Higher HWEC values indicate higher levels of readily decomposable carbon and this would imply elevated microbial biomass (Cavanagh, Drewry, et al., 2025).

It is generally accepted that soils exposed to more cultivation will lose soil carbon and consequently suffer from degraded soil structure. These soils typically show low HWEC readings and this infers reduced microbial biomass, reduced soil structure and consequently reduced ecosystem services such as water storage, water filtration and nutrient supply.

Hot Water Extractable Carbon is thought to measure the dissolved organic matter fraction of soil organic matter (SOM) (see Section 5.4 for more detail on soil organic matter fractions). The dissolved organic matter compounds are mainly root exuded compounds that are water soluble and can; improve nutrient availability, alleviate metal toxicity and serve as a carbon and energy source for microorganisms. Relationships between microbes and the soils dissolved organic carbon (and dissolved organic matter in general) are important in regulating the fluxes of carbon in surface soil horizons and can also play a critical role in stabilisation of SOM, carbon dynamics and contributes to soil water repellence (Cotrufo & Lavallee, 2022; Taylor et al., 2022). The soil carbon fractions measured by HWEC are important in the global soil carbon cycle as they represent the carbon most easily lost to the atmosphere as CO_2 (Cotrufo & Lavallee, 2022; Grunwald et al., 2011) and to water as dissolved carbon following cultivation and the use of N fertilisers (Boyd, 2015).

In 2025, twenty of the 35 samples (57%) reported values outside the reference range. (Table 5, Figure 14 and Figure 15). Four full ex-cropping vineyard sites (vine, wheel and interrow values- 12 samples) all report low HWEC values. The remaining four low HWEC values result from low under-vine values (three) One vineyard wheel track sample and four vineyard interrow samples report HWEC values higher than the upper reference range.

Soil Quality Recommendations

- Similar to total carbon, hot water carbon values show reduced organic matter levels in many soils. Cropping and under-vine areas are of particular concern.
- Testing for HWEC can now be performed by commercial soil laboratories and should be included when soil tests are performed on all land uses.
- To raise HWEC values to the soil quality targets, cropping farmers and vineyard managers should follow the steps outlined for total carbon in Section 3.3.2.

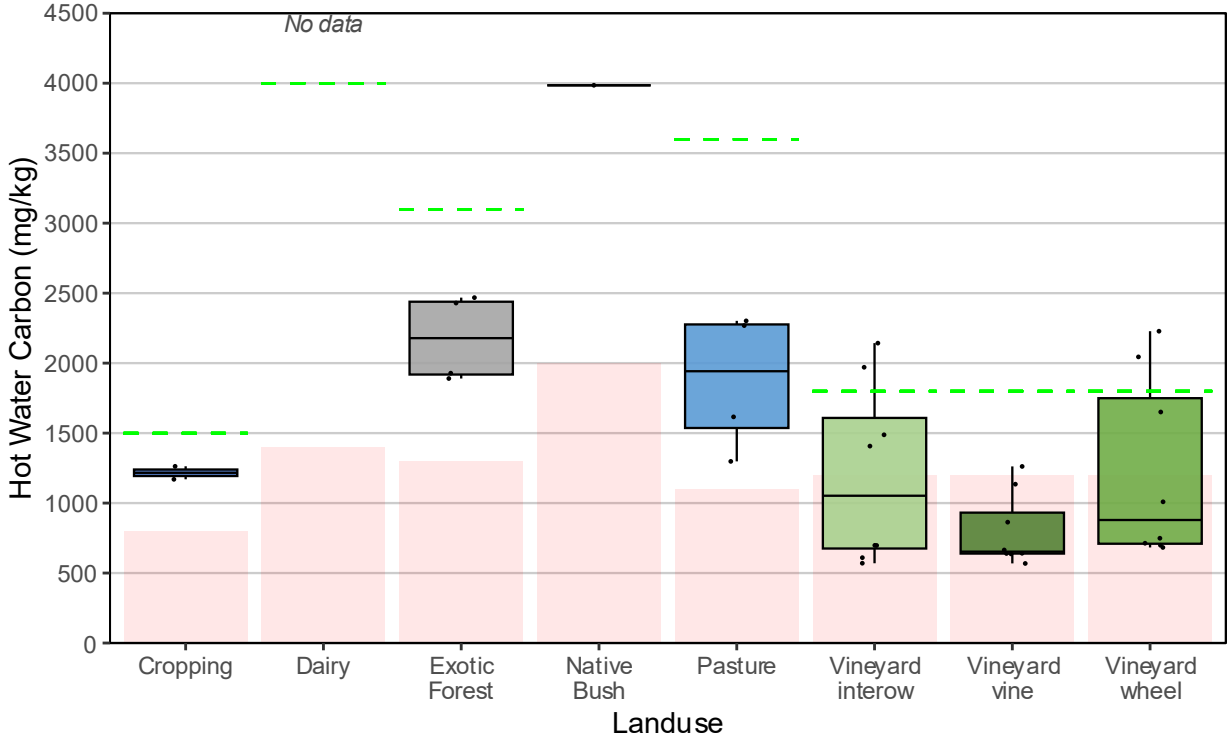


Figure 14: Hot water extractable carbon values for 2025. Lower reference ranges denoted by pink shading (environmental risk), upper reference range is set based on the national dataset but not considered either an environmental or agronomic risk (green dashed line). Refer Appendix B - Soil Reference Values.

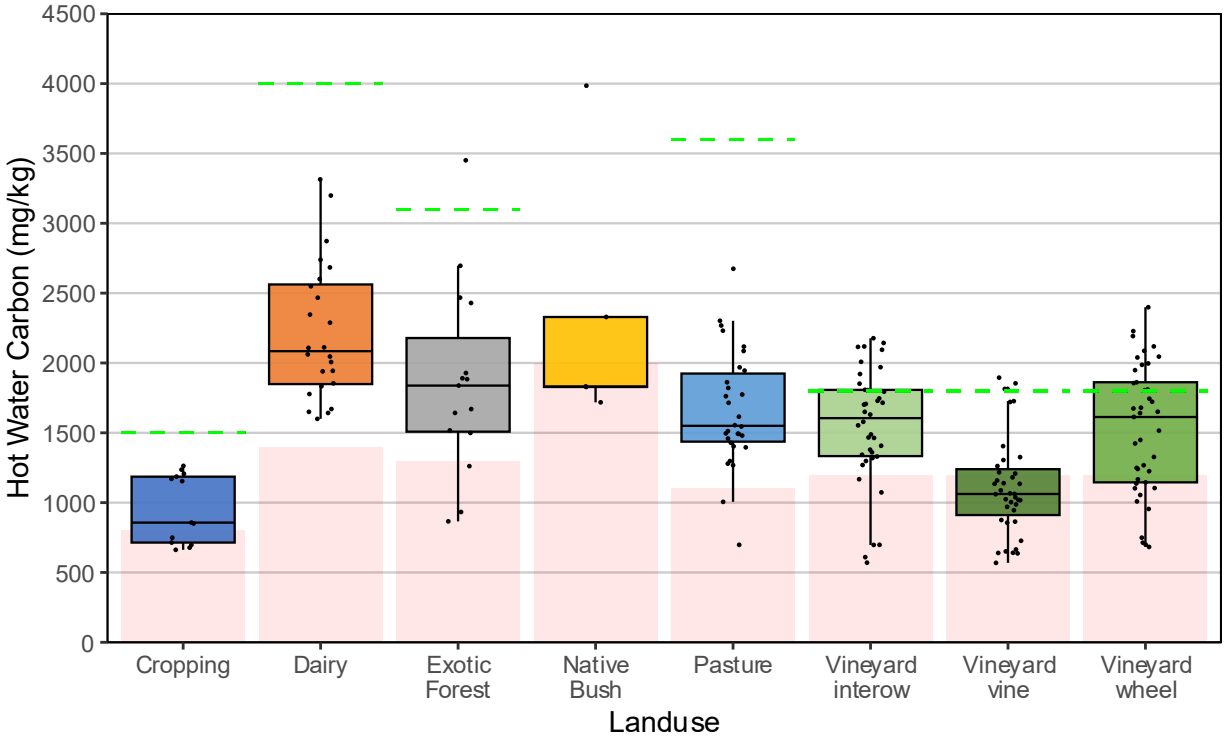


Figure 15: Hot water extractable carbon values since 2019. Lower reference ranges denoted by pink shading (environmental risk), upper reference range is set based on the national dataset but not considered either an environmental or agronomic risk. Refer Appendix B - Soil Reference Values.

3.3.4. Total Nitrogen

Nitrogen is an essential major nutrient for plants and animals, and the store of organic matter nitrogen is an important measure of soil fertility. Typically, in topsoil, organic matter nitrogen comprises more than 90% of the total nitrogen. However, organic matter nitrogen needs to be mineralised to inorganic forms (i.e. ammonium and nitrate) by soil microbes before it can be utilised by plants or lost from soil by leaching or denitrification. Typically, total nitrogen content is closely related to organic matter levels, soils with low inputs of organic matter or high loss rates caused by cultivation will have low total nitrogen.

The reference ranges for total nitrogen have changed in line with AMN, HWEC and total carbon. Allophanic and Organic soil orders are not present in the Marlborough dataset so are excluded, resulting in landuses each having a reference range set according to the relevant 10th to 90th percentile values in the national dataset.

In 2025, 7 sites (20%) returned values below the reference range for total nitrogen (Table 5, Figure 16). This result mirrors the results for the same ex-cropping vineyard sites as discussed for AMN and HWEC. Two exotic forest sites first sampled this year have reported low total N values.

Across all total nitrogen values, each landuse fits well within the reference ranges (Figure 17). The pattern of total nitrogen closely resembles total carbon. Landuses that have reduced carbon content have reduced total nitrogen. Dairy farming shows an elevated total nitrogen record, and this is likely due to the increased nitrogen inputs (fertiliser and clover N fixation) and cycling seen in this sector. Much of that nitrogen will be captured and cycled through organic matter before being mineralised by microbes and released back into the soil solution for plant uptake and potentially leaching loss. Future Soil quality reports will look to investigate the relationships between total carbon, total nitrogen and hot water extractable carbon to help understand the dynamics of the carbon and nitrogen system.

For further information regarding risks around nitrogen leaching, readers are directed to the Risk Index Tool for on-farm nutrient management at https://environment.govt.nz/what-government-is-doing/areas-of-work/freshwater/risk-index-tool/

Soil Quality Recommendations

- Total nitrogen is closely linked to carbon, understanding the carbon: nitrogen ratio is important when evaluating nitrogen dynamics in soils. If the ratio is low and total N is high then total nitrogen values will be reduced in many soils. Cropping and under-vine areas are of particular concern.
- Testing for total nitrogen should be included when soil tests are performed on all land uses.
- To raise total nitrogen levels to meet the soil quality targets, cropping farmers and vineyard managers should follow the steps outlined for total carbon in section 3.3.2.
- To lower total nitrogen levels to meet soil quality targets, land managers should refrain from additions of nitrogenous fertiliser and plant grass or cereal crops to soak up excess nitrogen especially prior to winter on cultivated land.
- The planting of post-winter grazing catch crops of grass or cereal is also recommended where intensive winter grazing has occurred.

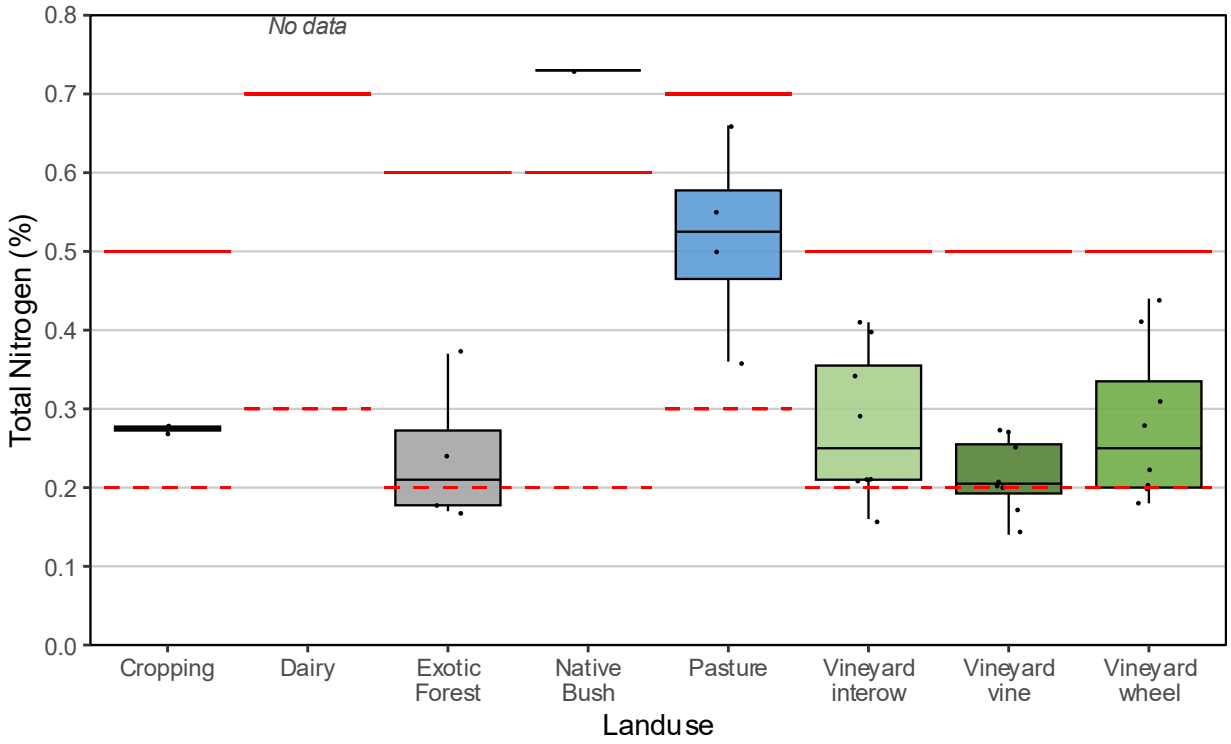


Figure 16: Total nitrogen values for 2025. Upper agronomic reference ranges denoted by solid red lines, lower agronomic ranges by dashed lines. Refer Appendix B - Soil Reference Values

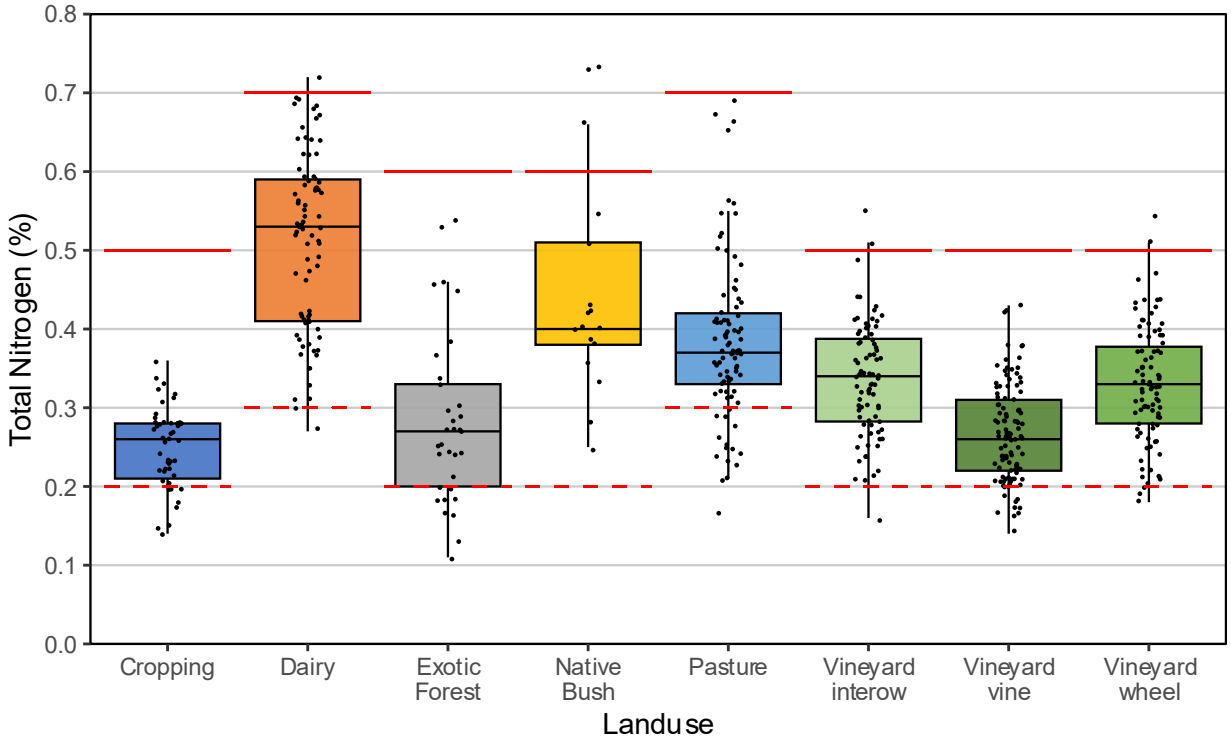


Figure 17: Total nitrogen values all values since 2000. Upper agronomic reference ranges denoted by solid red lines, lower agronomic ranges by dashed lines. Refer Appendix B - Soil Reference Values.

3.3.5. Carbon: Nitrogen Ratio

The balance of the amount of carbon to nitrogen in soil is called the carbon: nitrogen ratio (C:N). This ratio is important as a guide to the state of decomposition or likely ease of decomposition and mineralisation of nutrients i.e. production of nitrates and ammonium from organic residues in soils and is a measure of organic matter quality. It is therefore also a guide to the risk of N mobility (nitrate leaching) in soil (Cotrufo & Lavallee, 2022).

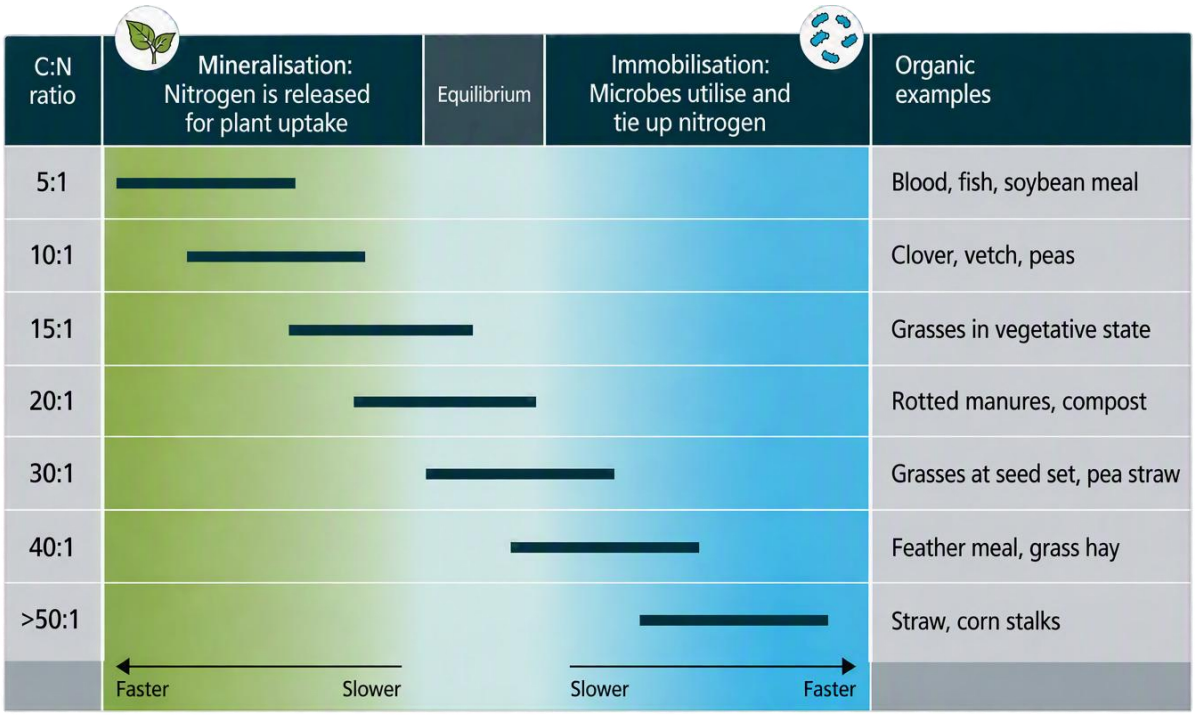


Figure 18: The C:N ratio of some organic materials and their mineralisation and immobilization rates. The C:N ratios vary over a range for any organic material and these represent an average of the range. Source adapted from Brust (2019).

As C: N ratio increases above 10:1 (nitrogen becomes scarce in relation to carbon), soluble nitrogen is immobilised (taken up) by soil microbes, the soil solution N concentration falls and the risk of nitrogen leaching decreases but plant deficiency risks increase (Havlin et al., 2017). Nitrogen cycling then becomes more dependent on microbial activity. Low C:N ratios (<10) may be of concern about leaching of nitrate, as low ratios suggest the storage of N in organic matter may be reaching saturation. A nitrogen saturated soil can no longer store more organic nitrogen and potentially any additional nitrogen added will be lost from the soil and may ultimately accumulate in drainage waters and aquifers as nitrate. Hence monitoring the C:N over the medium to long term will provide useful information.

In comparison, exotic forestry and native bush with few nitrogen fixing plants and low nitrogen status that have not received any additional nitrogen inputs (e.g. by stock grazing or fertiliser), often have relatively high C:N ratios and this is shown in Figure 20. Low nitrogen status is desirable for native ecosystems that have indigenous plants adapted to low nutrient conditions. Higher nutrient status may not be beneficial as this could encourage the growth of undesirable, weedy species. Implementation of the soil quality recommendations for total carbon, should ensure C:N ratio meets the reference range.

The revised reference ranges for C:N ratio reflect the national dataset with values set to typical ranges for three grouped sets of landuses. Exotic and native forest have their own ranges and all other landuses share a range of 10-13 (Cavanagh, Drewry, et al., 2025).

In 2025, aside from two exotic forestry sites, all samples had a C:N ratio within their reference ranges. These two sites are new to the programme this year so future sampling will determine if these values are correct (Figure 19).

