MARLBOROUGH DISTRICT COUNCIL

MAY 2021

Soil Quality in the Marlborough Region

MDC Technical Report No: 21-004

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MDC Technical Report No: 21-004

ISSN 1179-819X (Online)

ISBN 978-1-927159-97-2 (Online)

File Reference/Record No: E355-001-001-20/21110934

May 2021

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Acknowledgements:
The Marlborough District Council wish to thank the landowners and managers for providing access to their properties to allow soils to be sampled and supplying relevant site management information.

Executive Summary

Regional 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". To help meet these goals, the Council undertakes a soil quality monitoring programme that involves collecting soil samples from a network of sites that represent the main land use activities and soil types within the region and analysing these samples for a suite of soil physical, biological and chemical properties that have been shown to be robust indicators of soil quality. The aim of this report is to summarise both the current state of, and the long-term trends in, soil quality in the Marlborough region as determined by the results of soil analysis from sampling across a range of land use activities and soil types. Changes in soil quality take a long time to become evident. The Soil Quality Monitoring Programme has been operating for 20 years and has begun to clearly identify a declining trend in some soil quality parameters.

In this investigation, soils were sampled from thirteen monitoring sites that included four vineyards, three pasture sites and six cropping sites. These sites represented 11 different soil types from three soil orders.

This year's results are similar to last year's results. While many sites show good soil quality, most farmed soils show the effects of human land use with soil quality indicators for many of these falling outside target ranges. 76% of sites reported soil compaction measurements outside the target range. These results put these soils at risk of poor aeration and impeded drainage which may potentially affect pasture production and predispose the soil to surface runoff, nutrient loss, erosion and flooding. While soil compaction may not be permanent, it clearly should be avoided and remediated where necessary.

Soil carbon loss is a significant issue for some land uses in Marlborough. Total carbon and hot water carbon (HWC) measure sources of carbon in the soil. HWC can help understand what risks are posed to soil structure, nutrient availability and water retention from a loss of this soil carbon fraction. Similar to last year 90%of the HWC samples failed to reach the provisional target of >1900 mg/kg indicating that although more samples are required, Marlborough soils may have low microbial activity and face risks of structural degradation. In particular cropping and vineyard land uses show declining soil carbon levels.

Excess nutrients within soil are also identified as an environmental risk to water quality. Elevated levels of nitrogen in dairy farming, elevated phosphorus levels in most farmed land uses combined with soil compaction can indicate an increased risk to water quality from runoff and leaching.

The long-term analysis introduced in 2016 has been repeated this year. The results from a new set of samples confirm the concerns outlined in the 2016, 2017, 2018 and 2019 reports that soil compaction, soil organic matter loss and loss of nutrients to water are significant problems for Marlborough.

This year a series of soil quality recommendations have been added to each section of the report. These are intended as a guide to landowners on how to measure and improve soil quality parameters on their properties. There is potential for these recommendations to be used in planning processes should a regulatory approach be required to maintain or improve soil quality under some land uses.

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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". 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 such as dairying and viticulture 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 monitoring programme known as "The 500 Soils Project". At the completion of this project MDC implemented its own soil quality monitoring programme commencing in 2008 to continue assessing the quality of soils throughout the Marlborough region. This programme is largely based around the framework developed as part of the national programme and is in line with soil quality monitoring currently undertaken in other regions in New Zealand.

The objectives of the soil quality monitoring programme are to:

- 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 96 soil quality monitoring sites has been established in Marlborough. The report discusses if they meet their target ranges for soil quality. This report presents results for 13 sites last sampled in 2015.

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. Soil orders are the broadest classification of soils under the New Zealand Soil Classification (Hewitt, 2010). As examples, Raw soils come from areas where unweathered parent material has gathered such as stony riverbeds. Raw soils are young, undeveloped soils. In contrast, Brown soils are more developed, mature soils that can be found in many locations around New Zealand. Soil orders are further broken down into smaller groupings, these are Groups, sub-Groups, Families and Siblings. Soil type is a common term for a Soil Family. An example of a Raw Soil Family is Waimakariri which is named after the Waimakariri River and a Brown soil type is Wairau, named after the Wairau Plains.

2.1. Sampling Sites

Soils were sampled from 13 sites previously sampled in 2015. They include four vineyard sites, three pasture sites and six cropping sites. The sampled sites represent 11 different soil families from three soil orders (Table 1).

Table 1: Soil type, soil classification and land use management of sites sampled in Marlborough in 2020.

Site Code	Sampling years	Soil Type/Family	Soil Order*	Land use; management
SOE_Soils_Site61	2010, 2015, 2020	Seaview	Pallic	Cropping
SOE_Soils_Site62	2010, 2015, 2020	Galtymore	Recent	Cropping
SOE_Soils_Site63	2010, 2015, 2020	Marama	Pallic	Cropping
SOE_Soils_Site64	2010, 2015, 2020	Broadbridge	Pallic	Cropping
SOE_Soils_Site65	2010, 2015, 2020	Seaview	Pallic	Vineyard
SOE_Soils_Site66	2010, 2015, 2020	Kaituna	Brown	Vineyard
SOE_Soils_Site69	2010, 2015, 2020	Woodbourne	Pallic	Vineyard
SOE_Soils_Site70	2010, 2015, 2020	Wairau	Recent	Vineyard
SOE_Soils_Site71	2010, 2015, 2020	Renwick	Brown	Cropping
SOE_Soils_Site72	2010, 2015, 2020	Brancott	Pallic	Cropping
SOE_Soils_Site73	2010, 2015, 2020	Kaituna	Brown	Pasture
SOE_Soils_Site74	2010, 2015, 2020	Rai	Brown	Pasture
SOE_Soils_Site75	2010, 2015, 2020	Ronga	Recent	Pasture

***New Zealand Soil Classification**

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 1a). 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 1b). 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 2020, most sites had reasonable soil moisture conditions.

Plate 1: (a) Collecting a composite of core samples along a transect using a soil corer. (b) One of three intact core samples taken at each site, to establish the physical properties of the soil.

2.2.1. Changes to sampling sites

The location of sampling sites should not change. However, a key objective of this project is to monitor land use and landscape changes to these sites. The majority of the sites sampled in this round are being sampled for the third time. This means some sites are now up to 15 years old and may have changed markedly from the original. Field notes 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 2020, the location of one site (Site 65) was changed from previous due to the construction of a water storage dam over the original site. The relocated site is located on the same mapped soil type and is under the same land use.

2.2.2. Viticulture sampling sites

Because of the economic importance and scale of viticulture in Marlborough, it was decided in 2012 that vineyard monitoring should encompass three samples per vineyard site. Samples are taken from under the vines, in the wheel tracks and in the inter-row region. This is done to allow the impact of various management practices to be evaluated. These include:

- Under vine
    - banding of fertiliser
    - herbicide applications
    - maintenance of bare ground
    - absence of traffic

  - irrigation
  - transfer of inter-row mowing's
- Wheel tracks
  - soil compaction
- Inter-row
  - inputs of organic matter including pruning's
  - lower rates of fertiliser
  - rainfall inputs only

2.3. Soil Quality Measurements

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	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	Decomposition rate of organic matter	Calculated from above
Hot Water Carbon	Indicator of soil microbiological activity	Hot water extraction at 80°C for 16 hours followed by IR detection.
Physical properties		
Dry bulk density	Compaction, volumetric conversions	Soil cores
Total porosity, air capacity and macroporosity	Soil compaction, aeration, drainage	Pressure plates

2.4. Soil Analysis

Descriptions of the different soil analysis process are detailed below. In general, analysis follows the processes described by (Hill & Sparling, 2009) for soil quality parameters and Kim & Taylor, (2009) for trace element analysis.

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 with Olsen extraction followed by Molybdenum Blue colorimetry (Olsen, Cole, Watanabe, & Dean, 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 Hill 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). Air filled porosity (-10 kPa) and total porosity were calculated as described by Klute, (1986). Particle density was measured by the pipette method. An example of cores being processed is shown in Plate 2.

Plate 2: An example of dried cores inside their extraction rings following oven drying. Credit: D. Thornburrow, Manaaki Whenua Landcare Research.

It is worth noting that the general definition of macroporosity has recently been expanded to cover a slightly larger range of pores sizes than the original definition. Several regional councils have adopted macroporosity measurements based on the volumetric water content at - 10kPa (technically referred to as the air-filled porosity). So, in this report for consistency with other regions we now use the - 10kPa measurement (defined in this report as air filled porosity), although the - 5kPa data is included for reference because this has been used and reported by MDC and others in the past.

2.4.4. Targets and Ranges

To aid in the interpretation of soil quality indicators, an expert panel (in several workshops) developed guidelines for the seven soil quality indicators now commonly used by regional councils (Hill & Sparling, 2009). The panel determined target ranges for the assessment of soil quality (e.g. very low, optimal, very high etc.) for the predominant soil orders under different land uses. The interpretative ranges from Hill & Sparling, (2009) are presented in Appendix A. However, Olsen P targets have recently been revised with new target values reported in (Mackay, Dominati, & Taylor, 2013) and used in this report (Appendix A).

The trace element results (except for cadmium) have been compared against the soil limits presented in the New Zealand Water and Wastes Association (NZWWA, 2003) 'Guidelines for the Safe Application of Biosolids to Land in New Zealand' (referred to as the biosolids guidelines) (Appendix A). While guidelines containing soil contaminant values like the biosolids guidelines have been written for a specific activity (i.e. biosolids application), the values are generally transferable to other activities that share similar hazardous substances. Cadmium results were compared to values in the Tiered Fertiliser Management System (TFMS) from the New Zealand Cadmium Management Strategy (MAF, 2010).

2.4.5. Data Display and Analysis

Readers of early Soil Quality reports will note several changes in the presentation of the data. Firstly, the names of the sites were changed in 2016 in order to provide better referencing in the Council computer database. Sites were previously labelled using an "MDC" number e.g. MDC 15. These have now been renamed *SOE_Soils_Site15*. The number of each site remains the same. Vineyard sites are labelled *SOE_Soils_Site63a_vine, b_wheel* or *c_inter-row*.

The second change in data presentation from early reports has been to present data in groups according to soil order or land use. This change allows the reader to more clearly understand how a soil conforms to its target values which are set according to soil order or land use. Soil order and land use are the two factors that have the greatest influence on soil quality. Readers can refer to Appendix A for target ranges of soil quality indicators. Information on soil orders and the New Zealand Soil Classification can be found at https://soils.landcareresearch.co.nz/describing-soils/nzsc

This report displays data in two ways. Firstly, Table 3 and Table 4 show the raw chemical and biological data from the bulked sample. Table 5 shows the physical data for each sample as a single averaged value for the three soil cores extracted from each site. Secondly, the long-term data uses a five year rolling average. Each data point for a given year is the average of all data from the proceeding five years for that data. This is done to smooth data outliers and to help illustrate long-term trends in the data.

As a result of the on-going review process for the Soil Quality Monitoring programme, it has been identified that some land uses have insufficient sites to justify presenting this data as annual values (five year rolling average). Readers of the 2016 report will have noted the inconsistencies in native forestry results resulting from the low number of sites (five) that are available for sampling (a reflection of the small number of remaining lowland native forests in Marlborough). Previous procedure was to sample these on a 10-year rotation; however, this has resulted in only 11 sample points for this land use over the entire course of the programme. Exotic forestry follows a similar pattern although this land use has 17 total sample points. As a result, data from these land uses is no longer presented as a time series but as a single point derived from the average of all data for that land use. This provides a reference for these land uses while reducing the effect of individual outlier data points. Future options for this data are to identify more sites or sample more often although costs limitations may constrain this.

As mentioned in Section 2.4.3, previous Soil Quality Reports used the term macroporosity to refer to soil pore measurements. However, these measurements used data more correctly called air-filled porosity. This report now refers to air-filled porosity - 10kPa to clarify which measurement is being used.

This report discusses changes in soil quality indicators over time. This is done to improve the understanding of soil quality changes on a regional basis. This has allowed the determination of some key issues for land managers to be aware of. See section 4 for further details.

Where appropriate, data were expressed on a weight/volume or volume/volume basis to allow comparison between soils with differing bulk density. Olsen P values are reported in different units (mg/L) than previous reports to account for differences in soil bulk density between samples.

Data in this report is commonly displayed using box and whisker plots. Box and whisker plots show the maximum and minimum values (whiskers), first and third quartiles (top and bottom of the box) and the median (central line in the box). For data from this year, only the land uses sampled in this current year are displayed in the first plot in each section. 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. Readers are urged to pay careful attention to the vertical axes to better understand the relationships between the current and historic values.

3. Results and Discussion

3.1. Comparison of Target Ranges

Figure 1 shows the percentage of sites not meeting their target for a specific soil quality indicator. All sites for pH, trace elements, total C, total N met their target ranges. Olsen P, total carbon, anaerobically mineralisable nitrogen, hot water carbon and air-filled porosity all showed a large number of sites failing to meet the target ranges (15, 9, 21,16 sites respectively). C:N ratio, and bulk density had smaller numbers not meeting their soil quality target. 21 samples were taken from 13 sites in 2020.

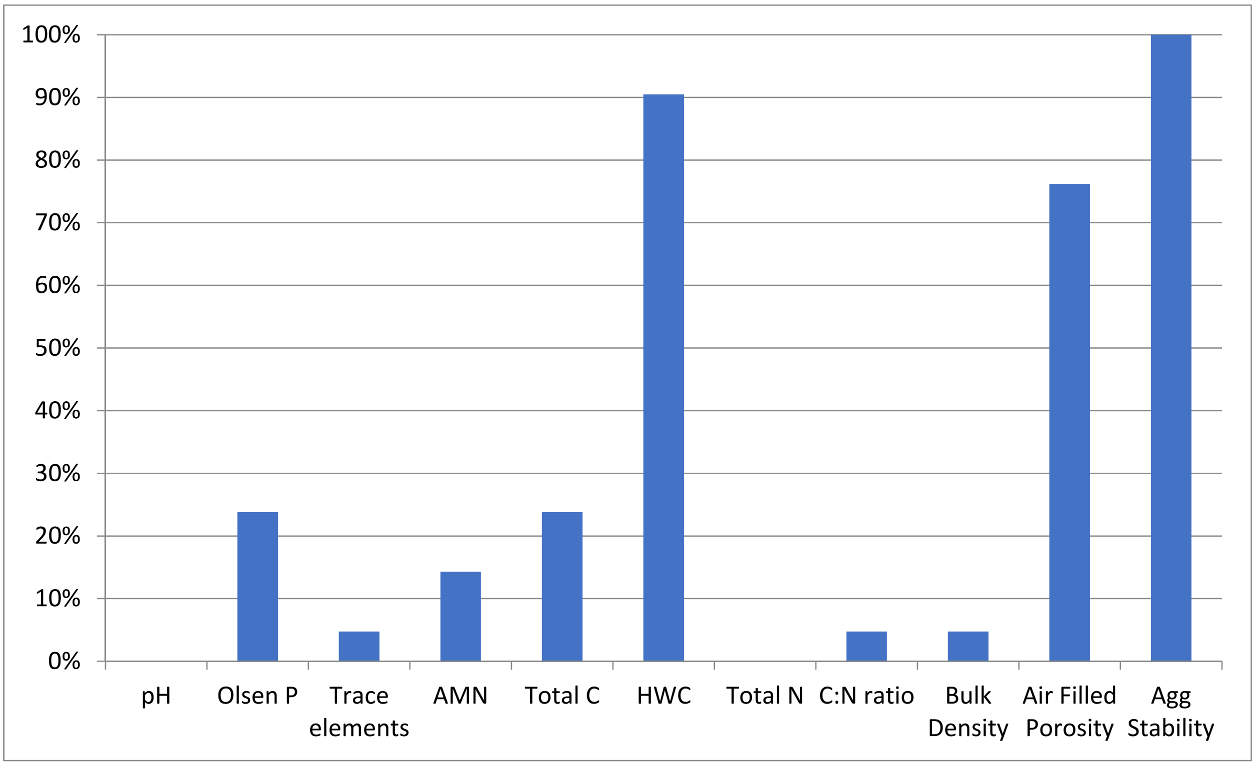

Figure 1. The percentage of sites not meeting their target range for a specific soil quality indicator.

The results of soil chemical, biological and physical analyses from soils sampled at each site are given in Table 3, Table 4 and Table 5 respectively and are discussed separately below.

3.2. Soil Chemical results

Results of soil chemical analysis (pH, Olsen P and Trace elements) are reported in Table 3. Each of the chemical properties is discussed individually. The target values appropriate to the relevant soil order can be found in Appendix A.

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 effects 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.

As indicated in Table 3, all sites had soil pH values within the acceptable target for their respective land use. Differences are evident between land uses. Vineyards have slightly higher pH than other land uses with exotic forestry having the lowest pH (most acidic) readings. Analysis of pH by soil type shows no significant difference in pH between soil types.

The differences seen in Figure 2 and 3 are most likely due to land use. This is probably a reflection of fertiliser practice under the different land uses. Low input land uses will tend to lower pH due to the natural acidifying effects of plant growth. Farmed land will often receive fertiliser (and lime) relative to the value of the products coming from this land. As a result, it is common practice to apply fertiliser and lime annually to vineyards with a consequent lift in pH. The lower returns and larger-scale of pastoral farming often restrict fertiliser applications to correction of limiting nutrients only. This seems to have led to an overall lower pH for pastoral land uses.

Interestingly, the average pH values shown for viticulture in 2020 are in the high end of the range that is normally preferred (6.2 - 6.7). This is similar to the longer-term samples (Figure 3). This would imply that some sites have much higher pH. Although it is not possible to determine with this data set, the implication is that pH management in vineyards may need to be improved. Because of the regular application of fertiliser to vineyards, often small amounts of nutrients will be applied. This often requires lime to be added to the other nutrients for these to be spread effectively. 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[1] should be tested.
- In general, soil pH can range widely with soils remaining 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 other than lime. Heavy additions of magnesium, potassium and sodium can change pH. This is especially relevant where grape marc or winery waste water is discharged and landowners should test more often where heavy nutrient additions are made.

