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Trends in soil quality monitoring data in the Waikato region 1995-2015

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Prepared by:
Matthew Taylor, Waikato Regional Council
Neil Cox, NeilStat Ltd
Ray Littler, University of Waikato
John Drewry, Greater Wellington Regional Council

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

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Peer reviewed by:
Amy Taylor Date August 2017

Approved for release by:
Dominique Noiton Date November 2017

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Executive summary

Waikato Regional Council monitors the life supporting capacity of soil to determine whether current land use practices will meet the foreseeable needs of future generations and identify any changes in the ability of the soil to sustain environmental quality. This report presents data and trends in statistical modelling for the seven soil quality targets for the period 1995-2015 and the main soil quality issues facing the Waikato Region.

Changes in soil quality for different soils and land uses over time and across the Waikato region have been identified. Overall, 10% of managed soil quality sampling sites corrected for land area in the region met all seven indicators in 2015. This result is similar to the percentage of sites meeting all seven indicators for the preceding four years, but is down from a high of 17% in 2006.

The main soil quality issues in the Waikato region are soil compaction, excessive nutrients and loss of soil organic matter (SOM) with the associated decrease in biological activity of microorganisms.

The main issues for pastoral land were compaction and excessive nutrients. There are about 1.4 Mha in pasture making this the most extensive productive land use in the region. Pastoral sites have been compacted since soil quality monitoring began. Recently (2013-2015), there has been an improvement but this trend needs to continue to meaningfully improve soil quality. In 2015 25% of pastoral sites met the compaction target. Nutrient indicators have increased significantly and are, on average, within high or excessive categories, while the average the number of sites meeting the nutrient targets has decreased. In 2015, 66% and 45% of pastoral sites met the targets for phosphorous (P) and nitrogen (N), respectively.

The main issues for arable land were loss of SOM, compaction and excessive nutrients. SOM is, on average, considerably lower for arable than for any other land use and trending lower. Loss of SOM leads to a consequent decrease in biological contribution to fertility and soil resilience. Despite the changes observed in SOM content, there appears little change in the percent of sites meeting the targets for SOM, suggesting these two indicators are somewhat insensitive. Compaction on arable sites is increasing with the number of sites meeting the compaction target declining. In 2015 59% of arable sites met the target for avoiding compaction. Phosphorous fertility increased and the percent of sites meeting the targets for phosphorous declined. In 2015, 24% of arable sites met the targets for phosphorous.

The main issues for horticulture were compaction and excessive nutrients. Compaction on horticultural land increased and the percent of sites meeting the target to avoid compaction decreased. In 2015 42% of pastoral sites met the target to avoid compaction. Similarly, nutrient fertility increased and the percent of sites meeting the nutrient targets has decreased. In 2015, 58% and 33% of horticultural sites met the targets for phosphorous and nitrogen, respectively.

The main issue for forestry is that it is often on unstable land with about ¼ to ⅓ of forestry sites located on loose soil. Trees reduce the erosion risk so forestry land use allows production on what would otherwise be unproductive land. However, care is needed at harvest or conversion of such land to another land use where this land is made bare. Conversely, sites where logging had occurred showed evidence of compaction from dragging logs and machinery, while there was also a loss of SOM, which could be due to erosion or mixing of topsoil and subsoil. In 2015, 71% and 95% of forestry sites meet the targets for avoiding loose soil, and SOM, respectively. There are about 285,000 ha in production forestry in the Waikato region making it the second most extensive productive land use in the region.

Compaction may result in decrease soil infiltration capacity and generation of surface runoff, increased peak and average stream flows, with increased annual flood exceedance probability,

transport of contaminants including sediment, nutrients and pathogens, and localised flooding and bank erosion. In addition, plant uptake of N and P was lower in compacted soils due to shallower rooting, and reduced available N concentrations.

The effects of soil compaction may last for decades unless remedial action is taken. Where compaction is moderate, recovery can be relatively quick, e.g. in 18 months. However, complete recovery from a larger event with lower macroporosity may take many years. Damage to the soil by grazing animals can be minimised by management of livestock and land, including reducing stocking density, moving livestock off wet pasture onto hard standings or into housing, and reducing the length of the grazing season. Precision agriculture techniques should be followed when using machinery for arable and forestry operations and machinery kept off wet soils. In some soils, installing drainage can increase the soils resistance to damage if the watertable can be kept below 500 mm. Tillage and reseeding can break up a surface pan but also accelerate the decomposition of SOM leading to an even worse situation.

Excessive nutrients in soils leads to increased risk of their transferring to water bodies where they can contribute to changes in the composition of local biological communities, the formation of algal blooms, or directly impact human and animal health. The greatest risk of P loss is on soils that are poorly drained, have lower structural resilience or are on slopes, while the greatest risk of N loss is on very well drained and excessively drained soils. When linked together, surface compaction and excessive nutrient concentrations in pasture have been linked to modified soil hydrological behaviour and, ultimately, the deterioration of water quality in ground and surface waters.

Diffuse contamination of surface waters with P and N could be reduced by applying no more than the amount of fertiliser needed for production, managing critical source areas, reducing surface runoff and riparian planting.

Loss of SOM is considered a key soil attribute as it affects many physical, chemical and biological properties that control soil services such as productivity, the adsorption of water and nutrients, and resistance to degradation. Low SOM is associated with reduced aggregate stability, infiltration, drainage, airflow, microbial biomass, microbial activity, and nutrient mineralisation due to a shortage of energy sources and loss of habitat. Low SOM results in less diversity in soil biota with a risk of the food chain equilibrium being disrupted, which can cause increases in accumulation of toxic substances, plant pests and diseases. Of particular significance to the Waikato catchment is SOM's role in retaining nitrogen in the soil. SOM state is measured using the total carbon (total C) measurement.

In arable systems, adding manures, adequate fertilisation, the return of plant material and crop rotation can all help reduce the decline in SOM. Nevertheless, re-establishment of pasture appears the most practical method of recovering SOM for these systems.

Considerable conversion of land from pine plantations to pasture has taken place on Pumice soils. Pumice soils are very light with weak structure and erode easily when disturbed. Impacts of this intensification can include loss of soil carbon and SOM, increased surface compaction, decreased aggregate stability and crusting with the associated issues of low water infiltration and storage, overland flow, causing soil erosion, and carrying nutrients, sediment, pathogens, organic matter and other contaminants to waterways. The impact of intensification on the biological, physical, and chemical condition of Pumice soils is likely to be greater than on Allophanic or Granular soils, both of which are weathered volcanic soils and traditionally more commonly used for pastoral land use.

In 2015 soils under native vegetation were on average acidic (pH 5.4), high in total C (mineral soils 15.3%), low in Olsen P (7 mg/L), low in bulk density (0.56 t/m^3) and had high macroporosity (25% v/v). Pine forestry soils had generally similar characteristics to native soils but had lower total C 8.6%). Soils under pasture were on average less acidic (pH 6.0) than forest soils, but with

more Olsen P (49 mg/L), and lower macroporosity (9%). Soils under horticulture were similar to pasture. Soil under arable land use had low total C (5.0%), high pH (6.4), Olsen P (91 mg/L), and bulk density (0.94 t/m3).

The representativeness of the soil quality monitoring sites was assessed. Compared to land area in each land use and soil type category, in 2015, land under native vegetation, Podzols, Pumice soils, Recent soils and Ultic soils were underrepresented. Ideally, the representativeness of the dataset can be improved by increasing the number of native sites; and increasing sites with Recent, Podzol, Pumice and Ultic soils.

Recommendations

Minimise soil compaction by reducing stocking density, moving livestock off wet pasture onto hard standings or into housing and reducing the length of the grazing season. Precision agriculture techniques should be followed when using machinery for arable and forestry operations and machinery kept off wet soils. In some soils, installing drainage can increase the soils resistance to damage if the watertable can be kept below 500 mm.

Minimise diffuse contamination of water by meeting the targets for phosphorous and nitrogen in soil, avoiding compaction, applying no more than the amount of fertiliser needed for production, managing critical source areas, reducing surface runoff and extending riparian planting.

Minimise loss of SOM by adding manures, adequate fertilisation, the return of plant material and crop rotation in arable systems. Loss of SOM can be reversed by re-establishing pasture under light to moderate intensity farming.

It is recommended that the total number of soil quality monitoring sites be increased to 190-200 to enable the sampling programme to be representative of all the major land uses and soil orders in the Waikato region. The exact number will depend on the mix of soil orders and the overlap with native sites.

Introduction

Waikato Regional Council (WRC) recognises that the region's economy and people's wellbeing depend on our natural capital, including soils, and has legislative responsibility to manage the soil resource. An established soil quality monitoring programme provides information for State of the Environment (SOE) reporting, policy development, and helps in understanding the interactions between soil and water. The soil quality trend measurements enable assessment of the sustainability of current land use management practices and the effectiveness of WRC policy by providing evidence of change or stability.

Soil consists of a complex combination of minerals, organic matter, organisms, air and water. Soils with high soil quality are considered healthy as they support important functions such as agricultural production, water filtration and storage, flood mitigation, nutrient and carbon storage, plant growth and biological diversity, and can act as a barrier to below surface contamination (Ministry of Primary Industries 2015). Soils with high soil quality are more resilient and durable to the pressures associated with man's activities, and are quick to recover if damaged. Typically, a soil with high soil quality has low leakage of nutrients and contaminants, low rates of erosion, has high biodiversity, will capture and hold water, and can sustain high levels of production. Such soils are also resistant to disturbance from intense storms and land use change.

Preliminary development of the soil quality programme was carried out with Landcare Research as early as 1995 with regional coverage achieved by 2005. This programme is aligned with national soil quality monitoring as established and administered through the Land Monitoring Forum (LMF). The quality of the regions soils are assessed by calculating the proportion of sites meeting seven soil quality targets and the direction of trends. This report presents trends in the data since 1995 and discusses the main soil quality issues facing the Waikato Region.

Regional programme objectives

By undertaking soil quality monitoring WRC will be able to comply with the requirements of the Environmental Reporting Act 2015, can keep our community informed of issues facing our productive land, and can guide land users in their management practices as well as develop well informed and appropriate policies and rules to help address issues as they emerge.

As soils take a long time to form, they should be regarded a finite resource by resource managers, i.e. natural capital. Healthy soils with suitable and sustainable land uses are needed to achieve the Waikato Regional Council's mission to build a Waikato region that has a healthy environment, a strong economy and vibrant communities and the rural economy can benefit greatly from the sustainable use and management of its soil resources.

The Soil Quality Monitoring Programme has three key objectives:

1. Develop and implement a long-term soil quality monitoring programme that represents the state of soil quality and identifies soil quality changes for different soils and land uses over time and across the region. Utilise these results for State of the Environment reporting and policy development.
2. Develop a database containing soil and site descriptions and periodic measurements of soil chemical, physical and biological indicators used to monitor changes in soil quality.
3. Provide an early-warning system to identify effects of primary land uses on long-term soil productivity (physical, chemical, biological). Relate changes in soil quality indicators to land use and land use practices, identifying those having the greatest impact on soil quality and the wider environment. Track specific, identified issues relating to the effects of land use on long-term soil productivity.

Reasons for soil monitoring

Regional councils are required to manage natural and physical resources in such a way that enables the purpose of the Resource Management Act and it amendments (RMA) to be achieved. The RMA has a purpose of sustainable management, which incorporates the requirement to maintain the life supporting capacity of land and ecosystems. Soils are living natural capital ecosystems and support a range of life forms, hence the concept of maintaining soil health is embodied in the purpose of the RMA.

The soil ecosystem has multiple roles in the environment, including filtering, water and greenhouse gas regulation, maintenance of productivity, habitat provision and buffering pollution to water resources (Ministry of Primary Industries 2015). Poor soil quality results in lower agricultural yields, a less resilient soil and land ecosystem and greater contamination of adjacent water bodies.

Soils can also be viewed in terms of degradation and depletion. Soil degradation is a deleterious change or ecological disturbance to the soil. Soil depletion occurs when the factors which contribute to fertility are removed or where the conditions which support soil's fertility are not maintained. Degradation and depletion of soils have adverse effects on soil quality, plant productivity, and ecosystem functions.

Soils can be degraded in several ways:

1. Structurally, by physical compaction and loss of aggregate stability. Compacted soils are often slow draining, becoming water-logged when wet and resulting in poor aeration which is unsuitable for plant roots and soil animals. Compaction results in lower yields, higher production costs and reduced profitability. Increased run-off may reduce water quality.
2. Through soil acidification, salinity and desertification. These are major causes of degradation in other parts of the world, but very localised in New Zealand.

Depleted soils have lost components essential for healthy plant and soil biology:

1. They may be depleted in nutrients, because nutrient stocks are not being replaced as fast as they are removed.
2. Soils may become too acid for some crops if insufficient lime is applied to counter natural acidification processes.
3. Soils depleted in organic matter have less ability to retain nutrients in the topsoil, are more prone to rapid structural decline, and have less capability to supply plant nutrients from organic reserves. If nutrients are not retained within soils they can contaminate surface and groundwater.
4. Soils low in biological activity are less able to detoxify wastes, and degrade contaminants and residues.

Soil monitoring programme design

Ideally, assuming that the variances for soil quality parameters are the same for all land uses, the number of sites selected for each land use should be representative of the land area for each land use (e.g., land uses that occupy the largest area within a region should have the most sites sampled). This is not always feasible and there are valid reasons for biasing sampling towards specific land uses, e.g. cropping and horticulture generally occupy a small total area, but as the most intensive land uses they could potentially have larger impacts than lower intensity land uses. Another consideration is to have a sample size meaningful for statistics, greater numbers of sites may be needed than would be called for by land representativeness. Although the original intent, as described in the LMF manual, was to proportionally sample each land-use/soil-type combinations, but accurate information on the area of soil type under each land use is lacking (land-use changes are frequent and difficult to predict by soil type), so land use alone has been used in the past.

The sample size requirements for soil quality sampling at a national level were statistically analysed (Hill et al. 2003). In theory, this provides some guidance for sampling requirements at a regional level if the same range of land use types and soil measurement variability were to be expected. However, given most regions are a likely to be less variable in terms of soil quality and land use types it is expected the sample size required to represent the true population to be less. In practice, a sample size for each land use type should be greater than 30 samples. In a statistical sense sample size for each land use type should aim to be confident of estimating the most variable soil indicator value to a predetermined confidence and variance about the mean value for that property is used (analysis during the preliminary development of the programme carried out with Landcare Research showed with 95% confidence that the mean level +/-20% is achieved, Hill & Sparling 2009). Further information on determining the number of representative samples are presented in Appendix I.

Native vegetation has grown at native sites from prehuman times, indicating current soil quality indicator values are suitable for this land use. So, native sites meet soil quality targets by definition and target values for native systems are not defined. However, native sites provide valuable baseline information on how land use change affects soil characteristics. Additionally, changes in soil parameters over time in indigenous systems can indicate the extent that these systems are being influenced by human activity.

The WRC soil quality monitoring programme is a screening tool designed to gather a large amount of information quickly and at a low cost to inform detailed environmental assessment of the regions soils. Currently there are 150 long-term monitoring sites (Table 1, Figure 1). Soil quality monitoring sites were chosen and sampled according to the methods set-out in the Land and Soil Monitoring Manual (Hill & Sparling. 2009). For reporting purposes, stratification is a useful means for categorising soil quality monitoring data at a national and regional scales. Research determined that Land Use Type and Soil Order contributed to the variability of soil quality indicators at a national scale. Also, sampling land use and soil combinations of small area extent can be justifiable if they are a potential higher risk category and are of local concern (Hill et al. 2003). Thus the sites chosen for the WRC soil quality monitoring programme represent dominant soils and land uses, and also include sites on sensitive soils such as peat soils, sites capturing the effects of land use change (e.g. production forestry to pasture) and sites with specific land use practices (such as organic farming).

Changes to land use and loss of sites due to a variety of reasons are recorded. New sites are established, keeping the number of active sites at 150 and preserving the representativeness of the dataset. Another consideration for minor land uses and soils types is that the number of sites need to be increased above representativeness to enable statistical analysis.

The representativeness of the current soil quality monitoring sites was assessed. Compared to land area in each land use category in 2015, native was under represented, while arable, horticulture and forest to pasture conversion were over represented and Podzols, Pumice soils, Recent soils and Ultic soils were underrepresented (Table 1). Land classified as urban/town, rock, permanent ice and snow, was not included as the soils in these areas are either highly modified by human occupation or are unlikely to change in the short to medium-term.

The representativeness of the dataset can be improved by increasing the numbers of under-representative sites. Ideally, this would be done by increasing the number of native sites by 33 to 45 sites; Recent soil sites by 9 to 15 sites; Podzol sites by 9 to 14 sites; Pumice sites by 12 to 38 and Ultic soil sites by 5 to 7 sites. The total number of soil quality monitoring sites would need to increase to about 190-200 for the sampling programme to be representative of all the major land uses and soil orders in the Waikato region. The exact number will depend on the overlap of native sites and the mix of soil orders available.