Across the entire dataset since 2000, most landuses have reported median values within the reference ranges (Figure 20). The exception is cropping which has a median value below the 10:1 reference range. This is related to the low organic matter levels found in this landuse as noted earlier. Forests of all kinds are noted to have C:N ratios that are higher than grassland systems (Blanco et al., 2023) and this is seen in the Soil Quality dataset. It should be noted that C:N ratio looks to be similar between the non-forest landuses in the dataset. However, closer examination would show that although similar ratios result, dairy and (to some extent pasture) have higher total carbon and total nitrogen compared to vineyard or cropping landuses. So, while the decomposability of the organic matter in these soils will be similar, the size of the organic matter pool in dairy and pasture is greater than in the other landuses.

No clear reason has been determined for elevated exotic forestry median compared to the lower Native bush median. Various authors attribute the low N levels to soil texture, forest species, pH of decomposing leaf litter, different microbial communities between the different landuses or more complete nitrogen assimilation by forests (for example: Spohn and Stendahl (2024), Cools et al. (2014), Reid et al. (2024) and Grigal and Vance (2000)). All these explanations could be supported by the data seen in the soil quality dataset and is likely to be highly complex and site specific. The high C:N ratio in forests implies that organic matter decomposition is likely to be slower and will favour carbon accumulation (Cools et al., 2014; Spohn & Stendahl, 2024) .

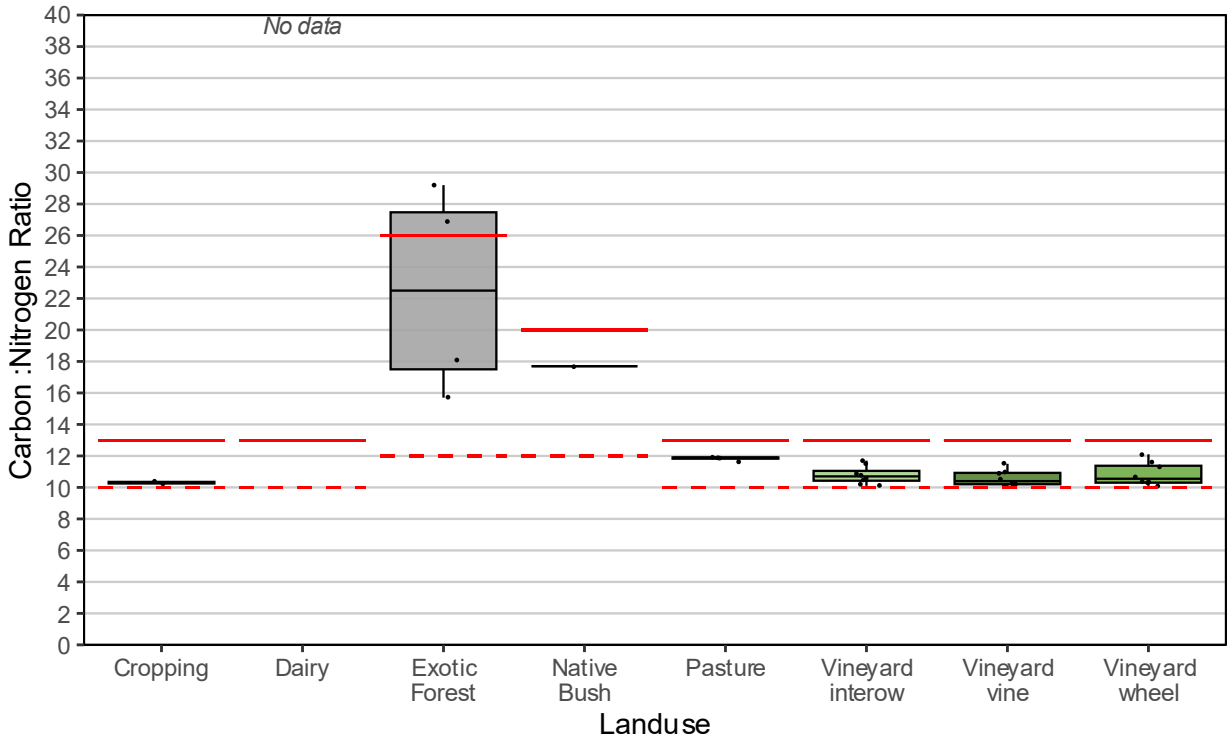


Figure 19: Carbon: nitrogen ratio for 2025. Upper Reference ranges denoted by solid red lines, lower ranges by dashed lines. Refer Appendix B - Soil Reference Values.

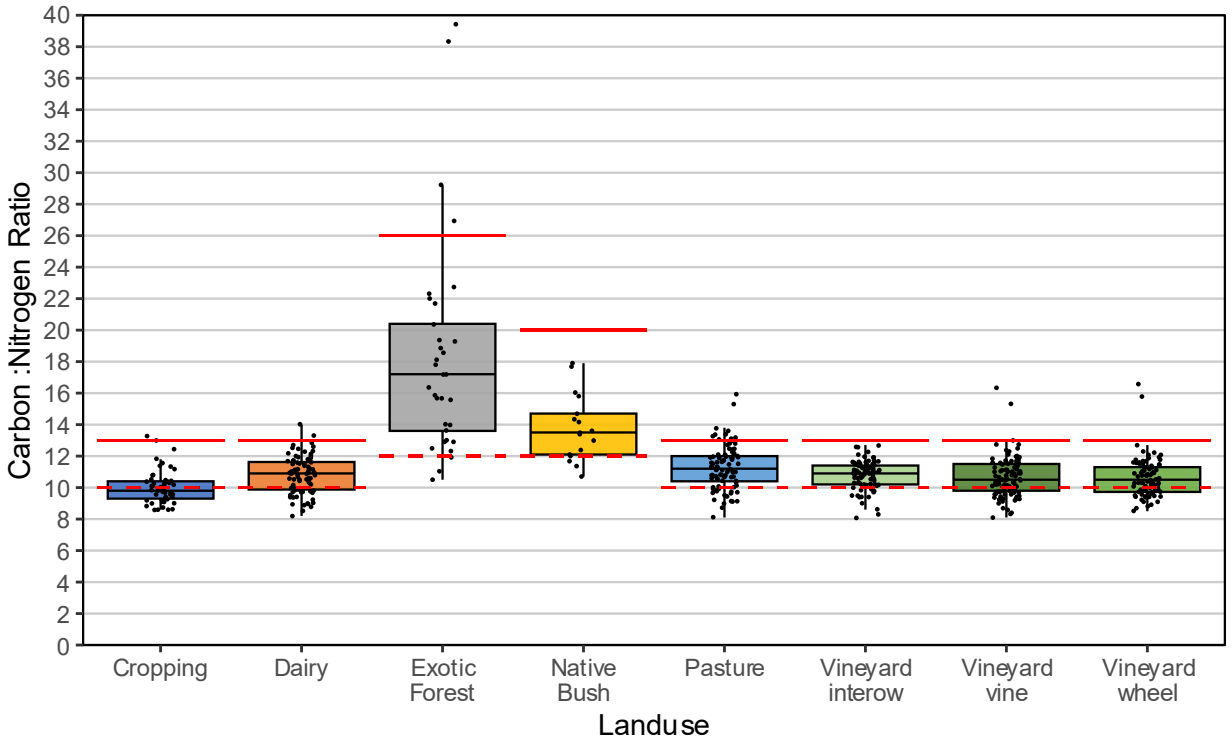


Figure 20: Carbon: nitrogen ratio values for all data since 2000. Upper Reference ranges denoted by solid red lines, lower ranges by dashed lines. Refer Appendix B - Soil Reference Values.

3.4. Soil Physical Results

Results of soil physical analysis (bulk density, air-filled porosity and aggregate stability) are reported in Table 6 (Appendix A - 2025 Soil Test Results). Each of these physical properties is discussed individually. The reference ranges appropriate to the relevant soil order can be found in Appendix B - Soil Reference Values.

Significant changes have been made to the reference ranges for soil physical parameters this year. The revised reference ranges have been derived from a separate dataset from the national Soil Quality set. This is due to strong evidence of degradation in the national dataset (Cavanagh, Drewry, et al., 2025). Two independent datasets have been used instead. The 'under fenceline/undisturbed' dataset (Curran Cournane et al., 2013) and the undisturbed forestry dataset (Garrett et al., 2022) are two small datasets specifically designed to provide a suitable baseline for soil physical parameters. The resulting reference ranges group exotic forest and native bush in one range and all other landuses in a second group (Appendix B - Soil Reference Values).

Cavanagh, Drewry, et al. (2025) recommend that the reference dataset for soil physical parameters is augmented by targeted sampling during future monitoring rounds. This will involve collecting additional samples from less or non-compacted sites. Council will seek to add an additional sampling point to all landuses where suitable non-compacted sites can be found near existing monitoring sites.

3.4.1. Bulk Density

Bulk density is the weight of soil in a specified volume and provides a measure of how loose or compacted a soil is. Low bulk density (loose) soils may be subject to increased risk of erosion, dry out quickly, and plant roots find it difficult to get purchase and absorb water and nutrients. In contrast, soils with a high bulk density are generally compacted with low soil porosity, have poor aeration and are slow draining. The consequences of compacted soil may include reduced supply of air to plant roots, increased resistance to root penetration that may limit root extension and germination, and reduced capacity of the soil to store water that is available to plants. Further, reduced water entry into the soil may increase water runoff over the soil surface (Cavanagh, Drewry, et al., 2025; Mclaren & Cameron, 1996).

The lowering of the bulk density reference ranges from the previous value of 1.4 Mg/m^3 to 1.0 Mg/m^3 has resulted in many sites now having bulk density values above the environmental risk range. The value of 1.4 Mg/m^3 has been retained in the new reference ranges as an upper limit where there is evidence of impacts on root growth (Cavanagh, Drewry, et al., 2025). In 2025, 26 out of 33 averaged samples (74%) had a bulk density value outside the environmental risk reference range for the relevant landuses (Table 6, Figure 21).

Figure 22 shows bulk density for different land uses since samples began in 2000. Bulk density values tend to reflect the level of farming activity. Intensive farming that involves soil disturbance, repeated trafficking by vehicles and livestock treading, all display higher bulk density readings. Low intensity sites show low bulk density readings with native bush again providing a baseline value. The median native bush value helps give confidence that the reference range datasets are reliable and that a bulk density value of 1.0Mg/m^3 is set appropriately to allow comparison with non-compacted soils.

Dairy farms provide an interesting counterpoint. As will be seen in coming sections, the higher organic matter inputs into dairy systems seem to protect the soil to some degree against developing higher bulk density despite the heavy treading effects of cattle. However, dairy soils are still regarded as compacted. This is because large pores are removed by the treading while smaller pores remain. Often this level of compaction is insufficient to cause a lift in bulk density. The removal of these large pores contrasts with the vehicle trafficking effects seen in vineyards which remove all pore sizes leading to the increase in bulk density (Wang et al., 2026).

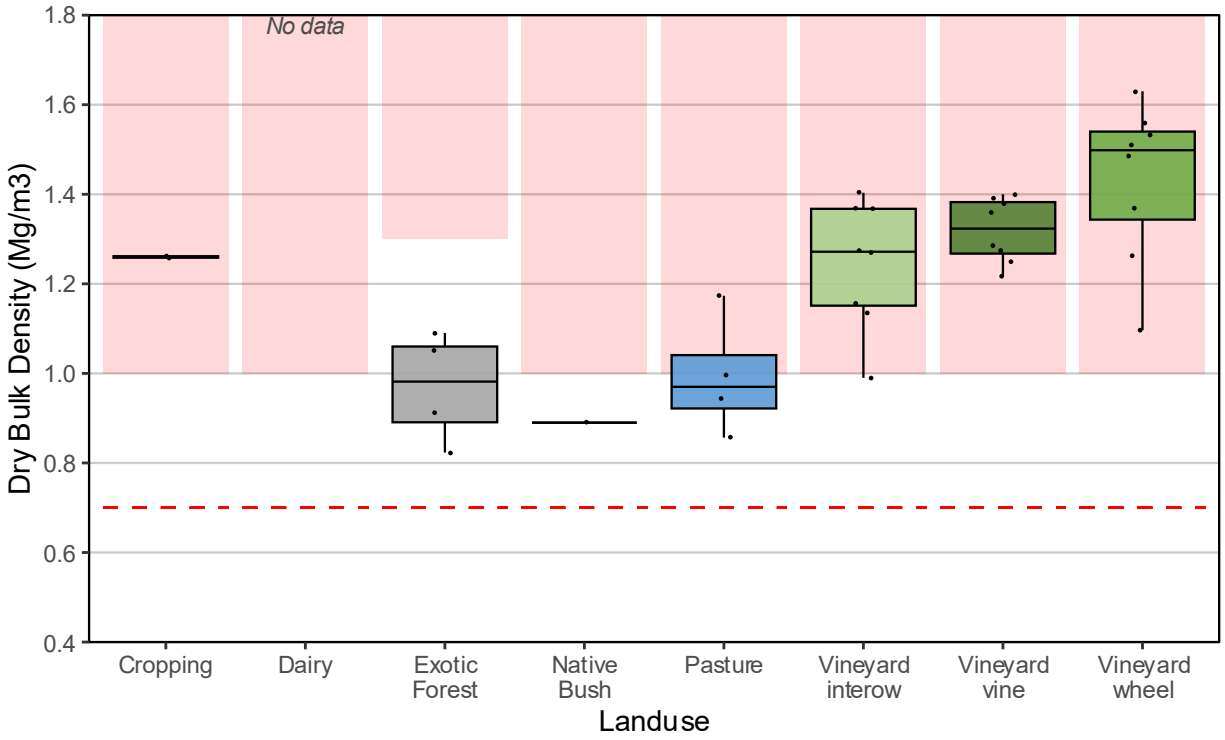


Figure 21: Dry bulk density by land use for 2025 samples. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (erosion risk minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

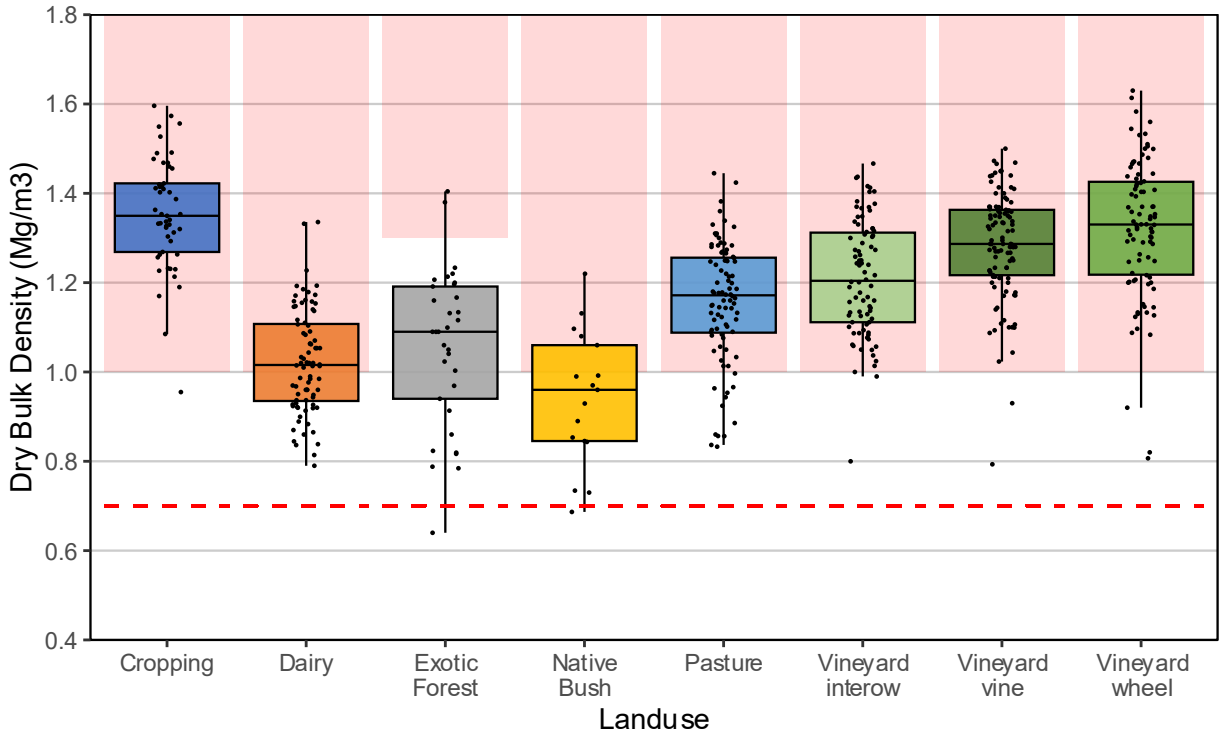


Figure 22: Soil dry bulk density values for all samples since 2000. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (erosion risk minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

Soil Quality Recommendations:

- Bulk density is a function of soil type and land management. Increased levels of organic matter can improve soil structure and protect against land management impacts.
- Cropping and vineyard land uses show the densest soils overall.
- Driving on, cultivating or stock treading of wet soils are the practices most likely to lead to high bulk density. These should be avoided at all times.
- Cropping land use should follow the recommendations for total carbon in particularly, reduce excessive cultivation practices, increase the frequency of pasture fallow rotations, and avoid bare soil periods.
- Vineyards should also follow the recommendations for total carbon, but consideration must be given to reduce vehicle trafficking of vineyard rows. The follow measures are recommended:
    - Use multi-row equipment for as many tasks as possible - e.g. spraying.
    - Use lighter equipment for low power tasks such as mowing.
    - Ensure tyre pressures are correct. Lower pressures can reduce compaction.
    - Ensure wheel tracks are well vegetated and ensure herbicide applications do not kill wheel track vegetation.
    - New vineyards are most vulnerable to soil compaction. Keep trafficking to a minimum for as long as possible while new swards establish and use light equipment.

3.4.2. Air Filled Porosity

Air filled porosity (AFP) is a measure of the proportion of large pores (macropores) in the soil. Macropores are important for penetration of air into soil, extension of roots down into the soil and drainage of water. Typically, macropores are the first to be lost when the soil is compacted. It is generally accepted that when air filled porosity represents less than 10% of the total soil porosity; plant growth will be affected (Mclaren and Cameron, 1996).

Soils with AFP below the lower end of the reference ranges are considered to be compacted. These soils are prone to lower water holding capacity, reduced root growth, crop yields and vegetative cover (Cavanagh, Drewry, et al., 2025; Houlbrooke et al., 2021). Recent research by Wang et al. (2026) in apple orchards supports this and notes that compaction by wheel traffic can result in significant reductions in total porosity, AFP, available water capacity and hydraulic conductivity as well as reduced soil aeration. These authors also note that "*older plantations did not consistently exhibit worse hydraulic conditions*, *indicating widespread decline in soil hydraulic functioning across orchards and plantation ages" (pp.8)*. This implies that compaction damage occurs very early following orchard/vineyard establishment which agrees with earlier findings of the SQMP (see the 2018 & 2019 reports for discussion). Soils with elevated AFP may have reduced water holding capacity and increased risk of erosion however there is little evidence to support this in the literature (Cavanagh, Drewry, et al., 2025)

Stats New Zealand Tatauranga Aotearoa recently summarised nationwide regional council soil quality data and found 65% of dairy sites and 46% of vineyard sites were below the reference range (Stats NZ, 2024).

In 2025, 13 out of 33 samples (37%) showed averaged AFP values below the reference ranges (Figure 23), with vineyard samples dominating this number (n=9). However, three out of four pasture samples also failed to reach the AFP lower reference range. Figure 24 shows air filled porosity data for all samples collected since 2000. While there is wide variance across the data, four land uses have issues with compaction (cropping, dairy, and pasture and vineyard wheel tracks). On animal grazing sites, the low values are likely related to heavy grazing or grazing under wet conditions where animal treading has reduced the large pore fraction in soils. Vehicle traffic is the main cause of pore reduction in vineyards. Interestingly, exotic forest regularly reports very high AFP readings. This cannot be explained with the data from the Soil Quality programme but may be a function of the elevated carbon status of these soils or a feature of the irregular soil disturbance that occurs on these sites.

Soil Quality Recommendations:

- Air filled porosity is closely related to soil disturbance and compaction. Where soils are heavily cultivated, air-filled porosity can rise to very high levels and then drop rapidly to very low levels especially where compacting forces are applied such as vehicles or stock treading.
- Cropping and vineyard land uses with issues from reduced AFP should follow the recommendations for Bulk density in section 3.4.1
- Land uses with livestock (Dairy and Pasture) are recommended to:
  - Avoid grazing on paddocks when soils are wet.
  - Allow newly resown paddocks to establish fully before grazing. Grazing newly re-grassed paddocks when wet should be always avoided.
  - When winter forage cropping or other forms of controlled grazing, utilise a back fence to prevent bare soil from being trodden repeatedly. If possible, retain or resow vegetation on the grazed area. Sowing a low-growing sward under taller winter forage such as brassicas can be useful.
  - Investigate alternative forms of winter feeding such as bale grazing.
  - Where possible, restrict driving heavy or heavily laden vehicles on paddocks especially when wet.