- [1] 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.

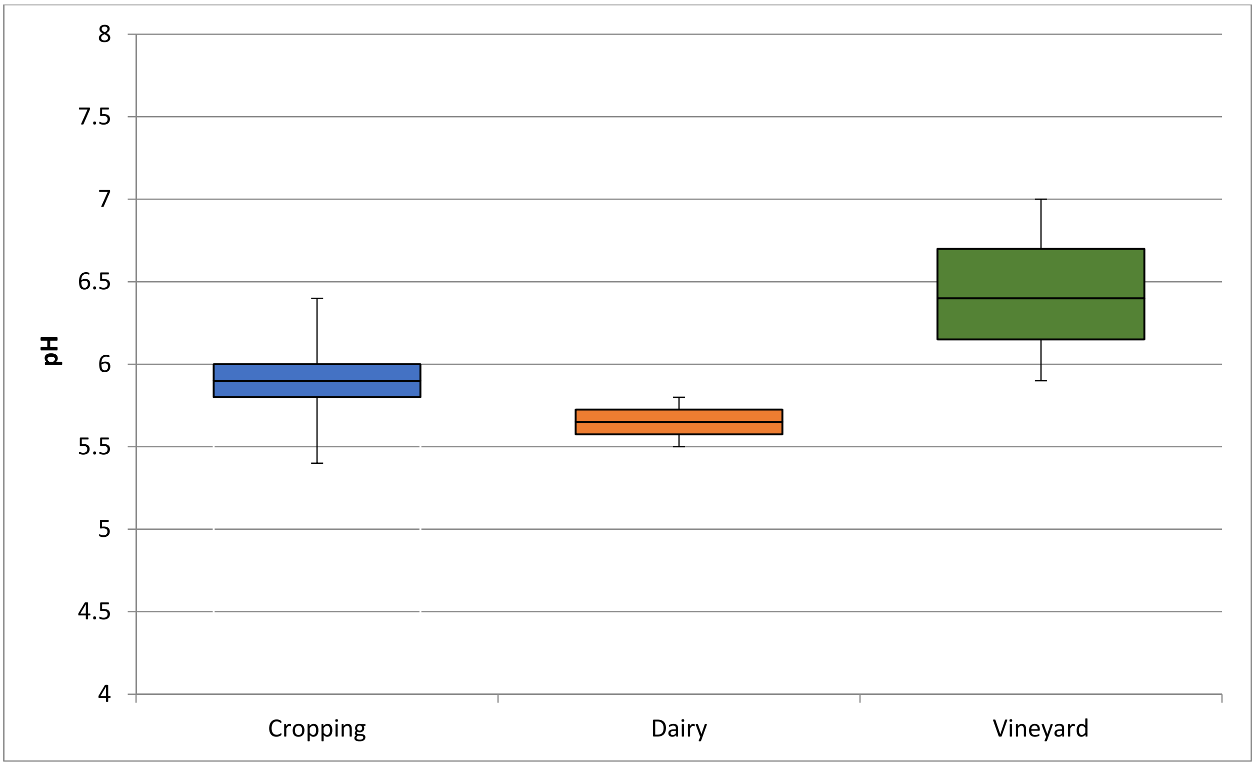

Figure 2: Soil pH by land use for 2020 samples. Target ranges vary for land uses. Refer Appendix A.

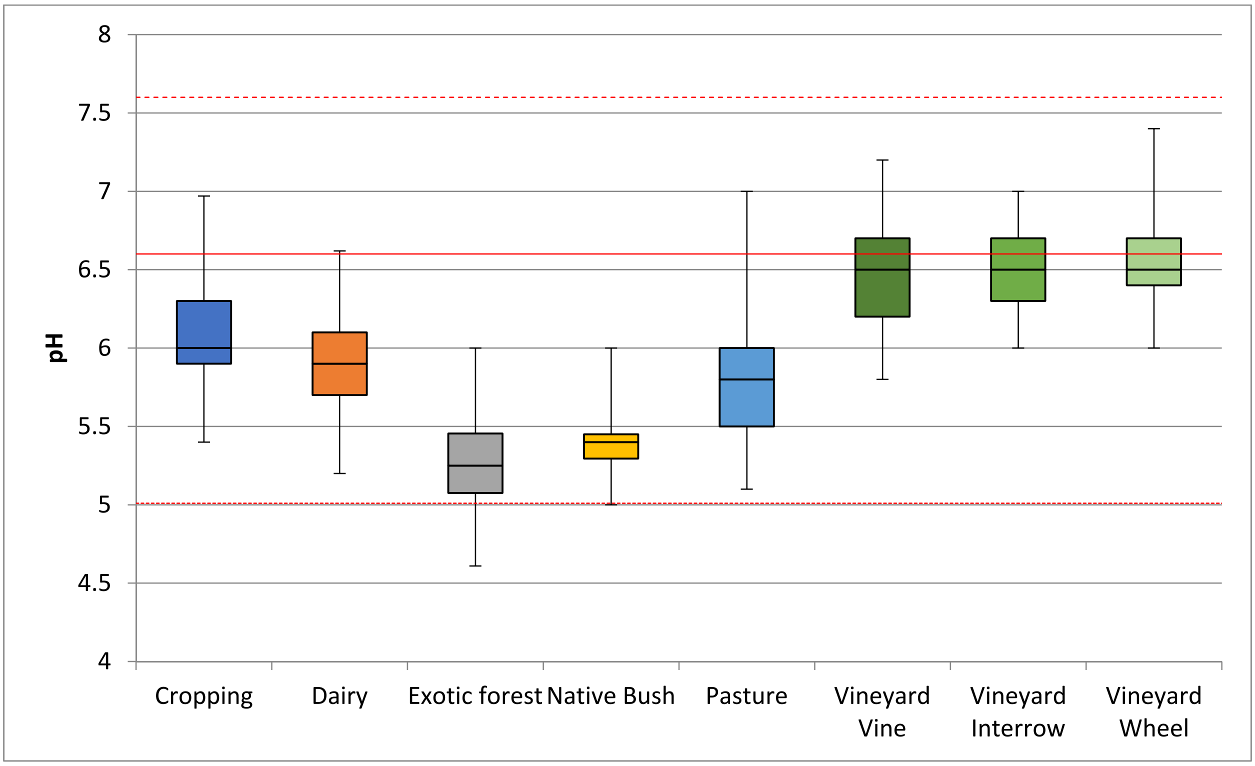

Figure 3: Soil pH by land use for all samples since 2000. Target ranges vary for land uses. Refer Appendix A. Target range for pastures 5 to 6.6, horticulture 5 to 7.6.

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, Drewry, Carey, Paton, & Condron, 2003).

From the 21 Olsen P samples taken in 2020, concentrations varied from 14mg/L to 68 mg/L. This year, the lowest values are found in pasture and vineyard samples (Figure 4). The highest values were found in cropping samples. The maximum Olsen P target for all soils is set at 50 ml/L (Mackay *et al*, 2013).

Four sites had Olsen P values below the optimal for their land use. These sites may be operating at Olsen P values below concentrations considered optimal for maximum pasture/crop production. These sites cover several different land uses.

The trends in the 2020 values are consistent with the longer-term samples (Figure 5). Farmed sites generally reflect higher Olsen P concentrations compared to unfarmed sites or sites with lower returns.

Soil Quality recommendations:

- Olsen P measurements should be included in regular soil testing. Phosphate fertiliser should only be applied following soil testing to ensure the application is necessary.
- 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.
- Olsen P Values higher than 50 represent a significant risk to water quality. Do not apply phosphate fertilisers when Olsen P is above 50.
- Olsen P values below 15 indicate reduced plant productivity. Depending on the crop grown, phosphate fertiliser should be applied to increase productivity in accordance to the relevant crop guide.
- 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.

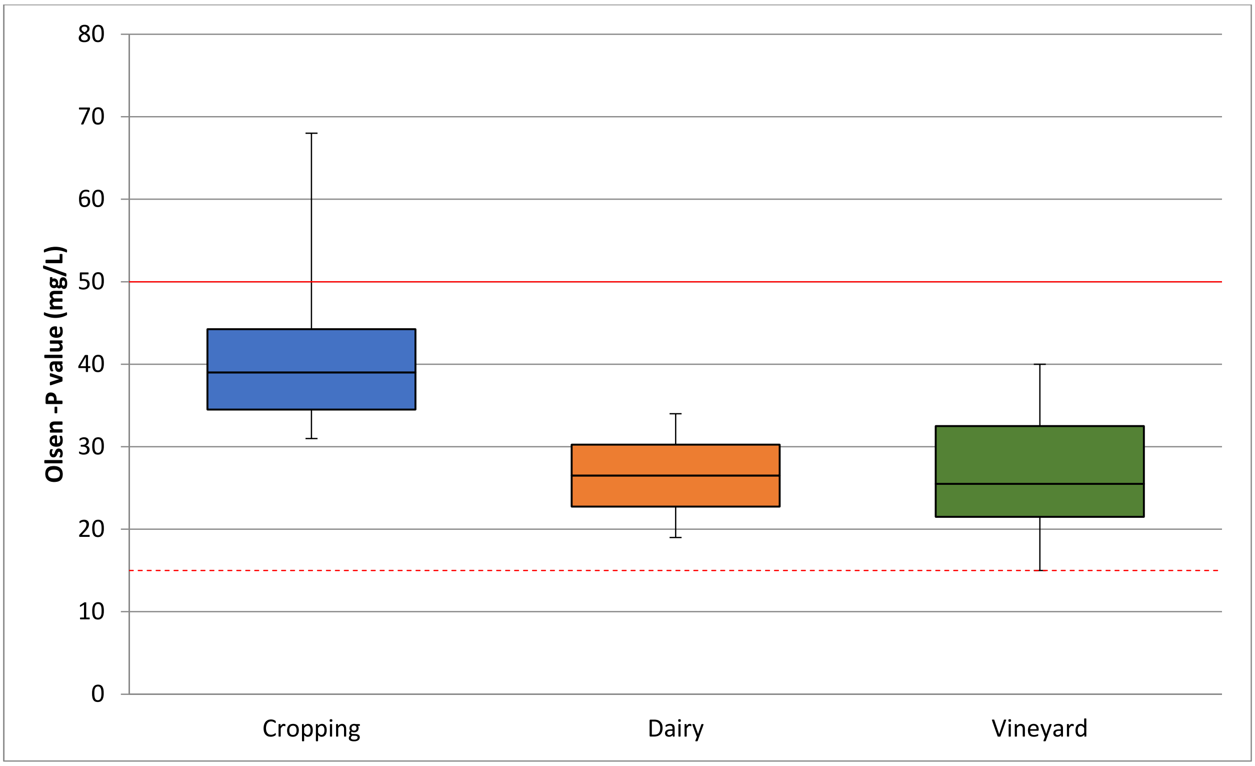

Figure 4: Olsen P values by land use for 2020 samples. Target maximum is 50 mg/L for all land uses, Target minimum for exotic forestry is 5, other land uses 15mg/L.

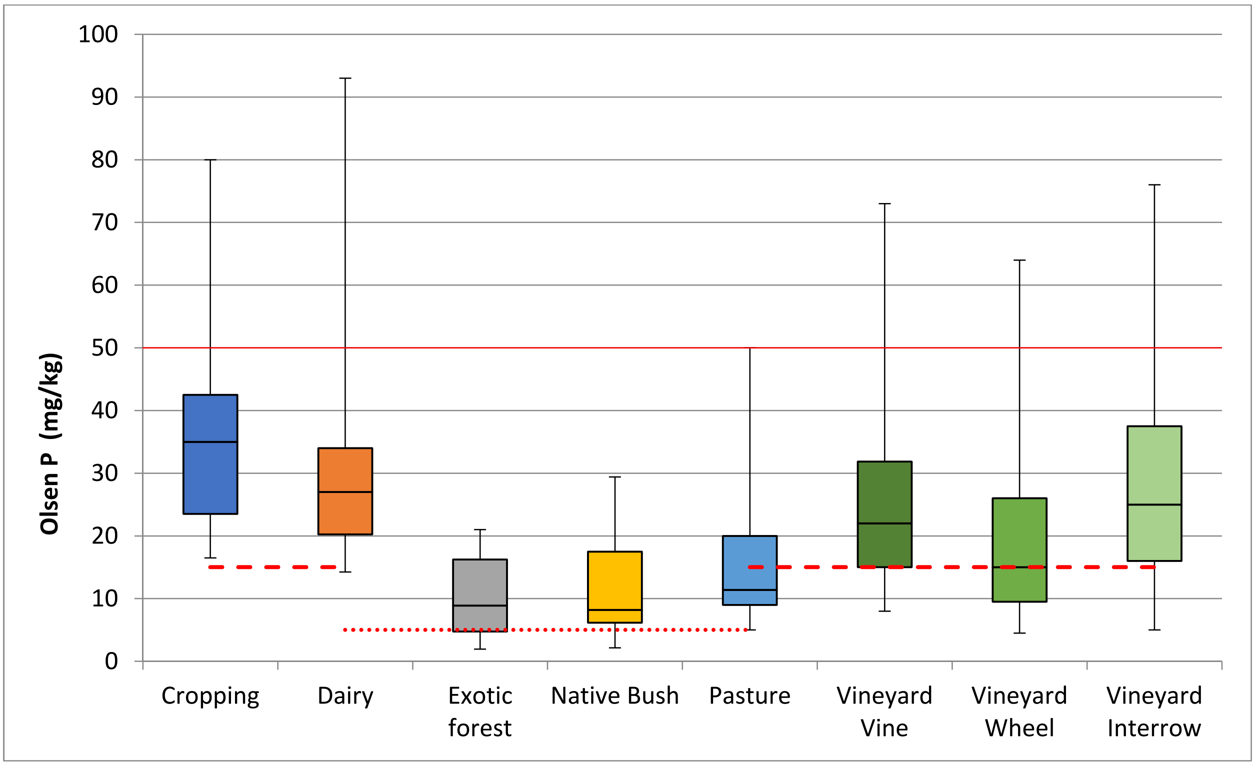

Figure 5: Soil Olsen P values for all samples since 2000. Target maximum is 50 mg/L for all land uses, Target minimum for exotic forestry is 5, other land uses 15mg/L.

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 are essential for healthy plant and animal growth, i.e. copper and zinc, at high concentrations in soils these can have a negative impact on soil fertility and plant and animal health. Furthermore, some trace elements, i.e. cadmium and arsenic are not essential in soils and their accumulation can also have a negative impact on soil, plant and animal health and in some cases, there is potential for them to accumulate in the human food chain.

Table 3 summarises trace element concentrations in soils from the monitoring sites. Only one site showed trace elements in excess of the guideline values in 2020. On average the 2020 sample concentrations were 4.6 mg kg^{-1} for arsenic, 0.20 mg kg^{-1} for cadmium, 21 mg kg^{-1} for chromium, 16.7 mg kg^{-1} for copper, 11.6 mg kg^{-1} for lead, 14.8 mg kg^{-1} for nickel, below detection for mercury and 69 mg kg^{-1} for zinc. These **average** concentrations are within the suggested upper limits for trace elements in soils as suggested by the New Zealand Water and Waste Association (NZWWA) (Appendix A). Concentrations are also similar to those that have been found in soils in other parts of New Zealand (Auckland Regional Council, 1999; Greater Wellington Regional Council, 2005; Canterbury Regional Council, 2006; Curran - Cournane & Taylor, 2012) and what has previously found in Marlborough (Gray C. , 2011b). Note that while the NZWWA guidelines suggest upper limit for Cadmium is 1 mg kg^{-1}, the Tiered Fertiliser Management Strategy (TFMS) indicates that soil cadmium levels above 0.6mg kg^{-1} require more active management of soil cadmium loading. [2]. Therefore 0.6mg kg^{-1} is used in this report as the target range for cadmium.

For cadmium, average concentrations in farmed soils were approximately double typical background concentrations found in soils (0.2mg/kg). Non-farmed soils such as native forest samples typically only show background levels of cadmium (Figure 6). The source of cadmium is most likely phosphate fertiliser which has been shown to contain cadmium as an incidental impurity (Longhurst, Roberts, & Waller, 2004).

Overall, the 2020 results reflect the wider situation of cadmium concentration. 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 generally higher in land uses that have higher value returns reflecting the frequency with which fertiliser is applied (Figure 7). 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.

Soil Quality Recommendations:

- In Marlborough, dairy farms have the highest levels of cadmium. All dairy farms should include cadmium in their soil test parameters.
- Add cadmium to the list of parameters tested where a soil testing programme already exists.
- Farms should test soil cadmium at least once every five years.
- The tested areas should be representative of a Land Management Unit (LMU). If greater understanding of the on-farm variability is needed see the TFMS guide.
- A graph of the soil cadmium results over time should be established for all LMUs. If the tests show results approaching 0.6 mg kg^{-1} or greater, follow the guidance in the TFMS guide and document the action taken for farm planning purposes.