Table 1: Land area of each land use and soil type, and representativeness of the current soil quality monitoring sites with recommendations.

Land use	Regional area (ha)	Number of sites	Average number of sites sampled per year	Percent of sites	Percent of region	How representative (1.00 = best)?	Number of additional samples recommended
Native	706,000	12	2-3	8	28.2	0.28	33
Forestry	285,000	21	4-5	14	11.4	1.23	No change
Arable	11,000	17	3-4	11	0.4	25.76	No change
Horticulture	2,000	12	2-3	8	0.1	100.00	No change
Pasture	1,420,000	80	15-17	53	56.9	0.94	No change
Conversion of forestry to pasture	35,000	8	1-2	5	1.3	4.10	No change
Allophanic	465,280	46	9-10	31	18.5	1.62	No change
Brown	310,187	25	4-6	17	12.3	1.32	No change
Gley	184,635	18	3-4	12	7.4	1.60	No change
Granular	172,326	16	3-4	11	6.9	1.52	No change
Organic (Peat)	108,319	6	1-2	4	4.3	0.91	No change
Podzol	231,409	5	1-2	3	9.2	0.35	9
Pumice	625,297	26	5-6	17	24.9	0.68	12
Recent	248,642	6	1-2	4	9.9	0.40	9
Ultic	110,781	2	0-1	1	4.4	0.30	5
Total	2,461,800	150	30	100	97.8		

Soil quality monitoring sites have been re-sampled over time to identify trends for each soil measurement. For continuity, the LMF recommended that a few of the sites be sampled each year, so to resample all the sites in a 5 – 10 year cycle. For the WRC soil quality monitoring programme, about 30 sites (20%) are sampled annually, meaning that it takes five years to sample all 150 sites. Note that it took several years to build the number of sites to 150 from the initiation of the programme.

There are a number of seasonal and weather related variables that were taken into consideration when carrying out resampling of the sites:

- To follow trends through time scales greater than one year, sites should be re-sampled at the same time of the year as the original sampling;
- Samples should not be collected when soils are under moisture deficit (excessively dry), frozen, or waterlogged;
- Preferred sampling time for cropping soils is just before harvesting operations.
- Preferred sampling time for other land uses is spring;

Thus, sampling for the WRC soil quality monitoring programme normally occurs during spring, with occasional exceptions for cropping soils or if a site is unsafe to sample, or disturbed by an event not related to the land use, e.g. traffic.

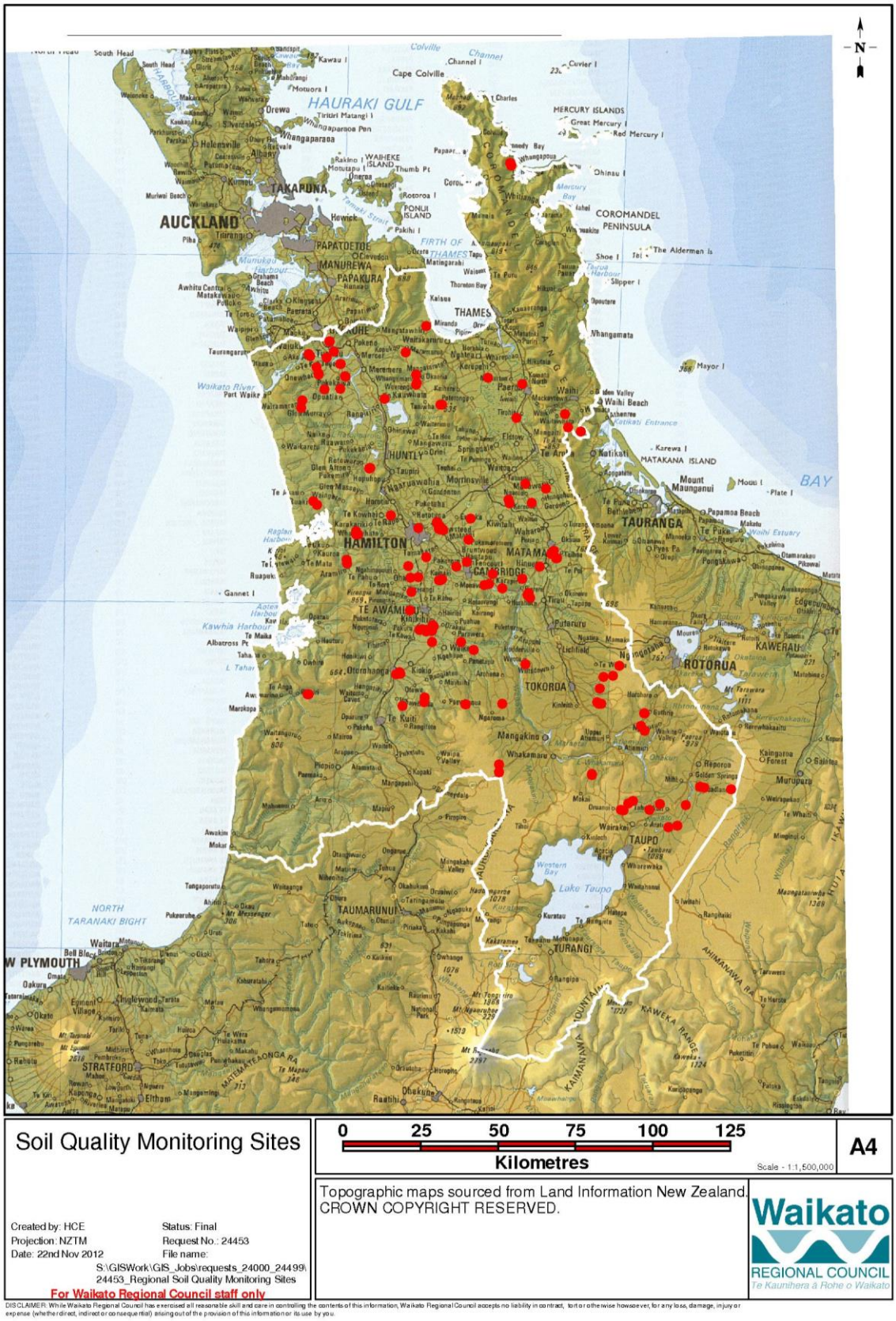

Figure 1: Map of soil quality site locations.

Soil quality indicators

Soil quality is the chemical, physical, and biological condition of a soil type for a given land use. There is no single test for soil quality, because there are many things about soil that affect its quality rating – the fertility, physical condition, amount of humus, and biology. After preliminary testing (1995-1998) followed by three years of trials (1998-2001) over more than 500 sites, the National Land Monitoring Forum has agreed on seven key measurements, which are termed indicators (Hill et al. 2003):

1. Olsen P. Olsen P is the method used to derive the concentration of phosphorous that is available for plant uptake;
2. pH; a measure of soil acidity
3. total carbon (C), a measurement of soil organic matter and carbon stocks;
4. total nitrogen (N), a measurement of soil organic matter and nitrogen stocks;
5. mineralisable nitrogen using the anaerobically mineralised N method (AMN) is used to assess soil microbial health and how much organic N is available to the plants;
6. bulk density, a measure of physical condition
7. macroporosity at -10 kPa (shortened to macroporosity for this publication), a measure of soil pores that air and water can use to enter the soil. Compacted soils will not allow water or air to penetrate, restrict root growth and do not drain easily, so have increased potential for run-off carrying sediment, nutrients and contaminants to surface waters.

The various properties monitored focus on the dynamic aspects of soil quality and are based on the fitness of the soil for its particular use. For each site, data from the seven key soil quality indicators are compared against target ranges specific to soil order and land use and the number of times a value fails to meet the target ranges recorded. Targets do not exist for native sites as these sites have been under this land use long-term and the native vegetation appears thriving. Values from native sites can be considered background.

Comparison of soil properties at individual sites over time are also used to assess the extent and direction of change in soil quality characteristics. Overall soil quality is calculated by the proportion of all indicators that met the target range using the formula

$P = I / N \times 100$

where P is the proportion of sites not meeting the target for that particular indicator, I is the count of sites exceeding the target range, and N is the total number of sites sampled. Data can also be grouped by land-use category to help identify areas of concern, and the proportion of sites meeting or not meeting soil quality targets calculated using the formula

$Pi = Ic / Ni \times 100$

where Pi is the proportion of sites not meeting the target for that particular indicator, Ic is the count of sites exceeding the target range, and Ni is the total number of sites sampled for that indicator.

Soil monitoring programme method

Sampling and analysis

Soils were sampled at each monitoring site following the methods in the LMF national guidelines (Hill & Sparling 2009). The same sampling methodology was followed to ensure consistency between results gathered from different regions and over time. The first time a site was sampled, a soil profile pit was dug on site to confirm soil type and to provide a basic soil profile description. For the first and subsequent samplings, a transect on a visually uniform strip of land with at least 10 m clearance from obstructions or constructions was accurately defined to enable relocation for future samples. The LMF manual recommends compositing 25 soil cores over a 50 m transect using a tube auger. In practice, it was been found that more samples were needed in order to have enough soil left over after analysis to archive. Archived soil samples have proved

extremely valuable when testing a change in analytical methods or testing an additional soil measurement on top of the existing seven key indicators. In addition, three undisturbed core samples for physical analyses were taken at 15m, 30m and 45m positions along the transect. In reality, these distances were approximate as it was necessary to avoid cow dung and areas not representative of the site. The individually numbered core liner, 75 mm depth by 100 mm diameter was placed on the surface of the soil from which the core sample was to be taken. The number of the liner was recorded in the site notes. The liner was then pressed into the soil, pushing downwards on the ring, e.g. with a block of wood. The field staff then cut round the outer part of the liner with a sharp knife and continue pressing down until the soil was approximately 5 mm below the top of the liner. The liner with the intact core of soil was carefully dug out of the surrounding soil, taking care not to break away the soil from the base of the liner. Excess soil below the bottom of the liner was cut off using a large spatula or knife. The entire liner and core were wrapped with self-adhesive plastic film (kitchen wrap), and packed into a padded crate for transport to the laboratory.

Soils were classified according to the New Zealand Soil Classification (Hewitt et al. 2010). Land use classes used were pasture, forestry to pasture (where land had recently changed from production forestry to pasture), arable (annual cultivation), horticulture (perennial plants left in place), production forestry and native (indigenous vegetation). Initially, the pasture classification was separated into dairy (milking cows) and pasture used for meat or fibre production. However, it has become more difficult in recent times to separate these two classifications as farms have diversified and the indicator results for both these land uses have come together, e.g. dry dairy cows are often run on what was previously only sheep and beef farms.

All analyses were carried out at IANZ-accredited laboratories, Landcare Research and Hill Laboratories, both of Hamilton, according to the Land and Soil Monitoring Manual (Hill & Sparling 2009). Detail about soil preparation for laboratory analyses and the preferred analytical methods are given in Appendix II. Briefly, the recommended procedures for analyses are:

- **Total C and N** – Analyses using high temperature combustion methods.
- **Soil pH** – measured by glass electrode in a slurry of 1 part by weight of soil to 2.5 parts water.
- **Olsen P** – Extraction by shaking for 2 hours at 1:20 ratio of air-dry soil to 0.5 M NaHCO3 at pH 8.5, filtered, and the phosphate concentration measured by the molybdenum blue reaction using Murphy-Riley reagent.
- **AMN** – estimated by the anaerobic incubation method for mineralisable N. Moist soil is incubated under waterlogged conditions (5 g equivalent dry weight with 10 ml water) for 7 days at 40°C. The increase in ammonium-N extracted in 2 M KCl over the 7 days gives a measure of potentially mineralisable N.
- **Dry bulk density** – Measured on a sub-sample core of known volume dried at 105°C. The weight of the oven-dry soil, expressed per unit volume, gives the bulk density. The bulk density is also needed to calculate porosity.
- **Macroporosity at -10 kPa** - is calculated from the total porosity and moisture retention data: $S_m = S_t - \theta$, where S_m is macroporosity, S_t is total porosity, and θ is the volumetric water content at -10 kPa tension.

Notes:
Air-dry, sieved (<2 mm) sub-samples are used for chemical analyses.
Intact soil cores (triplicate) are used for soil physical analyses.

Chemistry data was normally received from the laboratory on a gravimetric basis (weight/weight), and soil physical data on a weight/volume (bulk density) or volume/volume basis (macroporosity). Chemical data for Olsen P was converted from a gravimetric basis (weight/weight) to a volumetric basis (weight/volume) by multiplying by the bulk density. Note

that some New Zealand industry-based Olsen P target values are based on a volumetric basis, but on a 'modified' basis. Further explanation is available in Drewry et al. (2013; 2017).
A physical sample of the soil (air dried, <2 mm) was also stored for reference and for re-analysis if required. Physical samples were stored in screw-top plastic jars, at 18–25°C, with unambiguous identification.

All 150 sites were used to give the overall soil quality picture for the region. However, where the land use had recently changed from production forestry to pasture, results would have been significantly skewed if these sites were included in one of the pasture categories. Consequently, these eight sites were treated as their own category.

Each indicator measurement has a range within which the majority of national soil samples fall. From this process it has been possible to assign a range for each measurement that identifies levels from low, adequate/optimal, and high to excessive. For example bulk density is expressed as loose, adequate, or compact, as this is a measure of the weight of soil in a cubic metre. Targets levels for each indicator measurement are set where negative impacts on the environment occur and these are based on national guidelines (Sparling et al. 2003a) and updates (Hill & Sparling 2009, Mackay et al. 2013). These targets are presented in Appendix III.

The resulting data are stored in the WRC database system in Microsoft Excel as recommended by the LMF (Hill & Sparling 2009). Measurements were categorised by land use, and reported as meeting or not meeting targets. As it took several years to build up the number of sampling sites, this data are presented in the results section for 2005-2015.

Statistical analysis

Each indicator was assessed for statistical trends using linear mixed modelling with random splines overall (shortened to "mixed modelling" in the results and discussion sections), by soil order and by land use. Data for four of the indicators (total C, total N, Olsen P and AMN) required log transforming to get approximate constancy and normality of the residual variation (Appendix IV Statistical analysis). The back-transformed estimates were "bias-corrected" to make this the same as the overall arithmetic mean of all the original values in the data. Data calculated by this method are presented in the results section for 1995-2015.

Random terms were used to give an appropriate structure to the error terms, allowing for the correlations arising from repeated observation of the same sites. Random smoothing spline terms were used in the model for three reasons: firstly, they allow us to fit trend terms that are data driven, not requiring the choice of a particular functional form, secondly they allow us to estimate the trends as if every site had been measured at every date, and finally they allow modelling the serial correlation between successive observations on the same sites (Appendix IV).

The accuracy of estimated values in any one year was improved by utilising the information from sites before and after each time period, thus increasing the effective sample size (Appendix IV). Data calculated by this method are presented in the results section for 1995-2015.

Soil quality results

Results are first presented for the overall dataset, then broken down into soil order and land use to identify the contribution these make to driving change. Soil quality results for 29 sites monitored in 2015-16 are presented in Appendix IV and results for all 150 sites are presented in Appendix V.