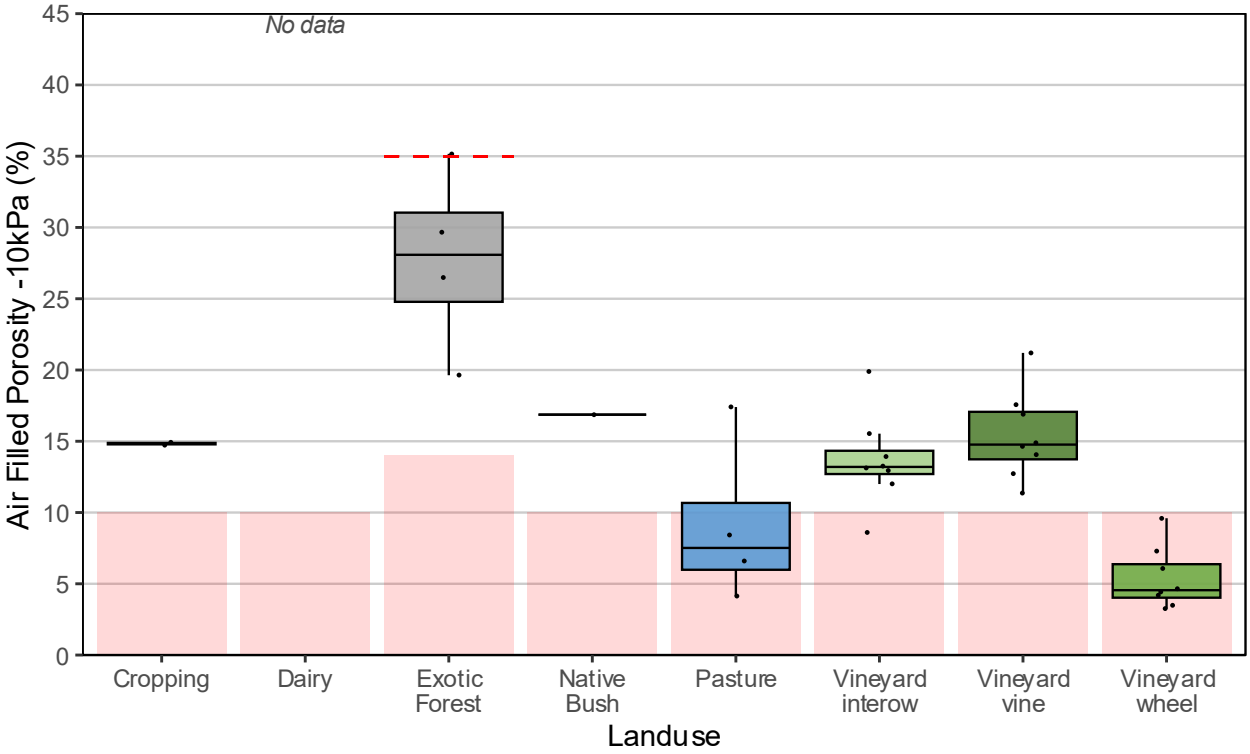


Figure 23: Air filled porosity by land use for 2025 values. Lower reference ranges denoted by pink shading (environmental risk), upper reference range indicates potentially increased erosion risk. Refer Appendix B - Soil Reference Values

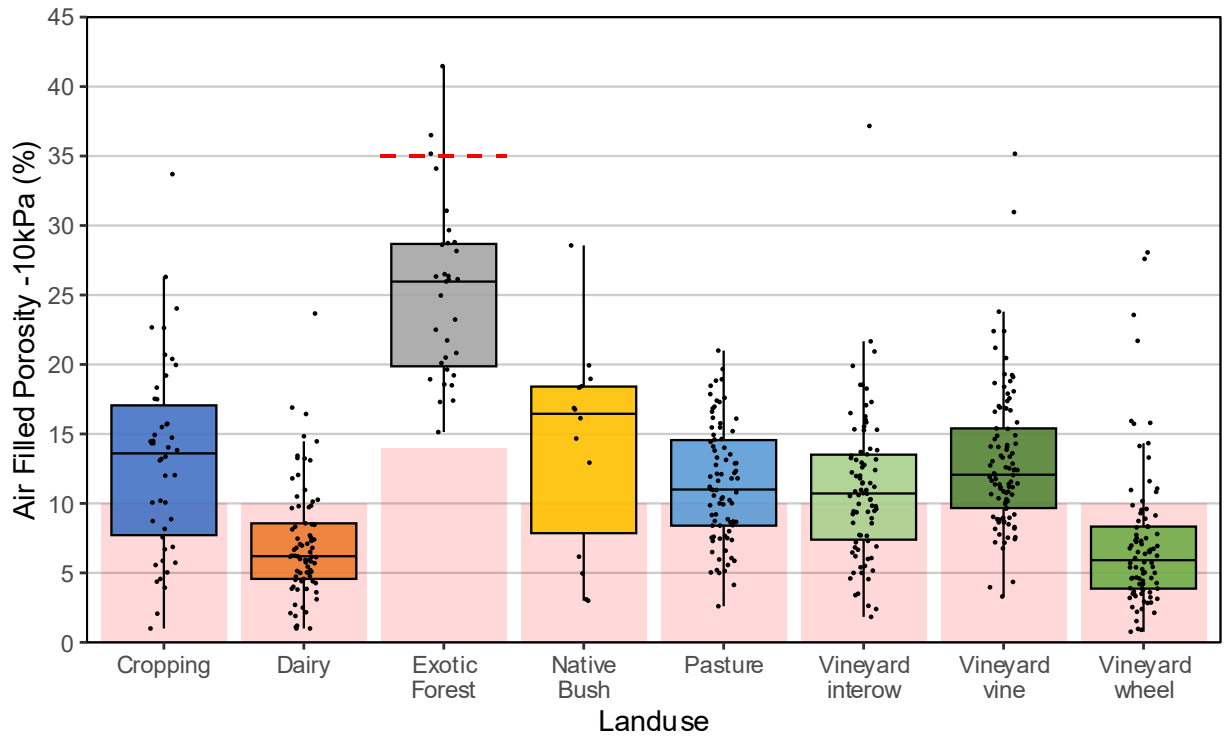


Figure 24: Air filled porosity by land use for all samples since 2000. Lower reference ranges denoted by pink shading (environmental risk), upper reference range indicates potentially increased erosion risk. Refer Appendix B - Soil Reference Values.

3.4.3. Aggregate Stability

Aggregate stability refers to the ability of soil aggregates to resist disruption when forces such as rapid wetting and mechanical abrasion are applied. In general, a soil with adequate amounts of soil organic matter will have stable soil aggregates and therefore a higher aggregate stability. A stable soil structure is important to allow water and air movement in soils and to minimise surface erosion (Mclaren & Cameron, 1996). Although there are no specific reference ranges available for aggregate stability, generally any value below about 1.5 mean weight diameter (MWD) is considered low and likely to have a negative effect on crop production (Francis et al., 1991; Sparling et al., 2008). Aggregate stability is only tested on cropping sites when they are in the crop production phase of the rotation. Pasture phases are not tested.

In 2025, two cropping sites were sampled but as they were not currently in a cropping phase, no samples were taken.

Soil Quality Recommendations:

- To improve soil aggregate stability, cropping farmers should follow the recommendations outlined in Section 3.3.2 for total carbon.

4. Analysis

4.1. Relationship of Fluoride and Cadmium to Olsen P

Scientific literature has long drawn correlations between use of phosphorus fertilisers and buildup of the contaminants, cadmium and fluoride (Drewry et al., 2021; Gray, 2018; Gray & Cavanagh, 2023; Loganathan et al., 2003; Mclaren & Cameron, 1996). While Gray (2011) documents the background concentration of cadmium in Marlborough, no soil quality data has been available on fluoride until this year's completion of fluoride analysis across all of the Soil Quality Monitoring sites. Consequently, it is timely to conduct a regional analysis of the relationship between cadmium and fluoride with phosphate fertiliser use.

Method

Statistical analysis was undertaken to establish if a relationship exists between cadmium or fluoride and Olsen P (as a proxy measurement for phosphate fertiliser use) within the Marlborough Soil Quality dataset. Olsen P is a test designed to be a measure of plant available P and only represents a fraction of the total P in soil. The tests for cadmium and fluoride are measures of the total Cd and F present in the soil. Therefore, Cd and F are likely to be more closely aligned to a different measure of P - total P. In this analysis, we use Olsen P as a proxy for total P because total P is not measured in the Soil Quality Monitoring Programme.

Olsen P values were first converted from volumetric units (mg/L) to gravimetric (mg/kg) by dividing by the volume-weight of the sample. This allows comparison of similar units and allows for the impact of soil density on phosphorus content.

Spearman's rank correlation was used to assess the relationships between Olsen P and cadmium / fluoride. This method evaluates whether variables change in a consistent direction without assuming linearity. Correlation coefficients describe the strength and direction of the association, while probability-values indicate whether observed relationships are unlikely to have occurred by chance. These relationships represent statistical associations, **not** direct causation. They indicate co-occurrence linked to shared management histories, rather than Olsen P directly causing increased contaminant concentrations.

There are two outputs from Spearman's analysis. The correlation coefficient ρ (Greek letter rho) indicates the strength and direction of any relationship between two ranked data sets. Where ρ-rho is greater than zero there is a positive relationship between the data sets (e.g. Olsen P ↑ → Cadmium ↑). Where ρ-rho is less than zero the relationship is negative (e.g. Olsen P ↑ → Cadmium ↓). The value of ρ-rho indicates the strength of the relationship (Table 3).

Table 3: Spearman ρ-rho values and interpretation

ρ value	Interpretation
0.1–0.2	weak
0.3–0.5	moderate
>0.5	strong (for environmental data)

In addition to Spearman ρ-rho, the probability value (p-prob) was also calculated. Where p-prob is greater than 0.05, there is no strong evidence of a relationship. Below or equal to 0.05, we accept that the relationship is likely a real one.

Results

The correlation between Olsen P and cadmium along with Spearman ρ-rho values for all landuses are shown in Figure 25. Across all landuses, there is a strong positive relationship between Olsen P and Cadmium with ρ-rho = 0.57. The value of p-prob is very small (<0.001). This means there is strong statistical evidence of an association between Olsen P and cadmium.

The relationship between Olsen P and fluoride is shown in Figure 26. The relationship between Olsen P and fluoride is also statistically valid with ρ-rho equal to 0.51 and p-prob also very small (<0.001). Olsen P and fluoride concentration are closely correlated.

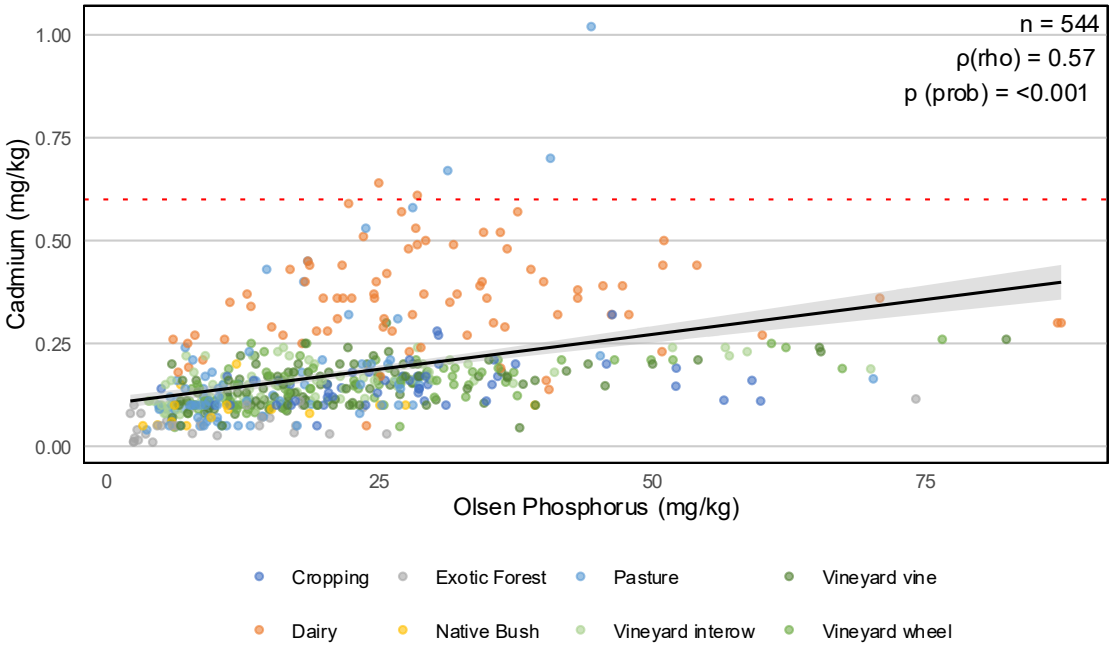


Figure 25: Correlation plot of cadmium vs Olsen P across all landuses. 0.6 mg/kg represents the Tier one TMFS threshold line.

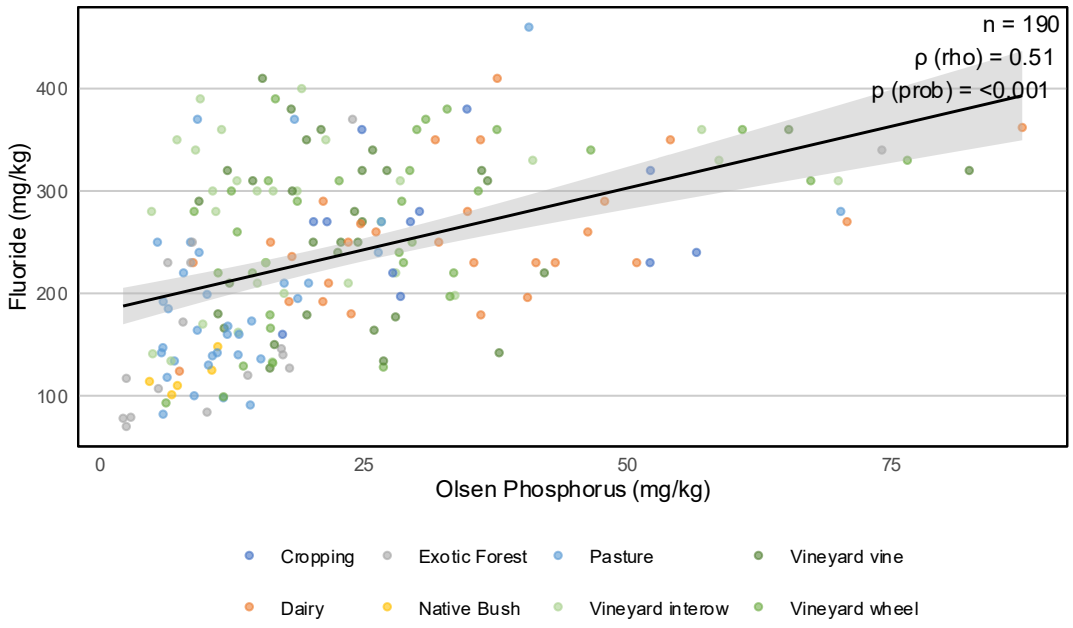


Figure 26: Correlation plot of fluoride vs Olsen P across all landuses.

The relationship between cadmium and fluoride was also investigated. A positive relationship between soil cadmium and fluoride concentrations is evident after accounting for land use ($p < 0.001$). This is consistent with both contaminants having a common source in phosphate fertilisers. The differences between land uses primarily reflect differences in average contaminant concentrations rather than fundamentally different cadmium-fluoride relationships (data not shown). In essence, the relationship between Cd and F is consistent irrespective of landuses implying that Cd and F levels reflect fertiliser inputs.

Results by Landuse

The results for both cadmium and fluoride were also calculated for each landuse and are shown in Figure 27 and Figure 28. The statistical relationship for each landuse is described in Figure 29.

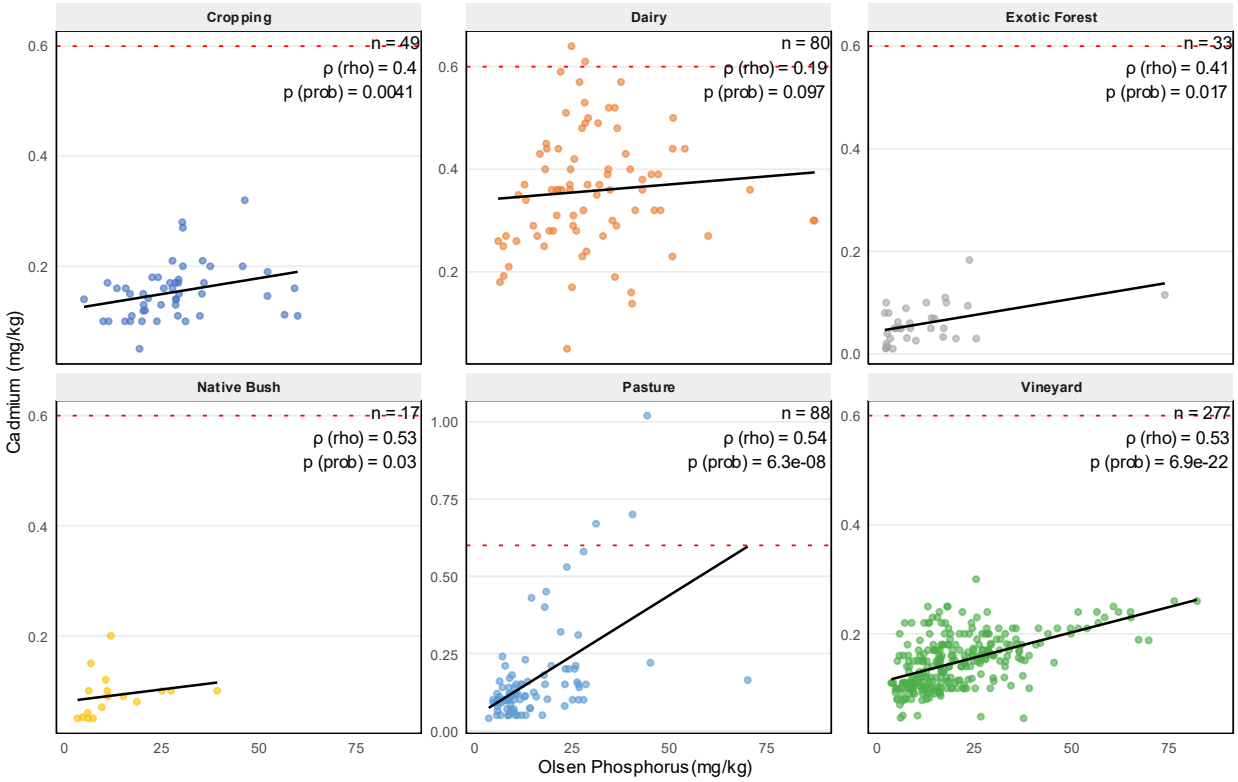


Figure 27: Cadmium vs Olsen P landuse correlation plots featuring ρ-rho and p-prob for individual landuses. 0.6 mg/kg threshold value indicated by dotted red line.

Across land uses, Olsen phosphorus expressed on a gravimetric basis (mg/kg) showed a consistent positive association with cadmium concentrations, with moderate to strong Spearman correlations observed in most land uses (ρ-rho = 0.40–0.54) and statistically significant relationships in cropping, exotic forest, native bush, pasture and vineyard systems.

The strongest and most robust relationships were observed in pasture and vineyard land uses ($\rho \approx 0.54$, $p < 0.001$), supported by large sample sizes, indicating a clear linkage between phosphorus fertiliser use and cadmium accumulation (Figure 29).

The weak and non-significant relationship between Olsen P and cadmium in dairy land uses may reflect several influences. As noted above, Olsen P only represents a fraction of total soil P. Increased inputs of phosphorus from dairy shed effluent can lead to increased Olsen P levels (Taylor, 2023) . Compaction from treading damage can change bulk density and lead to variations in measured Olsen P. Soil cultivation for pasture renewal or forage crop establishment practice is more common in dairy systems and could lead to a redistribution of P (and Cd) through the soil profile. Variable fertiliser history and elevated rates of biological activity (as evidenced by higher AMN and HWEC levels) may also all

contribute to greater variability in the dataset that reduces the strength of the fertiliser-linked accumulation signal observed in other land uses.

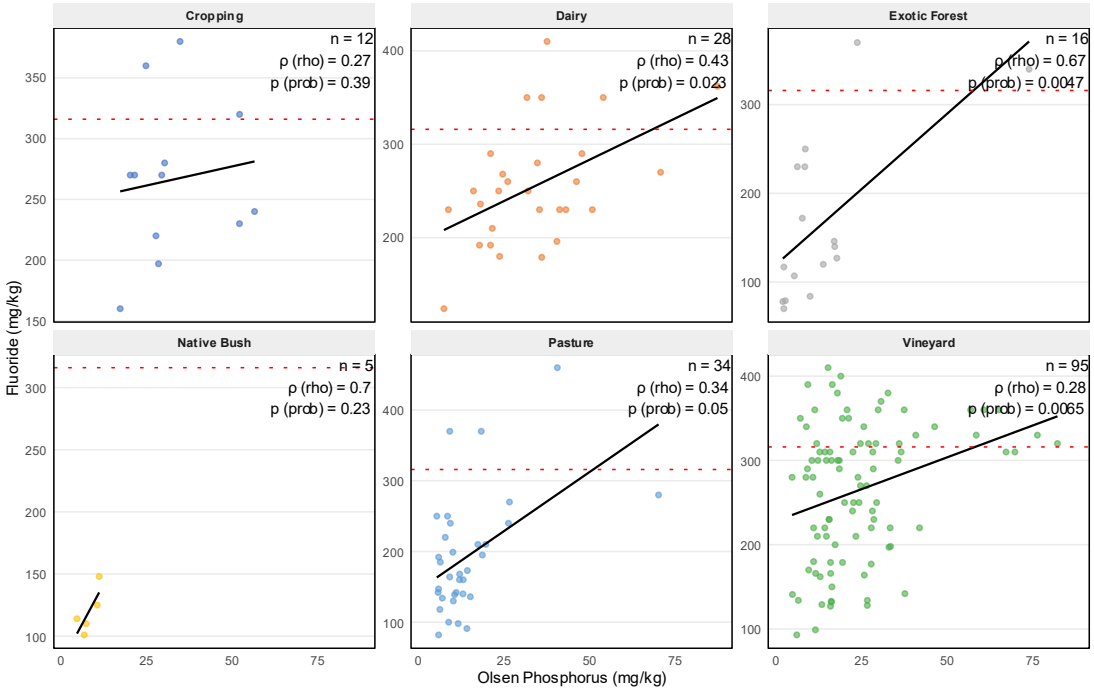


Figure 28: Fluoride vs Olsen P landuse correlation plots featuring ρ-rho and p-prob for individual landuses. Marlborough median value for fluoride from Gray (2011) 316 mg/kg shown as red dotted line.