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[2] See https://www.fertiliser.org.nz/Site/resources/tools.aspx#tiered

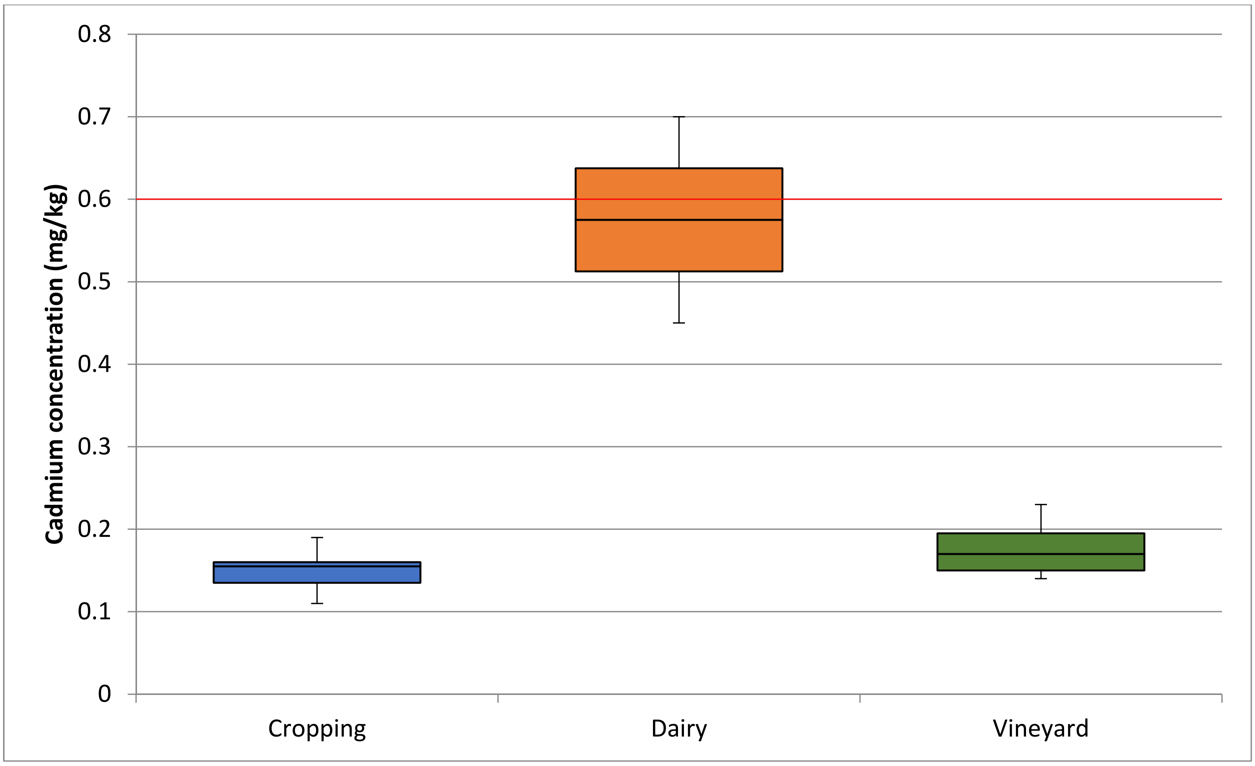

Figure 6: Soil cadmium concentrations by land use for 2020 samples. Maximum value 0.6mg/kg TMFS.

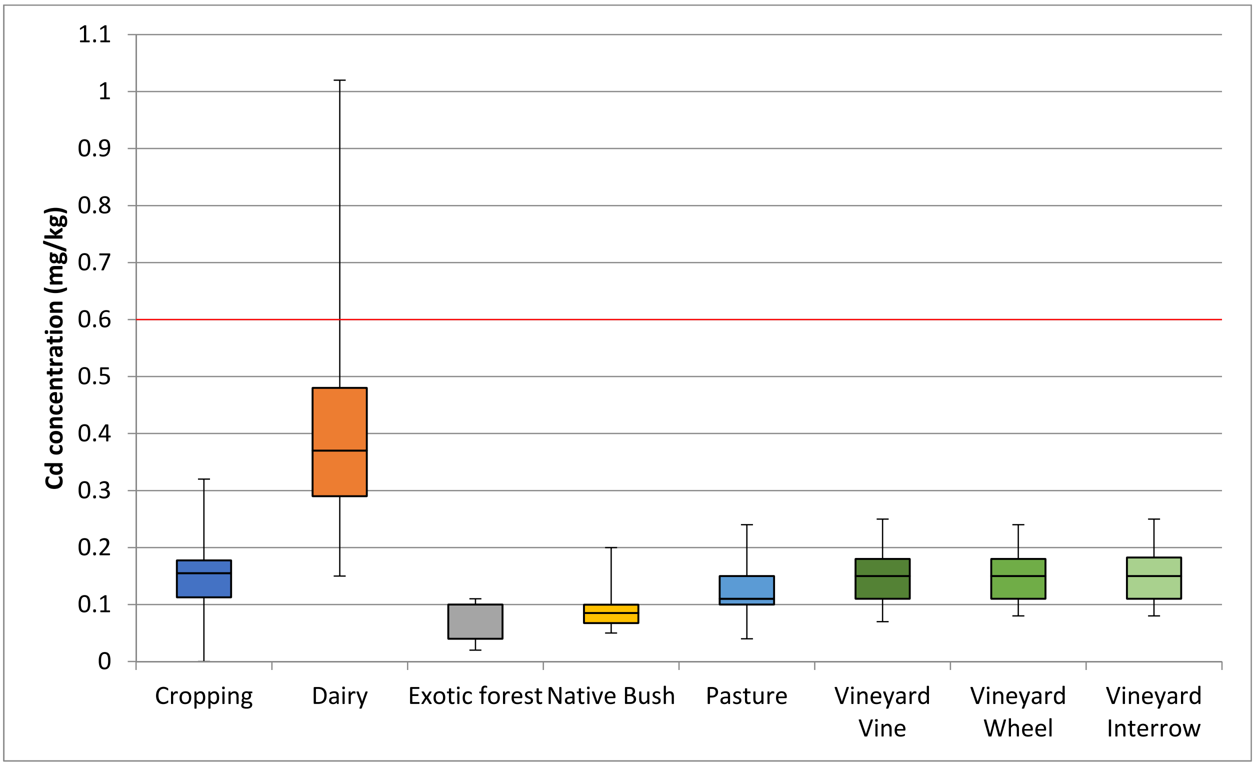

Figure 7: Soil cadmium concentrations by land use for all samples since 2000.

Table 3: Soil Chemical results.

				Trace Elements									
Site	Soil type	Soil Order	Landuse	pH	Olsen P (mg/L)	Zn (mg/kg)	Cu (mg/kg)	Cr (mg/kg)	As (mg/kg)	Pb (mg/kg)	Ni (mg/kg)	Hg (mg/kg)	Cd (mg/kg)
SOE_Soils_Site 61	Seaview	Pallic	Cropping	✓ 5.4	✗ 68	✓ 68	✓ 12	✓ 25	✓ 4.1	✓ 10.9	✓ 18.2	< 0.12	✓ 0.19
SOE_Soils_Site 62	Galtymore	Recent	Cropping	✓ 5.8	✓ 46	✓ 48	✓ 14	✓ 19.2	✓ 5.1	✓ 10.5	✓ 17.5	< 0.12	✓ 0.11
SOE_Soils_Site 63	Marama	Pallic	Cropping	✓ 6	✓ 39	✓ 62	✓ 13	✓ 21	✓ 4.2	✓ 9.9	✓ 17	< 0.12	✓ 0.13
SOE_Soils_Site 64	Broadbridge	Pallic	Cropping	✓ 5.8	✓ 39	✓ 56	✓ 11	✓ 26	✓ 3.8	✓ 10.7	✓ 14.4	< 0.12	✓ 0.15
SOE_Soils_Site 71	Renwick	Brown	Cropping	✓ 6.4	✓ 33	✓ 60	✓ 7	✓ 13.9	✓ 2.4	✓ 8.7	✓ 9.4	< 0.11	✓ 0.17
SOE_Soils_Site 72	Brancott	Pallic	Cropping	✓ 6	✓ 31	✓ 62	✓ 7	✓ 11.3	✓ 2.5	✓ 8.7	✓ 8.9	< 0.12	✓ 0.16
SOE_Soils_Site 65a_vine	Seaview	Pallic	Vineyard	✓ 6	✓ 24	✓ 82	✓ 14	✓ 28	✓ 5.2	✓ 11.1	✓ 18.9	< 0.11	✓ 0.16
SOE_Soils_Site 65b_wheel	Seaview	Pallic	Vineyard	✓ 7	✓ 31	✓ 80	✓ 14	✓ 23	✓ 3.6	✓ 10	✓ 16.5	< 0.12	✓ 0.16
SOE_Soils_Site 65c_interow	Seaview	Pallic	Vineyard	✓ 6.7	✓ 32	✓ 73	✓ 12	✓ 24	✓ 3.7	✓ 10.8	✓ 17.2	< 0.12	✓ 0.14
SOE_Soils_Site 66a_vine	Kaituna	Brown	Vineyard	✓ 6.3	↓ 17	✓ 100	✓ 31	✓ 24	✓ 6	✓ 11.2	✓ 17.4	< 0.12	✓ 0.22
SOE_Soils_Site 66b_wheel	Kaituna	Brown	Vineyard	✓ 6.2	✓ 25	✓ 73	✓ 24	✓ 15.3	✓ 5.6	✓ 10.7	✓ 13.5	< 0.12	✓ 0.21
SOE_Soils_Site 66c_interow	Kaituna	Brown	Vineyard	✓ 6.4	✓ 40	✓ 73	✓ 22	✓ 16	✓ 5.6	✓ 11.2	✓ 13.7	< 0.12	✓ 0.23
SOE_Soils_Site 69a_vine	Woodbourne	Pallic	Vineyard	✓ 6.7	✓ 23	✓ 90	✓ 20	✓ 22	✓ 6.6	✓ 11.2	✓ 16.5	< 0.12	✓ 0.17
SOE_Soils_Site 69b_wheel	Woodbourne	Pallic	Vineyard	✓ 6.5	↓ 17	✓ 68	✓ 19	✓ 19.9	✓ 5.9	✓ 17.4	✓ 15.9	< 0.12	✓ 0.19
SOE_Soils_Site 69c_interow	Woodbourne	Pallic	Vineyard	✓ 6.4	✓ 26	✓ 70	✓ 18	✓ 23	✓ 5.8	✓ 17.6	✓ 17.2	< 0.12	✓ 0.17
SOE_Soils_Site 70a_vine	Wairau	Recent	Vineyard	✓ 6.7	↓ 15	✓ 74	✓ 21	✓ 21	✓ 4.2	✓ 11.8	✓ 14.5	< 0.12	✓ 0.15
SOE_Soils_Site 70b_wheel	Wairau	Recent	Vineyard	✓ 5.9	✓ 35	✓ 55	✓ 21	✓ 20	✓ 4.2	✓ 11.1	✓ 13.9	< 0.12	✓ 0.14
SOE_Soils_Site 70c_interow	Wairau	Recent	Vineyard	✓ 5.9	✓ 34	✓ 59	✓ 23	✓ 21	✓ 4.1	✓ 11.3	✓ 14.7	< 0.12	✓ 0.15
SOE_Soils_Site 73	Kaituna	Brown	Pasture	✓ 5.4	↓ 14	✓ 70	✓ 15	✓ 14.2	✓ 4.3	✓ 10.3	✓ 11.2	< 0.12	✓ 0.15
SOE_Soils_Site 74	Rai	Brown	Dairy	✓ 5.5	✓ 34	✓ 61	✓ 16	✓ 26	✓ 4.7	✓ 14.8	✓ 10.4	< 0.12	! 0.7
SOE_Soils_Site 75	Ronga	Recent	Dairy	✓ 5.8	✓ 19	✓ 65	✓ 17	✓ 27	✓ 5.1	✓ 13.2	✓ 13.5	< 0.12	✓ 0.45

Red cross indicates exceeds target range, red arrow below target range, yellow exclamation indicates exceeds TMFS level 1.

3.3. Soil Biology Results

Results of soil biological analysis (anaerobically mineralisable nitrogen, total nitrogen, total carbon and C:N ratio) are reported in Table 4. A new analysis was introduced last year, hot water carbon. Each of these organic matter properties is discussed individually. The target values appropriate to the relevant soil order can be found in Appendix A.

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 useful measure of soil quality that determines the ability of organic matter to store nitrogen. However, 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 (Myrold, 1987).

AMN can provide an indication of N loading in soil as organic matter and plant residues are mineralised (converted by microbes to mineral N). 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, Tisdale, Nelson, & Beaton, 2013). Increased soil solution N increases the risk of nitrate leaching. However, NO_3^--N losses are also controlled by other factors such as soil texture and soil structure which affect the rate of water movement (drainage) in the soil and therefore the rate of NO_3^--N loss. In addition, because soils are only sampled to the 10-cm depth, this test may not accurately reflect other processes that may happen to the nitrate-N further down the soil profile such as denitrification.

Typically, anaerobically mineralisable nitrogen concentrations vary widely between sites with the lowest values found on unfarmed sites. Three sites had values higher than their target range in 2020 (Table 4 and Figure 8). Typically, sites with higher inputs of organic matter such as pasture grasses, manure and urine have higher readings of AMN (Figure 9 – dairy, native bush, pasture). Given the higher AMN values on these sites, organic matter may be providing a large portion of soil solution N. Tools such as Overseer can be used to estimate the nitrogen flux in soil.

Sites with lower organic matter inputs or with a high level of soil disturbance will report lower levels of AMN. Increased soil disturbance increases oxidation of soil organic matter. Few sites have fallen below the minimum AMN target level for their land use, but clear differences are seen between land uses (Figure 9). 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 continual 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. 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 11), it is likely that the low AMN levels are related to a lack of microbial activity in the soils possibly related to the high pH organic matter inputs (pine needles).

Soil Quality Recommendations

- Where AMN is high, an increased risk of nitrogen leaching losses to groundwater is present. Reconsider the need for nitrogen fertiliser use.
- Dairy farmers should incorporate AMN measurements in their soil testing regime. If high AMN is shown, then Overseer modelling is justified to more accurately determine nitrogen use and losses.
- Where AMN is low, reduced supply of nitrogen from organic matter decomposition may be limiting plant growth.

- 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.

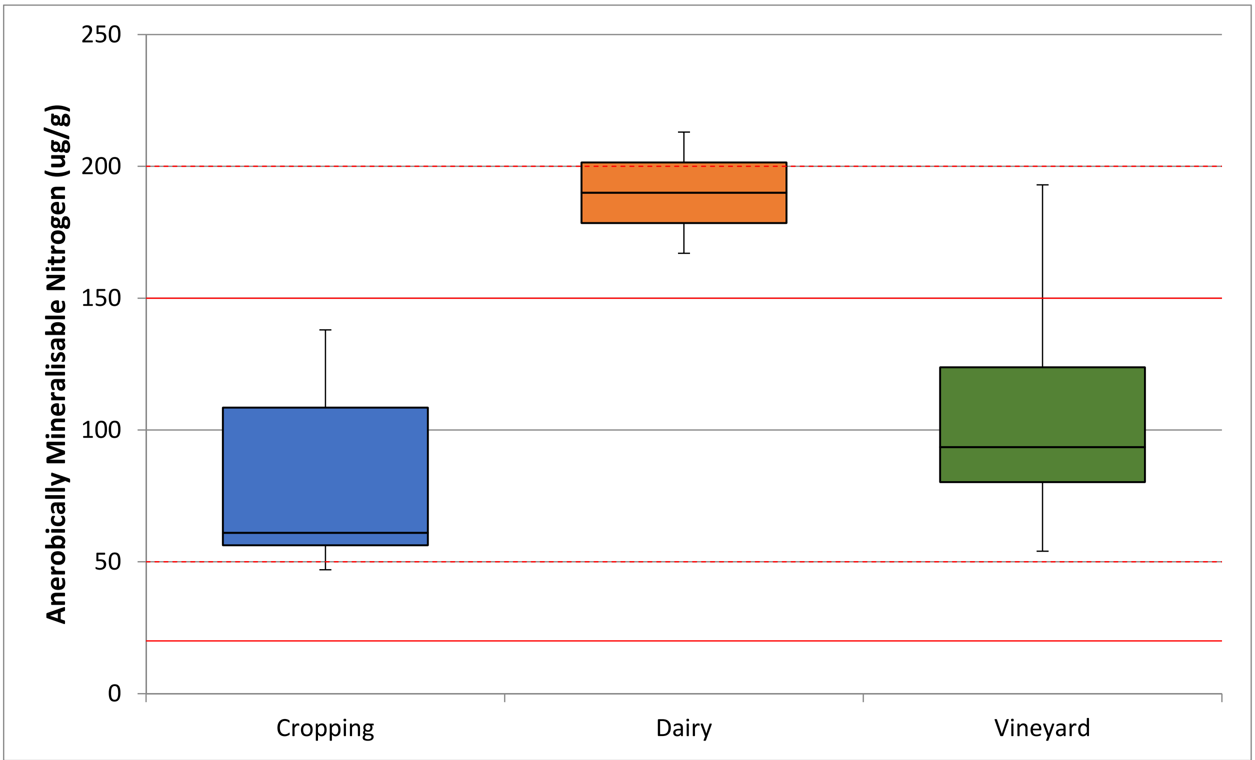

Figure 8: 2020 Anaerobically mineralisable nitrogen values for 2020. Target range for Pasture 50 to 200 ug/g (dashed line). All other landuses 150 to 20 ug/g (solid line).