Overall, 10% of soil quality sampling sites from land in farming or production forestry in the region, corrected for land area, met all seven indicators in 2015. This is similar to the percentage

of sites meeting all seven indicators for the preceding four years (Figure 2), but is down from a high of 17% in 2006. To meet all seven indicators the soil must fall within the adequate, optimal, or normal range as shown in Table 3 for each of the indicators. There has been a corresponding increase in the number of sites failing one or two indicators over the same time period. On an area weighted basis, the main soil quality issues for productive land in the Waikato region occur on pastoral land. (Figure 3). Further discussion of the soil quality issue identified is presented by land use in the discussion section

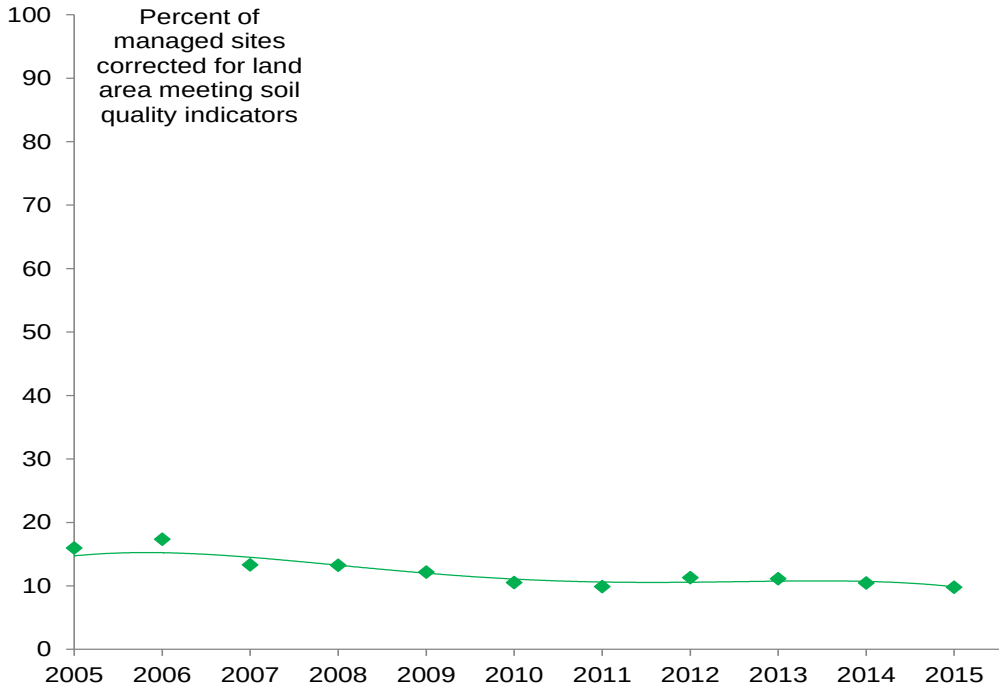

Figure 2: **Percentage of sites for all land uses meeting all seven soil quality monitoring indicators from 2005 to 2015 (% number of sites corrected for land area).**

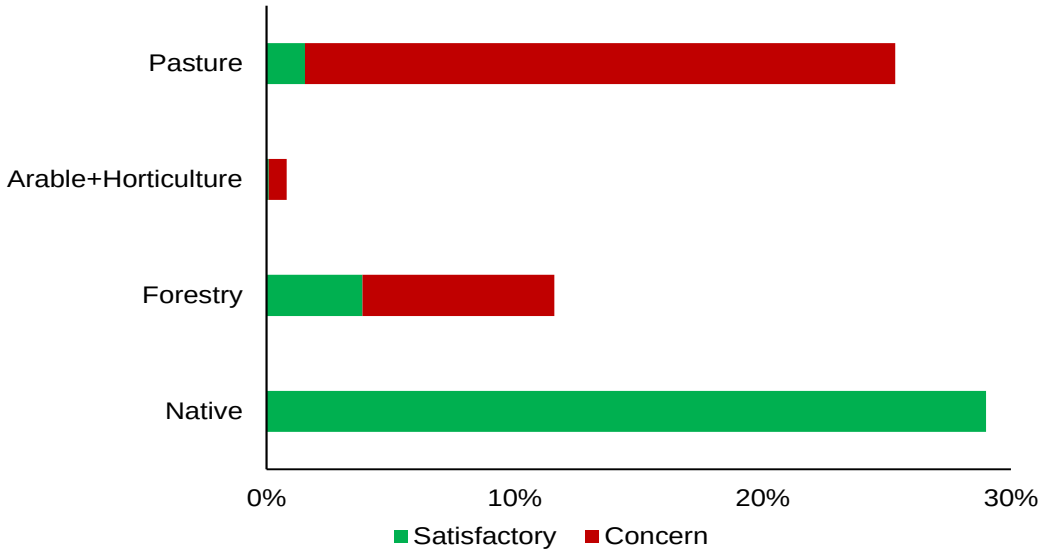

Figure 3: **Soil quality of productive land and land in native bush in the Waikato region in 2015 (% number of sites corrected for land area).**

Soils in 2015 under native were on average acidic (pH 5.4), high in total C (mineral soils 15.3%), low in Olsen P (7 mg/L) low bulk density (0.56 t/m3) and high macroporosity (25% v/v). Forestry soils had generally similar characteristics to native soils but had lower total C 8.6%). Soils under pasture were on average less acidic (pH 6.0) than forest soils, but with more Olsen P (49 mg/L),

and lower macroporosity (9%). Soils under horticulture were similar to pasture. Soil under arable had low total C (5.0%), but high pH (6.4), Olsen P (91 mg/L), and bulk density (0.94 t/m3).

Changes in bulk density 1995-2015.

The mixed modelling results showed no significant change in bulk density for the overall data (Figure 4) or when the results were broken down by soil order (Figure 5), but there were significant differences at the 5% level in linear trend when the results were broken down by land use, with arable increasing (Figure 6). However, only arable land uses showed a significant (at the 5% level) trend and changes in other land uses were not significant.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, assessment of sites meeting targets could only be done once an adequate number of sites representative of the region had been sampled, and data are presented for 2005-2015.

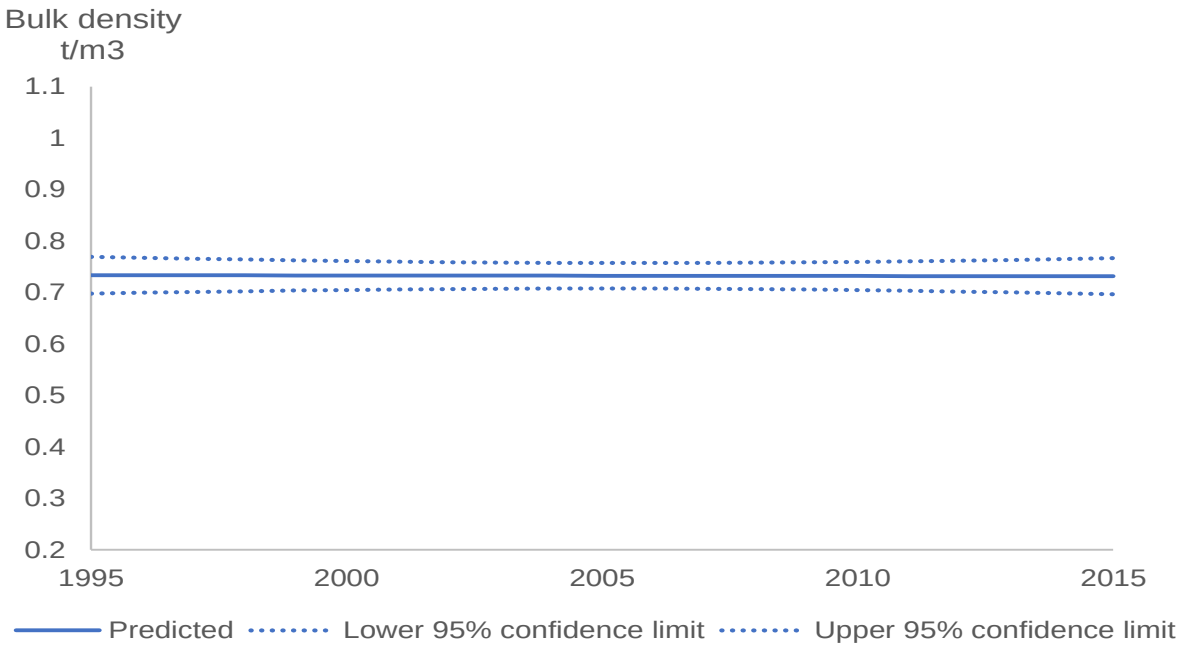

Figure 4: **Change in mixed modelling average bulk density 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.**

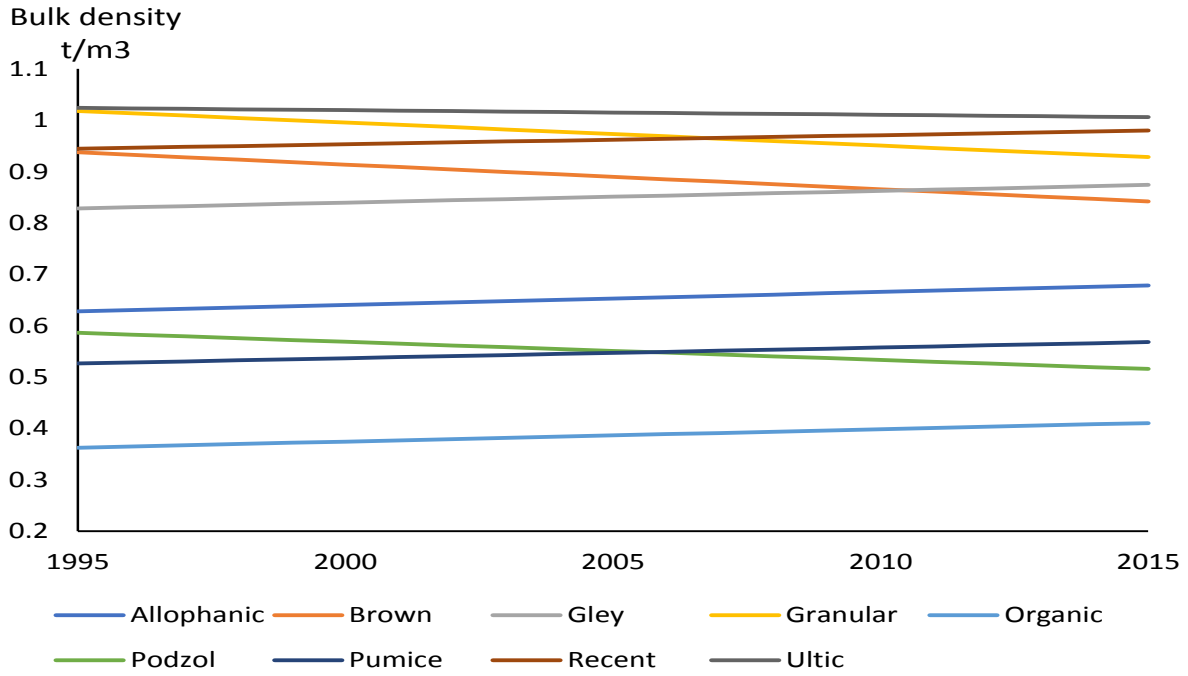

Figure 5: **Change in mixed modelling average bulk density 1995-2015 by soil order.**

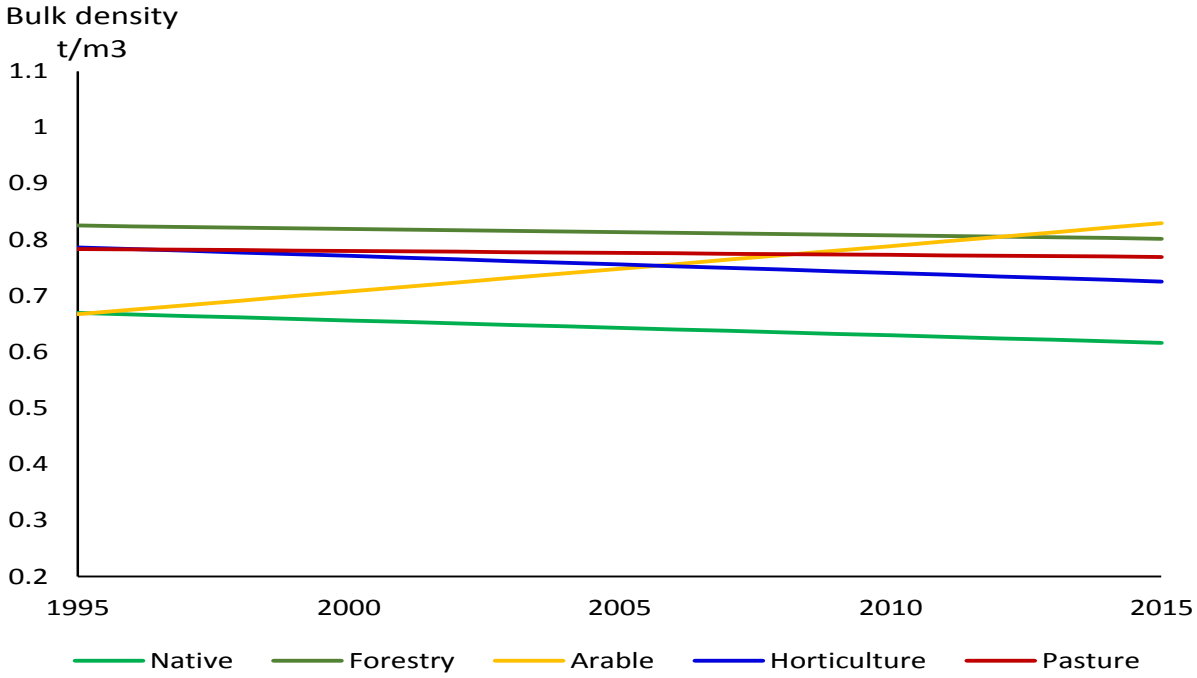

Figure 6: **Change in mixed modelling average bulk density 1995-2015 by land use.**

Measurements below lower targets for bulk density are considered to indicate loose soil, while results above upper targets are considered to indicate compaction. All sites (100%) meet the upper bulk density targets (1-1.4 t/m3 depending on soil type, Appendix III; data not shown) but a considerable percentage of forestry sites did not meet the lower bulk density targets (0.2-0.7 t/m3 depending on soil type, Appendix III; Figure 7). Nevertheless, the percentage of forestry sites meeting the low bulk density target has increased over time.

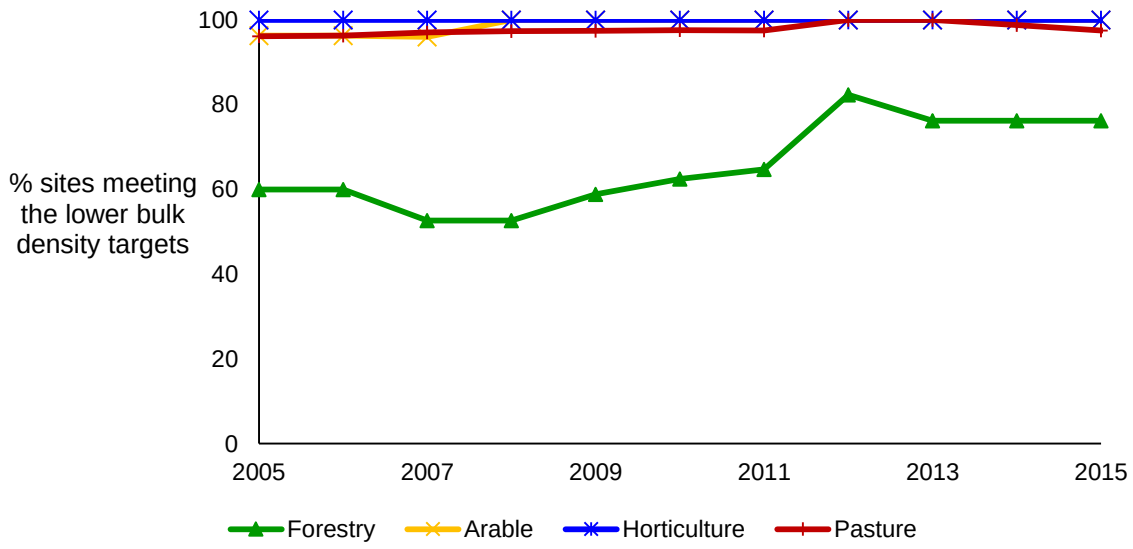

Figure 7: **Change in percent of sites meeting the lower bulk density targets 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.**

Changes in macroporosity @ -10 kPa 1995-2015.

The mixed modelling macroporosity results showed evidence of a non-linear pattern overall with time (Figure 8). Differences in pattern or linear trend between soil orders was not significant at the 5% level (Figure 9), but significant differences at the 5% level in pattern and non-linear trend were seen for arable and pasture land uses (Figure 10). Most notably, the pattern for arable starts and ends at about 10% but rises to about 23% around 2003 to 2006. Considerable work on improving the sustainability of vegetable growing was carried out in the Franklin Sustainability Project, which WRC was a part of (Pukekohe Vegetable Growers Association and Agriculture New Zealand (2000). However, pressure to intensify production increased as well and has continued to increase. In the last 5 years, macroporosity under arable has declined but under pasture has increased. A considerable decline in macroporosity under horticulture was also apparent, but this was not significant due to the low effective sample size - of 4.1 in 2015 (Table 5 in Appendix IV).