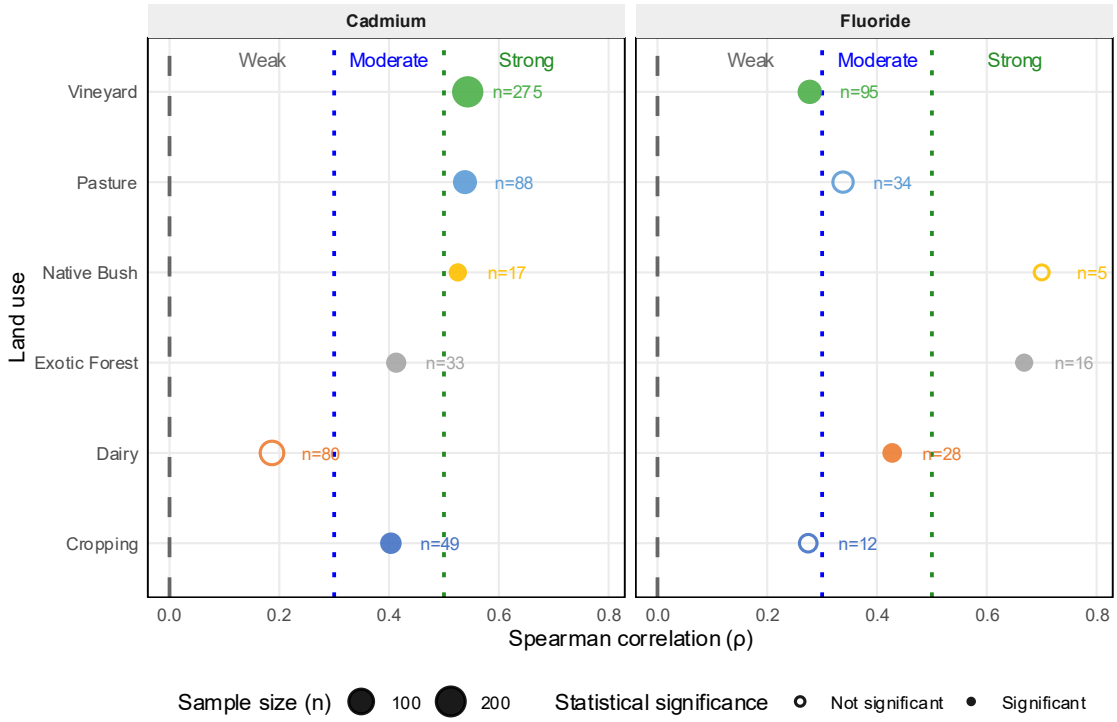


Figure 29: Cadmium and fluoride correlation and significance across landuses. Strength of rank correlation (ρ-rho) classed into weak, moderate, strong at top of the plot. Significance (p-prob) indicated by solid or hollow markers.

In contrast, relationships between Olsen P and fluoride were more variable and generally weaker (ρ = 0.27–0.70), with statistically significant associations in dairy, exotic forest, pasture (borderline), and vineyard land uses, but weaker or non-significant relationships in cropping and native bush due to smaller sample sizes and greater variability (Figure 29). The strength of this relationship may be related to the differences in fluoride sources for each landuse. Arable farmers tend toward use of imported ammonium phosphate fertilisers which have relatively low levels of contaminants. In contrast, landuses that utilise NZ-sourced superphosphate products more may have elevated fluoride levels due to the retention of fluoride in the products during the NZ manufacturing process. Native sites are likely to only receive F inputs from volcanic ash or fertiliser drift (M Taylor – pers. comm, 2026).

Discussion

Reporting on the relationship between cadmium, fluoride and phosphate fertiliser addition in Marlborough has not been attempted until now following the completion of the gathering of baseline fluoride data. The Marlborough dataset has produced a clear signal of a relationship between phosphate fertiliser use and the presence of both contaminants. As noted in Section 3.2.3, both cadmium and fluoride can pose health risks to animals and humans if not managed appropriately. While no health threat is identified in the Marlborough Soil Quality dataset, this analysis clearly links these contaminants to normal fertiliser practice and supports the message of careful and prudent phosphate fertiliser management. Further information on the management of cadmium can be obtained from https://www.fertiliser.org.nz/news/articles/updated-tiered-fertiliser-management-system.

Further information about the trends in cadmium concentration in Marlborough soils can be found in Section 5.5.

4.2. Correlation of Total Carbon to Plant Available Water.

The Marlborough Soil Quality Monitoring Programme identified in 2016 that a single sample taken from a vineyard may not adequately represent the effects that vineyard management may have on soils. The management inputs include compaction from vehicles in wheel tracks, continually bare soil under vines, targeted application of fertilisers and irrigation water to under vine areas and elevated organic matter inputs to interrow areas (from grassed swards and mulching of vine prunings).

In response, Council decided to add additional samples to vineyard monitoring sites. Samples are now taken from under vines, in the wheel tracks and in the (grassed) interrow area. The resulting data now consists of 82 observations each for wheel tracks and interrow areas with 113 observations of undervine areas collected (277 total).

While the impacts of vineyard management practice have been well canvassed in this and previous soil quality reports, the possibility of performing deeper analysis of managements effects on soil function has recently become available due to improved data handling methods. Soil quality monitoring typically reports directly on the results of laboratory analysis of the soil quality parameters with comparison of tested values made against a set of reference ranges. While some parameters measure soil functions (biological indicators such as AMN and HWEC), it is not common to be able to compare management inputs to measured soil functions.

The undervine and interrow parts of the vineyard dataset allow a direct comparison of a soil function namely plant available water (PAW – see fact box below and Figure 30). This will be done by comparing the normally bare soil undervine with the permanently grassed interrow area. This analysis will attempt to establish firstly if there are differences in PAW and total carbon between undervine and interrow areas in the Marlborough dataset. Then, if a relationship exists, can it be explained using total carbon content as a proxy for soil structure? Differences in carbon content (total and HWEC) between interrow and undervine areas is well documented in sections 3.3.2 and 3.3.3. In the scientific literature, low soil carbon is closely associated with poor soil water dynamics (Cotrufo & Lavallee, 2022; Hoffland et al., 2020; Houlbrooke et al., 2021; Hu et al., 2021; Mclaren & Cameron, 1996; Pelosi et al., 2026; Rawls et al., 2003; Sullivan et al., 2022; Weber et al., 2023). We are interested in understanding if the soil carbon-PAW relationship is replicated in Marlborough vineyards.

What is Plant Available Water?

The ability of a soil to retain water and make it available to plants is a complex phenomena (Pelosi et al., 2026; Rawls et al., 2003; Weber et al., 2023; Xiao et al., 2024). The soil pore network is a significant contributor to soil water dynamics and strongly controls PAW as well as several other important soil functions (infiltration, evaporation and drainage rates for example). Development of soil structure is key to retention of a resilient pore network and this is governed to a large degree by microbial processes that incorporate carbon binding agents into soil. (Pelosi et al., 2026; Sullivan et al., 2022). The measurement of soil carbon can serve as a proxy for this and integrates management practices that impact soil carbon.

Plant available water is a measure of the amount of water stored in soil that can be taken up by plants (Figure 30). It is defined as the difference between field capacity and permanent wilting point (Mclaren & Cameron, 1996). Saturation describes the state immediately after rainfall (or irrigation) has refilled the soil to the point where it is completely full and no air remains in the soil pores. Field capacity is the state where approximately 24 hours after saturation all the water in the large pores has drained from the soil. The water that remains can be held against gravity by capillary action. Permanent wilting point is defined as the level where plants are unable to 'suck' water from the soil and therefore wilt. These phenomena can be described in numeric terms. The ease with which water can be 'sucked' from the soil is measured as matric potential in kilopascals. At saturation, matric potential is zero. As the soil drains to field capacity it becomes progressively harder to 'suck' water from the soil and matric potential falls to -10 kPa. Permanent wilting point occurs at approximately -1500 kPa. The difference between the water content at -10kPa and -1500kPa is PAW.

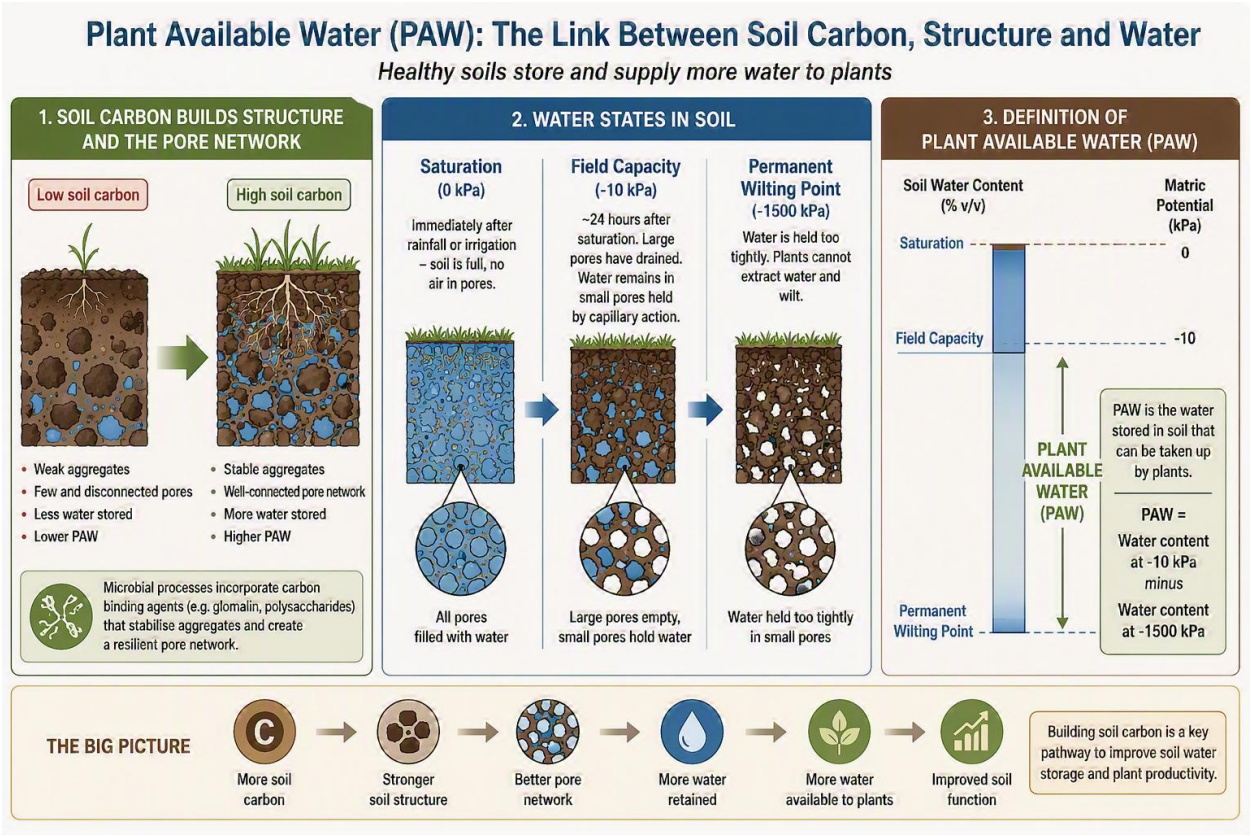


Figure 30: Conceptual relationship between soil carbon, soil structure and plant available water (PAW). Soil carbon supports the development of stable aggregates and resilient pore networks that improve water retention. Plant available water is defined as the difference between soil water content at field capacity (-10 kPa) and permanent wilting point (-1500 kPa), representing the water that can be extracted by plants. AI developed diagram.

Method

The Marlborough Soil Quality Monitoring dataset contains matric potential data as part of the soil physical parameters. These are calculated as part of the process to calculate air-filled porosity but are not usually included in the annual reporting. At each site three soil physical sample replicates are taken at 15, 30 and 45m along a 50m transect. A sample is taken at each distance for undervine, wheel track and interrow areas. For the purposes of this analysis only the undervine and interrow replicates were used. These data were processed in R statistical software and AWC was calculated from the matric potential data for each replicate pair at each vineyard site across all years. This approach controls for soil order variation between sites by calculating PAW between a replicate pair that is 1-2 metres apart in the vineyard.

Total carbon is carried out as part of the chemical and biological analysis of the SQMP work. This analysis is performed on each transect meaning that while we have three replicates for the soil physical attributes, only a single total carbon value is available for each transect. This same value was applied to each of the three soil physical replicates for each site.

Statistical differences in AWC between under-vine and inter-row soils were evaluated using a Wilcoxon rank-sum test, selected due to non-normal distributions and unequal variances typical of soil physical data. This test assesses whether the central tendency of AWC differs between undervine and interrow samples.

The relationship between AWC and total carbon were evaluated using Spearman's rank correlation to evaluate the strength of relationship between total carbon and PAW. Fuzzy c-means clustering was then used to identify functional structure in the relationship between soil carbon and available water capacity.

Fuzzy clustering allows each observation to have partial membership in multiple clusters, reflecting the continuous nature of soil processes. Two clusters were selected to represent low and high functional domains based on interpretability and consistency with observed gradients. Sites with lower PAW and total C were considered to belong to the low soil function cluster. Higher PAW and total C correlates to the higher soil function cluster. Membership values of each soil function cluster were calculated using the mean membership strength to quantify the degree to which each observation belonged to these functional domains. Fuzzy partition coefficient was calculated to indicate the degree of separation between the clusters.

Sites with more than three sets of PAW and total carbon samples since 2016 were investigated to understand the rates of change in both soil carbon and PAW through time. Only a small number of vineyard sites contained sufficient repeated observations to support this site-specific trend analysis with several sites undergoing substantial land-use change or redevelopment during the monitoring period. Consequently, this part of the results should be interpreted as exploratory rather than definitive evidence of directional change.

Temporal change was evaluated using site-specific linear regression analysis (using the lm function from the base R stats package). For each monitoring site with three or more sampling rounds, annual rates of change were estimated from the slope of a linear regression fitted between the measured soil property and year. Resulting slope estimates were summarised and compared between under-vine and interrow positions using Wilcoxon rank-sum tests, and relationships between carbon and PAW trends were assessed using Spearman rank correlation.

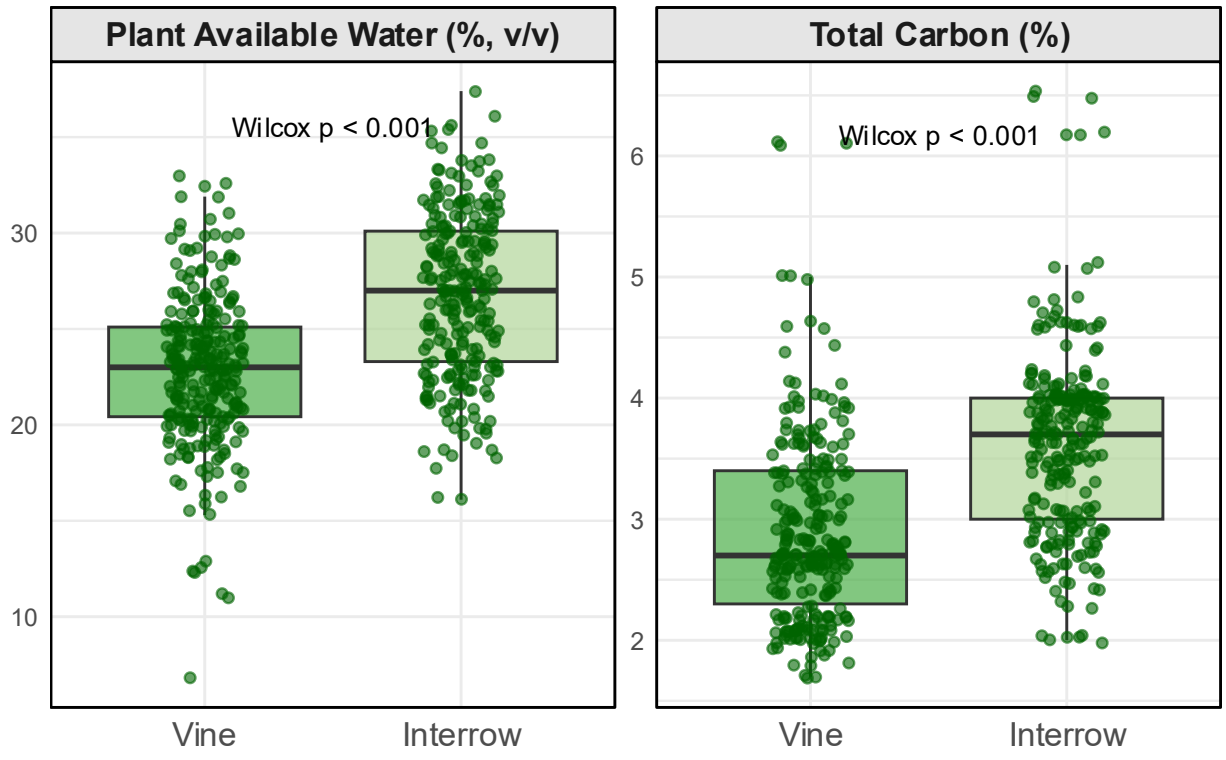


Figure 31: Comparisons of PAW and total carbon for undervine and interrow soils . Both parameters display statistically significant differences.

Results

Plant Available Water and total carbon differed between undervine and interrows. Under-vine soils exhibited significantly lower PAW and total carbon than interrow soils. Figure 31 compares the differences for PAW and total carbon. A significant statistical difference exists between interrow and undervine areas for both parameters (Wilcoxon test p <0.001).

Plant Available Water was positively associated with total carbon for both undervine and interrow areas. As total carbon increases, PAW increases. This relationship is supported with a statistical result of Spearmans ρ-rho = 0.45 with p-prob < 0.001. This indicates a moderately strong relationship between total carbon and PAW. These results indicate that soils with higher carbon content tend to retain more plant-available water, regardless of vineyard position. This suggests that while undervine management constrains soil physical function, carbon content remains an important control on water-holding capacity.

Fuzzy c-means clustering was applied using two functional domains (Figure 32). Cluster centroids were located at 2.8% C and 22.7% PAW for the low functional state and 3.7% C and 27.3% PAW for the high functional state. The mean membership strength (0.83) indicates that most observations were strongly associated with a single functional domain, while still exhibiting some degree of overlap. Fuzzy partition coefficient equalled 0.75 showing moderate separation between clusters, consistent with a system that is structured but not discrete. Together, these results indicate well-defined yet overlapping functional domains, supporting the interpretation of soil function as a continuous gradient rather than distinct classes.

Site-specific temporal analysis to investigate rates of change in both soil carbon and PAW showed that although carbon trends did not differ significantly between vine and interrow positions (Wilcoxon p = 0.857), PAW trends differed significantly (Wilcoxon p = 0.034 – data not shown). Interrow positions exhibited generally stable to increasing PAW, whereas undervine positions exhibited predominantly declining PAW. A significant negative relationship was observed between rates of carbon change and rates of PAW change (Spearman's ρ = -0.495, p = 0.022). While significant differences in PAW trend distributions were observed between undervine and interrow positions, inspection of individual site trajectories indicated substantial temporal variability and sensitivity to a small number of sites.

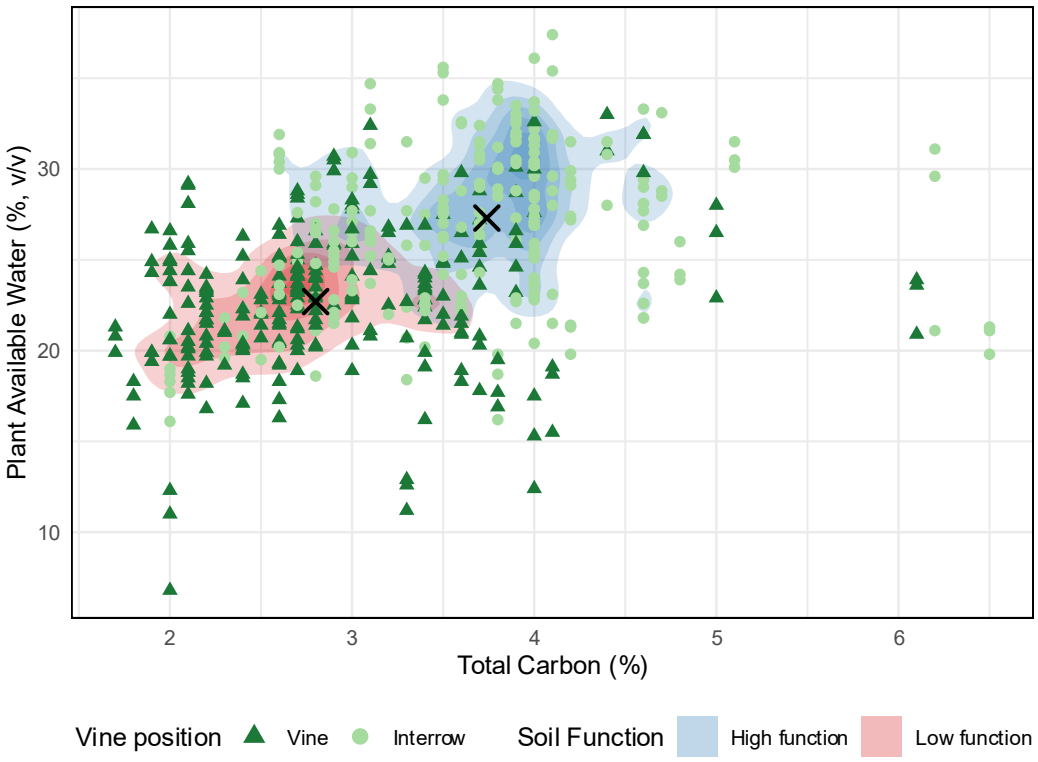


Figure 32: Fuzzy c-means cluster plot showing two separate clusters for PAW soil function . Cluster centroids indicated by black x markers.

Discussion

These results demonstrate that vineyard floor management has a strong spatial influence on soil functional condition. Undervine areas consistently exhibit reduced plant available water and lower carbon content relative to interrows, indicating a decline in soil physical function under current management practices. While increasing carbon is associated with improved water holding capacity across all areas, the clustering analysis shows that soils tend to occupy either a low or high functional domain, with limited overlap. This suggests that once soils fall into a lower functional state, recovery may require active management intervention rather than incremental change.

The temporal signal is much weaker and more site-specific than the strong spatial relationship observed between carbon and PAW. Temporal changes in plant available water (PAW) and soil carbon are difficult to quantify robustly at present due to the limited number of vineyard sites with long monitoring records and the presence of several sites that underwent substantial land-use change or redevelopment during the monitoring period. It is likely that as additional data are gathered in coming years, this analysis could be revisited.