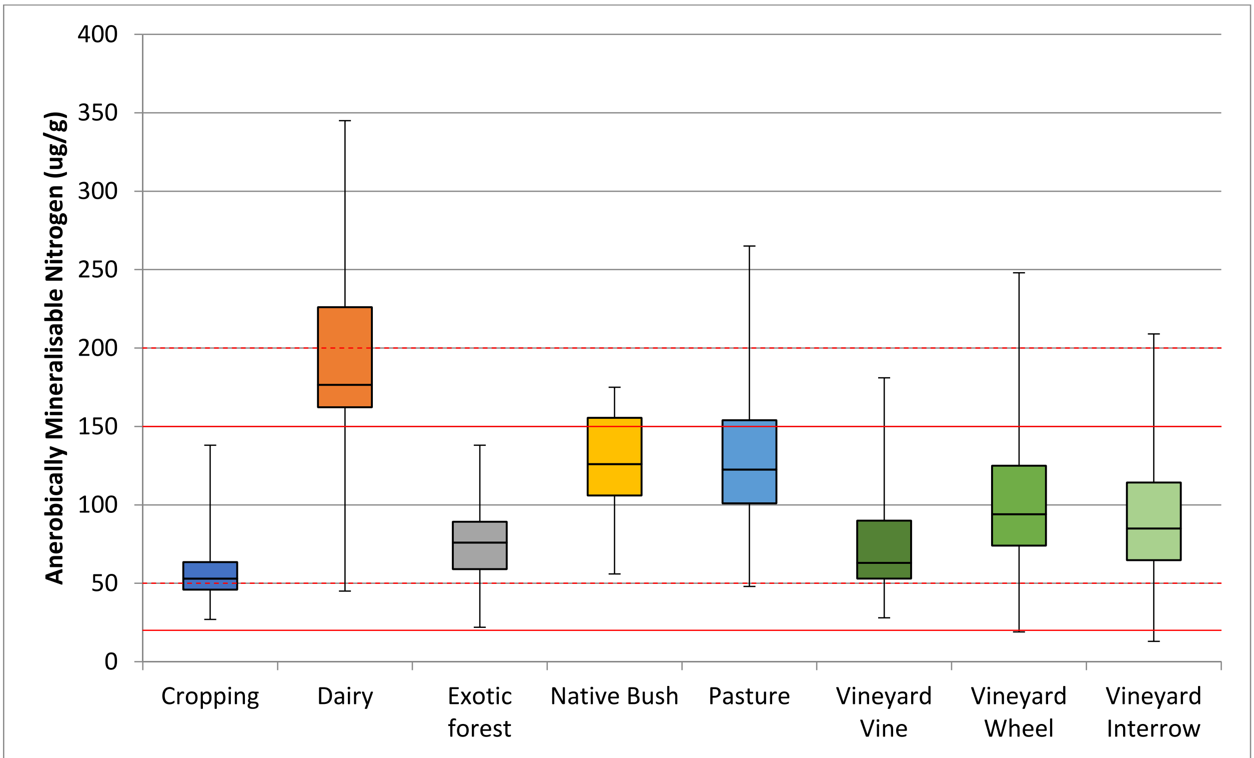

Figure 9: AMN concentrations by land uses for all samples since 2000. Target range for Pasture (includes Dairy) 50 to 200 ug/g (dashed line). All other landuses 150 to 20 ug/g (solid line.)

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; hence total carbon is generally considered a good measure of organic matter carbon 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. In contrast, low soil C 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.

In 2020, five sites had total soil carbon contents below the acceptable target ranges for their respective soil orders (Figure 10). The very low levels of soil carbon found in cropping sites this year underlines the effect that continual cultivation can have on this soil parameter. These sites show several properties consistent with poor soil quality all closely related to loss of soil carbon. These include low AMN, low total N, very low hot water carbon, high bulk density and very low aggregate stability.

It is clear from Figure 11 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, forest, pasture) have higher levels of total carbon. Land uses that involve the disturbance of soil (cultivation) have reduced total carbon. Vineyard establishment also involves a large amount of soil disturbance. Readers are referred to the two previous soil quality reports (2018 & 2019) for analysis of the effect of vineyard establishment on soil carbon.

Soil Quality Recommendations

- Total carbon is closely related to soil nutrient- and water-holding ability. Low total carbon will lead to reduced productivity through reductions in nutrient and water availability.
- Total carbon is closely related to the soil structure and its ability to resist physical damage. Low soil carbon will mean soils become compact more easily but are more prone to wind and water erosion when cultivated.
- The factors that influence 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 total carbon levels. To lift total carbon levels to the target ranges (ideally to 4% or greater), the following steps are recommended:
  - Increased use of pasture fallow periods in crop rotations
  - Ensure all soils are vegetated over winter (in crop or fallow)
  - Increased use of direct drilling
  - Reduced cultivation especially rotary hoe use
  - Increased inter-row and catch crop use.
- Vineyard under-vine areas show soil degradation from reduced carbon levels. The following steps are recommended:
  - 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.

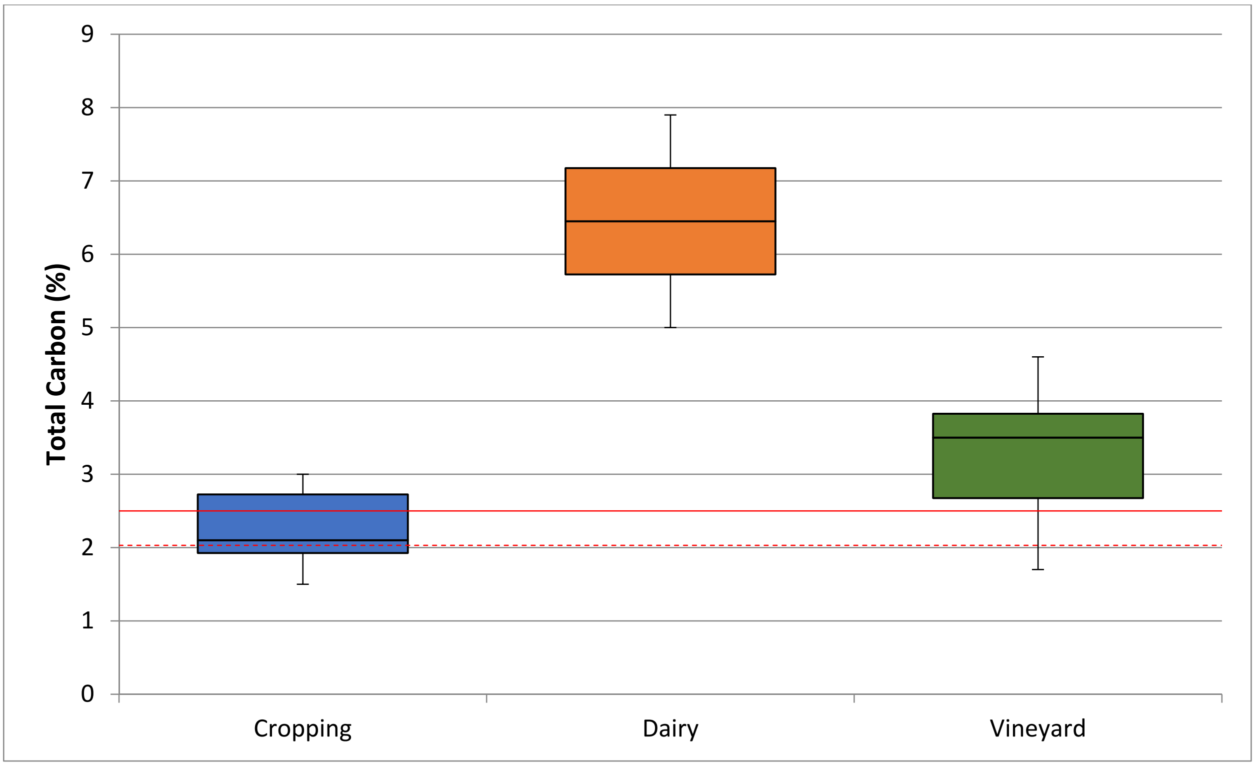

Figure 10: Total carbon values for 2020. Minimum values 2% for Pallic soils (dashed line), 2.5% all other soil orders.

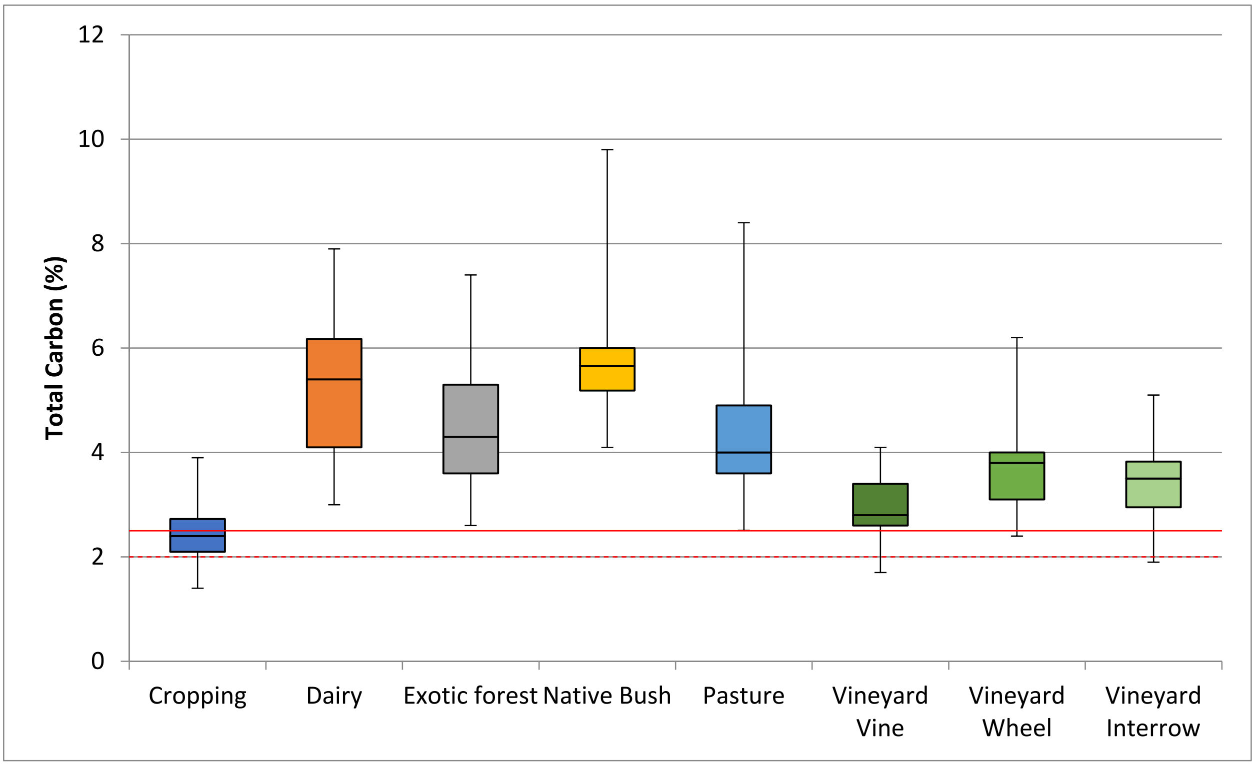

Figure 11: Total carbon by land use for all samples since 2000. Minimum values 2% for Pallic soils (dashed line), 2.5% all other soil orders.

3.3.3. Hot Water Carbon

Recent work by Taylor, et al., (2017), Curtin, et al., (2017) and (Lawrence-Smith, McNally, Beare, & Lehto, 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 Carbon analysis. Further work is currently underway regarding this indicator but a provisional target level has been set for all land uses and soil orders. This provisional level is set at >1900 mg of carbon per kg of soil (Taylor, et al., 2017).

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 HWC readings and this infers reduced microbial activity, reduced soil structure and consequently reduced ecosystem services such as water storage, water filtration and nutrient supply (Ghani, Mackay, Clothier, Curtin, & Sparling, 2009).

HWC is thought to consist of two pools of soil carbon, a very active pool and a slowly active pool. These are thought to represent both the dissolved organic fraction and some of the recalcitrant compounds that increase soil stability. These 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 (Taylor, et al., 2017). The soil carbon fractions measured by HWC are important in the global soil carbon cycle as they represent the carbon most easily lost to the atmosphere as $C0_2$ (Grunwald, Thompson, & Boettinger, 2011) and to water as dissolved carbon following cultivation and the use of N fertilisers (Boyd, 2015)

It is startling to see all but 2 out of 21 samples fall below the 1900mg/kg provisional limit in the 2020 samples (Figure 12 and Table 4). As the 1900 mg/kg limit is provisional, a lower limit of 1700 mg/kg is also included. However only 2 samples fell between the 1900 and the 1700mg limits and these are indicated by red arrows in Table 4.

As per the 2019 report, the most worrying aspect of this new data is the large gap between the median values and the target line. This would indicate that, in general, all land uses with the exception of dairy have reduced microbial activity with potential implications for soil structure, nutrient cycling and water retention. No samples have yet been taken from native bush sites in Marlborough but it is expected that these will have HWC values well above the provisional limit. This is supported by Taylor, et al., (2017) who found that the average HWC value in native areas (North Island study area) was 4670 mg/kg.

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 hot water carbon can now be performed by commercial soil laboratories and should be included when soil tests are performed on all land uses.
- To raise hot water carbon values to the soil quality targets, cropping farmers and vineyard managers should follow the steps outlined for total carbon in section 3.3.2.

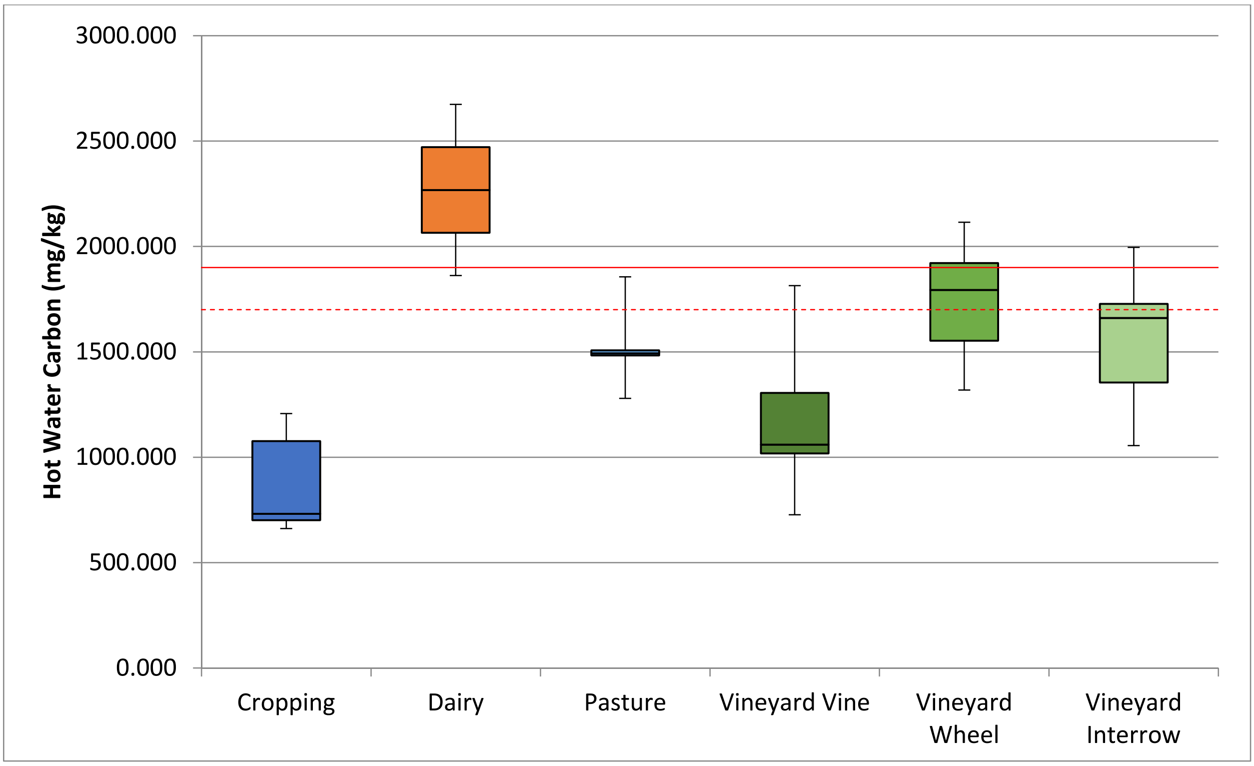

Figure 12: Hot Water Carbon values for 2020. Note provisional target value of 1900 mg/kg (solid red line), lower provisional target 1700 mg/kg (dotted red line). Values for exotic forestry and native bush have insufficient values to be reliably plotted at present.

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.

In 2020, all sites returned values above the target values for total nitrogen. Note that no target values are set for total nitrogen for cropping or horticulture (including vineyards). However, it is interesting to note the differences between the different vineyard samples. While all samples in 2020 would meet the pasture standard of 0.25% total N, the under-vine samples are notably lower and this has been a consistent finding of this work over time. This is likely due to the low inputs of organic matter from the herbicide strip under the vines (Figure 13).

As 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. This can be seen in Figure 14 in cropping, exotic forest and under-vine strips.

Soil Quality Recommendations

- Similar to total carbon, total nitrogen values show reduced organic matter levels in many soils. Cropping and under-vine areas are of particular concern.
- Testing for testing 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.

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.

Amongst the 2020 samples, only one out of 21 samples had C:N ratios below 10:1 (Table 4) though most are close to 10:1. 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 (Havlin et al, 2013). Nitrogen cycling then becomes more dependent on microbial activity. Low C:N ratios (<10) may be of concern with regard to leaching of nitrate, as low ratios suggest the storage of N in organic matter may be reaching saturation. It has been estimated that within 40 years, most soils under intensive livestock farming would be near nitrogen saturation (Schipper, Percival, & Sparling, 2004). 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, native ecosystems 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. 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. Exotic forest soils typically have C:N ratios >15 but are variable depending on whether they have been planted directly into cleared bush, a prepared site, second or third rotation, scrub, or former pasture. Implementation of the soil quality recommendations for total carbon, will ensure C:N ratio meets the target range.