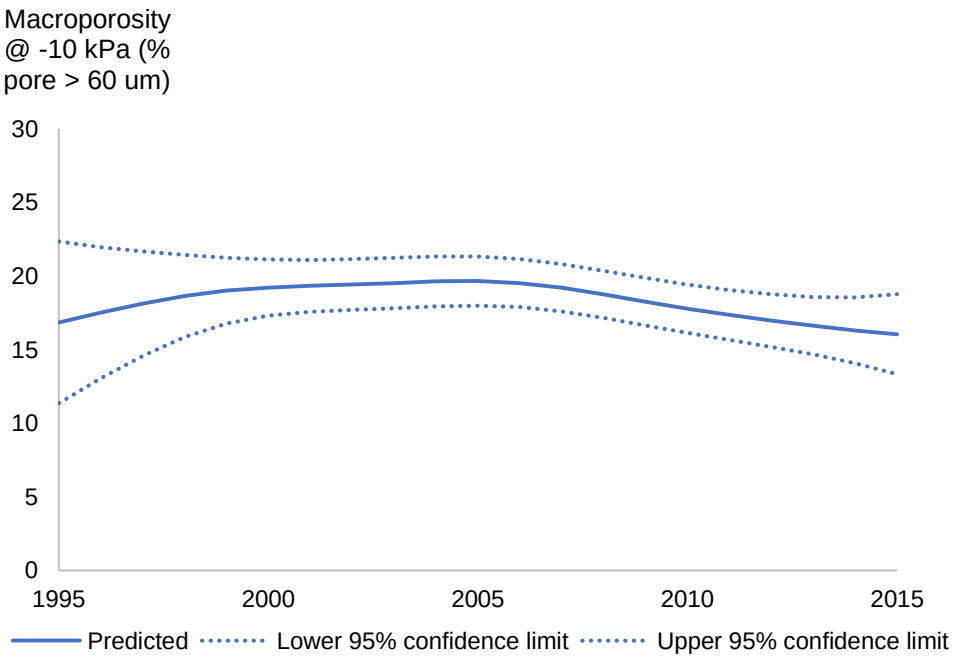

Figure 8: **Change in mixed modelling average macroporosity @ -10 kPa 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.**

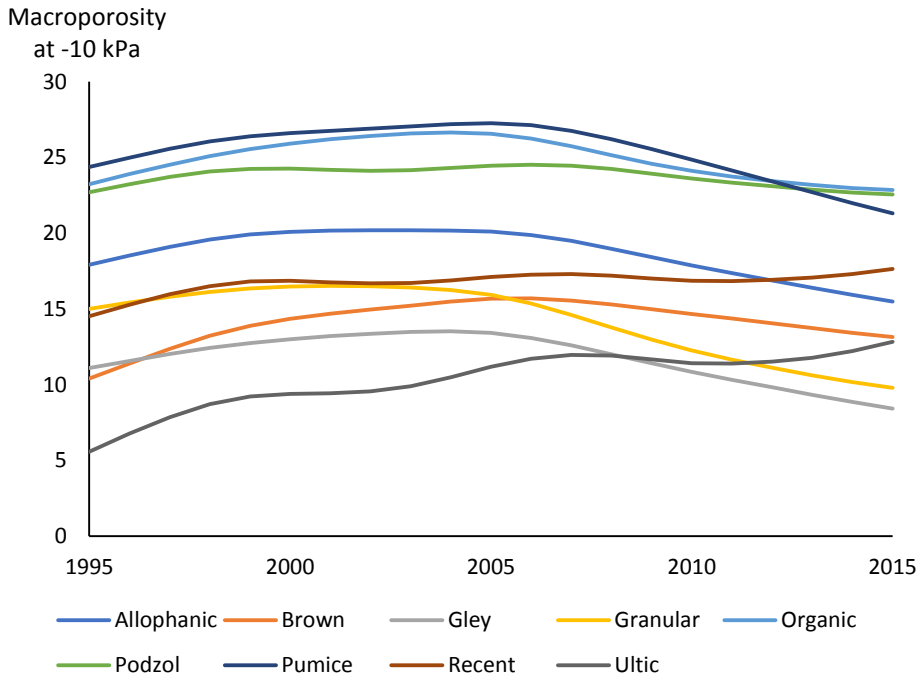

Figure 9: Change in mixed modelling average macroporosity @ -10 kPa 1995-2015 by soil order.

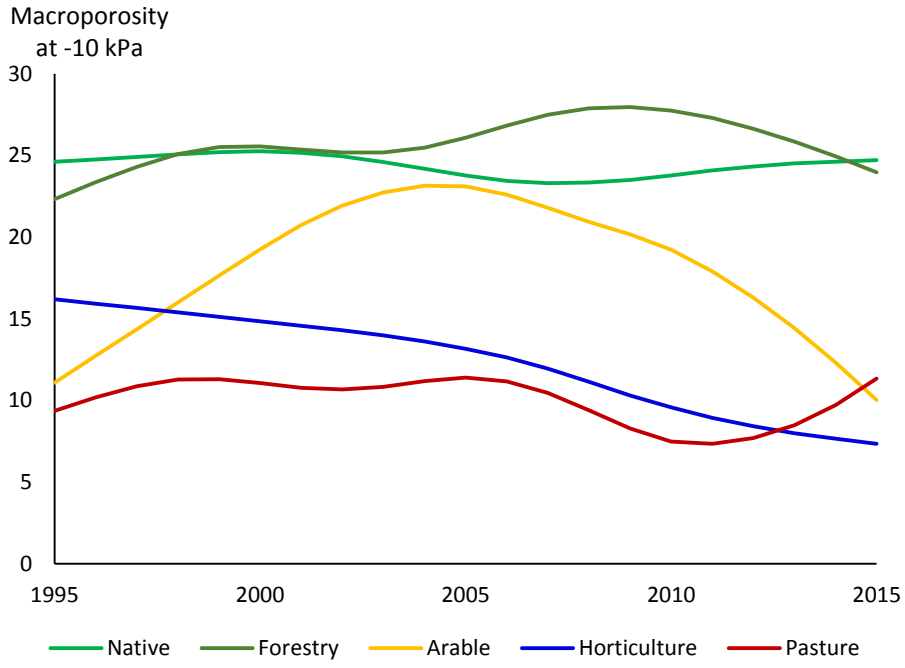

Figure 10: Change in mixed modelling average macroporosity @ -10 kPa 1995-2015 by land use.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, an assessment of sites meeting targets could only be done once an adequate number of sites, representative of the region, had been sampled, so data are presented for 2005-2015. Measurements below lower targets (8% for forestry, 10% other land uses, Appendix III) are considered to indicate compaction, while results above upper targets (30%, Appendix III) are considered to indicate loose soil.

The percentage of sites meeting the lower targets decreased over time for all productive land uses (Figure 11), and the percentage of sites meeting the upper target increased for arable and

forestry (Figure 12). Soils under horticulture showed the largest decrease in average macroporosity and in meeting the lower macroporosity target of 10%. Soils under pasture already had low macroporosity and only 25% of pasture sites meet the low macroporosity target in 2015, although this was a slight improvement on the previous three years.

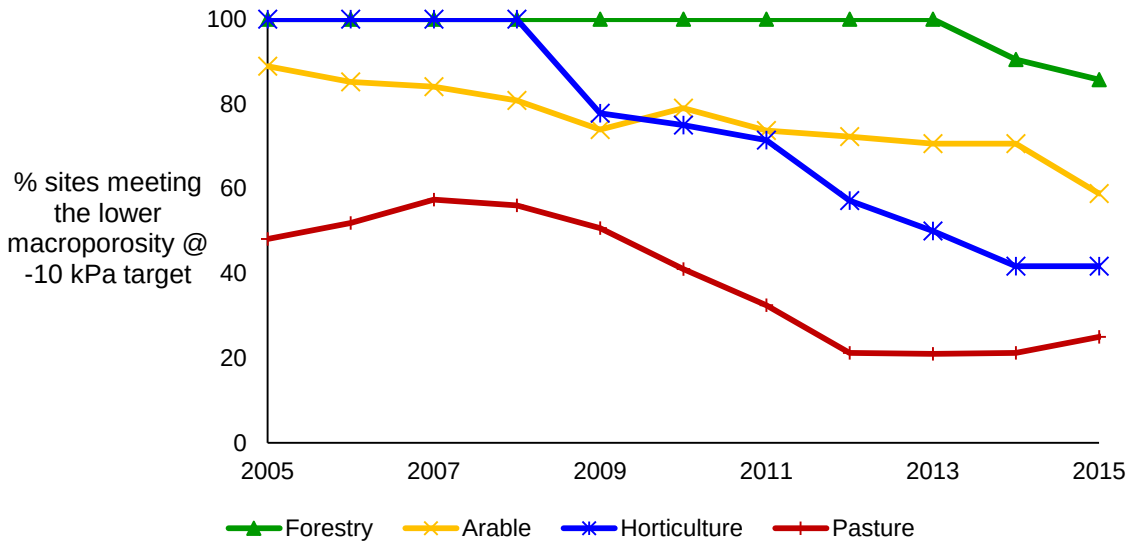

Figure 11: **Change in percent sites meeting the lower macroporosity @ -10 kPa target, 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.**

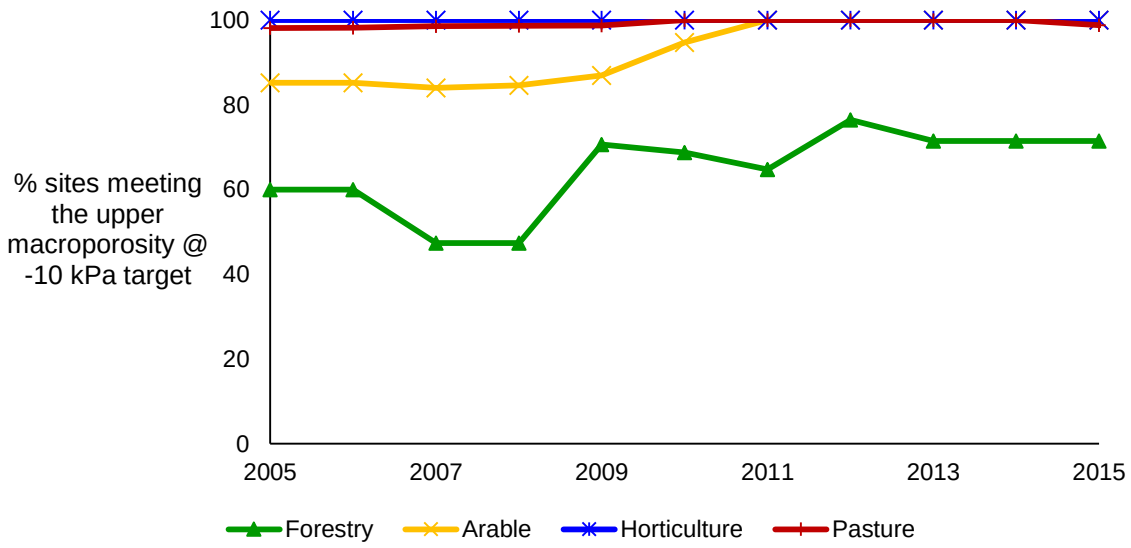

Figure 12: **Change in percent sites meeting the upper macroporosity @ -10 kPa target, 2005-2015 by land use.**

Changes in Olsen P 1995-2015.

The mixed modelling Olsen P results show a significant (at the 5% level), non-linear, increasing pattern over time for the overall dataset (Figure 13) that remained a consistent pattern with soil order or land use (Figures 14 & 15). In particular, results for horticulture increased then decreased 2005-2015. These changes match with world commodity prices, e.g. pasture follows the world milk commodity price (DairyNZ 2016), although horticulture may also be affected by the PSA infection in kiwifruit reducing profitability (Ministry of Primary Industries 2012).

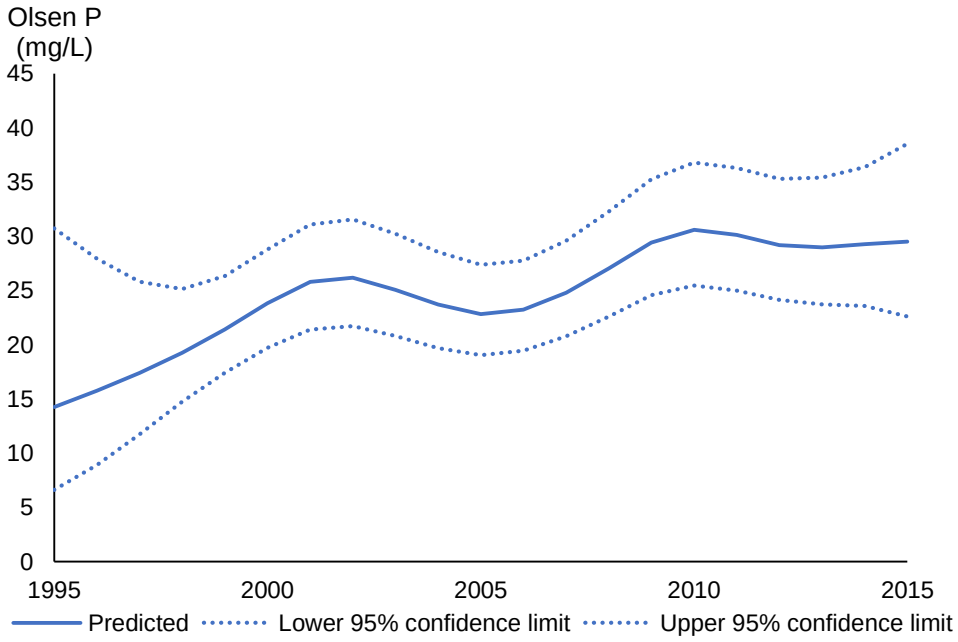

Figure 13: **Change in mixed modelling average Olsen P 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.**

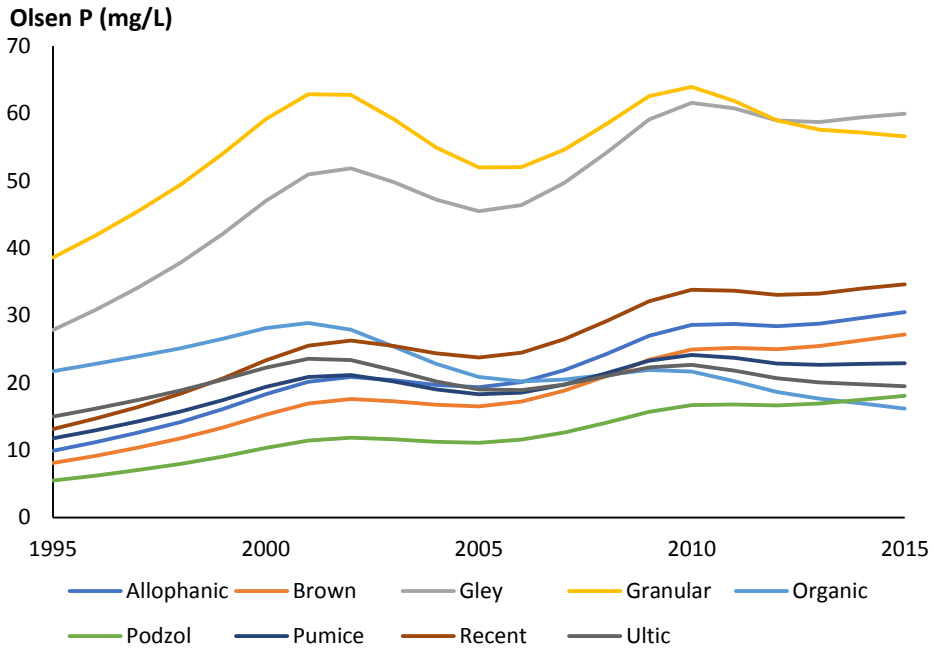

Figure 14: **Change in mixed modelling average Olsen P 1995-2015 by soil order.**

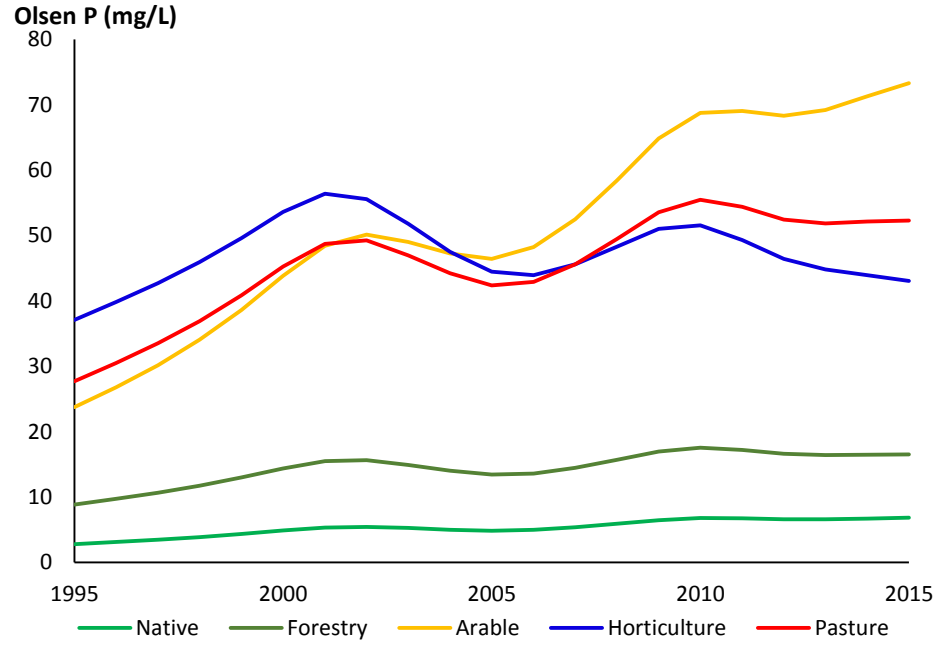

Figure 15: Change in mixed modelling average Olsen P 1995-2015 by land use.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, an assessment of sites meeting targets could only be done once an adequate number of sites representative of the region had been sampled, and data are presented for 2005-2015. Measurements below lower targets (5-25 mg/L depending on land use and soils type; Appendix III) are considered to indicate deficiency in P, while measurements above the upper target (50 mg/L, Appendix III) are considered to indicate increased risk of losing P from land.

The increases in Olsen P in soils under arable and horticulture were reflected in declines in the percent of sites meeting the high target for Olsen P, with similar but smaller changes for pasture (Figure 16). Interestingly, although average Olsen P increased slightly for forestry (Figure 15), there was an increase in the percent of sites below the lower Olsen P target, i.e. deficient P status (Figure 17).