These results suggest an important distinction between the spatial and temporal components of the dataset. The carbon–PAW analysis demonstrates a clear spatial relationship, where soils with higher carbon concentrations tended to have higher PAW. In contrast, the temporal analysis found limited evidence that changes in carbon were consistently accompanied by corresponding changes in PAW through time. Consequently, while soil carbon remains a useful indicator of soil functional capacity across sites, the available long-term monitoring data are currently insufficient to confidently quantify rates of change in PAW or establish a causal temporal relationship between carbon accumulation and PAW dynamics. Additional monitoring of established vineyard sites would be required before firm conclusions regarding temporal trends can be drawn.

Hot water extractable carbon may represent a more sensitive indicator of changes in soil functional capacity than total carbon. HWEC represents a biologically active carbon fraction that is closely linked to microbial processes and aggregate formation (Cotrufo & Lavallee, 2022). HWEC may respond more rapidly to management-induced changes in soil carbon. Future monitoring datasets with sufficient temporal coverage could therefore be used to investigate whether changes in HWEC are more strongly associated with changes in plant available water than changes in total carbon.

From a management perspective, this analysis indicates that practices which maintain or increase soil carbon in undervine zones are critical for improving water availability and overall soil function. Strategies such as those outlined in Section 3.3.2 such as reduced herbicide use, allowing limited weed growth undervine while integrating alternative weed management techniques or applying organic amendments may help shift soils toward the higher functional domain, improving resilience to dry conditions and supporting vine performance.

Marlborough vineyards are currently undergoing a transition with older vineyards being removed or replanted. If a vineyard is to be replanted, careful consideration of the setup of the new vineyard (rootstock choice, soil preparation, irrigation methodology etc) is strongly recommended. Developing the ability to productively grow vines without the need for permanent bare soil undervine will help to prevent further soil deterioration.

5. Changes in Soil Quality through time

5.1. Introduction

The Soil Quality Monitoring Program seeks to fulfil the Marlborough District Council's legislative responsibilities under the RMA to report on the "*life supporting capacity of soil*" and to determine whether current practices will meet the "*foreseeable needs of future generations*". Soil quality and land use are also key drivers in water quality. As a result, it has been a long-term goal of the MDC to report on regional-scale changes in soil quality to inform debate about environmental impacts of human activities in our region.

To meet these goals and obligations, we seek to answer three questions related to indicators for soil health. These include:

- What is the state and change of soil quality (based on soil order or land use)?
- To what extent and timeframe will the level of an indicator meet a reference range or critical level?
- What are the main drivers that influence state and change (anthropogenic and non-anthropogenic)?

Earlier Soil Quality Monitoring reports have not addressed changes in soil properties over time. Since the initial national 500 soils program was established in 2000, data has been gathered from 111 sites throughout Marlborough. With a five-year re-visit interval between sampling, it has taken until 2016 for sufficient data to be gathered to allow analysis of trends in soil quality.

The four key long-term issues identified in previous reports are still relevant. These include:

- Excess nutrients (especially Nitrogen and Phosphorous) increasing the risk of nutrients being lost to waterways
- The decline in soil carbon (organic matter) under some land uses
- Soil compaction under some landuses
- Trace element contamination for some land uses.

Method

The methodology for this process is to use a linear regression model to identify a trend in the data. The lm function from the stats package of R statistical software was used to calculate a standard linear regression line for each landuse. The slope (β) and p value were also calculated. Slope provides an indication of the annual rate of change for each landuse, with p providing an assessment of the evidence supporting that trend ($p < 0.001$ is strong evidence, $p > 0.1$ is little evidence supporting the trend).

Data is presented by land use. The aim is to provide a regional overview of changes in soil quality. This is a simple methodology and there are discrepancies in some data. These are noted where appropriate in the text. For some land uses (native & exotic forest especially) the number of samples and frequency of sampling is insufficient. As the regression method can incorporate all data, trendlines for these are presented but should be considered with the low sample numbers in mind.

5.2. Nutrient loss to water

Nutrients lost from land into waterways represent a detriment to both systems. Nutrients lost from land causes it to become less fertile and requires that fertiliser be used to maintain productivity. This becomes a significant expense to farmers. Often nutrients are manufactured and imported so require large amounts of energy and emissions to mine, process and transport. When lost nutrients reach waterways, they can promote growth of unwanted biological growths including plants and bacterial slimes. These can choke waterways and cause loss of habitat for fish and other plant species. Loss of nutrients into groundwater can lead to human health issues when that water is used for drinking (Boyd, 2015). Given Marlborough's reliance on ground and surface water resources for both drinking and irrigation water this is a potentially serious issue for the region.

Nutrients are lost to water in two main ways. Leaching is nutrient loss through soils beyond the reach of plant roots into deeper soil layers. These nutrients may eventually reach groundwater or drain into waterways. Total nitrogen and anaerobically mineralisable N were used to assess nitrogen leaching risk in previous reports. This analysis has been altered in this report as it is now understood that total N and AMN are not good measures of leaching risk. In future reports, this section will be replaced with an improved assessment of N leaching risk. The nitrogen risk section has been renamed nitrogen dynamics to enable continuity of data reporting until an alternative measure can be implemented.

The second pathway of loss is via surface runoff. Phosphorous is most susceptible to this pathway as it is carried on soil particles. Olsen P is monitored to assess the amount of phosphorous that might be carried in soil lost in surface runoff For both nitrogen and phosphorus loss, it should be noted that multiple other factors besides the amount of each element present in a soil, contribute to the overall risk these elements may pose to water (Cavanagh, Drewry, et al., 2025).

Assessment of soil compaction is also important to ascertain the ability of water to either infiltrate or runoff any given soil surface. Bare or very loose soils are vulnerable to leaching and erosion (runoff). Compacted soils prevent water infiltration and promote runoff. These properties are assessed by measuring air-filled porosity and bulk density respectively (Mclaren & Cameron, 1996).

5.2.1. Phosphorus risk

In general, soils in Marlborough have moderate P levels. Monitoring has shown that many sites have Olsen P levels above the new reference ranges. Of note, are the elevated levels of Olsen P found in the more intensive farming systems of dairy, cropping and viticulture (Figure 6). These soils will pose more risk of runoff compared to the less intensive farming systems shown simply because of the elevated P concentration (McDowell et al., 2004; McDowell et al., 2015).

Cropping system risk depends mainly on the type of cultivation practice used to sow crops, the length of time land is left bare before sowing and weather during this time. These factors contribute to runoff risk because of the amount of loosened soil that is exposed to rainfall.

Risk on dairy farms is posed by the volume of dung left on the soil surface and the ability of the soil to assimilate this prior to rainfall or irrigation. Also of concern is the pugging of soils in wet conditions and the amount of residual grass cover left following grazing. The practice of winter forage cropping has been highlighted recently and while this practice has not been widespread in Marlborough, it has become much more common. The very heavy grazing pressure caused by this practice can increase compaction, soil erosion and runoff risks substantially (McDowell et al., 2003; Mcdowell et al., 2008). Each of these factors contributes to runoff risk of P by increased mobilisation of soil particles, soil compaction and by reducing the vegetation's ability to hold soil together under erosive conditions (McDowell et al., 2015).

Vineyard risk is lower but practices such as banding fertiliser, maintaining bare soil year-round (under-vine, inter-row or both) and planting on slopes can increase P runoff risk. Compacted soils in vineyards can increase runoff risk.

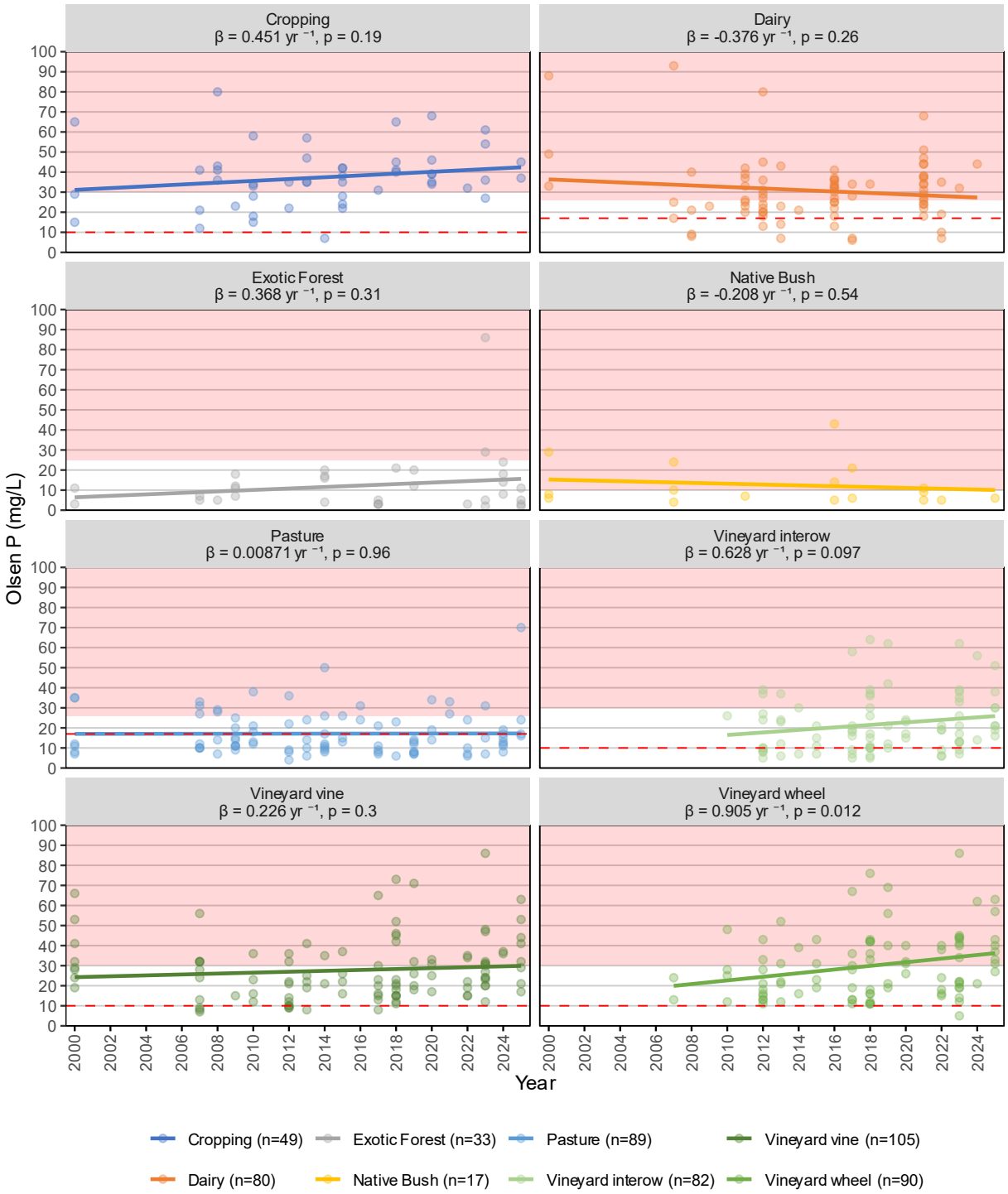


Figure 33: Long-term trend in regional Olsen P averages by land use. Annual rate of change shown as slope (β). Upper reference ranges denoted by pink shading (environmental risk), lower ranges (agronomic minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

There has been extensive national and international research to show that as soil P concentrations increase, the risk to waterways can also increase (Dymond et al., 2013; McDowell et al., 2003; McDowell et al., 2004; McDowell et al., 2015). On the back of these findings, a range of P mitigation strategies have been identified and tested to minimise P loss from soil to water. Some of these include achieving the optimal soil P test, use of low solubility P fertilisers, sediment traps, grass buffer strips, constructed wetlands, and application of amendments to sorb P in soil and drainage water (McDowell & Nash, 2012). Regular soil testing and implementation of nutrient budget and nutrient management plans will help minimise excessive nutrient accumulation in soils and potential losses from soils and this is advocated to land managers. The introduction of Dung Beetles to pastoral farming systems can reduce runoff risk.

These insects can bury dung below the soil surface thus increasing soil organic matter, improving water infiltration rates, lowering soil compaction and reducing the risk that dung may be entrained in runoff water. See https://dungbeetles.co.nz/references/

The long-term trend in phosphate is generally stable for most land uses (Figure 33). A slight downward trend can be seen for dairy farms and upward trends from cropping and viticulture. The increasing trends for cropping would imply increased application of fertiliser beyond plant requirements however, as many cropping farms are currently being converted to vineyards in Marlborough, this trend could also be an artifact of reduced sample size. Increased P content of viticulture soils is driven by increases in all vineyard sample locations which would imply additions in excess of vine requirements. For native bush and exotic forest, insufficient samples mean the trend data should be regarded with caution. Overall, the conclusions must be that in dairy, phosphate loss risk is elevated but declining, in vineyards the risk is increasing and reaching environmental risk levels. In pasture, low Olsen p trends probably indicate many farms will be below optimal productivity. The remaining landuses have no clear trend.

5.2.2. Nitrogen dynamics

Nitrogen leaching risk is no longer assessed using AMN and total N. In future soil quality reporting an alternative indicator will be used. The use of total N and AMN for assessing N leaching risk is now understood to be not well supported by evidence. This section has been re-named nitrogen dynamics to retain continuity until an alternative N risk indicator can be implemented. The total N test reports the complete content of N in the soil. This includes both the mineral and organic matter content. Anaerobically mineralisable N reports the ability of soil microbes to make soluble N by decomposing organic matter in the soil. AMN can be seen as a valuable indicator of microbial activity with elevated values indicating high levels of nitrogen cycling.

We see in Figure 34 & Figure 35 that farm systems that involve animals (dairy and pasture) report higher rates of AMN and total N compared to non-animal farm systems (cropping, viticulture, forestry). This reflects the size of the nitrogen pool within the soil. While the majority of soil N is held within organic matter, the total size of the pool can be influenced by factors such as fixation of N by clover, N fertiliser additions and imported feed with grazing animals ingesting and then returning large amounts of N to the soil pool as dung and urine (Mclaren & Cameron, 1996). The size of the soil N pool can be highly variable on a spatial (farm to farm, paddock to paddock) and temporal (day to day, season to season) basis (Havlin et al., 2017). Variables such as slope, seasonal weather conditions, stocking rate, effluent disposal regimes, fertiliser application rates and frequency can all influence nitrogen dynamics at various times.

Non-animal farm systems (cropping, viticulture and forestry), show total N and AMN levels toward the bottom of the reference bands. As will be seen in Section 5.4, this is a result of lower organic matter content in these soils and hence a smaller soil N pool. It should be noted that cropping and horticulture have no general reference ranges specified for total N. This is due to the large number of possible crops, each with its own reference range. The lower levels of AMN found in the non-animal systems is likely to reduce the soils' ability to produce nitrogen from organic matter.

The lower levels of AMN and total N seen in vineyard undervine samples will be due to the close association of N with organic matter. As seen in Section 4.2, total carbon (the other main constituent of organic matter) is lower in undervine soils likely due to management practice that promotes bare soil undervine.

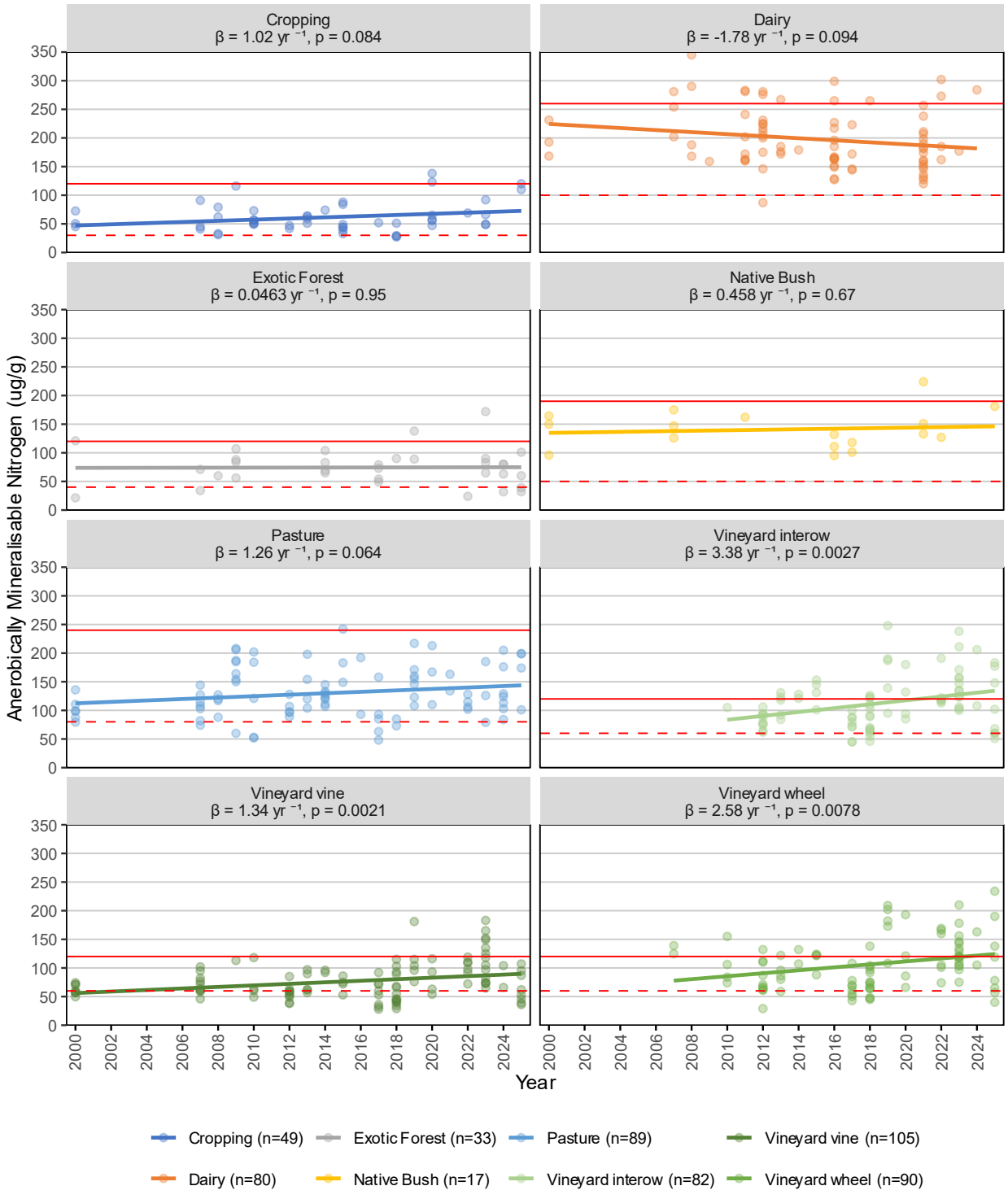


Figure 34: Long-term trend in AMN by land use. Upper reference ranges denoted by pink shading (environmental risk), lower ranges (agronomic minimums) by dashed lines. Refer Appendix B - Soil Reference Values.

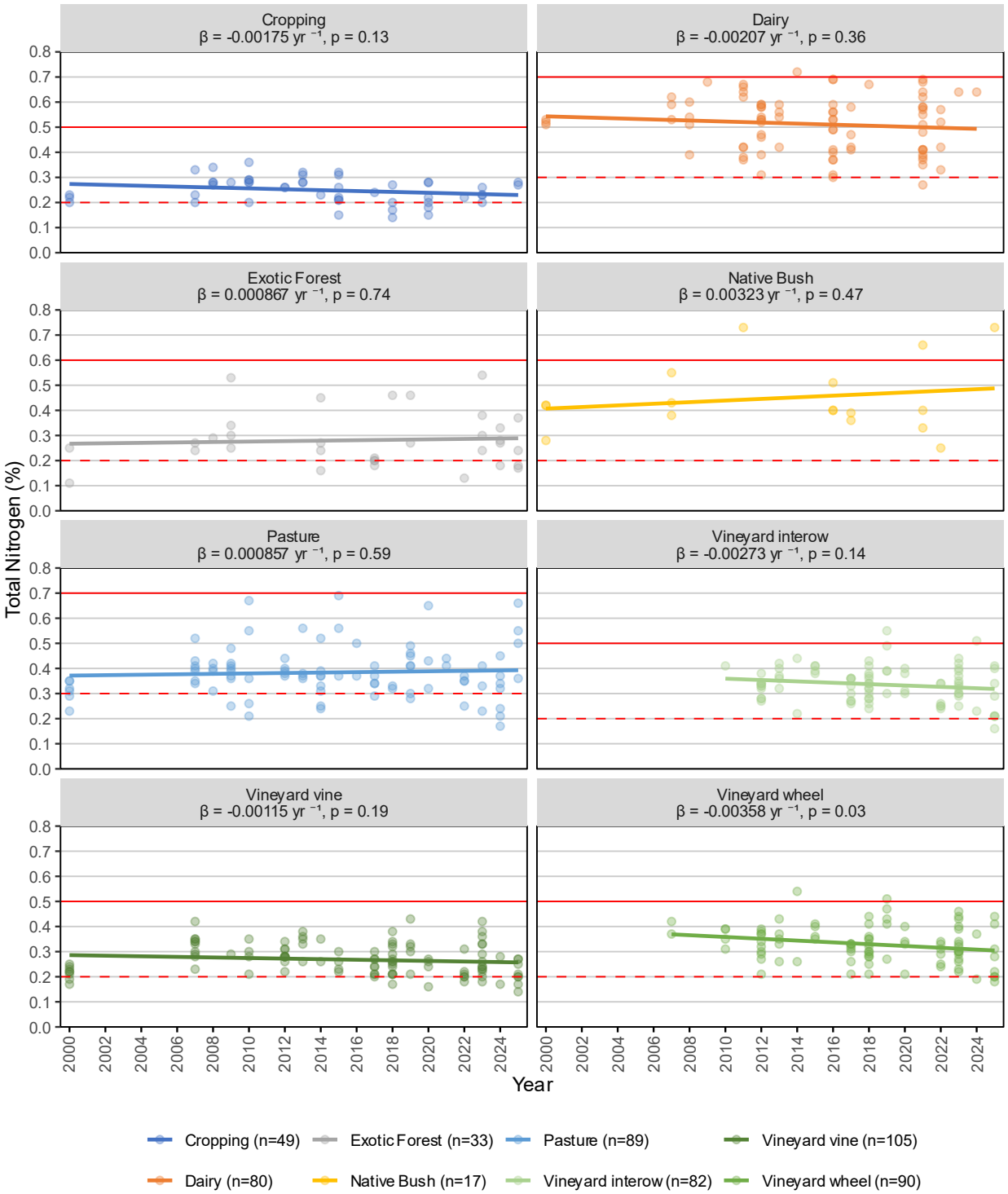


Figure 35: Long-term trend in total nitrogen by land use. Upper Reference ranges denoted by solid red lines, lower ranges by dashed lines. Refer Appendix B - Soil Reference Values.