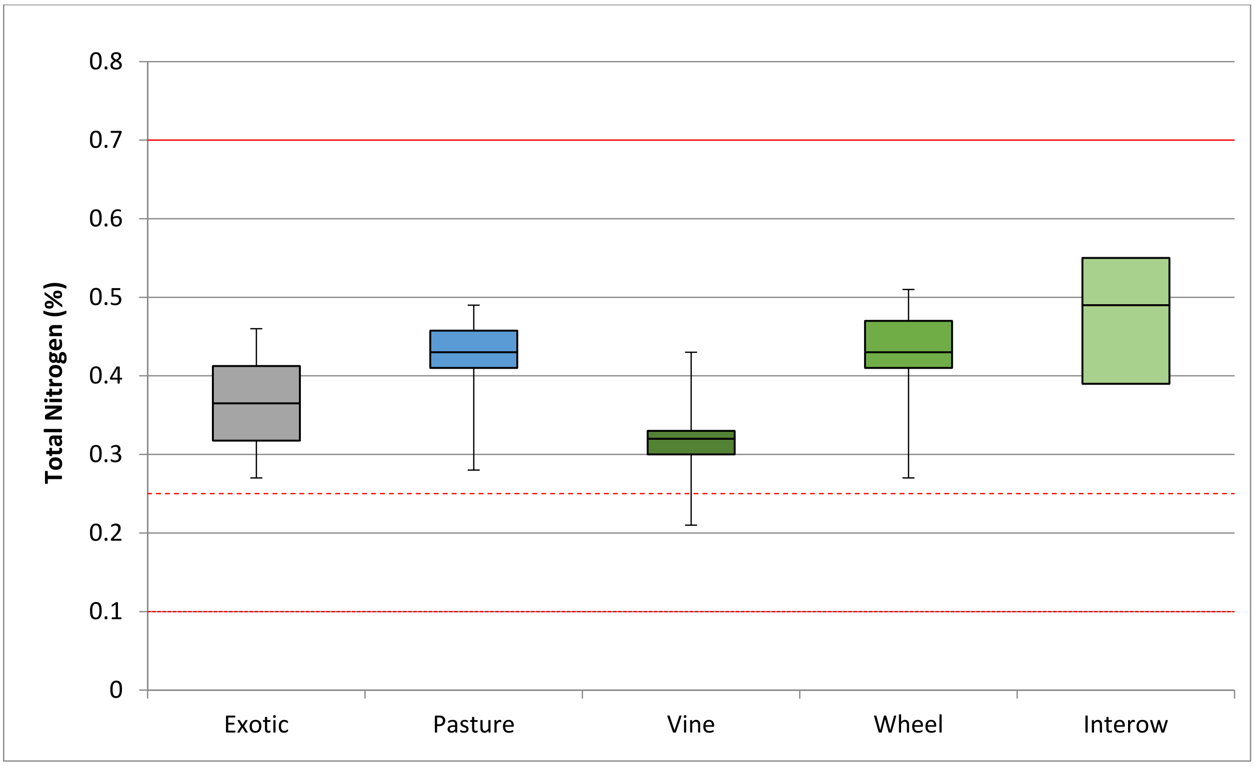

Figure 13: Total Nitrogen values for 2020. Target ranges are 0.7% max for all land uses (solid line), 0.1% min for forestry (dotted line) and 0.25% min (dashed line) for all other land uses.

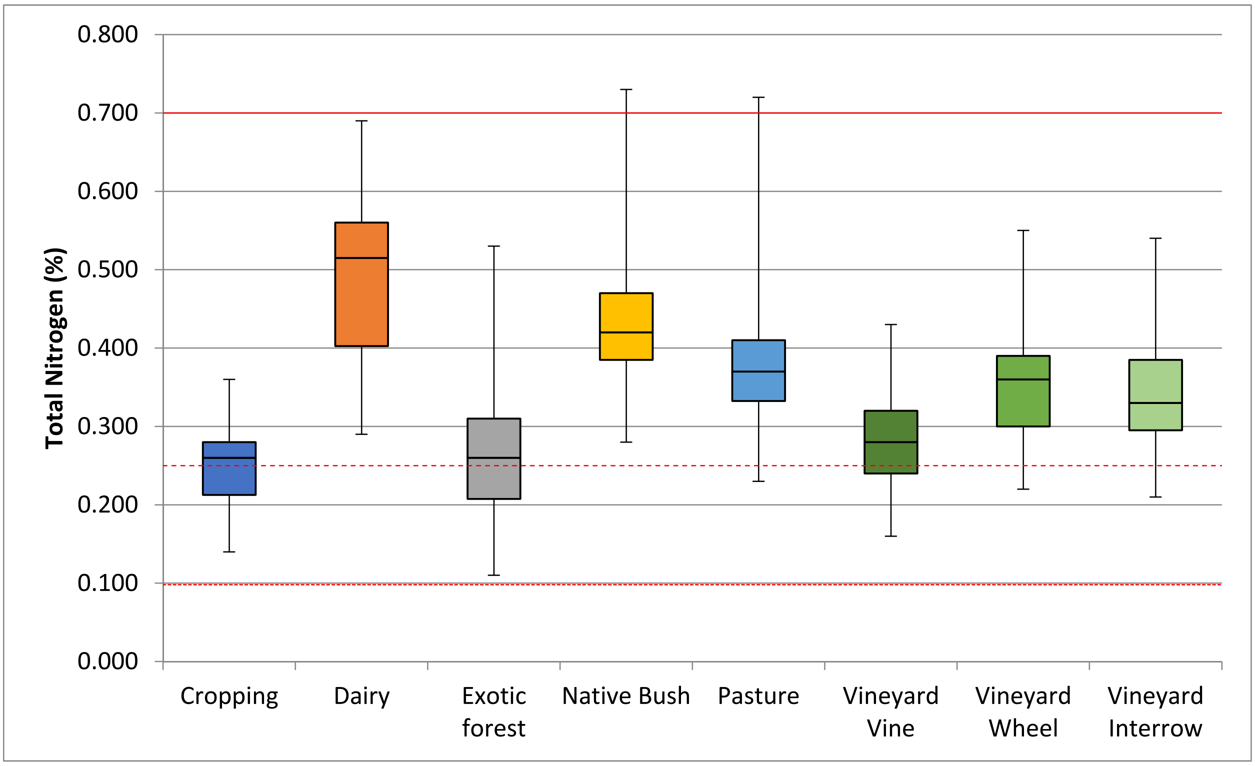

Figure 14: Total Nitrogen by land use for all samples since 2000. Target ranges are 0.7% max for all land uses (solid line), 0.1% min for forestry (dotted line) and 0.25% min (dashed line) for all other land uses.

Table 4: Soil Biological results

Site	Soil type	Soil Order	Landuse	AMN µg/g	Total Carbon %	Total Nitrogen %	Hot Water Carbon mg/kg	C:N Ratio
SOE_Soils_Site 61	Seaview	Pallic	Cropping	65	2.2	0.22	697	10
SOE_Soils_Site 62	Galtymore	Recent	Cropping	47	1.5	0.15	662	10.1
SOE_Soils_Site 63	Marama	Pallic	Cropping	56	2	0.18	749	10.8
SOE_Soils_Site 64	Broadbridge	Pallic	Cropping	57	1.9	0.2	714	9.6
SOE_Soils_Site 71	Renwick	Brown	Cropping	138	2.9	0.3	1,186	10.5
SOE_Soils_Site 72	Brancott	Pallic	Cropping	123	3	0.28	1,207	10.5
SOE_Soils_Site 65a_vine	Seaview	Pallic	Vineyard	63	2.9	0.27	1,181	10.5
SOE_Soils_Site 65b_wheel	Seaview	Pallic	Vineyard	86	3.5	0.33	1,424	10.8
SOE_Soils_Site 65c_interow	Seaview	Pallic	Vineyard	94	3.5	0.31	1,553	11.1
SOE_Soils_Site 66a_vine	Kaituna	Brown	Vineyard	116	2.6	0.24	1,018	11
SOE_Soils_Site 66b_wheel	Kaituna	Brown	Vineyard	193	4.6	0.4	1,722	11.6
SOE_Soils_Site 66c_interow	Kaituna	Brown	Vineyard	180	4.2	0.38	2,115	11
SOE_Soils_Site 69a_vine	Woodbourne	Pallic	Vineyard	93	2.7	0.26	1,060	10.2
SOE_Soils_Site 69b_wheel	Woodbourne	Pallic	Vineyard	121	3.7	0.34	1,641	10.8
SOE_Soils_Site 69c_interow	Woodbourne	Pallic	Vineyard	132	4.6	0.4	1,794	11.4
SOE_Soils_Site 70a_vine	Wairau	Recent	Vineyard	54	1.7	0.16	727	11.1
SOE_Soils_Site 70b_wheel	Wairau	Recent	Vineyard	66	2.4	0.21	1,055	11.1
SOE_Soils_Site 70c_interow	Wairau	Recent	Vineyard	85	3.5	0.3	1,360	11.5
SOE_Soils_Site 73	Kaituna	Brown	Pasture	110	3.9	0.32	1,494	12.1
SOE_Soils_Site 74	Rai	Brown	Dairy	213	7.9	0.65	2,674	12.2
SOE_Soils_Site 75	Ronga	Recent	Dairy	167	5	0.43	1,862	11.7

AMN: Green tick= within range, red cross exceeds target range or red arrow under target range.

Total C: Green tick= above minimum, red cross below minimum.

Total N: Green tick= above minimum, No target values for horticulture or cropping.

Hot Water Carbon. Green tick= above 1900mg/kg, red arrow between 1700 and 1900 mg/kg, red cross below 1700 mg/kg.

C:N ratio: Red cross= below 10.

3.4. Soil Physical Results

Results of soil physical analysis (bulk density, Air-filled porosity and aggregate stability) are reported in Table 5. Each of these physical properties is discussed individually. The target values appropriate to the relevant soil order can be found in Appendix A.

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. 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, have poor aeration and are slow draining. The consequences of compacted soil may include reduced supply of air to plant roots, increased resistance to 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 (Mclaren & Cameron, 1996).

The two sites of the 21samples from 2020 that had bulk density values above the target ranges for their relevant soil orders (Table 5, Figure 15).

Figure 16 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. Dairy farms provide an interesting counterpoint however. 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. Often this is insufficient to cause a lift in bulk density. The removal of these large pores contrasts with the regular vehicle trafficking seen in vineyards which remove all pore sizes leading to the increase in bulk density.

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 most likely practices 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.

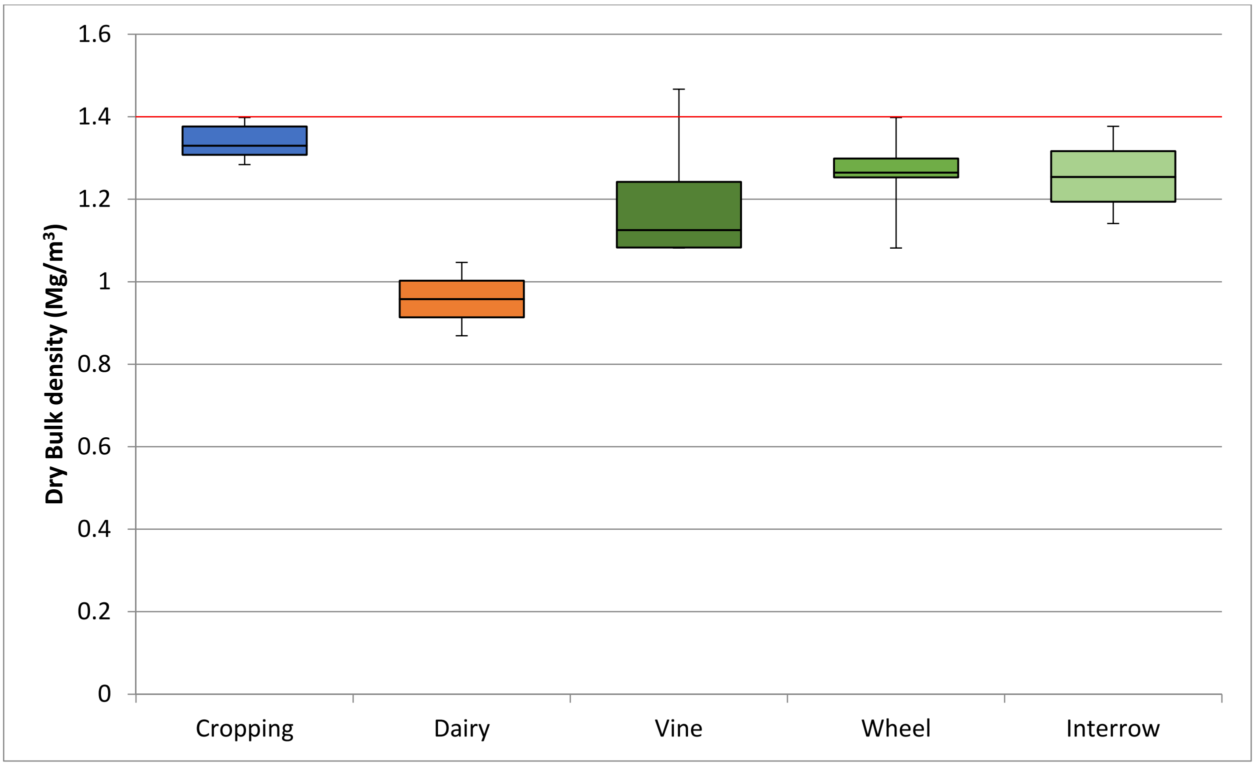

Figure 15: Dry bulk density by land use for 2020 samples. Target value for all land uses is 1.4 Mg/m^3 (solid red line).

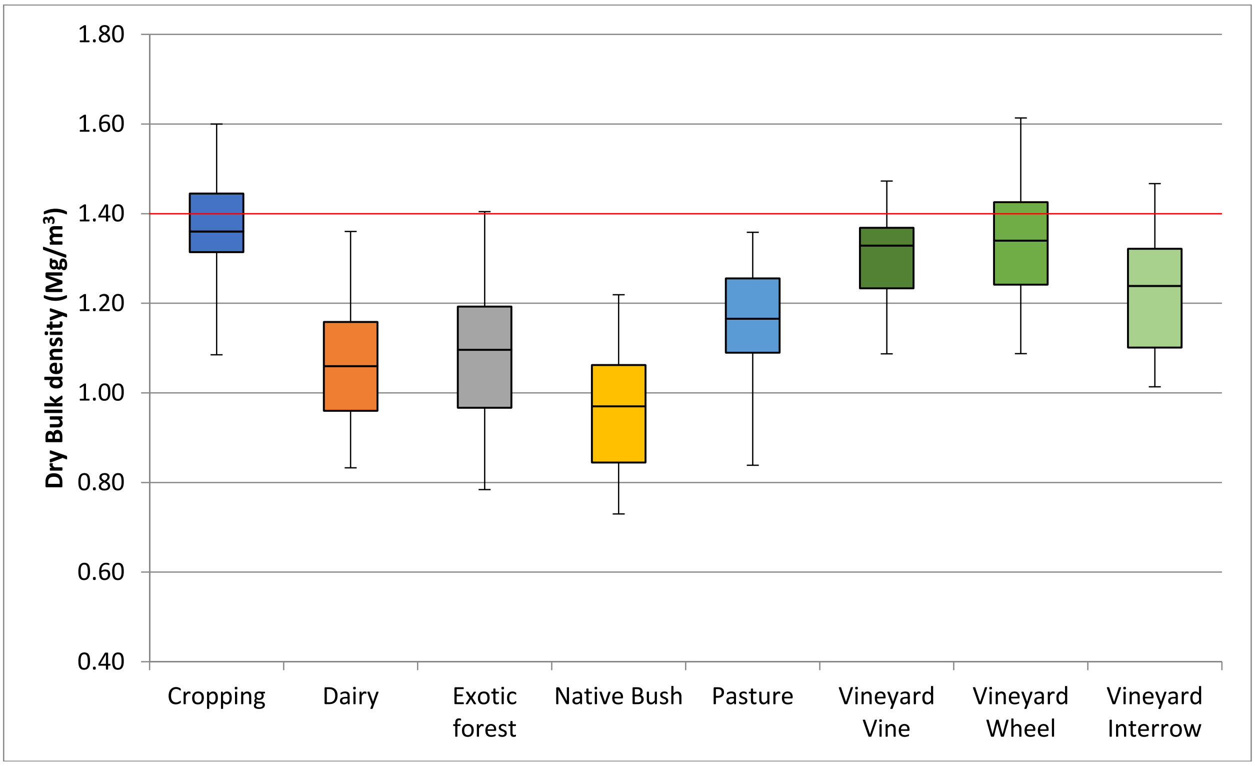

Figure 16: Soil dry bulk density values for all samples since 2000. Target value for all land uses is 1.4 (solid red line).

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).

Air filled porosity readings in past Soil Quality reports have identified compacted soils under all forms of farmed land in Marlborough and this is again the case in 2020. The 2020 samples show clear examples of soil compaction (Figure 17). All land uses show AFP readings under the target limit (Figure 18).

Low air-filled porosity has been noted previously in Marlborough (Gray, 2011a) and has been observed in other regions of New Zealand (Taylor et al., 2010; Fraser and Stevenson, 2011; Stevenson, 2010; Sorensen, 2012). The Ministry of the Environment recently summarised nationwide regional council soil quality data and found 65% of dairy sites were below the target range (MfE, 2021). On dairy 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.

A uniquely Marlborough problem is soil compaction under vineyard wheel tracks. This trend was discussed in the 2016 Soil Quality Report (MDC, 2017). This year however, three of the four of the vineyard wheel AFP samples have returned results that meet the target ranges. In these three cases, good vineyard management practice in the form of well vegetated wheel tracks were observed during sample collection. Compaction is also evident in other vineyard areas but seems to be dependent on the length of time a vineyard has been in production and the management regime. Older vineyards tend to have reduced AFP in vine, wheel and inter-row samples whereas younger vineyards often only show compaction under wheel tracks. Compaction is possibly increased where vineyard soils are stony due to the practice of using heavy rollers to bury stones.