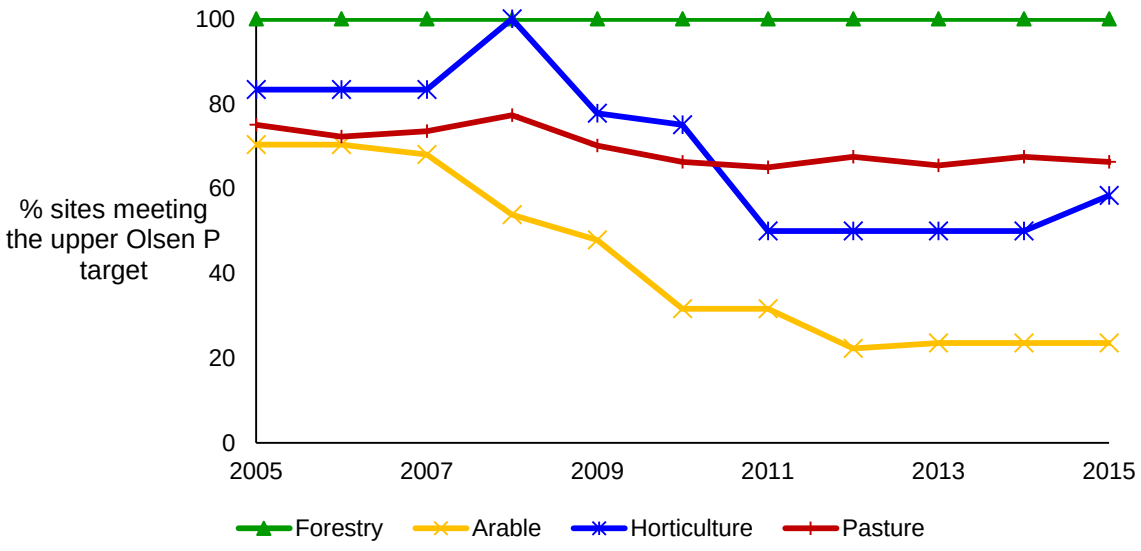

Figure 16: Change percent sites meeting the upper Olsen P target 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.

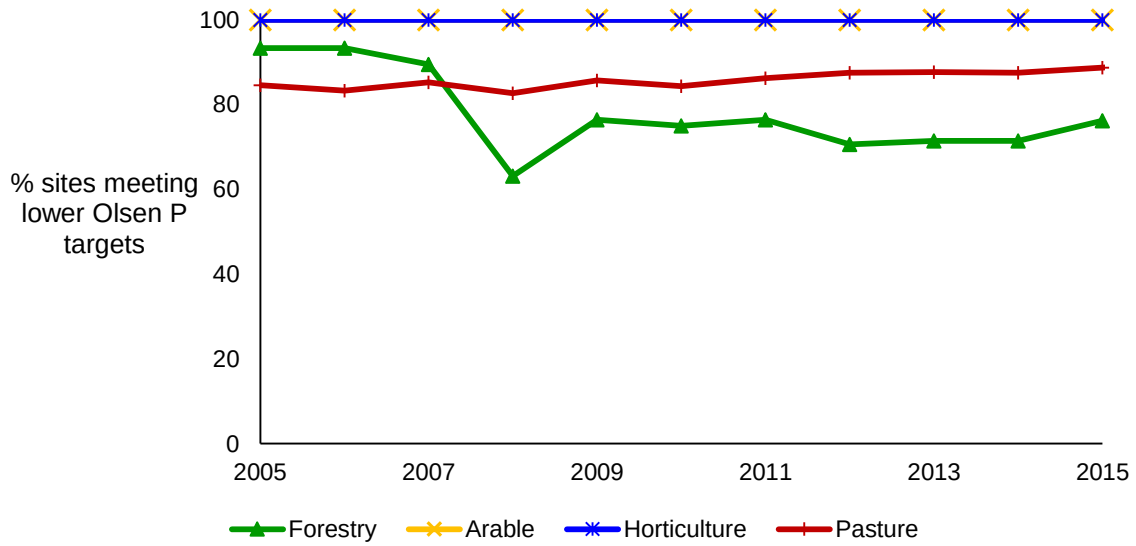

Figure 17: Change percent sites meeting the lower Olsen P target 2005-2015 by land use.

Changes in total N 1995-2015.

For the overall dataset, mixed modelling total N results showed a nonsignificant (at the 5% level), non-linear pattern over time (Figure 18) and there were no significant differences (at the 5% level) in pattern or linear trend between soil orders (Figure 19). Conversely, the linear trend did vary significantly (at the 5% level) between land uses (Figure 20). Notably, arable declined, while all the other land uses showed an increase over time, with the increases for native and pasture land uses significant at the 5% level.

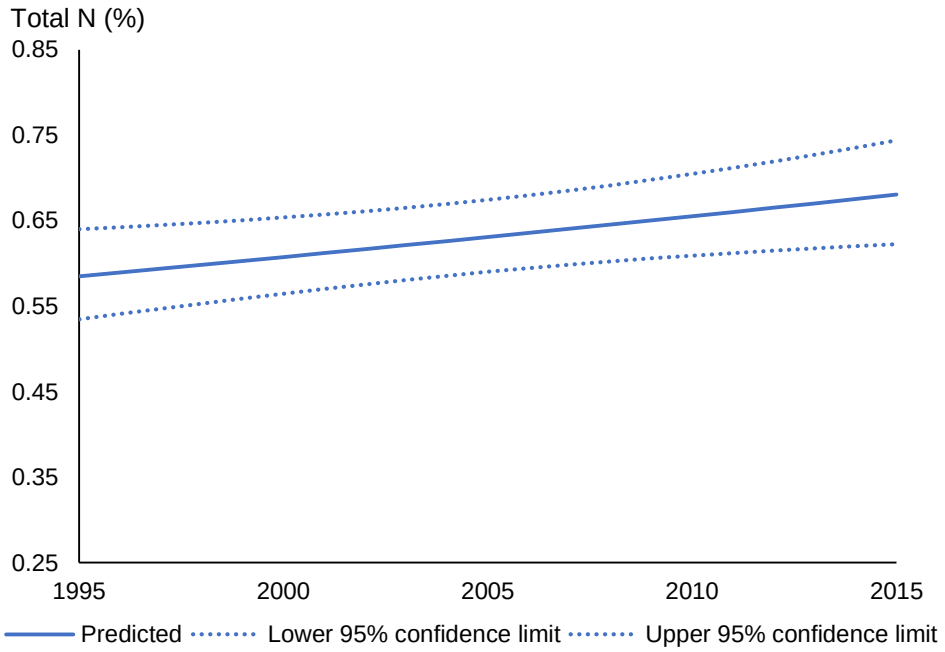

Figure 18: Change in mixed modelling average total N 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.

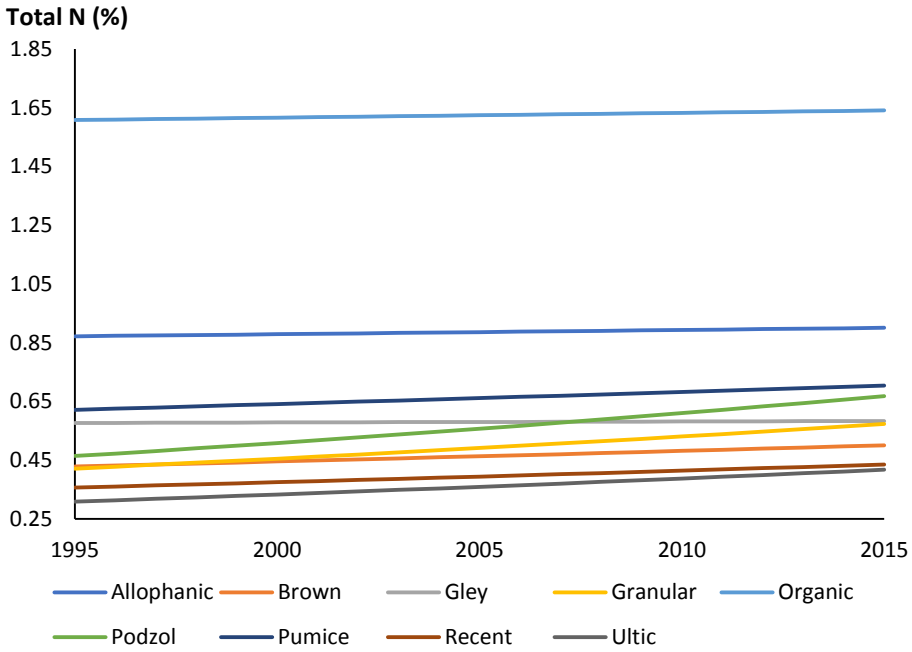

Figure 19: Change in mixed modelling total N 1995-2015 by soil order.

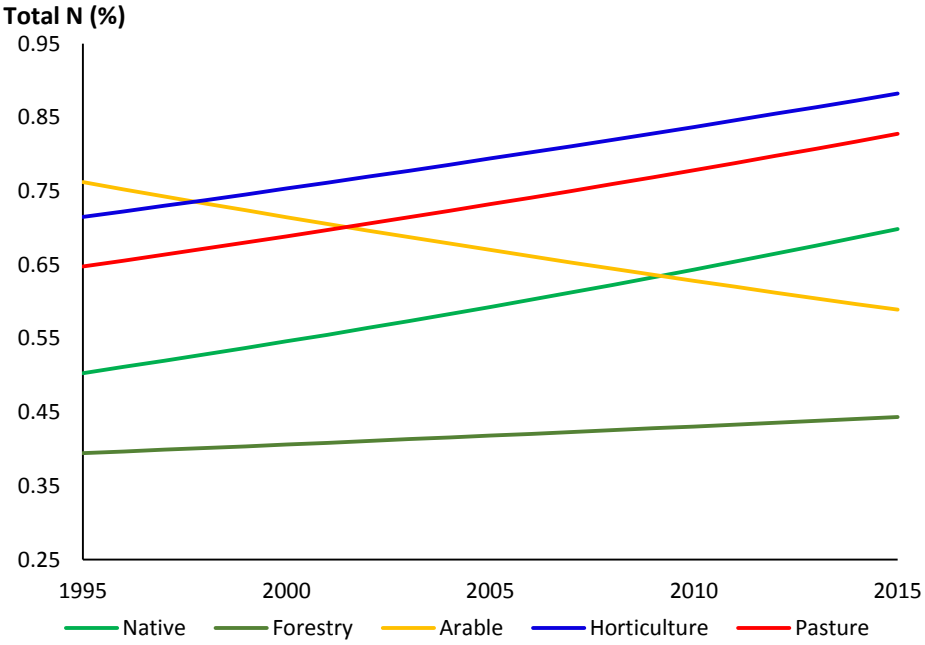

Figure 20: Change in mixed modelling total N 1995-2015 by land use.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, assessment of sites meeting target could only be done once an adequate number of sites representative of the region had been sampled, and data are presented for 2005-2015. Measurements below lower targets (0.1% for forestry and 0.25% for other land uses, Appendix III) are considered to indicate depleted nitrogen soil status, while measurements above the upper target (0.7%, Appendix III) are considered to indicate increased risk of losing N from land.

Generally, there is an analogous relationship between mixed modelling results from 2005-2015 with changes in the percentage sites meeting the total N upper target (Figure 21). Increases in total N in soils under pasture and horticulture were reflected in declines in the percentage of sites meeting the high target. However, declines in total N in soil under arable were not sufficient

to obviously increase the percentage of sites meeting the high target. However, from 2011, a small percentage of arable (and forestry) sites no longer met the lower target for total N (Figure 22). Before that, all sites met the lower total N target.

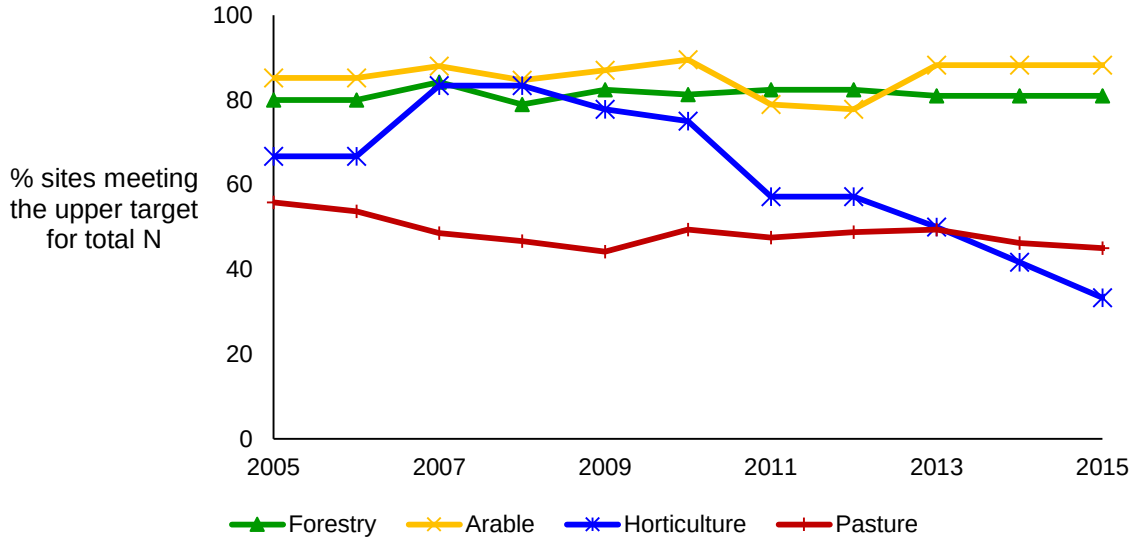

Figure 21: **Change in percent sites meeting the upper target for total N 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.**

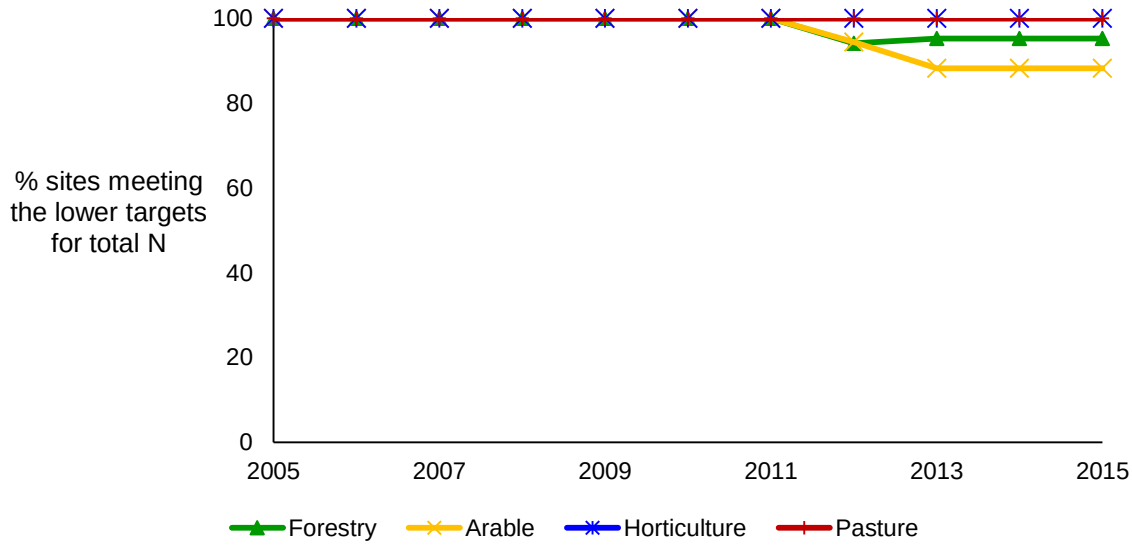

Figure 22: **Change in percent sites meeting the lower target for total N 2005-2015 by land use.**

Changes in AMN 1995-2015.

For the overall dataset, mixed modelling results showed there was a significant (at the 5% level) linear trend over time, but little evidence of any non-linear trend (Figure 23). All soil orders except Podzols and all land uses except arable showed increases in AMN with time, with significant increases at the 5% level in Allophanic, Granular and Pumice soils (Figure 24) and the horticulture land use (Figure 25). The decline observed for podzols was not significant due to low numbers of samples (Figure 24).