5.3. Soil compaction risks

Soil compaction increases the risk of nutrient loss to water due to its role in reducing infiltration and therefore increasing runoff. Soil compaction is measured by bulk density and air-filled porosity. Bulk density measures the weight of a given volume of soil. It includes the pore space in that volume and is strongly influenced by management practices that compact the soil (reduce pore space). Air filled porosity measures how much of the soil is normally filled by air (as opposed to water) at field capacity and represents a pore size of approximately 30µm in diameter (Houlbrooke et al., 2021; Mclaren & Cameron, 1996).

There are a range of potential soil, plant and environmental effects of soil compaction/pugging. One of the most important is the effect on crop/pasture production. For example, animal grazing and treading, particularly in wet conditions, can affect pasture yield directly through leaf burial in mud, crushing, bruising and a reduction in dry matter production (Houlbrooke et al., 2021; Hu et al., 2021; Nie et al., 2001). For both crops and pasture, indirect effects of soil compaction include; restriction of root penetration and radial growth of roots, reduced aeration, increased water logging potential due to slower drainage, reduced nutrient availability and water infiltration leading to reduced water storage in a soil. Reduced infiltration of water increases the potential for surface runoff of water. This runoff contributes to increased risk of flooding. If runoff contains nutrients i.e. N, P or contaminants (i.e. bacteria), this may negatively impact on stream and lake water quality (Houlbrooke et al., 2021; McDowell et al., 2003; Nguyen et al., 1998).

The extent of soil compaction in Marlborough mirrors national reporting (Ministry for the Environment and Stats NZ, 2021, 2024). The SQMP has shown that farmed systems have higher bulk density and lower air-filled porosity (AFP) compared to non-farmed (forest) systems. Figure 22 & Figure 24 illustrate these differences. Cropping and viticulture report the most compact soils but for different reasons. Cropping soils have the highest bulk density readings but very low AFP (with large variability in samples). This would indicate that both large and small pore spaces have been damaged by repeated cultivation. Cropping soils are also vulnerable to soil erosion when soils are cultivated prior to planting.

Soil compaction in viticulture is driven by trafficking of wheel tracks along rows. This repeated trafficking has also removed both the large and small soil pores (Figure 24 & Figure 36). It should be noted that soil quality measurements are confined to in-vineyard sites. Vineyard headlands could reasonably be expected to have similarly compact soils due to high vehicle traffic. This would increase the area vulnerable to runoff.

Both dairy and pasture systems show marginal bulk density readings but very low AFP (Figure 36 & Figure 37). This may be due to treading damage by livestock compacting the large soil pores but not small pores (Houlbrooke et al., 2021). Combined with the raised levels of nitrogen and phosphate noted above, soil compaction in these landuses presents an elevated risk of nutrient loss to water. Even though both N & P are within the reference ranges, the level of soil compaction increases the risk of loss of these nutrients to water. Risk is increased when other factors such as slope, seasonal weather conditions, stocking rate, effluent disposal regimes, fertiliser application rates and frequency are considered.

It is noted that all landuses appear to have a slight improving trend both for Bulk density and AFP. Vineyards seem to be showing improvement in both bulk density and AFP readings over time (Figure 36 and Figure 37) which may reflect changes in practice around 2010 in viticulture (to maintain grass coverage of wheel tracks) and an increased emphasis on improvements in sward and undervine weed management. For cropping, an improvement in BD and AFP is noted however, this trend may be a relic of inadequate sample size and the effects of crop rotation within the cropping system so should be treated with some caution. It is also noted that the reduction in cropping area in Marlborough has meant that few cropping sites have been sampled during the arable phase of the rotation in recent years. Pasture and Dairy also show slow improvements in soil physical conditions.

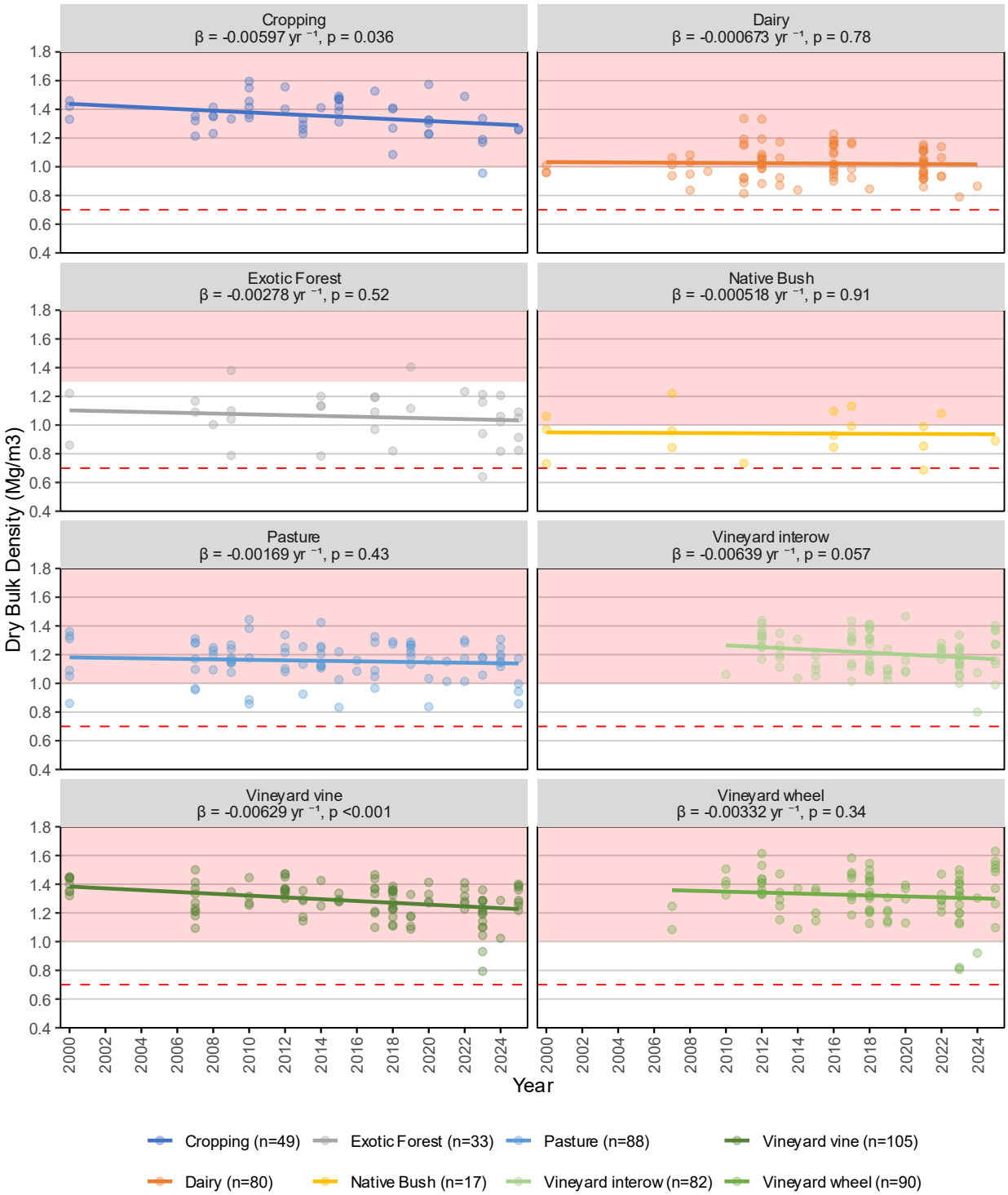


Figure 36: Long-term trend in bulk density for all land uses . Upper reference ranges denoted by pink shading (environmental risk), lower reference range indicates potentially increased erosion risk. Refer Appendix B - Soil Reference Values.

There are several potential mitigation options that can be employed to prevent or minimise the effects of soil compaction. For pasture soils, some practices could include on/off grazing of animals; grazing wetter paddocks before the wet part of the season; maintaining good pasture cover which gives better protection against pugging; use of feeding platforms and/or standoff areas; decreasing winter stock numbers and moving stock onto well drained soil types (Burgess et al., 2000; Houlbrooke et al., 2021). For cropping soils, maintaining practices that increase soil organic matter are important as well as minimising activity on soils during wet soil conditions that will compress and disrupt soil structure (Ghani et al., 2009; Hu et al., 2021).

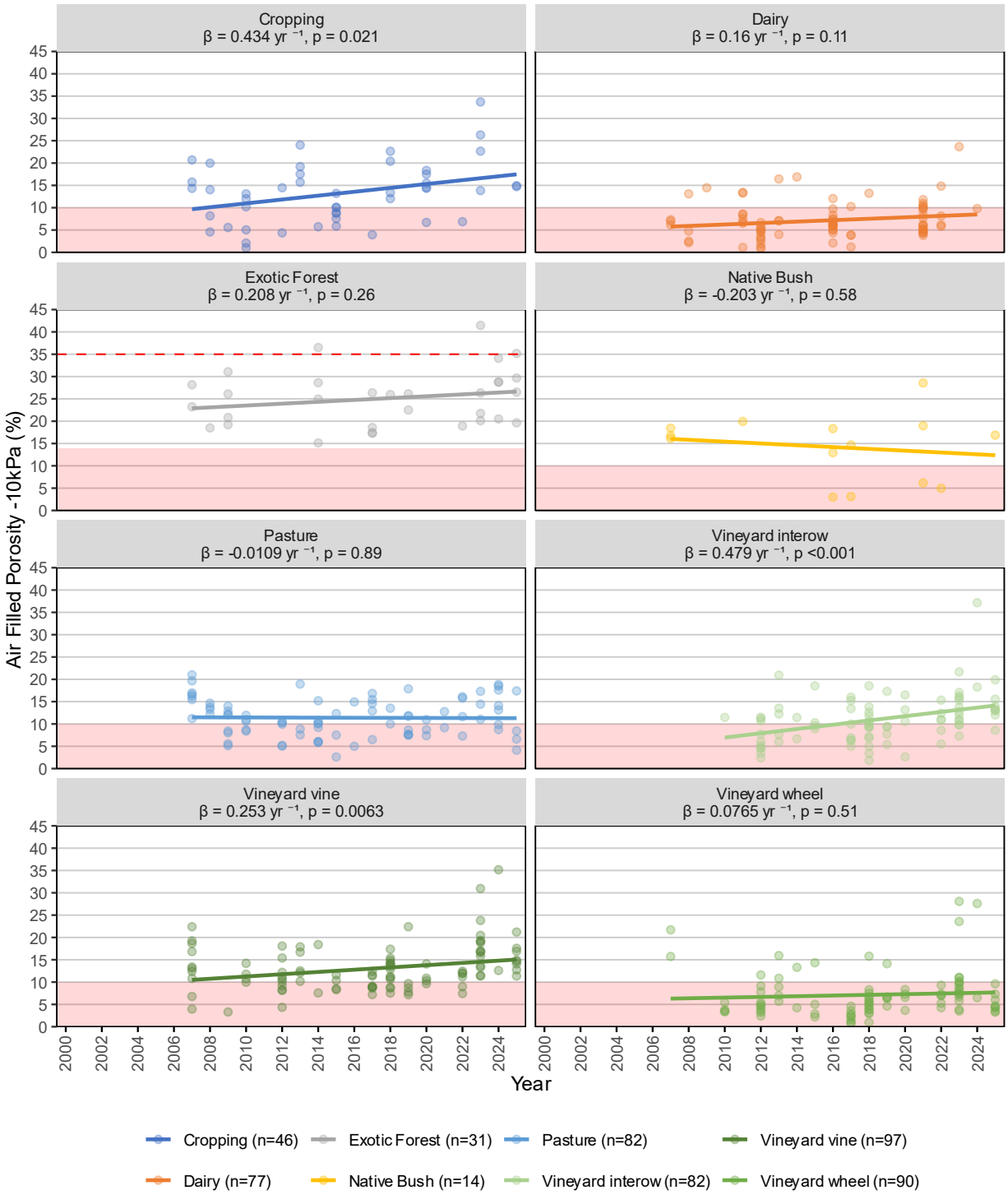


Figure 37: Long-term trend in AFP for all land uses . Lower reference ranges denoted by pink shading (environmental risk), upper reference range indicates potentially increased erosion risk. Refer Appendix B - Soil Reference Values

For viticulture, mitigation is more difficult due to the need to drive rows frequently for various canopy management operations. Maintaining grassed wheel tracks and using mechanical loosening techniques may help in the short-term. Longer term solutions include raising soil organic matter and calcium levels and changing management techniques (multifunction machinery, over-row machinery) to minimise trafficking especially in the initial years of vineyard establishment (Wang et al., 2026).

5.4. Loss of Soil Organic Matter

Soil organic matter plays a significant role in the structural stability of soils and supports several soil functions. These include carbon sequestration (and thus climate regulation effects), nutrient supply for plants and soil biota, erosion protection, biodiversity habitat as well as retention of water and contaminants (Hoffland et al., 2020). Low soil carbon (organic matter) increases the risk of soil structural degradation in soils e.g. low aggregate stability, high bulk density, low AFP and formation of surface crusts (Plate 3). In turn, poor soil structure can negatively affect soil aeration, drainage, water infiltration rates, water holding capacity, seed germination etc. In addition, loss of soil organic matter reduces the soil's ability to retain nutrients from leaching and hold soil particles against runoff or erosion (Cotrufo & Lavallee, 2022; Hoffland et al., 2020). These changes all have implications both for farm productivity and water quality.



Plate 3: Compacted topsoil at one of the cropping sites sampled with low soil carbon content. Note the surface crust which reduces water infiltration, can increase surface run-off and reduce seed germination.

The indicator for organic matter status is total carbon. While the landuse median values for this indicator have not dropped below the reference range, and is showing little change over time, it is noticeable that farmed land uses have lower organic matter levels than native forest (Figure 13 & Figure 39). We could regard the higher native forest median level of around 5.6% as the pre-farming benchmark for soil organic matter.

Recent work has highlighted that the form of carbon stored in soils may differ between agricultural and forested land (Cotrufo & Lavallee, 2022). These authors divide soil organic matter into three general types (Figure 38). Particulate organic matter (POM) represents plant matter in various stages of decomposition. Dissolved organic matter is water-soluble carbon forms derived from root exudates and decomposition residues. Mineral associated organic matter (MAOM) is derived from microbial processes or DOM that is subsequently reacted or otherwise attached to soil mineral particles. Each type represents different forms of carbon-based molecules, and each type has different transition or residence time in the soil. DOM is rapidly assimilated by soil microbes or lost from the soil as leachate, converted to MAOM or respired by microbes into CO_2, POM may reside in the soil for longer depending on the makeup of the plant matter and the environmental conditions that prevail. MAOM can persist for much longer

periods due to the protective nature of its association with soil minerals. Forest, wetland and cold ecosystems are dominated by POM, farmed landscapes by MAOM with DOM contributing to both.

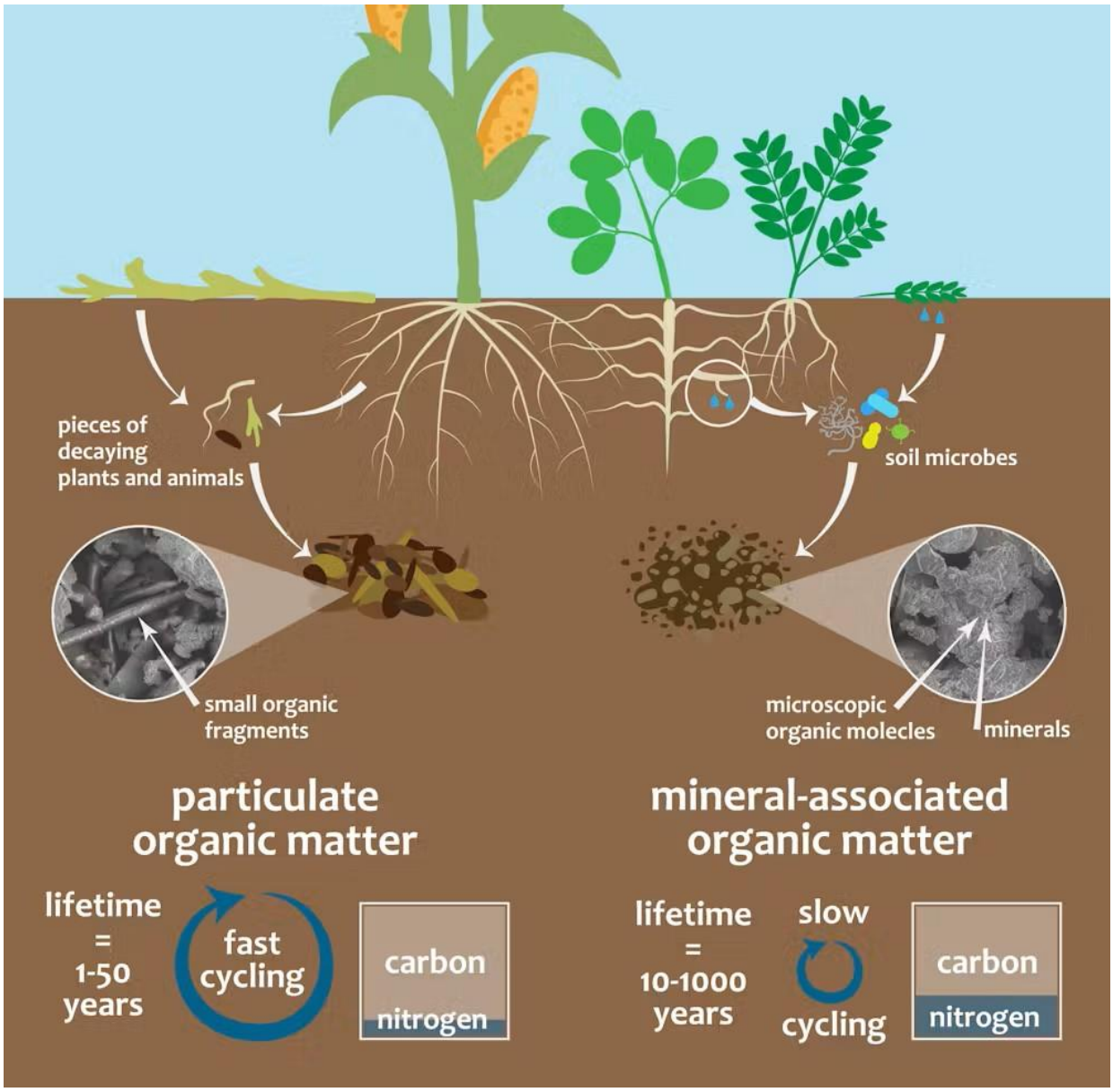


Figure 38: Key differences between particulate and mineral-associated organic matter and their dominant formation pathways. Redrawn after Cotrufo and Lavallee (2022)

At present it is not possible to use the SQMP data to distinguish between the three organic matter types as only total carbon is used to report on this parameter. However, this approach helps to build our understanding on why different landuses have different carbon content and as the HWEC dataset builds in coming years, reporting on this parameter should help to improve clarity on the situation.

It is interesting to note the difference between total carbon content of exotic and native forest soils. Exotic forest reports carbon levels around 60% of native forest levels (Figure 13 and Figure 39). This is most likely due to historic land clearance, burning, pastoral farming and erosion prior to exotic forest planting as well as soil disturbance during forest harvesting.

Cropping reports statistically significant low organic matter levels (Figure 13 and Figure 39) and this may have serious implications for soil and water quality. Cropping sites have the lowest carbon contents of the measured land uses but don't show a statistically significant decline (Figure 39). These results are consistent with trends observed during soil quality monitoring studies in the Auckland, Waikato and Wellington regions (Guinto, 2025; Ministry for the Environment and Stats NZ, 2024; Sorensen, 2012;

Taylor, 2015) where cropping sites had depleted soil carbon. Most of the cropping sites in Marlborough have soil carbon contents at the lower boundary of their reference range.