Figure 18 shows air filled porosity data for all samples collected since 2000. While there is wide variance across the data, it is clear that four land uses have issues with compaction (cropping, dairy, and pasture and vineyard wheel tracks). Interestingly, exotic forest regularly reports very high AFP readings. This may be a function 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 regressed paddocks to establish fully before grazing. Grazing newly re-grassed paddocks when wet should be avoided at all times.
  - 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.
  - Where possible, restrict driving heavy or heavily laden vehicles on paddocks especially when wet.

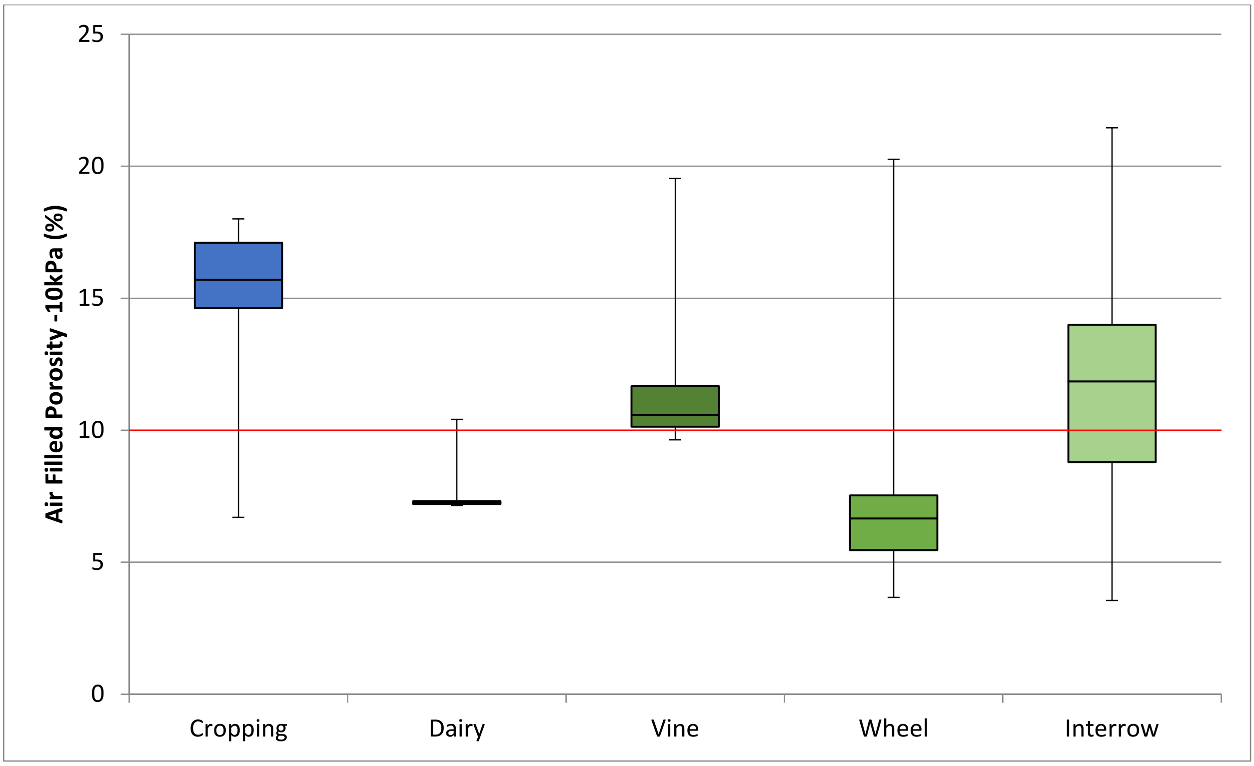

Figure 17: Air filled porosity by land use for 2020 values. Minimum level for displayed land uses 10% (solid red line).

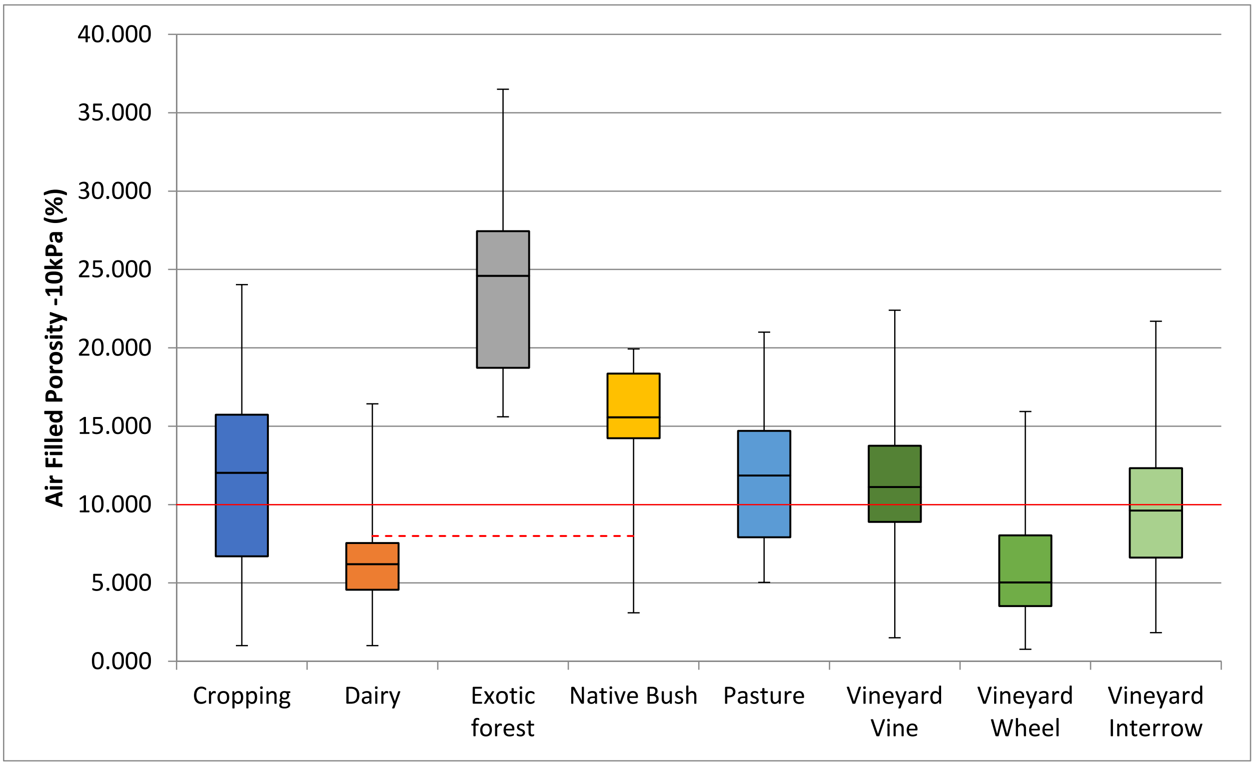

Figure 18: Air filled porosity by land use for all samples since 2000. Minimum level for exotic forest is 8% (dashed red line), other land uses 10% (solid red line).

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 target 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, Tabley, & White, 1991). 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 2020, six cropping sites were sampled. Of these three were in the crop production phase and were sampled for aggregate stability.

All three sampled sites were found to be well below 1.5 MWD (Table 5). All three sites were sampled following extensive cultivation and the results are not surprising as a result.

Soil Quality Recommendations:

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

Table 5: Soil Physical Results.

Site	Soil Type	Soil Order	Landuse	Dry Bulk Density (Mg/m3)	Macro Porosity (-5kPa) (%, v/v)	Air Filled Porosity (-10kPa) (%, v/v)	Aggregate Stability (MWD)
SOE_Soils_Site 61	Seaview	Pallic	Cropping	1.28	11.90	15.90	0.41
SOE_Soils_Site 62	Galtymore	Recent	Cropping	1.31	13.30	17.50	0.53
SOE_Soils_Site 63	Marama	Pallic	Cropping	1.56	4.57	6.70	
SOE_Soils_Site 64	Broadbridge	Pallic	Cropping	1.35	11.93	14.33	0.37
SOE_Soils_Site 71	Renwick	Brown	Cropping	1.31	8.50	10.30	
SOE_Soils_Site 72	Brancott	Pallic	Cropping	1.39	4.67	6.05	
SOE_Soils_Site 65a	Seaview	Pallic	Vineyard	1.47	1.65	3.55	
SOE_Soils_Site 65b	Seaview	Pallic	Vineyard	1.26	8.30	9.63	
SOE_Soils_Site 65c	Seaview	Pallic	Vineyard	1.14	5.60	7.27	
SOE_Soils_Site 66a	Kaituna	Brown	Vineyard	1.08	9.27	10.53	
SOE_Soils_Site 66b	Kaituna	Brown	Vineyard	1.27	9.37	10.87	
SOE_Soils_Site 66c	Kaituna	Brown	Vineyard	1.30	2.33	3.67	
SOE_Soils_Site 69a	Woodbourne	Pallic	Vineyard	1.08	11.17	13.17	
SOE_Soils_Site 69b	Woodbourne	Pallic	Vineyard	1.40	12.17	14.07	
SOE_Soils_Site 69c	Woodbourne	Pallic	Vineyard	1.38	6.80	8.33	
SOE_Soils_Site 70a	Wairau	Recent	Vineyard	1.17	13.17	16.50	
SOE_Soils_Site 70b	Wairau	Recent	Vineyard	1.22	13.67	15.50	
SOE_Soils_Site 70c	Wairau	Recent	Vineyard	1.21	15.87	18.33	
SOE_Soils_Site 73	Kaituna	Brown	Pasture	1.15	5.70	8.70	
SOE_Soils_Site 74	Rai	Brown	Dairy	0.87	4.70	7.15	
SOE_Soils_Site 75	Ronga	Recent	Dairy	1.05	5.03	7.37	

Bulk Density: Green tick- within range, red cross-exceeds range.
Air filled porosity: Green tick above target limit, red cross below target limit. 10% target limit for most land uses except for 8% in forestry.
Aggregate stability red cross = below target range of <1.5 MWD

4. Changes in Soil Quality through time

4.1. 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 target 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 96 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 some analysis of trends in soil quality.

The methodology for this process is to use five year rolling averages for each soil indicator on each land use (M. Taylor, Pers. Comm., 2017). All the data from the previous five years is included in any given year's average (i.e. 2020 data is averaged with all data since 2016). This data is then presented by land use or soil order. The aim of this 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. Readers of the 2016 soil quality report will have noted the excessive influence of outlier values with some graphs unduly biased as a result. In this section of the report, values for land uses with insufficient sample numbers (exotic and native forest) have been presented as a single point on the graph. This point is derived using all sample values since 2000 and is to provide a baseline value to compare with other land uses.

Since the recommendation in the 2016 report to review the number of sites and the frequency of monitoring in all land uses, the following changes have been made; no further sites have been established due to cost constraints and some sites have been deferred or brought forward to provide better temporal coverage for particular land uses. Ideally, the number of each type of site should be proportional to the regional land use percentage. Sampling frequency should reflect the nominal five yearly sampling cycles, that is, one-fifth of sites should be sampled per land use per year.

In 2018 the full data set was sent to a statistician for analysis and redesign to ensure the results are robust and different land uses and soil orders are adequately represented. The results of this analysis suggested that while the conclusions drawn from the data are statistically valid, the variation around the data is not well understood. To address this issue, spline statistics were used to derive the variation from the entire data set rather than from the five - year rolling averages. This method was due to be employed in this report to describe the data variation but significant delays in receiving the soil physical data from the laboratory has prevented the use of spline statistics this year.

In addition to this, the statistician recommended that the spread of sites be re-evaluated to ensure that Marlborough's soils and land uses are fully represented in light of the extensive land use change that has occurred since 2000. This analysis will be similar to the process carried out at the commencement of the sampling in 2000 and will address the Primary Component Analysis underpinning the programme. This work is now expected to be carried out prior to the 2021 sampling round. Avid readers can expect extensive changes to the statistical reporting in the 2021 report.

The three key long-term issues identified in previous reports are still relevant. These include the risk of nutrients being lost to waterways (especially Nitrogen and Phosphorous), the decline in soil organic matter under some land uses and the potential risks of trace element contamination for some land uses.

4.2. 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 in order to maintain productivity. This becomes a significant expense to farmers. Often nutrients are manufactured and imported so require large amounts of energy to create and ship. 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 groundwater 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 the 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 are monitored to evaluate the risk leaching may pose to water. The second pathway of loss is via surface runoff. Phosphorous is most susceptible to this pathway as it is carried on soil particles. Assessment of soil compaction is also important to ascertain the ability of water to infiltrate or runoff any given soil surface. Bare or very loose soils are vulnerable to leaching and erosion (runoff). Compacted soils prevent water (and fertiliser) infiltration and promote runoff (Mclaren & Cameron, 1996).

4.2.1. Phosphorus risk

In general, soils in Marlborough have moderate P levels. Monitoring has shown that most sites have Olsen P levels well within the target ranges. Of note, are the elevated levels of Olsen P found in the more intensive farming systems of dairy, cropping and viticulture (Figure 5). These soils will pose more risk of runoff than the less intensive farming systems shown simply because of the elevated P concentration.

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 residual grass cover left following grazing. The practice of winter forage cropping has been highlighted recently and while this practice is not widespread in Marlborough, it does occur. The very heavy grazing pressure caused by this practice can raise compaction, soil erosion and runoff risks substantially. Each of these factors contributes to runoff risk of P by increasing soil compaction and by reducing the vegetation's ability to hold soil together under erosive conditions (Burgess, Chapman, Singleton, & Thom, 2000).

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.

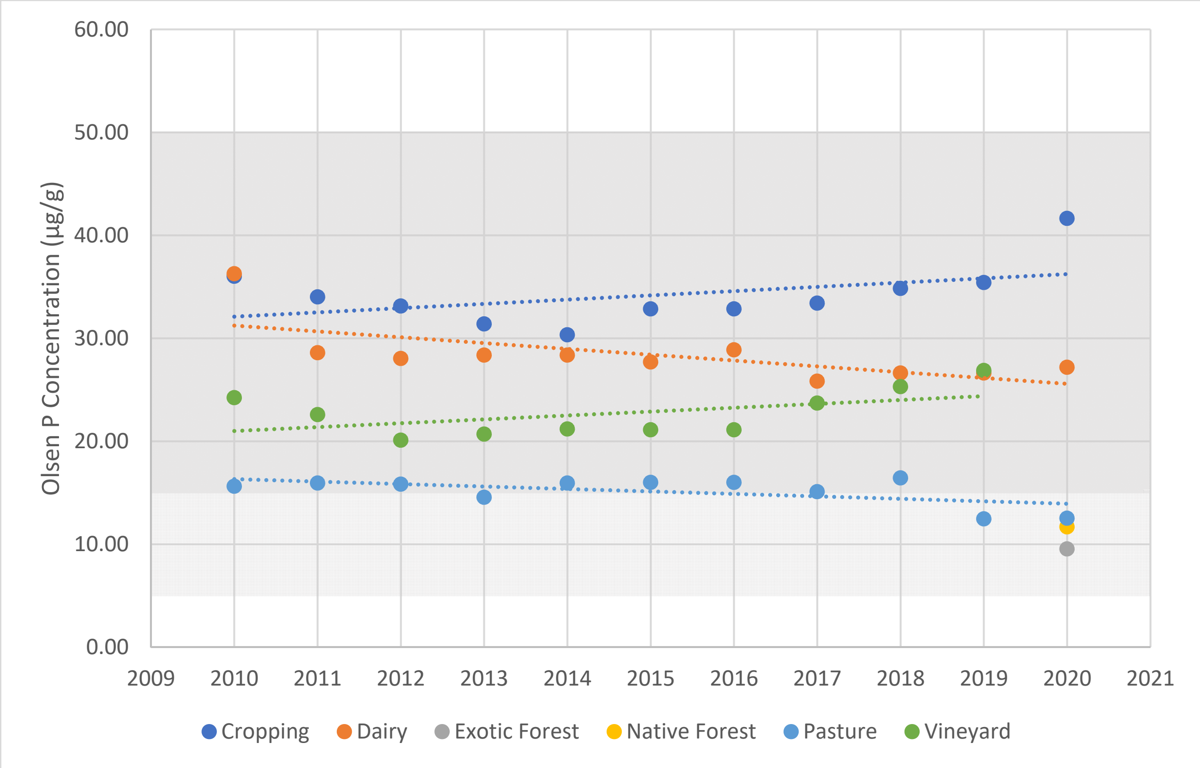

Figure 19: Regional Olsen P averages by Land use. Target ranges forestry – 5 to 50 µg/g, Pasture - 15 to 50 µg/g, cropping and vineyard 20 to 50 µg/g.

There has been extensive national and international research to show that as soil P concentrations increase, the risk to waterways can also increase (McDowell, Drewry, Carey, Paton, & Condron, 2003). 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 management plans will help minimise excessive nutrient accumulation in soils and potential losses from soils and this is advocated to land managers. A recent innovation could be the introduction of Dung Beetles to pastoral farming systems. These insects can bury dung below the soil surface this 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 19). A slight downward trend can be seen for dairy farms, but this is within the margin of error for the data. Cropping risk has increased following the sampling of six sites this year. Combined with the soil compaction data discussed earlier, this means phosphate loss risk is moderate but stable.

4.2.2. Nitrogen risk

The risk nitrogen poses to water quality is assessed by two tests. 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.

We see in Figure 20 & Figure 21 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).