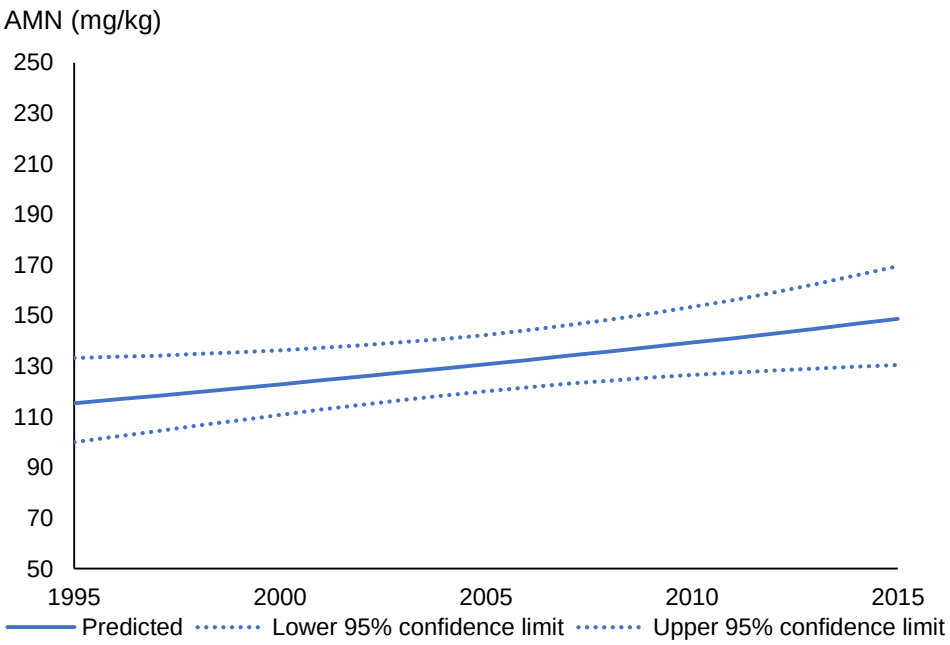

Figure 23: **Change in mixed modelling average AMN 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.**

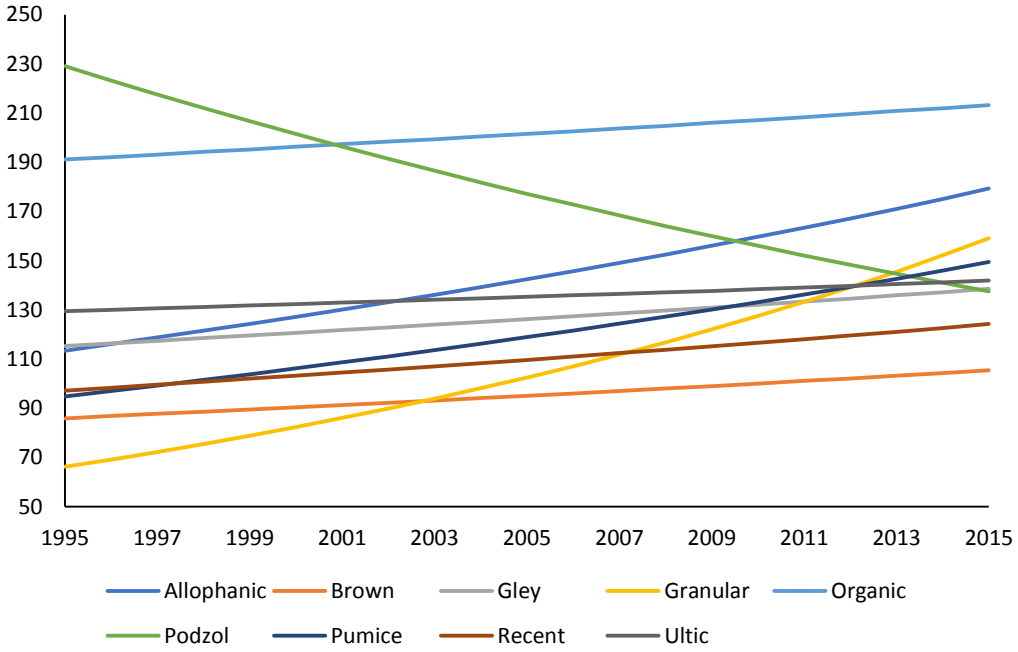

Figure 24: **Change in mixed modelling average AMN 1995-2015 by soil order.**

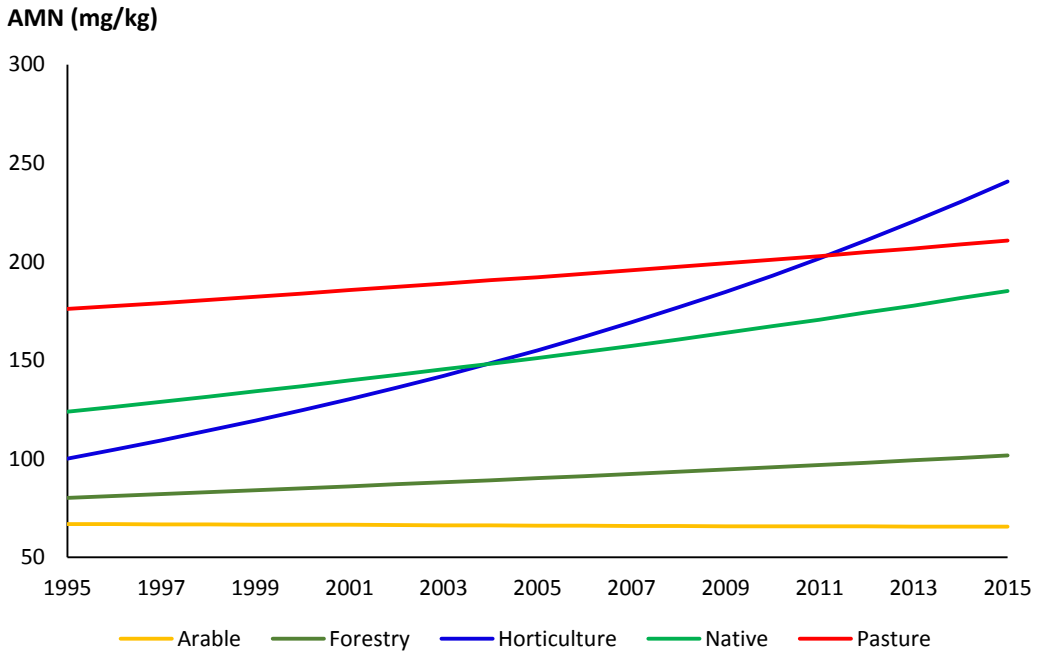

Figure 25: Change in mixed modelling average AMN 1995-2015 by land use.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, assessment of sites meeting targets could only be done once an adequate number of sites representative of the region had been sampled, and data are present for 2005-2015. Measurements below lower targets (50 mg/kg for pasture, 20 mg/kg for other land uses, Appendix III) are considered indicative of low levels of nitrogen that can be potentially mineralised from soil organic matter, which also relates to microbial activity. There is currently no upper target for AMN.

Consistent with the mixed modelling results, only arable showed a decline in meeting the AMN (low) targets, while 100% of all other land uses met targets (Figure 26).

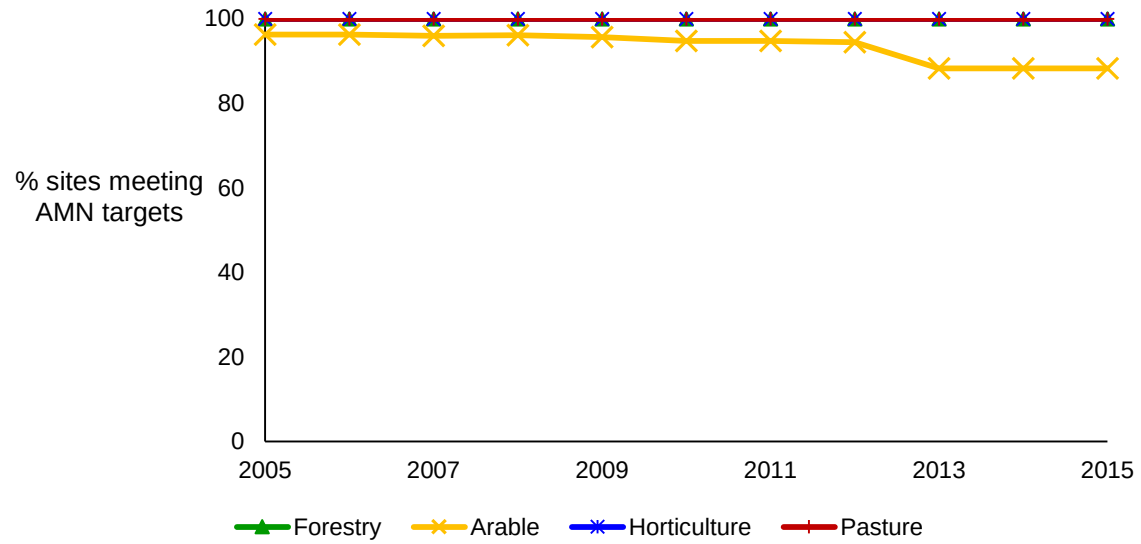

Figure 26: Change in percent sites meeting the target for AMN 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.

Changes in total C 1995-2015.

For the overall dataset, mixed modelling results showed no significant (at the 5% level) non-linearity in the pattern over time (Figure 27). When soil order and land use were assessed, there was a significant (at the 5% level) increase for total C in Podzols (Figure 28) and a significant decrease (at the 5% level) in arable land use (Figure 29). Most of the Podzol soils were under native or forestry land use. Notably, the pattern for arable declined, while all the other land uses increased over time.

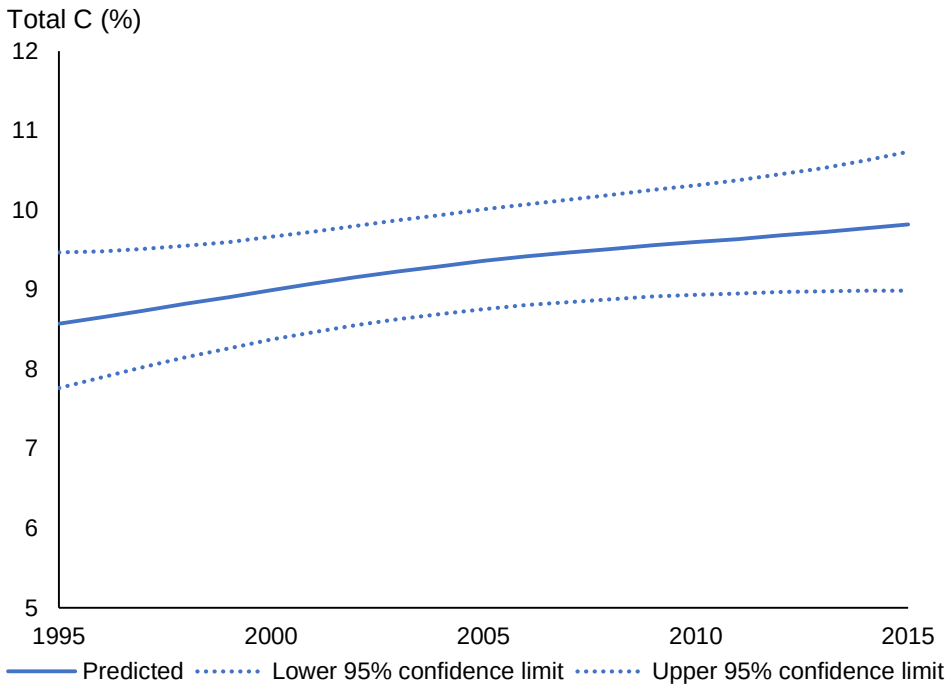

Figure 27: **Change in mixed modelling average total C 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.**

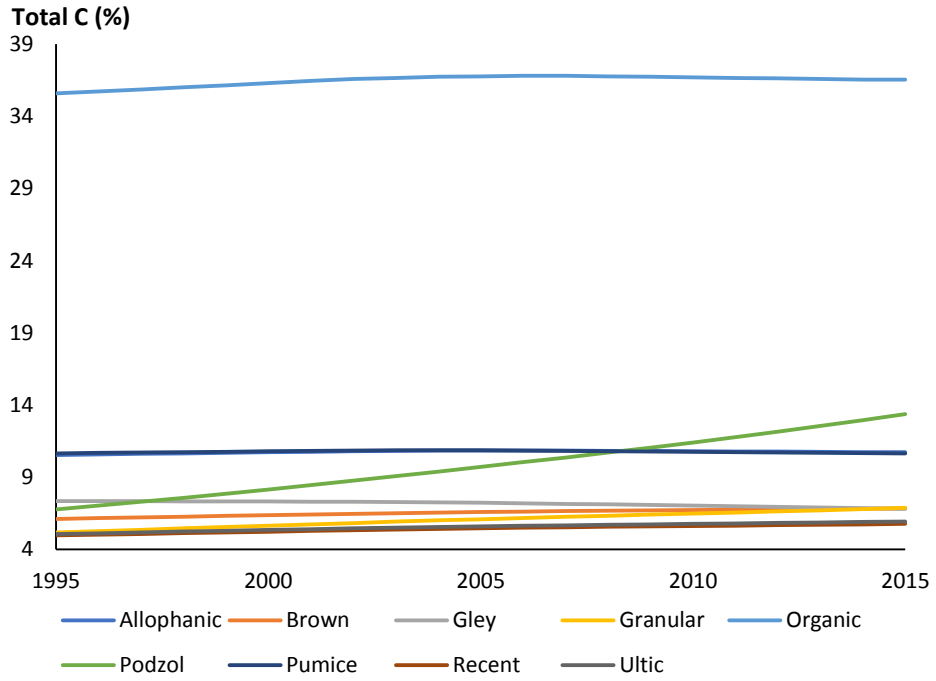

Figure 28: **Change in mixed modelling average total C 1995-2015 by soil order. Note the change in scale due to Organic Soils.**

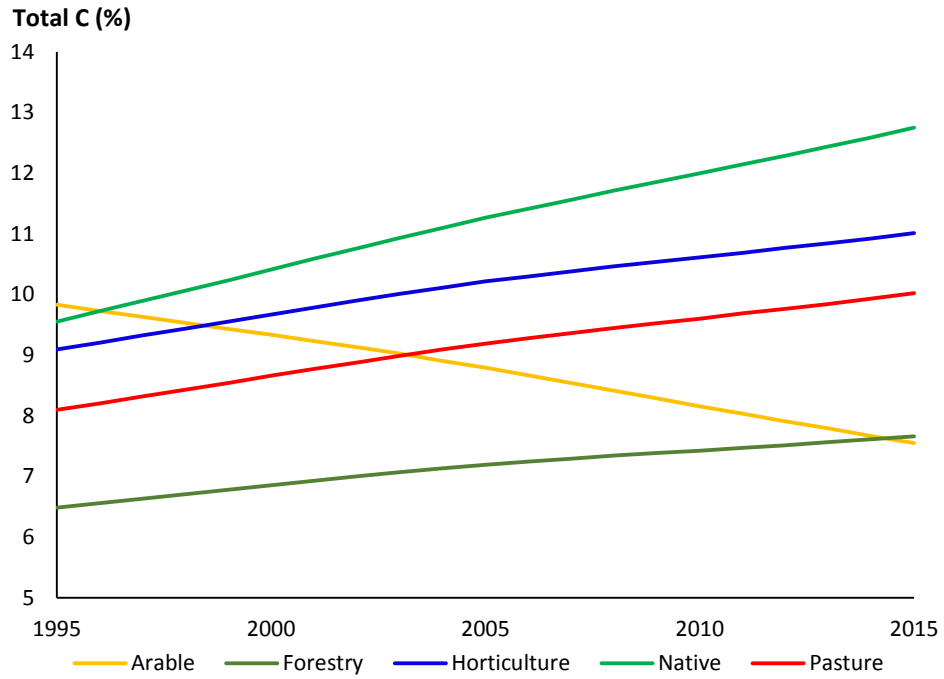

Figure 29: Change in mixed modelling average total C 1995-2015 by land use.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, assessment of sites meeting targets could only be done once an adequate number of sites representative of the region had been sampled, and data are present for 2005-2015. Measurements below lower targets ((2-3% depending on soil type – note that Organic soils must have 18% C to be classified as Organic so could never fail, Appendix III) are considered indicative of depleted soil carbon and soil organic matter. There is no upper target for total C.

Despite the changes observed in the mixed modelling results in Figure 29, there appeared little change in the percent of sites meeting the total C targets, except for forestry. Although total C content for forestry sites as a group increased, some sites had decreased total C after harvest leading to their not meeting targets (Figure 30).

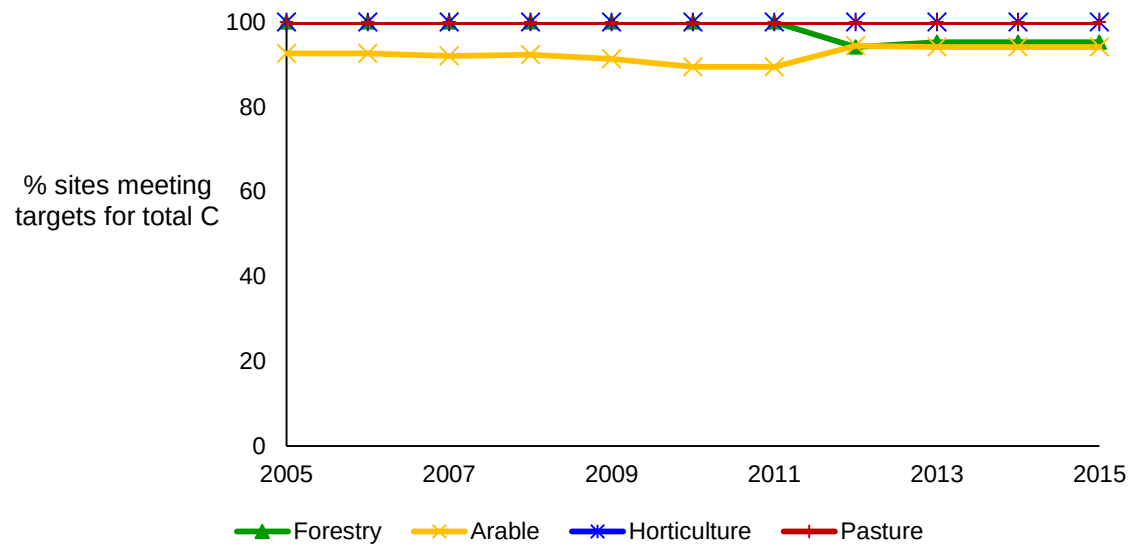

Figure 30: Change in percent sites meeting the target for total C 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.