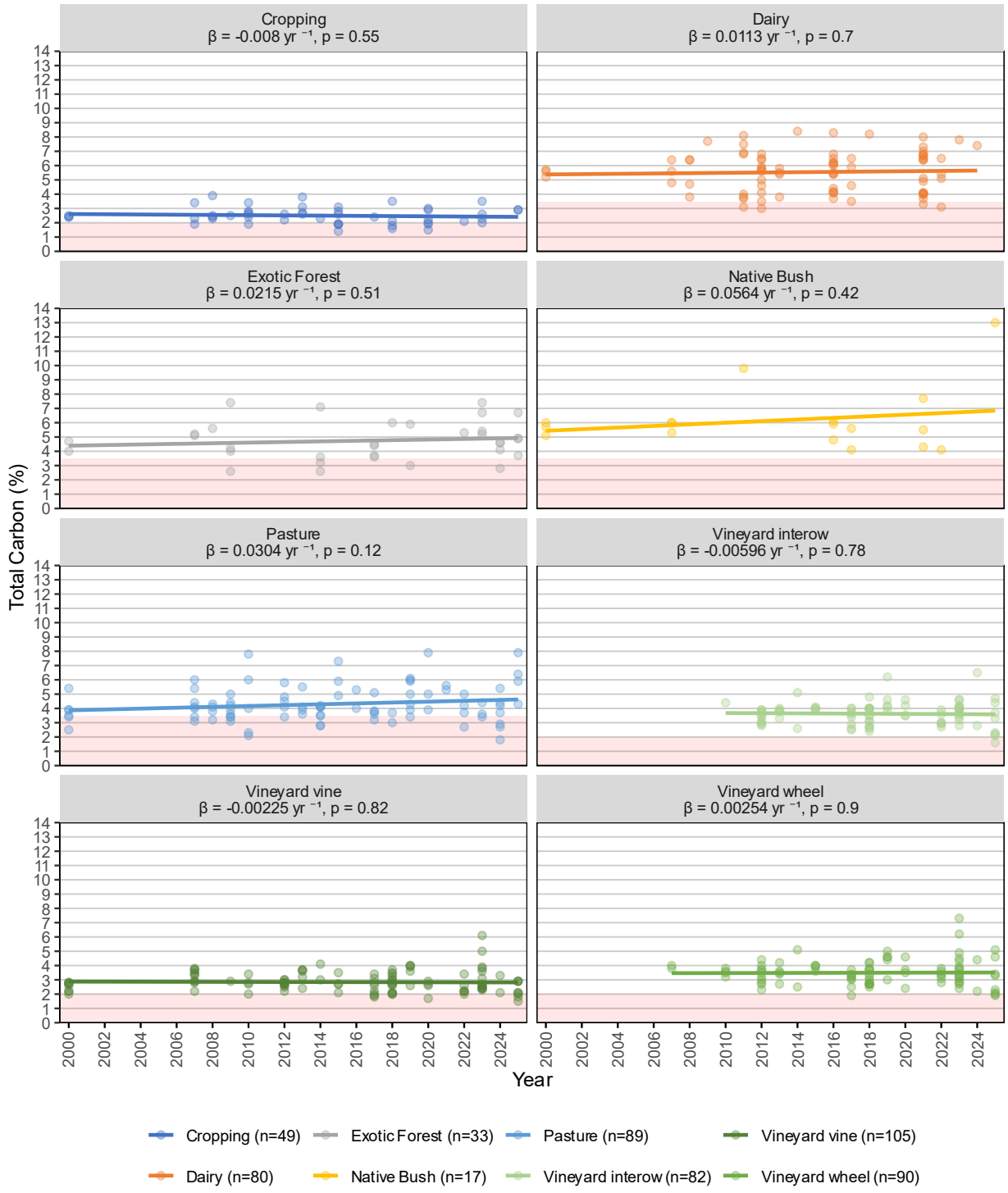


Figure 39: Long-term trend in total carbon by landuse. Lower reference ranges denoted by pink shading (environmental risk), no upper reference range set. Refer Appendix B - Soil Reference Values.

In comparison to cropping sites, dairy sites have higher total carbon content. It is well understood that soil under pasture will accumulate carbon. If the pasture is under a higher rainfall regime, irrigated, and fertilised, production of organic matter is increased, and rates of carbon accumulation increase in response. This carbon can replace that lost through cultivation, decomposition, respiration and consumption.

Land managers urgently need to adopt cultural practices that increase the amount of soil carbon, either by increasing carbon inputs or reducing the rate of decomposition of carbon. Carbon input practices include maintaining living roots in the soil (by growing cover crops rather than leaving land bare over winter, more frequent use of a pasture phase or catch crop in rotations) and addition of plant residues or compost. Reducing the rate of C decomposition can be aided by protecting peat and wetlands, minimising erosion and reducing cultivation as much as possible. (Cotrufo & Lavallee, 2022; Hoffland et al., 2020). These practices also all help to reduce erosion, leaching and runoff and as such have a beneficial effect on downstream water quality and soil organic matter levels. Readers are directed to Sections 3.3.2 & 4.2 for more detail on soil carbon dynamics and measures to protect soil carbon.

5.5. Trace Element Accumulation

The Soil Quality Monitoring Programme reports on many different trace elements found in soils. Many of these are toxic elements that are known to cause human and animal health problems (e.g. copper, chromium, lead, mercury, cadmium, fluoride and arsenic). The purpose of this is to inform Council of the risks of contamination from these elements. Monitoring has shown that there is little trace element contamination evident in most Marlborough soils. As noted in Section 3.2.3, for lead, mercury, arsenic and fluoride, the median levels are below the respective reference ranges. No trend is evident in any of these trace elements. For fluoride, there are insufficient samples to establish a clear trend across time. Due to cost, it is recommended that fluoride testing is progressively repeated starting in five years' time.

5.5.1. Cadmium trends

As a contaminant of phosphate fertiliser, cadmium can accumulate through time and is of concern for future land use change (Cavanagh et al., 2019). Cadmium can have human health impacts at low levels and the soil quality reference range has been set to match the Tiered Fertiliser Management Strategy level of 0.6mg/kg (see fact box page 39 for further detail). Figure 41 illustrates cadmium levels over time and calculates a linear trend line for each landuse. The R^2 and p values are calculated for Dairy and for all other landuses. No statistically significant trends are evident in the data. Dairy landuse shows a clearly higher concentration of cadmium than other landuses but no significant trend is evident (a non-significant, slightly negative/decreasing trend is shown). Non-Dairy landuses also show that temporal changes in cadmium concentration are small relative to the variation between sites and across time and no significant increasing trend is evident.

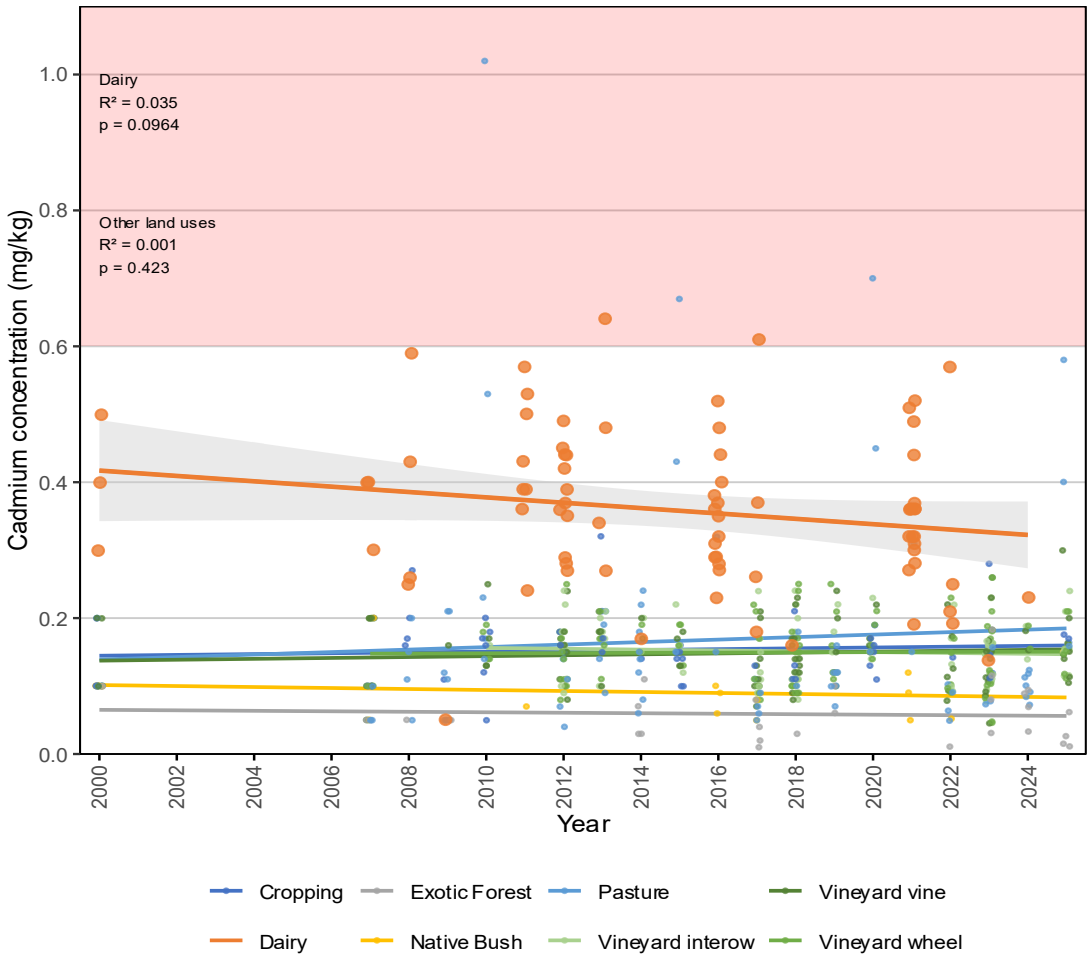


Figure 40: Long-term trends in cadmium since 2000. 0.6 mg/kg represents the Tier one TMFS threshold line.

While the trend-over-time relationships are weak (p>0.05) for both landuse groups, there are two points to note in the data. Firstly, Dairy landuse shows consistently elevated levels compared to all other landuses. Secondly, some sites show consistently high levels above or close to the 0.6 mg/kg reference range. Closer inspection of these outlier data shows that they are restricted to three sites, all current or former dairy farms. Site 41 (pasture) consistently has the highest cadmium levels. This site is a former dairy farm now used for drystock grazing. The trend for this property has been a slow decline in both cadmium and Olsen P suggesting a reduction in phosphate fertiliser use since sampling began in 2010. This illustrates that cadmium levels can fall when fertiliser practice changes. The other two elevated sites show similar behaviour.

Identification of the outlier sites inspired a closer investigation using a site-specific trend analysis for both dairy and non-dairy data. Linear regression models were fitted to individual monitoring sites with three or more sampling rounds, and the slope of each regression was used to estimate the annual rate of change in cadmium concentration (mg/kg/year) for each site. Site-specific slopes were then summarised across the two land-use groups to calculate mean and median rates of change and the proportion of sites exhibiting increasing/decreasing cadmium concentrations. Differences in the distribution of site-specific slopes between dairy and non-dairy land uses were evaluated using a Wilcoxon rank-sum test. These differences are shown as a probability density plot in Figure 41. This approach enabled assessment of temporal change within individual monitoring sites while reducing the influence of spatial variability among sites.

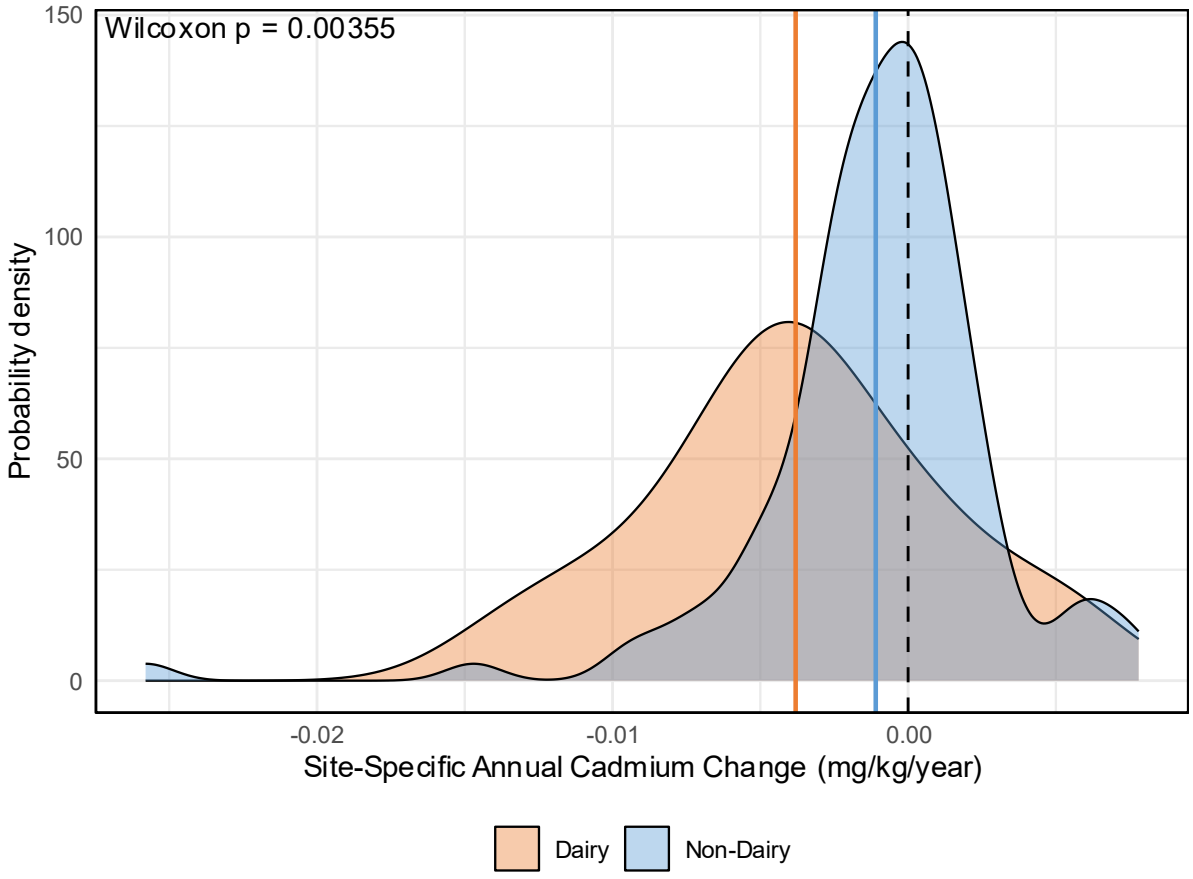


Figure 41: Site-Specific change in cadmium for all sites with more than 3 data points. Black dashed line represents no change. Orange and blue lines represent the mean change for dairy and non-dairy landuses respectively. Note the non-dairy landuses clustered tightly around the mean with smaller rates of change compared to higher rates of decline per year for dairy sites.

Site-specific trend analysis revealed a significant difference in annual cadmium change between dairy and non-dairy sites (Wilcoxon rank-sum test, W = 732, p = 0.0036). Dairy sites exhibited a stronger tendency towards declining cadmium concentrations, with a mean annual change of −0.0038 mg/kg/year. In contrast, non-dairy sites exhibited weaker declines, with a mean annual change of −0.0011 mg/kg/year. Only 22.7% of Dairy sites showed increasing cadmium concentrations compared with 40% of non-dairy sites. These results indicate that cadmium concentrations are generally stable or declining across the region, with declines being most pronounced in dairy soils.

The TFMS Cadmium Management System Explained.

The Tiered Fertiliser Management Strategy (TFMS) is a system for managing soil cadmium concentrations with different types of management action. For soils with cadmium concentrations up to 0.6 mg kg^{-1} (Tier 1) there are no limits on phosphate fertiliser application, but there is a recommendation that soils are tested for cadmium every five years. For soils which exceed 0.6 mg kg^{-1} but are below 1 mg kg^{-1} (Tier 2), phosphate fertiliser application rates are restricted to a specific set of products and application rates to manage cadmium accumulation to ensure cadmium concentrations don't exceed acceptable thresholds within the next 50 years. For soils which exceed 1 mg kg^{-1} but are below 1.4 mg kg^{-1} (Tier 3), application rates are further managed by use of a cadmium balance programme to ensure that cadmium does not exceed an acceptable threshold within 50 years. While the monitoring of soil cadmium is the responsibility of Regional Councils, the implementation of these strategies is the responsibility of the fertiliser industry.

At current rates, the TFMS strategy Tier one level (0.6 mg kg^{-1}) would not be exceeded by viticulture, cropping or pastureland uses before 2076 (using the 50-year threshold time). However, because different land uses have different Maximum Residue Levels for cadmium, land use change could lead to contamination. For example, a soil that has accumulated cadmium under a pasture or vineyard regime that is then converted to vegetable production (cropping) may have sufficient cadmium to cause contamination problems in product (Cavanagh et al., 2019). Understanding this, and given the high levels seen in some sites, it is suggested that land users test their soils for cadmium regularly and prior to land use change.

Further information can be found at :
https://www.fertiliser.org.nz/news/articles/updated-tiered-fertiliser-management-system

6. Discussion and Summary

The 2025 Soil Quality Monitoring round showed results consistent with all previous results. Despite the changes to the reference ranges, soil compaction, soil nutrient levels and loss of organic matter remain the persistent concerns with little prospect of improvement evident. Similar to previous reports, these concerns were noted across all soil orders sampled but only on farmed land.

Thirty-seven percent of sites showed low air-filled porosity indicating a reduction in pore space in the soil with 74% of sites outside the reference ranges for bulk density. Total nitrogen levels were found to be outside the reference ranges for 20% of samples. Hot water exchangeable carbon measurements provide information on the quality of soil carbon specifically, the microbial and dissolvable carbon fraction in the soil. Fifty-seven percent of HWEC measurements had levels outside the reference range. This suggests some land uses have reduced microbial activity with potential implications for soil structure, nutrient cycling and water retention. More measurements will be taken in coming years to help enhance Councils understanding of the situation.

This year a major change has been made to the programme. The introduction of new reference ranges has altered the way some parameters have been reported. These changes introduce more rigour to the programme and to improved analysis of the national dataset. However, the same issues are still of concern, these being the risk of nutrient loss to water, soil compaction, loss of organic matter and presence of trace element with some elevation above background levels. It has now been nine years since these overall trends were identified by the SQMP. The findings in Marlborough mirror national trends.

More detailed analysis of two aspects of the soil quality data has been carried out this year. With the completion of baseline fluoride testing for all sites, the corelation between both fluoride and cadmium with Olsen P has been investigated to understand the links between these contaminants and phosphate fertiliser use. A clear signal of a relationship between phosphate fertiliser use and the presence of both contaminants is documented. This relationship varies between landuses and is stronger for cadmium than for fluoride. Many sites show slowly declining cadmium levels with dairy sites reducing faster than other landuses. Both cadmium and fluoride can pose health risks to animals and humans if not managed appropriately. While no actual health threat is identified, this analysis clearly links these contaminants to normal fertiliser practice and supports the message of careful and prudent phosphate fertiliser management.

Vineyard data within the SQMP has been analysed to identify any relationship between reduced soil carbon and reduced soil function. Vineyard undervine areas commonly have low soil carbon likely due to undervine weed management practice. The comparative data with vineyard interrow areas shows statistical differences in carbon and plant available water between the two areas. Cluster analysis has shown that the soils in these areas are statistically separated into a ‘high’ and ‘low’ function area. High function corelates to interrow areas with elevated plant available water and soil carbon. Low function corelates to undervine areas with reduced plant available water and soil carbon. These results agree with soil literature and imply that undervine management does impact soil health and productive capacity. While there is a strong spatial relationship, temporal analysis of carbon and plant available water show limited evidence that changes in carbon were consistently accompanied by corresponding changes in PAW through time

Discussion of long-term trends introduced in 2016 continues in this report. The programme continues to document the decline in quality of Marlborough’s soil resource. Improved statistical analysis of these trends has been added this year to further reinforce the message of the need to improve soil management practice. To aid in addressing this, a series of soil quality recommendations have been made to help improve the soil quality indicators. The recommendations include a series of practice changes for many land users including changing practice to lift soil carbon levels, reduce excess nutrient levels and reduce soil compaction. Some of these changes may have far-reaching consequences for farm practice. Cropping farms urgently need to lift soil carbon levels to improve soil structure and reduce erosion risks. Farmers managing more intensive farms need to be aware of and manage elevated nutrient levels to reduce the risk of nutrient losses to water as well as reduce soil compaction risks from

animal treading. Vineyard managers need to improve soil carbon management of the under-vine area and soil compaction of wheel tracks.

To help address the decline in soil quality, since 2024 Council has partnered with NZ Landcare Trust to deliver a programme of free on-farm workshops on soil health. These workshops seek to engage with landowners about soil and describe how soil health issues might be addressed in practical terms. At publication, five soil health workshops had been conducted. Workshops are planned to continue over the coming years. These on-farm workshops cover basic soil identification, include input from industry experts and look to engage attendees in simple soil health measures that can be used on-farm. In addition, Council engages with students from local high schools, Lincoln University and NMIT on soil education. In 2025 approximately 75 members of the public and students have participated in soil related training.

The soil quality recommendations made in this report could provide the basis for changes to Marlborough's regulatory regime to improve soil quality and meet the Anticipated Environmental Results required under the proposed Marlborough Environment Plan (Appendix C – MEP Environmental Outcome).



Plate 4: Attendees at a soil heath workshop enjoy Marlborough sunshine while discussing soils.

7. References

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8. Appendix A - 2025 Soil Test Results

Table 4: Soil Chemical results.