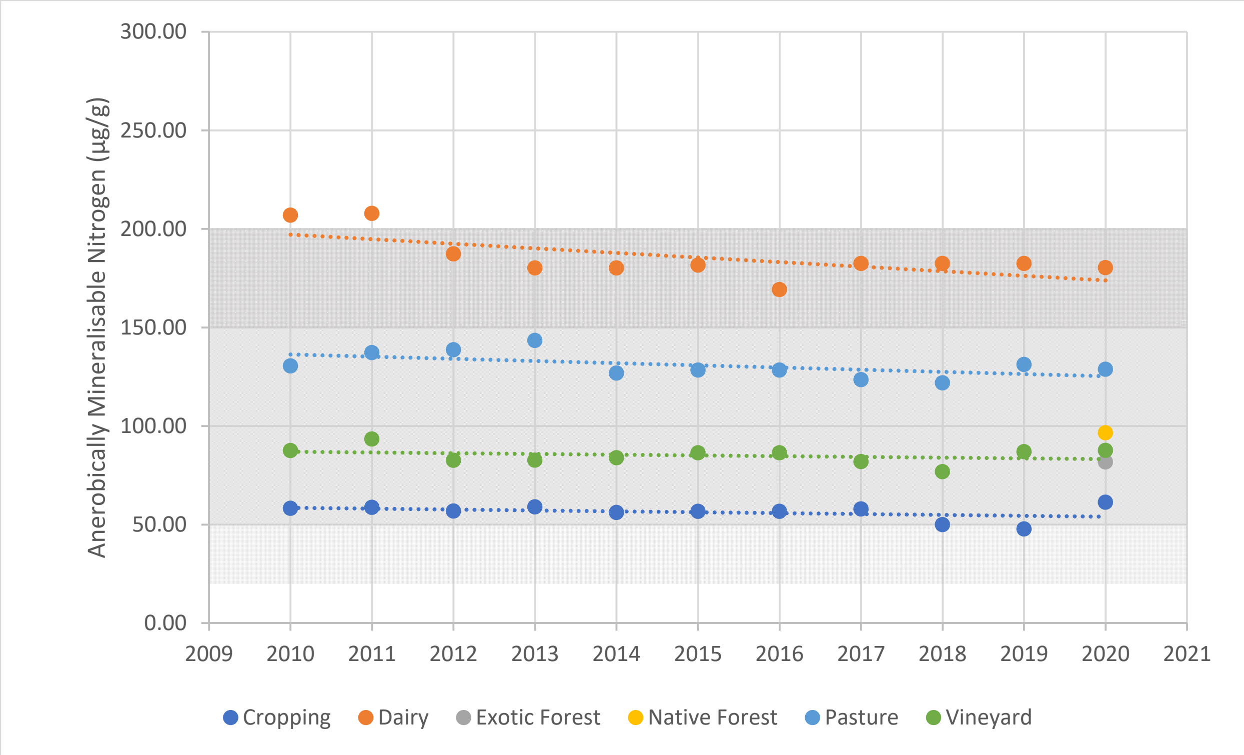

Figure 20: Anaerobically mineralisable nitrogen by land use*. Target range vineyard, forest and cropping 20 to 150, pasture and dairy 50 to 200 µg/g,*

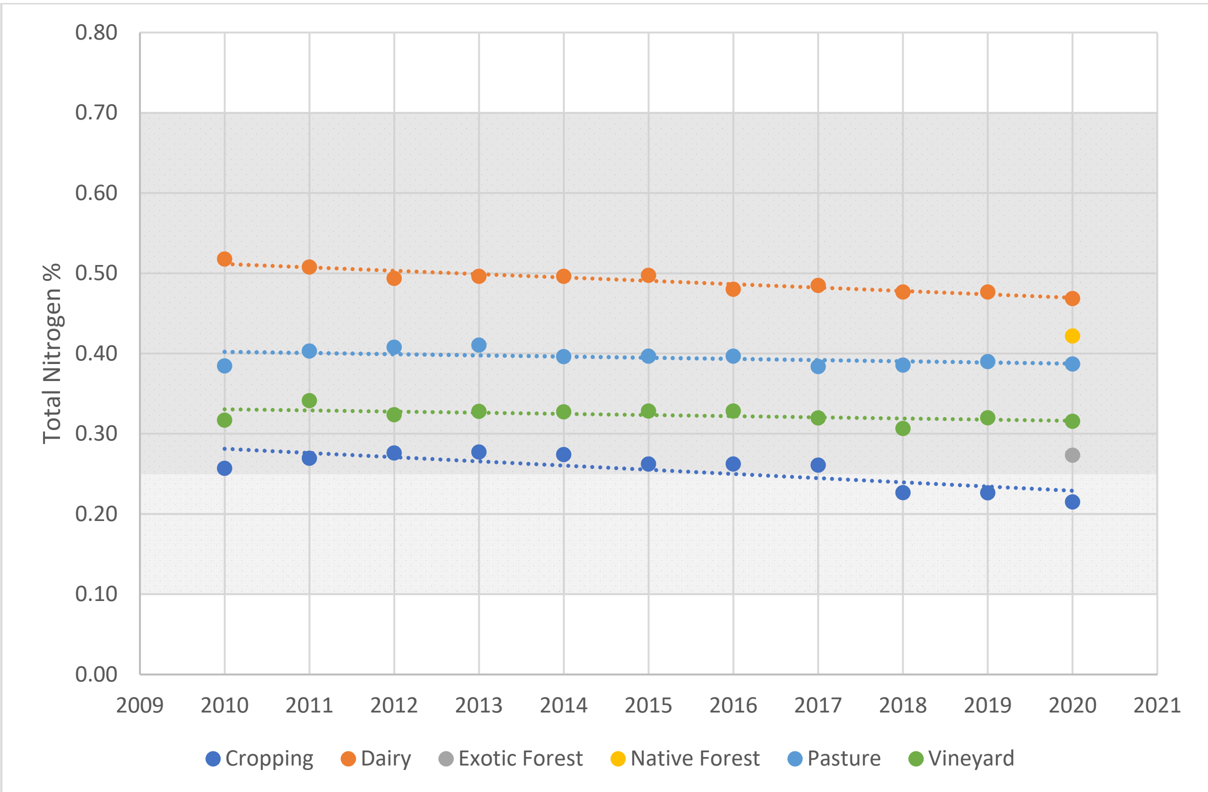

Figure 21: Total nitrogen by land use. *Target value forest 0.1 to 0.7%, Target value pasture 0.25 to 0.7%. No values set for cropping and vineyard.*

This reflects increased fertiliser input, the increased production of easily decomposed organic matter (dung) and mineral N in urine. While both production systems are well within the target ranges on a regional basis, these measures 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*, 2013). Elevated levels in these farm systems indicate that they pose greater risk to water quality than the non-animal systems.

When variables such as slope, seasonal weather conditions, stocking rate, effluent disposal regimes, fertiliser application rates and frequency are included, there are likely to be locations that do exceed the target ranges at various times.

Non-animal farm systems (cropping, viticulture and forestry), show total N and AMN levels toward the bottom of the target bands. As will be seen in section 4.3, this is a result of lower organic matter content in these soils. It should be noted that cropping and horticulture have no general target ranges specified for total N. This is due to the large number of possible crops, each with its own target 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. To compensate, farmers will likely require increased nitrogen fertiliser inputs. This may lead to increased risks to water from nitrogen loss depending on management practices such as application rates and timing.

4.3. 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 (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 (Nie, Ward, & Michael, 2001). For both crops and pasture, indirect effects 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 (Nguyen, Shealth, Smith, & Copper, 1998; McDowell et al, 2003).

The long-term trends in soil compaction in Marlborough mirror national trends (MfE, 2021). The Soil Quality Monitoring Programme has shown that farmed systems have higher bulk density and lower air-filled porosity (AFP) compared to non-farmed (forest) systems. Figure 16 & Figure 18 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 (Figure 23 & Figure 25). This repeated trafficking has removed the large soil pores but not small soil pores hence the lower bulk density readings compared to cropping soils (Figure 19 & Figure 24). 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. It is noted that vineyard wheel tracks and cropping seem to be showing improvement in AFP readings over time. This may reflect changes in practice around 2010 in viticulture (to maintain grass coverage of wheel tracks) and later in cropping. However, for cropping, this trend may be a relic of inadequate sample size and the effects of crop rotation within the cropping system.

Both dairy and pasture systems show reasonable bulk density readings but very low and declining AFP (Figure 19 & Figure 24). This will be due to treading damage by livestock compacting the large soil pores but not small pores. Combined with the raised levels of nitrogen and phosphate noted above, Marlborough's soil compaction presents a quite high risk of nutrient loss to water. Even though both N & P are within the target 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.

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; installing drainage in some areas; use of feeding platforms and/or standoff areas; decreasing winter stock numbers and moving stock onto well drained soil types off-site (Burgess et al, 2000). 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, Mackay, Clothier, Curtin, & Sparling, 2009). 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 to minimise trafficking (multifunction machinery, over-row machinery).

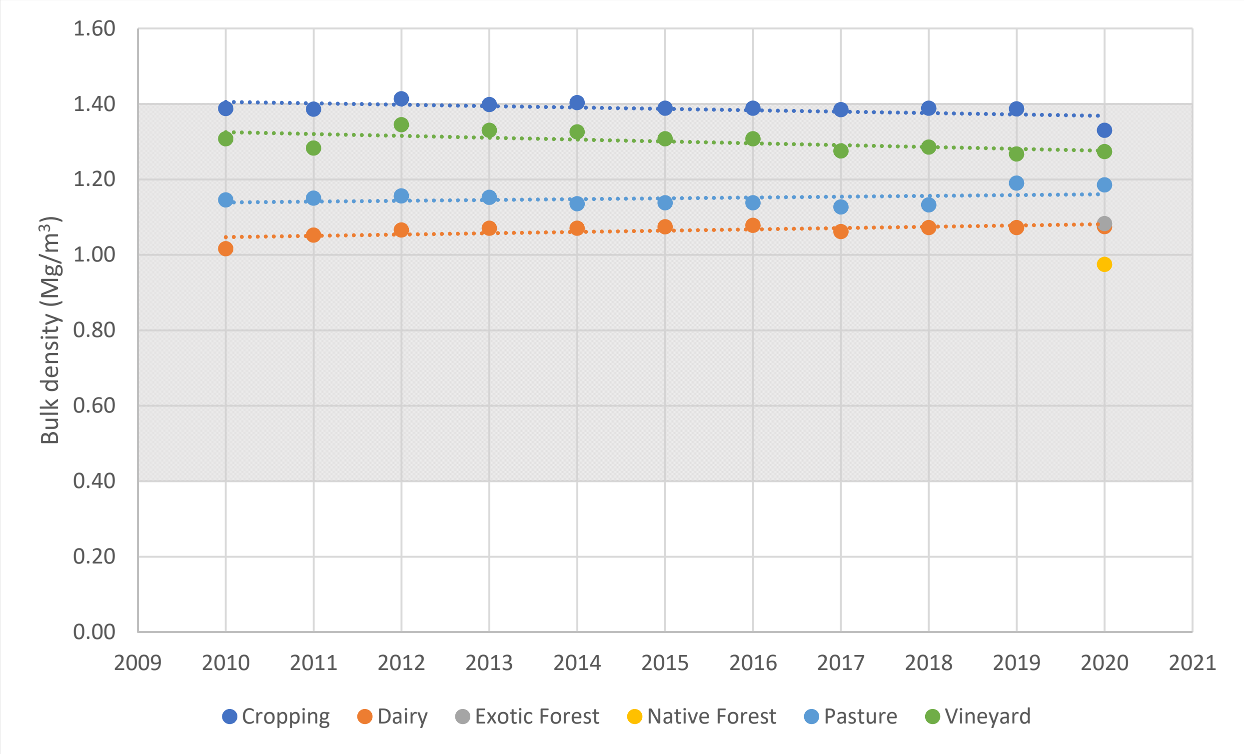

Figure 22: Change in bulk density for all land uses Target value for all land uses is 1.4 Mg/m^3

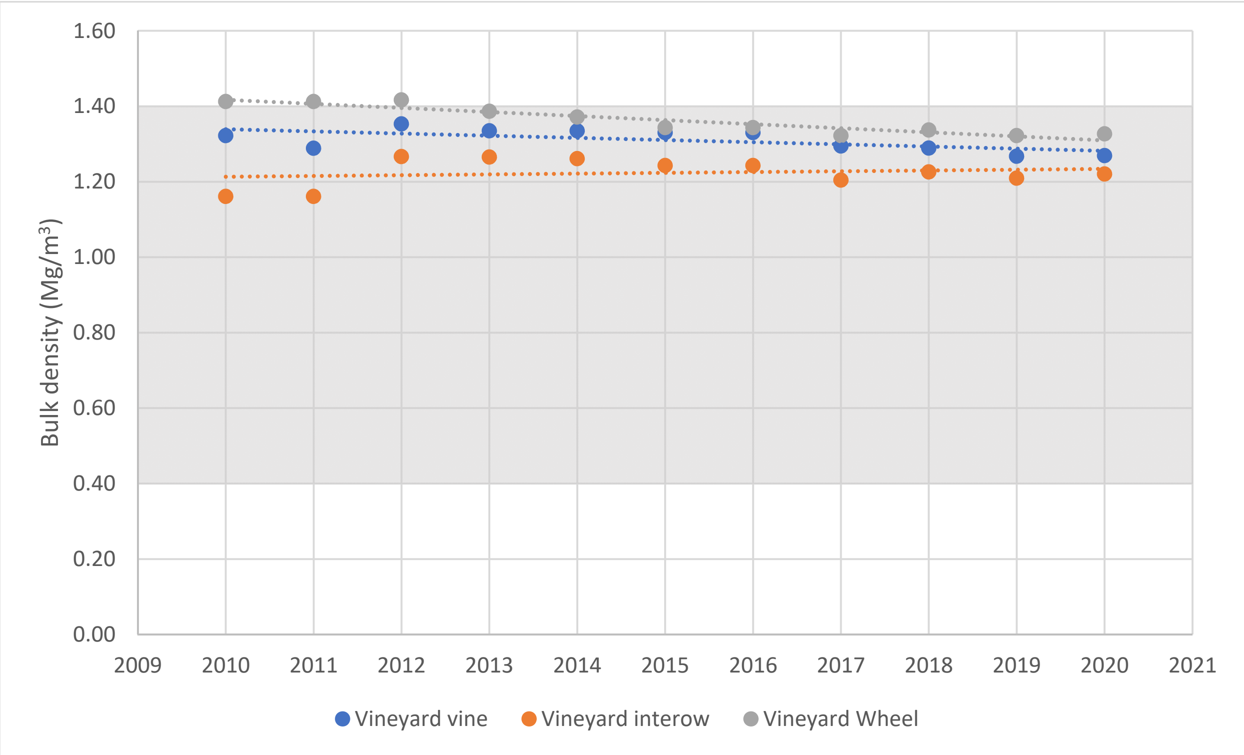

Figure 23: Change in bulk density for vineyards. Target value for all land uses is 1.4 Mg/m^3

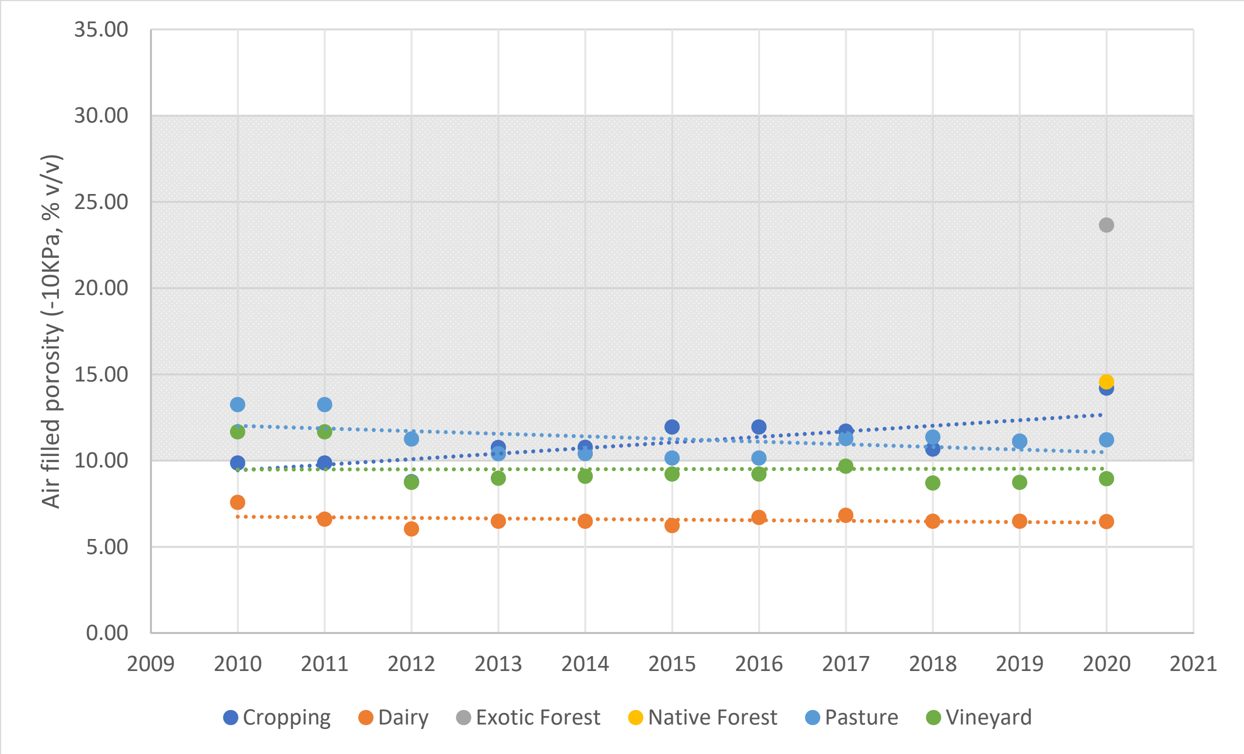

Figure 24: Change in AFP for all land uses. Minimum level for exotic forest is 8%, other land uses 10%.