Changes in pH 1995-2015.

For the overall dataset, mixed modelling results showed evidence of a non-linear pattern over time (Figure 31), while there were non-significant (at the 5% level) differences between soil orders (Figure 32) and land uses (Figure 33).

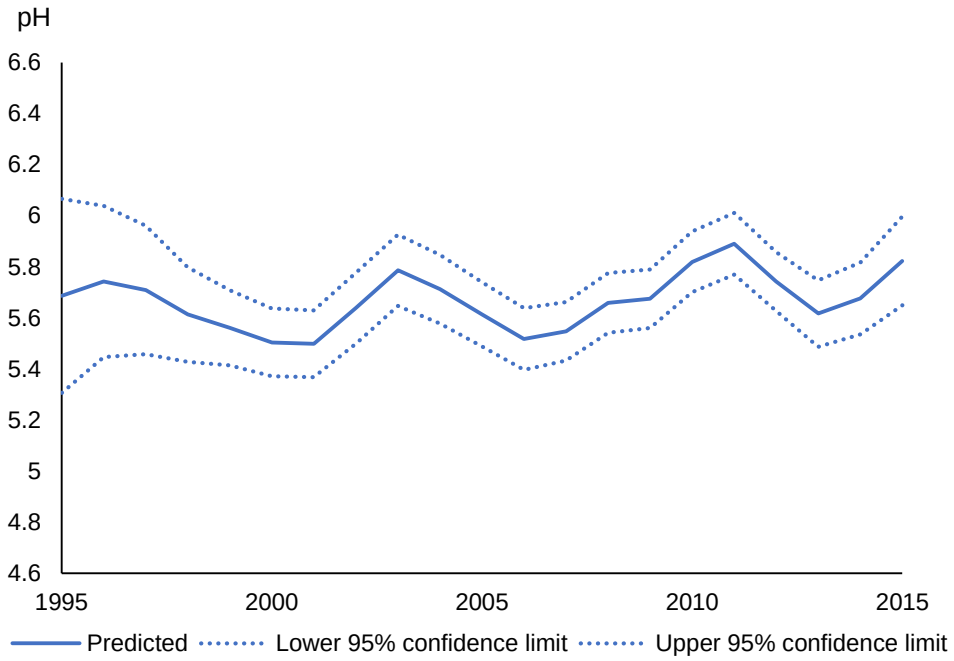

Figure 31: Change in mixed modelling average pH 1995-2015 for all sites (all land uses and soil orders) with 95% confidence limits.

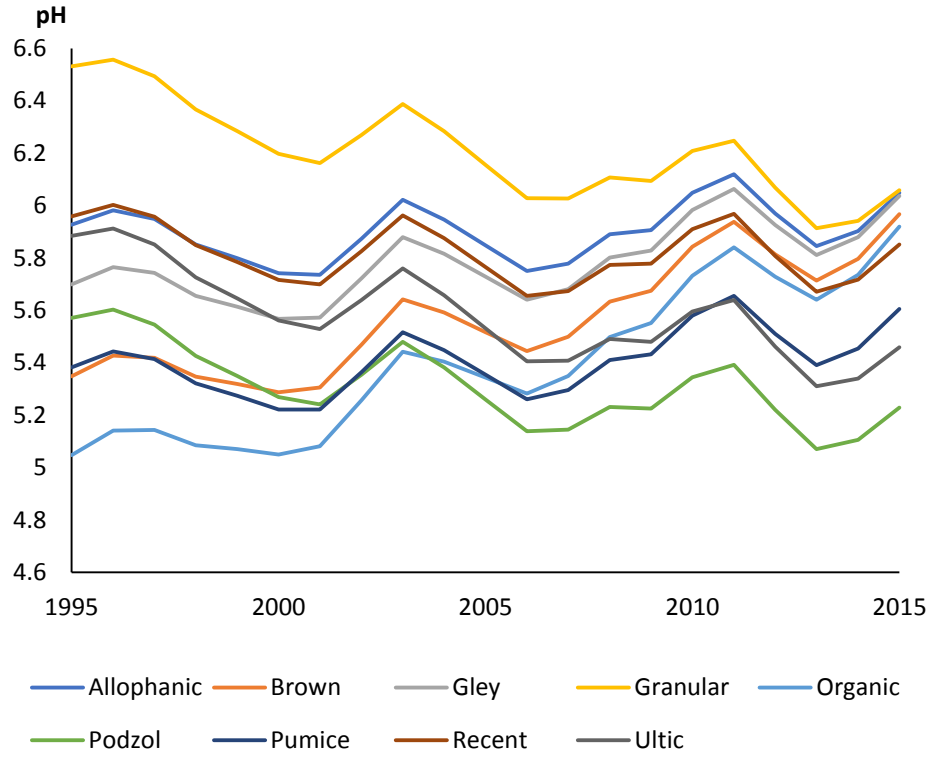

Figure 32: Change in mixed modelling average pH 1995-2015 by soil order.

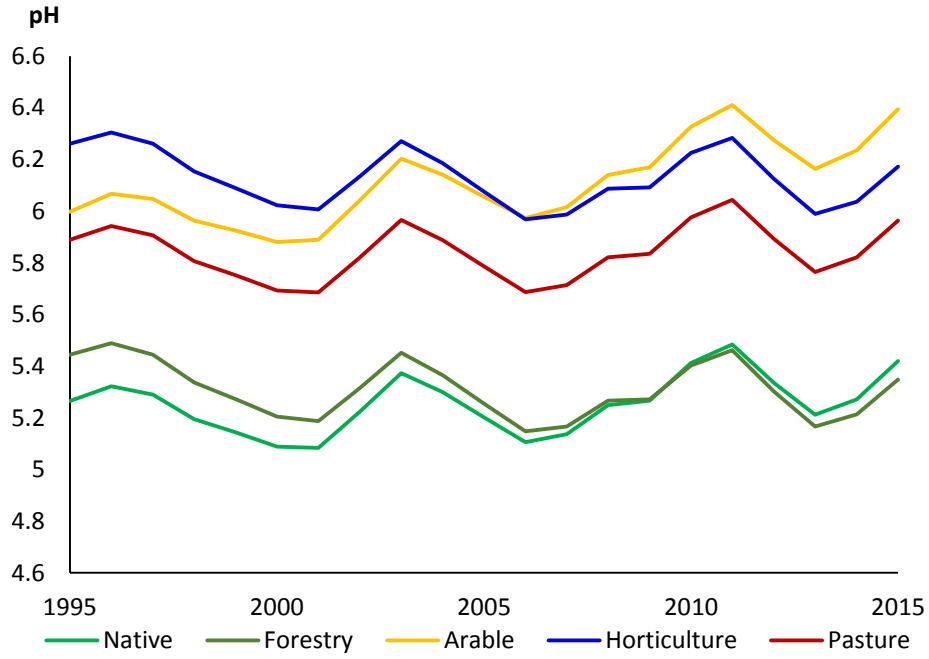

Figure 33: Change in mixed modelling average pH 1995-2015 by land use.

Mixed modelling data are presented for 1995-2015 as the modelling process increased the effective number of samples in each year. However, assessment of sites meeting targets could only be done once an adequate number of sites representative of the region had been sampled, and data are present for 2005-2015. Measurements below the lower targets (3.5-5.5 dependent on land use and soil type; Appendix III) are considered indicative of increased acidification, while those above the upper target (6.6-7.6 dependent on land use and soil type; Appendix III) are considered indicative of increased alkalisation.

Consistent with the mixed modelling results, there appeared little change in the percent of sites meeting the lower pH target, except for a slight decrease for pasture (Figure 34). All sites met the upper targets (data not shown).

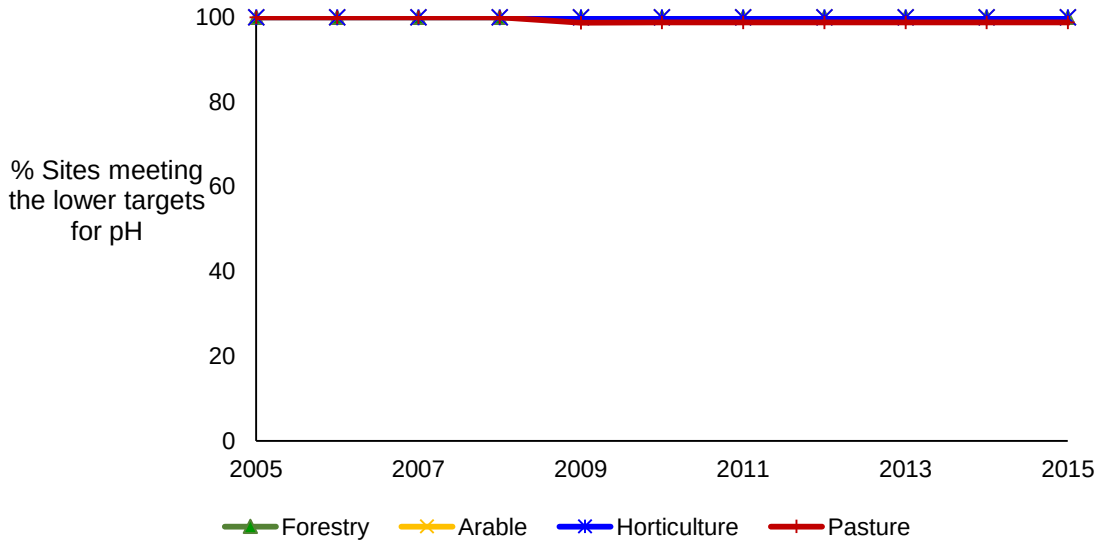

Figure 34: Change in percent sites meeting the lower target for pH 2005-2015 by land use. All native sites meet targets (100%) in all years so are not shown.

Results for 2015

Soils in 2015 under native vegetation were on average acidic (pH 5.4), high in total C (mineral soils 15.3%), low in Olsen P (7 mg/L), low in bulk density (0.56 t/m3) and had high macroporosity (25% v/v). Soils under forestry had generally similar characteristics to soils under native but had lower total C 8.6%). Soils under pasture were on average less acidic (pH 6.0) than forest soils, but with more Olsen P (49 mg/L), and lower macroporosity (9%). Soils under horticulture were similar to pasture. Soil under arable were most different from soils under native vegetation. These had low total C (5.0%), indicating loss of SOM, very high Olsen P (91 mg/L) indicating excessive fertility, and bulk density (0.94 t/m3), indicating compaction. Arable soils also had high pH (6.4).

Discussion

Soil does not remain constant but is constantly changing. Some processes are natural but human activity can accelerate these processes or cause new processes resulting in changes to soil quality. These changes can be positive, e.g. increased vegetative coverage can reduce erosion, but many anthropogenic activities increase pressure on the soil resource and reduce the soils capacity to carry out functions and services. Ministry of Primary Industries (2015) identified four drivers of pressure, agricultural intensification, land use change, climate change and legacy effects from forest clearance, land development, fertiliser application and cultivation. Monitoring allows assessment of the severity and extent of any adverse effects. On an area weighted basis, the main soil quality issues for productive land in the Waikato region occurred on pastoral land, but issues also occurred on arable, horticultural and forestry land. (Figure 3).

Pastoral land

There is extensive land under pasture in the Waikato region, about 1.4 million ha. The main soil quality concerns on pastoral land include surface compaction and excessive nutrients. Surface compaction is assessed by two indicators, bulk density and macroporosity. As soils become more compact, bulk density increases and macroporosity increases. Macroporosity is considered the better indicator of soil physical quality as it is sensitive to structural changes (Drewry 2008; Ball et al. 2007).

All sites met the upper target for bulk density (Figure 7), but this result reflects the insensitivity of the bulk density measurement for the light volcanic soils found in the Waikato. In contrast with bulk density, only 25% of pastoral sites meet the lower macroporosity target of 10% macropores in 2015 (Figure 11). However, this is an improvement on the previous three years and is reflected in a significant increase in modelled macroporosity over the last five years (Figure 10). This trend needs to continue to meaningfully improve soil quality.

Yet, soils under pasture have had low average macroporosity since soil quality monitoring began. When soils are already compacted, it is difficult to compact them further and many pastoral soils appear to have come to a steady state, i.e. they are unlikely to become more compact under the present land use. Nearly three quarters of pastoral sites were below the target of 10% macroporosity (Figure 11), which showed the widespread nature of compaction. At such compacted pastoral sites, the grazing animals reduce vegetative cover, while hooves physically compacted the soil surface (treading) leading to poor structure, such as surface caps, platy structure, or increased clods of massive structure (Drewry et al. 2008; Bilotta et al. 2007). This in turn can decrease soil infiltration capacity, promoting generation of surface runoff causing localised flooding and bank erosion (Taylor et al. 2009). Sediment, pathogen and particulate P fractions in overland flow also increase with treading due to increased soil disturbance and decreased protection from erosion by grass cover leading to increased transport of contaminants (Bilotta et al. 2007; McDowell et al. 2003a). In addition, plant uptake of N and P was lower in compacted soils due to shallower rooting, and reduced available N concentrations (Lipiec & Stepniewski 1995). Increased effects are seen with increased intensification, e.g. stocking density (Bilotta et al. 2007).

Recovery of macroporosity, once pastoral animals are removed, varies depending on soil type, the extent of initial damage, management methods, and climate, but may take anything from weeks to months, or years (Drewry 2006). It can be relatively quick for moderate compaction events, e.g. from a macroporosity measurement of 12% to 18% in 18 months (Drewry et al. 2004), although complete recovery from a larger event with lower macroporosity may take many years (Drewry & Paton 2000).

Damage to the soil by grazing animals can be minimised by management of livestock and land. Bilotta et al. (2007) discussed several options including reducing stocking density, moving livestock off wet pasture onto hard standings or into housing, or reducing the length of the grazing season. In some soils, installing drainage can increase the soils resistance to damage if the watertable can be kept below 500 mm. Tillage and reseeding can break up a surface pan but also accelerate the decomposition of SOM, which could lead to an even worse situation.

Nutrients were assessed by two indicators, Olsen P and total N. Olsen P estimates plant available P, thus fertility of a soil, and is a factor in assessing the risk of P loss from soil (McDowell et al. 2003b). Total N measures all the different fractions of N in soils. This measurement is influenced by the N fertility status of a soil as well as the amount of soil organic matter, which provides sites for N adsorption.

There were two main risks associated with nutrients in soil, too much and too little. Too much leads to increased risk of transferring nutrients to water bodies where they can contribute to changes in the composition of local biological communities, the formation of algal blooms, or directly impact human and animal health (Buckley & Carney 2013; Monaghan 2012). Fertilisation with N significantly increased losses of N in drainage (Monaghan et al 2005). When too much N and P are present in surface water, algae grow faster than ecosystems can manage. Substantial increases in algae harm water quality, food resources and habitats, and decrease the oxygen that fish and other aquatic life need to survive. Some algal blooms are harmful to humans and animals because they produce elevated toxins and bacterial growth. Human infants are vulnerable to nitrate in drinking water, which is often sourced from groundwater or surface water. Conversely, deficient nutrient status reduces plant growth and productivity

Results showed average Olsen P and total N are within the high or excessive categories for these indicators and have increased significantly. In keeping with this increased soil fertility (Figures 15 & 20), the average number of sites meeting the upper Olsen P and total N targets has decreased (Figures 16 & 21). This increase in fertility appears to be widespread with 34% and 55% of pastoral sites in 2015 not meeting the targets for Olsen P and total N, respectively.

Of note was the C:N ratio decreasing or narrowing as average total N increased more quickly than average total C. Total C is indicative of organic matter, which retains N as one of its functions (Dick & Gregorich 2004). Narrow C:N ratios have been associated with losses of N (Lovett et al 2002; Tiquia & Tam 2000). A possible mechanism could be reduced competition of available N by microorganisms and consequently enhanced decomposition of plant residues by maintaining high microbial activity (Kumar & Goh 1999). This hypothesis is supported by the AMN results that are generally higher for pastoral sites than for other land uses (Figure 25).