					Trace Elements								
Site Name	Soil Order	Landuse	Olsen P	pH	Arsenic	Cadmium	Chromium	Copper	Fluoride	Lead	Mercury	Nickel	Zinc
			mg/L		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Soil Site 61 - interow	Pallic	Vineyard interow	51	6.2	4.3	0.15	25	13.1		10.5	0.03	18.3	78
Soil Site 61 - vine	Pallic	Vineyard vine	63	5.8	4	0.15	23	12.1		10.5	0.03	17.2	76
Soil Site 61 - wheel	Pallic	Vineyard wheel	57	6	4	0.16	23	12.1		10.3	0.03	17.7	76
Soil Site 62 - interow	Recent	Vineyard interow	30	6.5	5.3	0.12	21	13.8		10.4	0.03	17.9	53
Soil Site 62 - vine	Recent	Vineyard vine	44	6.4	5.4	0.11	20	13.9		10.1	0.03	17.8	55
Soil Site 62 - wheel	Recent	Vineyard wheel	33	6.5	5.1	0.11	19.6	13.7		10	0.03	17.6	53
Soil Site 63 - interow	Pallic	Vineyard interow	30	6	4.4	0.12	21	11.1		10	0.03	16.2	64
Soil Site 63 - vine	Pallic	Vineyard vine	41	6.2	5.9	0.11	23	12.8		10	0.02	16.4	66
Soil Site 63 - wheel	Pallic	Vineyard wheel	37	6	4.4	0.12	23	11.8		10	0.03	16.9	66
Soil Site 64 - interow	Pallic	Vineyard interow	38	6.1	3.8	0.16	25	10.7		10.7	0.05	15.8	68
Soil Site 64 - vine	Pallic	Vineyard vine	53	5.8	4.4	0.15	25	10.8		10.5	0.04	14.9	66
Soil Site 64 - wheel	Pallic	Vineyard wheel	43	6	4.1	0.16	25	10.8		10.6	0.04	15.6	68
Soil Site 65 - interow	Pallic	Vineyard interow	19	5.9	3.6	0.15	24	13.2		10.4	0.01	16.5	77
Soil Site 65 - vine	Pallic	Vineyard vine	21	6.4	6.7	0.14	25	14.7		10.3	0.03	16.2	86
Soil Site 65 - wheel	Pallic	Vineyard wheel	31	6.2	4	0.15	24	13.4		11	0.03	17.8	85
Soil Site 66 - interow	Brown	Vineyard interow	16	6.1	6	0.24	15.8	26		11.8	0.05	14.5	89
Soil Site 66 - vine	Brown	Vineyard vine	29	6.3	6.2	0.2	14.6	41		10.8	0.04	13.3	111
Soil Site 66 - wheel	Brown	Vineyard wheel	27	6.2	5.3	0.21	13.7	27		10.7	0.04	12.9	82
Soil Site 69 - interow	Pallic	Vineyard interow	21	6.4	6.3	0.21	21	19.5		20	0.04	17	81
Soil Site 69 - vine	Pallic	Vineyard vine	32	6.3	7	0.3	22	23		19.6	0.04	17.2	105
Soil Site 69 - wheel	Pallic	Vineyard wheel	63	6.7	6.6	0.21	20	22		18.9	0.04	16.3	84
Soil Site 70 - interow	Recent	Vineyard interow	21	6.3	4.3	0.16	21	18.6		11.7	0.03	14.6	60
Soil Site 70 - vine	Recent	Vineyard vine	17	6.7	4.8	0.16	19.8	20		11.7	0.03	14.7	84
Soil Site 70 - wheel	Recent	Vineyard wheel	40	6.5	3.9	0.15	19.4	21		11.4	0.03	14.2	80

					Trace Elements								
Site Name	Soil Order	Landuse	Olsen P	pH	Arsenic	Cadmium	Chromium	Copper	Fluoride	Lead	Mercury	Nickel	Zinc
Soil Site 71	Brown	Cropping	45	5.8	2.5	0.17	10.7	6.3		9.4	0.02	8.9	63
Soil Site 72	Pallic	Cropping	37	5.9	2.7	0.18	11.2	6.6		9.4	0.02	9.2	65
Soil Site 73	Brown	Pasture	16	5.3	5.1	0.16	13	16.9		10.7	0.04	11.4	81
Soil Site 74	Brown	Pasture	24	5.7	4.4	0.58	23	13.4		13.3	0.11	9.2	60
Soil Site 75	Recent	Pasture	17	5.6	4.7	0.4	25	13.3		13.3	0.1	11	58
Soil Site 104	Pallic	Exotic Forest	11	5.2	2.1	0.03	9.7	4.7	84	9	0.03	8.5	36
Soil Site 107	Ultic	Native Bush	6	5	3.3	0.15	36	30	101	12.4	0.19	19.4	65
Soil Site 108	Ultic	Exotic Forest	5	5.5	2.8	0.06	21	14.9	107	10.8	0.1	12	58
Soil Site 109	Brown	Exotic Forest	2	4.5	2.4	0.01	17.2	7.1	70	5.9	0.03	8.3	22
Soil Site 110	Brown	Exotic Forest	3	4.7	3.3	0.02	23	16.1	79	5.6	0.03	10	33
Soil Site 111	Brown	Pasture	70	6.4	2	0.16	0.164	7.1	280	17.4	0.03	18.5	62

Table 5: Soil Biological results.

			AMN	Total Carbon	Total Nitrogen	Hot Water Extractable Carbon	C:N Ratio
Site Name	Soil Order	Landuse	µg/g	%	%	mg/kg	
Soil Site 61 - interow	Pallic	Vineyard interow	60	2.3	0.21	697	10.6
Soil Site 61 - vine	Pallic	Vineyard vine	39	2.1	0.2	637	10.2
Soil Site 61 - wheel	Pallic	Vineyard wheel	40	2.1	0.2	699	10.3
Soil Site 62 - interow	Recent	Vineyard interow	68	1.6	0.16	698	10.1
Soil Site 62 - vine	Recent	Vineyard vine	53	1.8	0.17	640	10.3
Soil Site 62 - wheel	Recent	Vineyard wheel	65	1.9	0.18	749	10.3
Soil Site 63 - interow	Pallic	Vineyard interow	60	2.2	0.21	610	10.5
Soil Site 63 - vine	Pallic	Vineyard vine	62	2.1	0.21	641	10.1
Soil Site 63 - wheel	Pallic	Vineyard wheel	57	2	0.2	713	10.1
Soil Site 64 - interow	Pallic	Vineyard interow	51	2.1	0.21	570	10.2
Soil Site 64 - vine	Pallic	Vineyard vine	36	2	0.2	569	10.2
Soil Site 64 - wheel	Pallic	Vineyard wheel	78	2.3	0.22	683	10.4
Soil Site 65 - interow	Pallic	Vineyard interow	148	3.7	0.34	1407	10.9
Soil Site 65 - vine	Pallic	Vineyard vine	87	2.9	0.27	864	10.5
Soil Site 65 - wheel	Pallic	Vineyard wheel	119	3.3	0.31	1009	10.7
Soil Site 66 - interow	Brown	Vineyard interow	177	4.7	0.4	2143	11.5
Soil Site 66 - vine	Brown	Vineyard vine	107	2.9	0.25	1262	11.5
Soil Site 66 - wheel	Brown	Vineyard wheel	234	4.6	0.41	2045	11.3
Soil Site 69 - interow	Pallic	Vineyard interow	183	4.4	0.41	1970	10.8
Soil Site 69 - vine	Pallic	Vineyard vine	95	2.9	0.27	1135	10.9
Soil Site 69 - wheel	Pallic	Vineyard wheel	190	5.1	0.44	2228	11.6
Soil Site 70 - interow	Recent	Vineyard interow	102	3.3	0.29	1488	11.7
Soil Site 70 - vine	Recent	Vineyard vine	46	1.5	0.14	665	11
Soil Site 70 - wheel	Recent	Vineyard wheel	138	3.4	0.28	1651	12.1
Soil Site 71	Brown	Cropping	110	2.9	0.27	1263	10.4
Soil Site 72	Pallic	Cropping	120	2.9	0.28	1170	10.2
Soil Site 73	Brown	Pasture	101	4.3	0.36	1616	11.9
Soil Site 74	Brown	Pasture	199	7.9	0.66	2302	11.9
Soil Site 75	Recent	Pasture	174	6.4	0.55	1298	11.6
Soil Site 104	Pallic	Exotic Forest	60	3.7	0.24	1890	15.7
Soil Site 107	Ultic	Native Bush	181	13	0.73	3985	17.7
Soil Site 108	Ultic	Exotic Forest	101	6.7	0.37	1928	18.1
Soil Site 109	Brown	Exotic Forest	32	4.9	0.17	2429	29.2
Soil Site 110	Brown	Exotic Forest	39	4.9	0.18	2468	26.9
Soil Site 111	Brown	Pasture	199	5.9	0.5	2268	11.9

Table 6: Soil Physical Results.

			Bulk Density	Air Filled Porosity	Macroporosity (-5kPa)	Plant Available Water (average)
Site Name	Soil Order	Landuse	(Mg/m3)	(%, v/v)	(%, v/v)	(%, v/v)
Soil Site 61 - interow	Pallic	Vineyard interow	1.37	12.9	11	18.6
Soil Site 61 - vine	Pallic	Vineyard vine	1.38	14.6	12.8	16.7
Soil Site 61 - wheel	Pallic	Vineyard wheel	1.56	3.5	2.2	18
Soil Site 62 - interow	Recent	Vineyard interow	1.4	13.3	7.5	23.5
Soil Site 62 - vine	Recent	Vineyard vine	1.27	21.2	18.2	20.7
Soil Site 62 - wheel	Recent	Vineyard wheel	1.63	3.3	1.6	23.8
Soil Site 63 - interow	Pallic	Vineyard interow	1.27	19.9	16.4	19
Soil Site 63 - vine	Pallic	Vineyard vine	1.36	17.6	15.1	16.5
Soil Site 63 - wheel	Pallic	Vineyard wheel	1.51	9.6	7.3	16.9
Soil Site 64 - interow	Pallic	Vineyard interow	1.37	13.9	11.6	16.5
Soil Site 64 - vine	Pallic	Vineyard vine	1.39	14.9	12.8	15.4
Soil Site 64 - wheel	Pallic	Vineyard wheel	1.53	4.2	6.7	20.2
Soil Site 65 - interow	Pallic	Vineyard interow	1.16	13.1	9.6	24.5
Soil Site 65 - vine	Pallic	Vineyard vine	1.29	12.7	9.9	19
Soil Site 65 - wheel	Pallic	Vineyard wheel	1.37	6.1	3.9	21.2
Soil Site 66 - interow	Brown	Vineyard interow	0.99	15.5	13	27.7
Soil Site 66 - vine	Brown	Vineyard vine	1.22	14.1	12.1	21.3
Soil Site 66 - wheel	Brown	Vineyard wheel	1.1	7.3	5	28.8
Soil Site 69 - interow	Pallic	Vineyard interow	1.14	8.6	5.2	28.6
Soil Site 69 - vine	Pallic	Vineyard vine	1.25	11.4	9	22.9
Soil Site 69 - wheel	Pallic	Vineyard wheel	1.26	4.7	3.2	26.2
Soil Site 70 - interow	Recent	Vineyard interow	1.27	12	8.9	25.2
Soil Site 70 - vine	Recent	Vineyard vine	1.4	16.9	14.2	18.4
Soil Site 70 - wheel	Recent	Vineyard wheel	1.49	4.4	2.8	23.4
Soil Site 71	Brown	Cropping	1.26	14.7	12.7	21.5
Soil Site 72	Pallic	Cropping	1.26	14.9	12.3	20.9
Soil Site 73	Brown	Pasture	1.17	8.4	3.8	24.7
Soil Site 74	Brown	Pasture	0.86	6.6	4	27.7
Soil Site 75	Recent	Pasture	0.94	4.1	3.3	29.2
Soil Site 104	Pallic	Exotic Forest	1.09	26.5	22.3	18.8
Soil Site 107	Ultic	Native Bush	0.89	16.9	14.6	16.6
Soil Site 108	Ultic	Exotic Forest	0.91	19.6	17.9	15.6
Soil Site 109	Brown	Exotic Forest	0.82	35.2	31.8	19
Soil Site 110	Brown	Exotic Forest	1.05	29.7	28.3	14.9
Soil Site 111	Brown	Pasture	1	17.4	14.1	24.1

9. Appendix B - Soil Reference Values

Soil quality reference ranges from Cavanagh, Drewry, et al. (2025) are outlined in the tables below. For clarity, only reference ranges for landuses and soil order that occur in Marlborough have been included. For further information refer to https://environment.govt.nz/publications/revision-of-soil-quality-indicator-target-ranges/

pH

Table 7: Reference ranges for soil pH

Land use group	Basis of reference range	Reference range
Cropping & orchards	Agronomic optima	5–6.5
Vineyard	Agronomic optima	6–7
Dairy	Agronomic optima	5.5–6.2
Pasture	Agronomic optima	5.5–6.2
Exotic Forest	Distribution	4.7–6.0
Native Bush	Distribution	4.7–6.2

Olsen P

Table 8: Reference range for Olsen P for different land-use categories and soil orders

	Volumetric Reference range	Gravimetric reference ranges for soil orders				
		Olsen P[a] (mg/kg)				
Land use category	Olsen P (mg/L)	Pumice	Organic, Podzol	Recent, Granular	All	Raw[b]
Cropping & Orchards	10–30	15–55	15–45	10–30	10–35	10–40
Vegetable cropping	10–50	15–95	15–85	10–60	10–70	10–75
Pastoral[c] (sedimentary, ash soils)	17–26	NA	30–45[d]	20–30	25–35	25–40
Native Bush[e]	<10	<15	<15	<10	<10	<10
Exotic Forest[f]	NA			<25		

Notes:

- Soil orders with similar gravimetric values have been grouped and rounded to the nearest 5 mg/kg for ease of use. The exact conversions are shown in Cavanagh, Drewry, et al. (2025).
- In the absence of accessible agronomic recommendations based on soil Olsen P values for perennial horticulture crops, Olsen P values for cropping are considered to be applicable for perennial horticulture crops such as viticulture (Cavanagh, Drewry, et al., 2025).

[a] Converted to gravimetric values using relationships developed by Drewry et al. (2022) and described in Cavanagh, Drewry, et al. (2025).

[b] Conversion of values for Raw soils is based on limited data. See Cavanagh, Drewry, et al. (2025)
[c] Depth-adjusted value for conversion of recommendations for pasture based on 7.5 cm depth to 10 cm depth equivalent. See Cavanagh, Drewry, et al. (2025) for details.
[d] Podzol
[e] For indigenous sites, the lower-end agronomic recommendations for pasture in sedimentary soils of 10 mg/L is used as an upper threshold. Naturally high Olsen-P may be observed in some specific ecosystems (Cavanagh, Drewry, et al., 2025)
[f] Olsen P is recognised to overestimate available P at lower soil pH; Bray P is a more common measure for forestry soils (Cavanagh, Drewry, et al., 2025).

Anaerobically mineralisable nitrogen

Table 9: Reference range for AMN for different land-use categories and soil-orders

Land use group	Soil order	Reference range (mg/kg)
Cropping	All soils (excl. Allophanic)	30[a]–120
Orchard	All soils (excl. Allophanic)	40–150
Vineyard	All soils (excl. Allophanic)	60–120
Dairy	All soils (excl. Allophanic)	100–260
Pasture	All soils (excl. Allophanic)	80–240
Exotic Forest	All soils (excl. Allophanic)	40–120
Native Bush	All soils (excl. Allophanic)	50–190

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

Total Carbon

Table 10: Reference range for total carbon for different land-use categories and soil-order groups

Land use group	Soil order	Reference range (%)[a]
Cropping	All soils (excl. Organic, Raw and Allophanic)	2[b]–4.5
Orchard	All soils (excl. Organic, Raw and Allophanic)	2.5–6
Vineyard	All soils (excl. Organic, Raw and Allophanic)	2–5
Dairy	All soils (excl. Organic, Raw and Allophanic)	3.5–8.5
Pasture	All soils (excl. Organic, Raw and Allophanic)	3.5 –8.5
Exotic Forest	All soils (excl. Organic, Raw and Allophanic)	3.5–8
Native Bush	All soils (excl. Organic, Raw and Allophanic)	3.5–11

[a] Values rounded to nearest 0.5%.

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

Hot Water Extractable Carbon

Table 11: Distribution of HWEC results in the monitoring data set for different land-use categories for all mineral soils[a]

Land use group	Reference range (mg/kg)
Cropping	800[b]–1,500
Orchard	850–2,500
Vineyard	1,200–1,800
Dairy	1,400–4,000
Pasture	1,100–3,600
Exotic Forest	1,300–3,100
Native Bush	2,000–6,500

[a] Insufficient Organic soil samples were available to develop reference ranges.
[b] 16th percentile in non-allophanic mineral cropping soils.

Total Nitrogen

Table 12: Reference ranges for total N (%) in mineral soils for aggregated land-use categories and soil orders

Land use group	Soil order	Reference range (%)
Cropping, orchard, vineyard	All soils (excl. Organic, Raw and Allophanic)	0.2–0.5
Dairy & pasture	All soils (excl. Organic, Raw and Allophanic)	0.3–0.7
Exotic Forest, Native Bush	All soils (excl. Organic, Raw and Allophanic)	0.2–0.6

C:N ratio

Table 13: Reference ranges for C:N ratio across all soil orders

Land use group	Soil order	Reference range
Dairy, pasture, cropping, vineyard	All	10–13
Exotic Forest	All	12–26
Native Bush	All	12–20

Bulk density

Table 14: Reference ranges for bulk density for landuse and soil order groups

Land use group	Soil order	Reference range (Mg/m^3)	Upper limit (Mg/m^3)
All land uses excluding forestry	All	0.7–1.0	1.4
Exotic Forest	All	0.7–1.3	1.4

Note: An upper limit of 1.4 Mg/m3 has been specified which has been associated with reduced crop yield as a result of excessive mechanical resistance to root elongation (Cavanagh, Drewry, et al., 2025).

Air filled porosity (-10kPa)

Table 15: Reference ranges for air filled porosity (-10kPa) for landuse groups

Land use group	Reference range (%)*
Exotic Forest, Native Bush	14–35
All other landuses	10–21

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

Aggregate stability

Aggregate stability was not included in the recent Cavanagh, Drewry, et al. (2025) reference range review. There are no specific reference ranges available for aggregate stability, generally any value below about 1.5 mean weight diameter (MWD) is considered low and likely to have a negative effect on crop production (Francis et al., 1991; Sparling et al., 2008).

Trace Elements

Table 16: Reference ranges for trace elements and source citations

Trace element	Guideline values (mg/kg)	Source
Arsenic	20	Eco-SGV (Cavanagh & Harmsworth, 2023)
Cadmium	0.6	Tiered Fertiliser Management Strategy (Warne, 2011)
Chromium	200	Eco-SGV (Cavanagh & Harmsworth, 2023)
Copper	95	Eco-SGV (Cavanagh & Harmsworth, 2023)
Fluoride	316	Marlborough median (Gray, 2011)
	43 to 166	National range (Loganathan et al., 2003)
Lead	290	Eco-SGV (Cavanagh & Harmsworth, 2023)
Mercury	0.7	Cavanagh (2006)
Nickel	45	Canadian Council of Ministers of the Environment (2015)
Zinc	180	Eco-SGV (Cavanagh & Harmsworth, 2023)

10. Appendix C – MEP Environmental Outcome

Proposed Marlborough Environment Plan - Anticipated Environmental Outcome - 15.AER.8	
The biological, chemical and physical state Marlborough's soils enables safe and productive use of the soils on an ongoing basis.	The values of the following soil parameters for soils routinely monitored fall within reference ranges, as defined by Landcare Research (Landcare Research, 2003)[1]: • total carbon; • total nitrogen; • anaerobically mineralisable nitrogen; • soil pH; • Olsen phosphorus; • bulk density • macro porosity; • aggregate stability; and • trace elements

1. Now updated by Cavanagh, Drewry, et al. (2025) on behalf of Ministry for the Environment.

11. Appendix D - Use of Artificial Intelligence Disclosure

This appendix describes the use of artificial intelligence (AI) in the development of the 2025 Soil Quality in the Marlborough Region report. It records scope and purpose of AI use and discloses the parts of the report where AI input was used.

Scope of AI Use

AI was used strictly as a technical support tool. It assisted with:

- Redeveloping and standardising R scripts for plotting of graphs and statistical analysis.
- Improving reproducibility and consistency of graphs.
- Supporting development and interpretation of statistical outputs under subject matter expert supervision.
- Creation of two explanatory diagrams.

AI Disclosure Statement

An artificial intelligence tool (Microsoft Copilot) was used to support R code development for graphing and statistical analysis. This enabled code standardisation, more advanced statistical analysis and data visualisation. AI was also used to aid interpretation of statistical analysis and to generate an explanatory diagram. Statistical methods were suggested by the AI and verified for suitability by the author using standard search methods.

AI was not used to generate data, determine regulatory thresholds, make compliance decisions, act as an authoritative source of scientific interpretation, or substitute for professional judgement. All analytical decisions, statistical methods, parameter selections, interpretations, conclusions, and final outputs were reviewed and validated by the author prior to use.

Section-Specific AI Use

Consolidation of R code for graph production.

Boxplot and trend graphs already existed as individual R-ggplot code blocks with repeated logic for themes, scales, thresholds, and colours. AI assistance was used across all graphs within the report to restructure these into reusable R ggplot plotting code. This reduced duplication and ensured that all indicators used consistent visual and analytical standards. The outcome was a single script for each type of graph capable of generating plots consistently. This code is now capable of rapidly reproducing graphs for future reporting purposes.

Parameter Table Introduction

A parameter table was introduced to separate scientific decisions (reference ranges, axis limits, breaks, thresholds) from plotting code and to enable independent review and traceability. AI assistance supported designing this structure and integrating it into plotting code. The separate parameter table enables changes to scientific decisions without altering code.

R code error and exclusion checking

AI was used to investigate and identify R code errors and warnings related to data exclusion. Exclusions were confirmed to result from deliberate reporting limits, source data errors and non-numeric values rather than coding errors. Source data errors were manually checked, corrected and verified by the author.

Section 3.1 – Comparison of reference ranges

Comparison of reference ranges was previously a manual process. AI assistance was used to develop investigative and graphing code to determine the sites with data outside of the reference ranges. The same source data and parameter tables used to create the other graphs within the report are used. The resulting graph (Figure 2) was cross-checked against the rest manually by the author. This code

automates out-of-range reporting, reduces errors and provides an important cross-check for all the graphs.

Section 3.3.5 Carbon: Nitrogen Ratio

The C:N Ratio diagram (**Error! Reference source not found.**) was regenerated by AI without alteration from a poor-quality original following a recommendation by a reviewer.

Section 4 Standalone Analysis

In section 4.1 a standalone correlation analysis was developed to assess relationships between Olsen P and associated contaminants. AI assistance supported workflow structure and plotting (Figure 25 & Figure 26), while statistical method selection and interpretation were made by the author. AI was used to stratify this analysis by land use to avoid masking management-specific patterns. The AI developed code for faceted plots (Figure 27 to Figure 28) showing raw data, trendlines, thresholds, and per-facet correlation statistics.

A standalone analysis was developed in section 4.2 to investigate relationships between vineyard soil carbon and plant available water. AI assistance was used to support code development, data reshaping, plotting, and statistical workflow design. Statistical testing and interpretation remained the responsibility of the analyst. AI was used to develop the conceptual diagram in Figure 30. Author-written report text was used as prompts for diagram development. This graphic was used solely as an explanatory aid and did not introduce new analytical results. Fuzzy c-means clustering was applied to carbon and plant available water data to identify functional structure within vineyard soils. AI assistance was used to develop R code for both statistics and graphing (Figure 31 & Figure 32) in this analysis. Several statistical methods were suggested by AI. C-means was selected by the author based on applicability to the analysis.

Section 5.5– Site-Specific Cadmium Trend Analysis

Cadmium trend analysis was developed to better understand changes in cadmium levels. AI assistance was used to redevelop R code for the Cadmium trend graphic (Figure 40). More detailed analysis was requested by the author, and AI suggested a site-specific probability density methodology to identify average rates of change. This statistical methodology was unfamiliar to the author and AI was used to develop the statistical and graphing code for this (Figure 41). AI produced draft interpretive text for this section which was rewritten by the author.

Appendix D- AI Disclosure

The text for this appendix was drafted by the AI by reviewing the entire chat, all prompts and uploaded material. The draft was rewritten by the author. All AI drafted material has been retained.