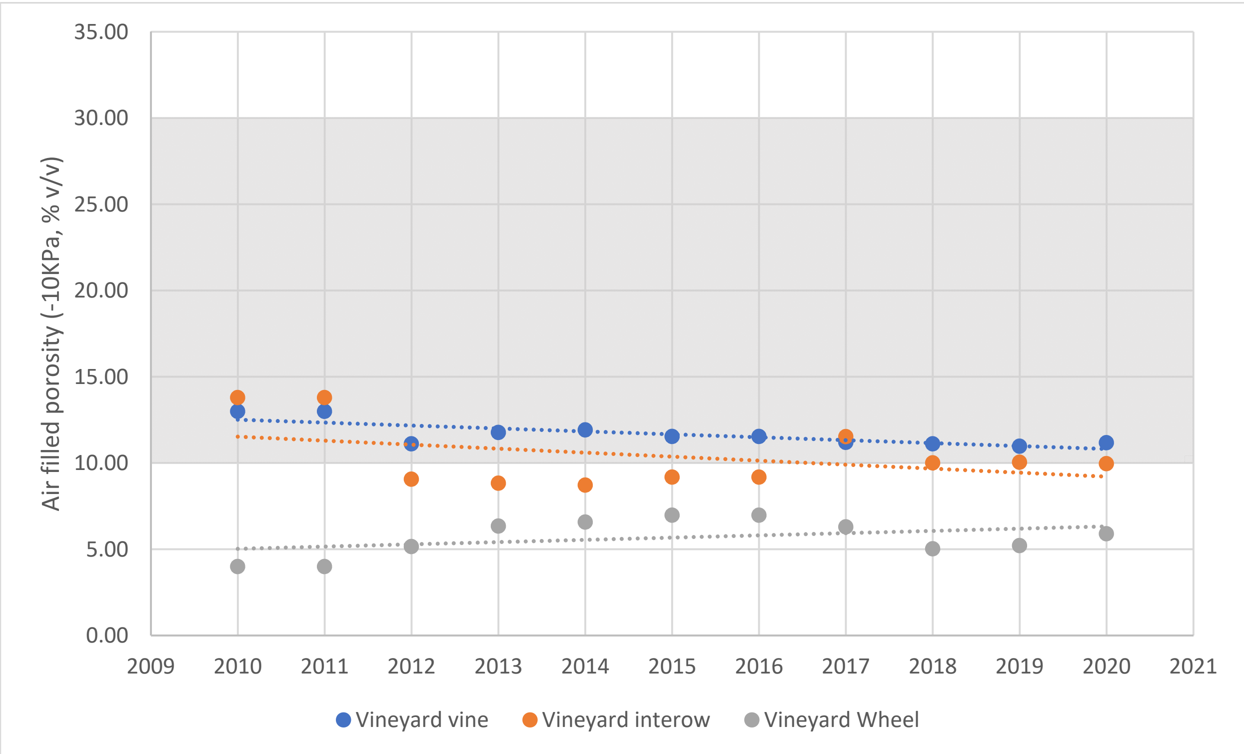

Figure 25: Change in AFP for vineyards. Minimum level for vineyards 10%.

4.4. Loss of Soil Organic Matter

Soil organic matter plays a significant role in the structural stability of soils as well as provision of nitrogen and carbon for use by soil microbes and plants. 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 soils ability to retain nutrients from leaching and hold soil particles against runoff or erosion (Ghani, *et al*, 2009). 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 (2012). 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 this indicator has not dropped below the target values for any land use, and is showing little change over time, it is noticeable that farmed land uses have lower organic matter levels than native forest (Figure 26). We could regard the higher native forest level of around 5.6% as the pre-farming benchmark for soil organic matter. 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. This is most likely due to historic land clearance, pastoral farming and erosion prior to exotic forest planting as well as soil disturbance during forest harvesting.

One land use (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. These results are consistent with trends observed during soil quality monitoring studies in both the Waikato and Wellington regions (Taylor , 2015; Sorensen, 2012) where cropping sites had depleted soil carbon contents compared to carbon at native vegetation sites. Most of the cropping sites had soil carbon contents at the lower boundary of their target range. Land managers 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. Such practices include residue management practices that maximise carbon returns to the soil, grow cover crops rather than leaving land bare over winter, more frequent use of a pasture phase in rotations or adopt minimal tillage (Francis et al., 1991). These practices all help to reduce leaching and runoff and as such have a beneficial effect on downstream water quality and soil organic matter levels.

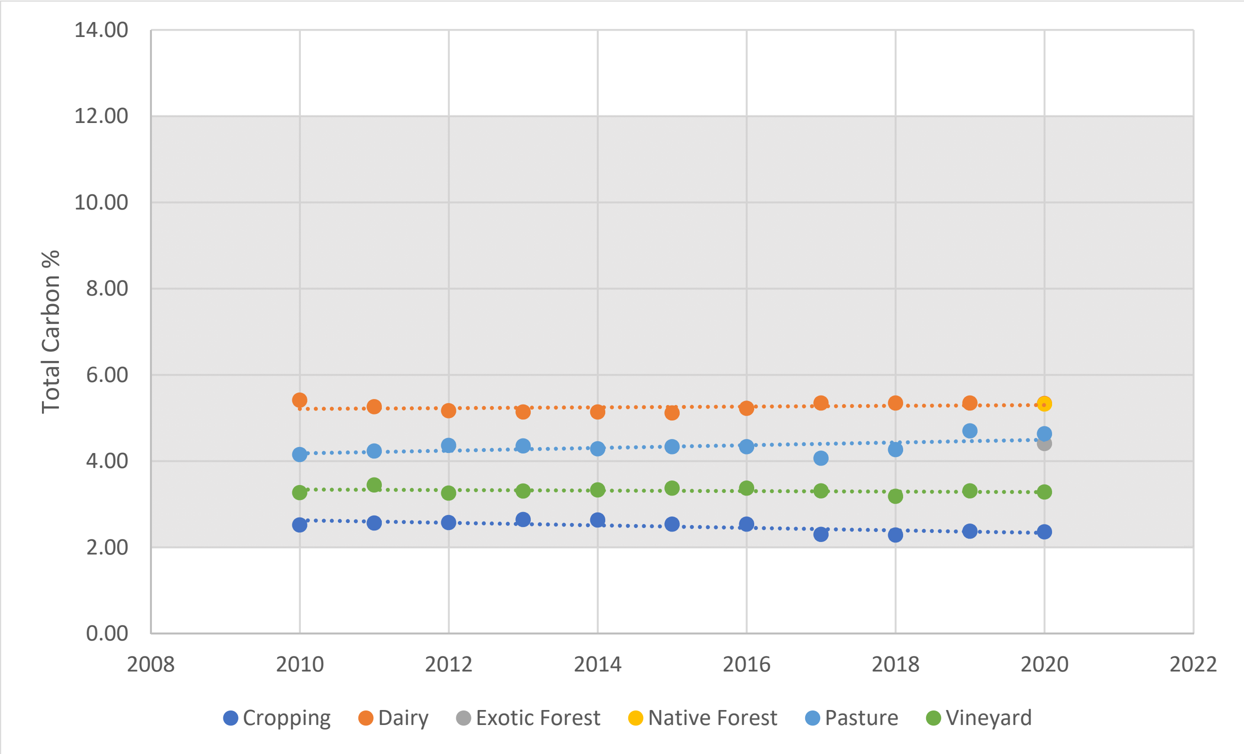

Figure 26: Total carbon by Land use. Target range 2 to 12% depending on soil order

In comparison to cropping sites, the 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.

Council has introduced a hot water carbon test into the Soil Quality Monitoring Programme. This test can help to determine the quality of the carbon in soils as well as the quantity. This will provide more information to help guide land management decisions. As test data accumulates in coming years changes in HWC will be reported on in this section.

4.5. Trace Element Contamination

The Soil Quality Monitoring Programme reports on many different trace elements found in soils (Gray, 2007a, Gray, 2007b). Many of these are toxic elements that are known to cause human and animal health problems (e.g. lead, mercury, cadmium 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.

The only trace element of concern is cadmium. As a contaminant of phosphate fertiliser, cadmium accumulates through time and is of concern for future land use change. A number of land uses (viticulture, cropping, and pasture) show a slow increase in their cadmium content over time (Figure 27). 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 pasture land uses before 2069 (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. 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.

The situation with dairy cadmium levels is more problematic. The regional average levels are already concerning. See section 3.2.3. It should be noted that while the dairy trendline is down at present, there is considerable statistical error in this (see Figure 27). Only minor changes in future sample results could cause the trendline to shift up or down. If dairy cadmium levels were to increase at the same rate as pasture levels are increasing, TFMS tier one would be exceeded around 2030.

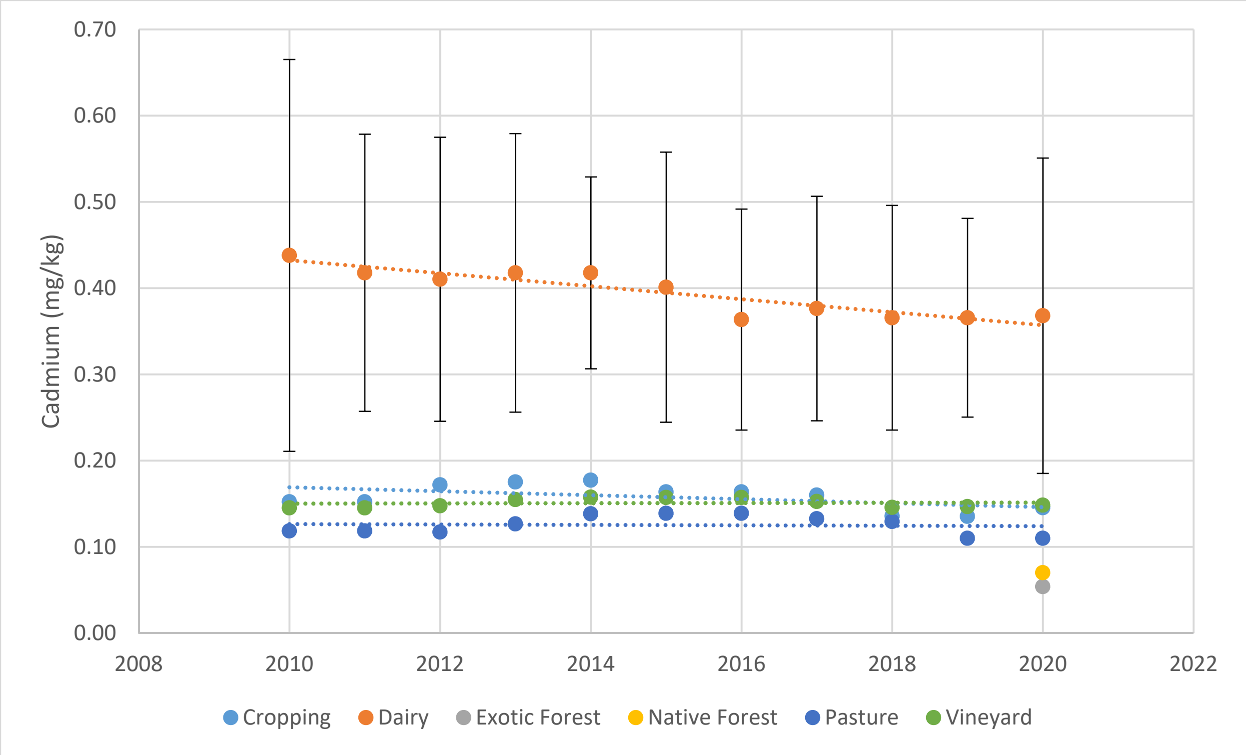

Figure 27: Cadmium levels by land use. Concentration limit is 0.6mg/kg for Tier 1 of TFMS. Error bars for Dairy equal 1 Standard Deviation

5. Discussion and Summary

Results for the 2020 Soil Quality Monitoring round showed trends consistent with all previous results. Soil compaction, soil phosphate levels and loss of organic matter are the persistent concerns with little prospect of improvement evident. Seventy-six percent of sites showed low air-filled porosity indicating a reduction in pore space in the soil. Similar to previous reports, these concerns were noted across all soil types sampled but only on farmed land. Forest sites reported both low bulk density and high air-filled porosity indicating no soil compaction. Soil phosphate levels were found to be outside the target ranges for 24% of samples. While only one site had excessive phosphate levels, four sites had levels below the agronomic optimal levels indicating they may be performing below optimal levels.

A new soil quality indicator was introduced last year. Hot water carbon measurements provide information on the quality of soil carbon in particular, the microbial and dissolvable carbon fraction in the soil. Similar to last year, the majority of samples (90%) failed to meet the provisional target of 1900mg/L indicating all land uses are implicated in 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.

Discussion of long-term trends introduced in 2016 continues in this report. The same issues are still of concern, these being the risk of nutrient loss to water, soil compaction and loss of organic matter. It has now been five years since these overall trends were identified by the Soil Quality Monitoring Programme. In the intervening years, small changes have been made to improve the reliability of the programme and these have reinforced the findings. These results have been combined with soil quality measurements from other Regional Councils and recently presented in the Our Land 2021 Report from the Ministry of the Environment (MfE, 2021). The findings in Marlborough mirror national trends.

The programme is now effectively documenting the decline in quality of Marlborough's soil resource. 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. In particular, cropping farms urgently need to lift soil carbon levels to improve soil structure and reduce erosion risks. Dairy farmers need to be aware of and manage elevated nitrogen 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.

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

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7. Appendix A. Soil Target Values

Soil quality indicator target (or optimal) ranges from Hill and Sparling (2009) are outlined in the tables below along with guideline values for trace element concentrations in soil, adapted from NZWWA (2003). Olsen P values as set by Taylor and Mackay (2012).

Bulk density target ranges (t/m^3 or Mg/m^3)

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

Notes: Applicable to all land uses. Target ranges for cropping and horticulture are poorly defined.

Air filled porosity target ranges (% @ -10 kPa)

	Very low	Low	Adequate	High	
Pastures, cropping and horticulture	0	6	10[1]	30	40
Forestry	0	8	10	30	40

Notes: 1: Revised based on Mackay et al (2006). Applicable to all Soil Orders Target ranges for cropping and horticulture are poorly defined.

Total carbon target ranges (% w/w)

	Very depleted	Depleted	Normal	Ample	
Allophanic	0.5	3	4	9	12
Semi-arid, Pallic and Recent	0	2	3	5	12
Organic	exclusion				
All other Soil Orders	0.5	2.5	3.5	7	12

Notes: Applicable to all Soil Orders. Organic soils by definition must have >15% total C content, hence C content is not a quality indicator for that order and is defined as an "exclusion" Target ranges for cropping and horticulture are poorly defined.

Total nitrogen target ranges (% w/w)

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

Notes: Applicable to all Soil Orders. Target ranges for cropping and horticulture are not specified as target values will depend on the specific crop grown.

Anaerobic mineralisable nitrogen (AMN) target ranges (mg/kg)

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

Notes: Applicable to all Soil Orders. Target ranges for cropping and horticulture are poorly defined.

Soil pH target ranges

	Very acid	Slightly acid	Optimal	Sub-optimal	Very alkaline	
Pastures on all soils except Organic	4	5	5.5	6.3	6.6	8.5
Pastures on Organic soils	4	4.5	5	6	7.0	
Cropping and horticulture on all soils except Organic	4	5	5.5	7.2	7.6	8.5
Cropping and horticulture on Organic soils	4	4.5	5	7	7.6	
Forestry on all soils except Organic		3.5	4	7	7.6	
Forestry on Organic soils	exclusion					

Notes: Applicable to all Soil Orders. Target ranges for cropping and horticulture are general averages and target values will depend on the specific crop grown. Exclusion is given for forestry on organic soils as this combination is unlikely because of wind throw.

Olsen P target ranges (mg/L or µg/cm^3)

	Very low	Low	Adequate	High	
Pasture on Sedimentary and Allophanic soils	0	15	20	50	200
Pasture on Pumice and Organic soils	0	15	35	50	200
Cropping and horticulture on Sedimentary and Allophanic soils	0	20	50	50	200
Cropping and horticulture on Pumice and Organic soils	0	25	60	50	200
Forestry on all Soil Orders	0	5	10	50	200

Notes: Sedimentary soil includes all other Soil Orders except Allophanic (volcanic ash), Pumice, Organic and Recent (AgResearch classification system).

Guideline values for trace element concentrations in soil, adapted from NZWWWA (2003)

Trace element	Soil Limit (mg/kg)
Arsenic (As)	20
Cadmium (Cd)	1*
Chromium (Cr)	600
Copper (Cu)	100
Lead (Pb)	300
Nickel (Ni)	60
Zinc (Zn)	300

*Note: Note that while the NZWWA guidelines suggest upper limit for Cadmium is 1 mg kg^{-1}, the Tiered Fertiliser Management Strategy indicates that soil cadmium levels above 0.6mg kg^{-1} require more active management of soil cadmium loading. Therefore 0.6mg kg^{-1} is used in this report as the target range for cadmium.

See: https://www.fertiliser.org.nz/site/news/articles/updated-tiered-fertiliser-management-system.aspx

8. Appendix B.

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 target ranges, as defined by Landcare Research (Landcare Research, 2003): • total carbon; • total nitrogen; • anaerobically mineralisable nitrogen; • soil pH; • Olsen phosphorus; • bulk density • macro porosity; • aggregate stability; and • trace elements