As could be expected, the results presented here are consistent with Ministry for the Environment & Statistics NZ (2017), which found nitrogen leaching from agricultural soils was estimated to have increased 29 % from 1990 to 2012, nitrate-nitrogen concentration was 10 times higher and dissolved reactive phosphorus concentration was 2.5 times higher in the pastoral class compared with the native class for the period 2009–13.

The accumulation of P has been referred to as legacy P (Motew et al. 2017), which can provide a long-term source of P to plants, as a nutrient and in the wider environment, as a contaminant. Enclosed water bodies, such as lakes can be significantly affected by legacy P and water quality is more vulnerable to heavy rain events when catchments have higher amounts of legacy P

(Motew et al. 2017). Increased heavy precipitation is expected with climate change (Intergovernmental Panel on Climate Change 2014). The greatest risk of P loss is on soils that are poorly drained, have lower structural resilience or are on slopes, while the greatest risk of N loss is on very well drained and excessively drained soils (Monaghan 2012). The air and water quality impacts of the N exports in agricultural systems have been reported as cause for great concern (Davidson et al. 2012). When linked together, surface compaction and excessive nutrient concentrations in pasture have been linked to modified soil hydrological behaviour and, ultimately, the deterioration of water quality in ground and surface waters (Biolotta et al 2007).

Diffuse contamination of surface waters with P and N could be reduced by reducing surplus nutrient flows to groundwater and waterways by reducing surface runoff (overland flow) during high intensity storms and maximising the efficiency of fertiliser use. Methods could include applying no more than the amount of fertiliser needed for production (Buckley & Carney 2013), managing critical source areas (McDowell & Srinivasan 2009) and riparian planting (Lee et al. 2003; Parkyn et al. 2003), e.g. A management practice of sowing a low-P-requiring grass in near stream areas has been suggested (McDowell et al. 2014).

Conversely, deficient P nutrient status was apparent at 11% pasture sites (Figure 17), despite increased phosphorous fertility at most and on average for all pasture sites. These sites with P deficit are all on hilly country where topdressing with aircraft may be required. Some of these sites have not met the lower pH target in recent year (Figure 34), suggesting they are not receiving sufficient lime. Low phosphorous status has been recognised as a major factor limiting pasture production on hill country soils (Gillingham et al 2007; Edmeades et al. 1984) but economic application of fertilisers and lime appears a major challenge.

Arable land

Although the extent of arable land in the Waikato region is small (about 18,000 ha, with about 11,000 ha in maize in 2015), local impacts can be considerable (Figure 35). The main soil quality concerns on arable land include loss of total C and N, indicating loss of soil organic matter (SOM), compaction and excessive nutrients.

Soil organic matter (SOM) is considered a key soil attribute as it affects many physical, chemical and biological properties that control soil services such as productivity, the adsorption of water and nutrients, and resistance to degradation (Dick & Gregorich, 2004). SOM is essential for the viability and life-sustaining function of the soil. For instance, organic acids (e.g. oxalic acid), commonly released from decomposing organic residues and manures, prevents phosphorus fixation by clay minerals and improve its plant availability. Also, polysaccharides (sugars) bind mineral particles together into microaggregates. Glomalin, a SOM substance that may account for 20% of soil carbon, glues aggregates together and stabilises soil structure making soil more resistant to erosion, but porous enough to allow air, water and plant roots to move through the soil.

A direct effect of low SOC is reduced microbial biomass, activity, and nutrient mineralisation due to a shortage of energy sources and loss of habitat. In the soils of the Waikato region, aggregate stability, infiltration, drainage, and airflow are reduced. Scarce SOC results in less diversity in soil biota with a risk of the food chain equilibrium being disrupted, which can cause disturbance in the soil environment (e.g. plant pest and disease increase, accumulation of toxic substances etc.). Of particular significance to water quality in the Waikato region is SOM's role in retaining nitrogen in the soil.

The significant decrease in total C (at the 5% level) for arable land use, indicating loss of SOM is particularly notable as total C for all the other land uses increased over time (Figure 29). Also, average total C is considerably lower for arable than for any other land use. Similarly to total C, total N and AMN for arable declined, while all the other land uses showed an increase over time (Figure 20). Loss of total C, total N and SOM leads to a consequent decrease in biological contribution to fertility and soil resilience, as indicated by the AMN results (Kumar & Goh 1999).

In arable systems, changes in SOM tend to be controlled by the amount of organic C supplied in crop residues and the preservation of microaggregates, which protect SOM within them (Kumar & Goh 1999; Rasmussen et al. 1980). Microaggregates are broken down during cultivation exposing the C within them to oxidation, while plant residues may be minimal if the whole plant is harvested. Irrigation in dryer locations can also assist decomposition of SOM by keeping soil conditions suitably moist for microorganisms to be active.

Figure 35: A stock water supply pond (above) filled with sediment originating from an upstream field being cropped for potatoes (below) after a one in two year rain event.

Yet, despite the changes observed in total C content, there appeared little change in the percent of sites meeting the total C targets (Figure 30). Similarly, despite declines in total N in soil under arable the percentage of sites meeting the high target (too much N) did not obviously change (Figure 21). In comparison, from 2011, a small percentage of arable sites no longer met the lower

target for total N (Figure 22) indicating decreased soil fertility due to declines in SOM. Before that, all sites met the lower total N target. Also, only arable showed a decline in meeting the AMN targets, while 100% of all other land uses met targets (Figure 26), again consistent with declining SOM and reduced N fertility.

SOM retains N as one of its functions (Dick & Gregorich 2004). Of note was the C:N ratio decreasing or narrowing as average total N increased more quickly than total C. Narrow C:N ratios have been associated with losses of N (Lovett et al 2002; Tiquia & Tam 2000) and with decreased mineralisation of N (Janssen 1996). However, cultivation can itself lead to greater loss of C than N, thus narrowing the C:N ratio (Campbell & Souster 1982). Results for AMN appeared consistent with Janssen (1996) as arable was the only land use measured where average AMN content did not increase and where meeting the AMN target declined.

Maintenance and improving SOM content where cropping is continuous is critical to maintaining soil quality. Long-term studies have consistently shown the benefit of manures, adequate fertilisation, the return of plant material, including legume cover crops and crop rotation on maintaining agronomic productivity by increasing C inputs into the soil (Diekow et al. 2005, Dick & Gregorich 2004; Kumar & Goh 1999). Nevertheless, even with crop rotation and manure additions, continuous cropping results in an overall decline in SOM (Reeves 1997).

Re-establishment of pasture appears the most practical method of recovering SOM for these systems. The recovery of carbon and SOM in arable land including a lightly grazed pasture rotation of about four years or longer has been found very variable with no sites re-established to the levels found under permanent pasture (Kirschbaum et al. 2017). This result is consistent with studies looking at the regaining of carbon after erosion, where recovery of SOM has been seen to take 14-45 years (Larney et al. 2016; Sparling et al. 2003b), and with Hedley et al. (2009) who found carbon accumulated at a mean rate of 4.07 mg/cm3 per year at sites in the central North Island that had undergone deforestation and conversion to pasture over 20 years.

In addition to the loss of SOM, total C and total N, increased compaction and excessive P were apparent for arable land. Increased compaction was indicated by the increased average bulk density and decreased macroporosity (Figures 6 & 10). Consistent with these results, the number of sites meeting targets for these two indicators had decreased (Figures 7 & 11). Compaction in arable land can be minimised with the adoption of techniques such as precision agriculture and not driving on the soil when it is wet (Raper 2005). Similarly, increased P fertility was indicated by increased Olsen P and reflected in declines in the percent of sites that met the high target for Olsen P (Figures 15 & 16). The effects of compaction and excessive nutrients were discussed in the pastoral section above.

Horticulture

The extent of horticultural land in the Waikato region is very small (about 2000 ha). The main soil quality concerns on horticultural land include compaction and excessive nutrients. Increased compaction was indicated by a considerable decline in macroporosity but this was not significant due to the low effective sample size - of 4.1 in 2015 (Table 5 in Appendix IV). However, soils under horticulture also showed a large decrease in meeting the lower macroporosity target of 10% (Figure 10).

Similarly, increased nutrient fertility was indicated by increased total N and Olsen P and reflected in declines in the percent of sites that met targets (Figures 15 & 16, 20 & 21). Consistent with increased fertility, there were significant increases at the 5% level in AMN with time, suggesting increased microbial activity (Figure 25). As discussed in the pastoral section above, the effects of compaction and excessive nutrients also apply to horticultural land.

Forestry

About 285,000 ha of land in the Waikato is under production forestry. About ¼ to ⅓ of forestry sites did not meet the low bulk density and high macroporosity targets, indicating loose soil (Figures 7 & 12). No significant trends in either indicator were noted indicating the situation was stable. Many soils within the region are naturally 'light-textured' and with an 'open' structure (e.g. Pumice) or unstable, making them vulnerable to erosion. Trees reduce the amount of rain impacting the ground and increase the drainage time, thus reducing erosion risk, while bare ground has a higher erosion risk, e.g. peak flows from pine catchments are 20% of those from pasture (Duncan 1995). Thus, forestry is a land management option that allows production on what would otherwise be unproductive land. However, care is needed at harvest or conversion of such land to another land use, where this land is made bare.

In comparison, about 10% of forestry sites in 2014 and 2015 failed to meet the low macroporosity target. Also, a small percentage of forestry sites from 2011 no longer met the lower target for total N, consistent with the loss of SOM, which could be due to erosion or mixing of topsoil and subsoil (Figure 22). These were sites where logging had occurred, disturbing the soil, and new saplings were still establishing. Ground-based logging equipment may cause soil disturbance by displacing or mixing litter and soil, and/or compacting the soil. In particular, the effects of soil compaction may last for decades unless remedial action is taken, while loss of topsoil may lead to reduced production in subsequent harvests (Murphy et al 2004). The effects of compaction were discussed in the pastoral section above.

Interestingly, although average Olsen P increased slightly for forestry (Figure 15), there was an increase in the percent of sites below the lower Olsen P target, i.e. deficient P status (Figure 17). This result suggests fertiliser management of production forestry varies considerably.

Conversion of forestry to pasture on pumice soils

Land use intensity and stock density on all soil types has an impact, but it is notable on pumice soils where considerable conversion of land from pine plantations to pasture has taken place. Pumice soils are very light with weak structure and erode easily when disturbed (Paripovic 2011). As described in the Forestry section above, it is a management practice to leave erosion prone soils, such as Pumice soils, in native bush or planted in production forestry to help control erosion. Intensification of agriculture, generally, is reported to have negative impacts on water quality, both in New Zealand (Monaghan et al. 2007) and overseas (Taniwaki et al. 2017; Matson et al. 1997). The inherent lightness and weak structure of Pumice soils may make them more vulnerable to these impacts than Allophanic or Granular soils, both of which are weathered volcanic soils and traditionally more commonly used for pastoral land use. Paripovic (2011) reported there was increased soil compaction in the A horizon of Pumice soils on recently converted sites compared to pine forest sites. Also, the plant root depth of much of the pasture on farms recently converted from forest was relatively shallow (about 10 cm), making pasture especially prone to moisture stress during dry periods. The effects of compaction were discussed in the pastoral section above.

Landscape recontouring of land converted from forestry to pasture was commonly observed while collecting soil quality monitoring samples. Recontouring land for viticulture in New Zealand has degraded soil structure, lowered subsoil bulk density and decreased aggregate stability (Scott 2013), while forest to pasture conversion and increasing grazing intensity can both result in loss of soil carbon and SOM (Steffens et al. 2008; Verde et al 2008, Alfredsson et al. 1998). Nevertheless, SOM will likely recover over 3-4 decades to a new steady state (Schipper et al. 2017; Hedley et al. 2009).

There are also considerable effects on hydrology as peak flows during floods for forest are 20% of those from pasture, while average flow, annual flood exceedance probability and sediment yield for forests are half those from pasture (Ausseil & Dymond 2010; Duncan 1995). The

differences in flow can be attributed to greater interception of rain by pine trees and greater soil moisture storage.

Thus, the conversion process can be expected to result in loss of soil carbon and SOM, increased surface compaction and crusting, while animal grazing also tends to increase surface compaction. The increased compaction may result in increased transport of sediment and contaminants with peak-flows causing localised flooding and bank erosion (Taylor et al. 2009).

Soil acidification

There were no clear trends with soil pH, the indicator for acidification and nearly all sites met targets for pH. So, acidification appears not to be an issue in the Waikato region.

Conclusions

Soil quality changes for different soils and land uses across the Waikato region for 2005-2015 have been identified. Overall, 10% of managed soil quality sampling sites corrected for land area in the region met all seven indicators in 2015. This result is similar to the percentage of sites meeting all seven indicators for the preceding four years, but is down from a high of 17% in 2006.

Land use

The main issues for pastoral land were compaction and excessive nutrients with significant (at the 5% level) trends for macroporosity, Olsen P, total N and AMN. There are about 1.4 Mha in pasture making this the most extensive productive land use in the region. Pastoral sites have had low average macroporosity since soil quality monitoring began. Recently, there has been an improvement in macroporosity over 2013-2015 but this trend needs to continue to meaningfully improve soil quality. In 2015 25% of pastoral sites met the lower macroporosity target. Average Olsen P and total N are within the high or excessive categories for these indicators and have increased significantly, while the average number of sites meeting the upper Olsen P and total N targets has decreased. In 2015, 66% and 45% of pastoral sites met the targets for Olsen P and total N, respectively.

The main issues for arable land were loss of total C (significant at the 5% level) and N, indicating loss of soil organic matter (SOM), compaction and excessive nutrients. Average total C is considerably lower for arable than for any other land use, while average total N in arable is only higher than forestry. Both total C and total N are trending lower indicating loss of SOM. Loss of SOM leads to a consequent decrease in biological contribution to fertility and soil resilience, as indicated by average AMN, a decline in meeting the AMN targets, a lower C:N ratio and a small percentage of arable sites no longer meeting the lower target for total N. However, despite the changes observed in total C and total N content, there appeared little change in the percent of sites meeting the total C or upper total N targets, suggesting these two indicators are somewhat insensitive. In 2015, 94% and 89% of arable sites meet the targets for total C and total N, respectively. Increased compaction was indicated by the increased average bulk density and decreased macroporosity while the number of sites meeting these indicators declined. In 2015 59% of arable sites met the lower macroporosity target. Increased P fertility was indicated by increased Olsen P and declines in the percent of sites meeting the high target for Olsen P. In 2015, 24% of arable sites meet the targets for Olsen P.

The main issues for horticulture were compaction and excessive nutrients. Increased compaction was indicated by a decline in macroporosity and a decrease in meeting the lower macroporosity target, although this was not significant due to the small number of samples. In 2015 42% of pastoral sites met the lower macroporosity target. Similarly, increased nutrient fertility was indicated by increased total N and Olsen P and declines in the percent of sites that met targets for these two indicators. In 2015, 58% and 33% of horticultural sites met the targets

for Olsen P and total N, respectively. Consistent with increased fertility, there were increases in AMN content (significant at the 5% level) suggesting increased microbial activity.

There are about 285,000 ha in production forestry in the Waikato region making it the second most extensive productive land use in the region. The main issues for forestry are that it is often located on unstable land with about ¼ to ⅓ of forestry sites were on loose soil. Trees reduce the erosion risk so forestry land use allows production on what would otherwise be unproductive land. However, care is needed at harvest or conversion of such land to another land use where this land is made bare. Conversely, sites where logging had occurred showed evidence of compaction from dragging logs and machinery, while there was also a loss of SOM, which could be due to erosion or mixing of topsoil and subsoil. In 2015, 71%, 95% and 95% of arable sites meet the targets for macroporosity, total N and total C, respectively.

Indicators

Compaction may result in decrease soil infiltration capacity and generation of surface runoff, increased peak and average stream flows, with increased annual flood exceedance probability, transport of contaminants including sediment, nutrients and pathogens, and localised flooding and bank erosion. In addition, plant uptake of N and P was lower in compacted soils due to shallower rooting, and reduced available N concentrations.

The effects of soil compaction may last for decades unless remedial action is taken. Where compaction is moderate, recovery can be relatively quick, e.g. from a macroporosity measurement of 12% to 18% in 18 months. However, complete recovery from a larger event with lower macroporosity may take many years. Damage to the soil by grazing animals can be minimised by management of livestock and land including reducing stocking density, moving livestock off wet pasture onto hard standings or into housing, reducing the length of the grazing season. Precision agriculture techniques should be followed when using machinery for arable and forestry operations and machinery kept off wet soils. In some soils, installing drainage can increase the soils resistance to damage if the watertable can be kept below 500 mm. Tillage and reseeding can break up a surface pan but also accelerate the decomposition of SOM leading to an even worse situation.

Excessive nutrients in soils leads to an increased risk of diffuse contamination of water bodies where they can contribute to changes in the composition of local biological communities, the formation of algal blooms, or directly impact human and animal health. The greatest risk of P loss is on soils that are poorly drained, have lower structural resilience or are on slopes, while the greatest risk of N loss is on very well drained and excessively drained soils. When linked together, surface compaction and excessive nutrient concentrations in pasture have been linked to modified soil hydrological behaviour and, ultimately, the deterioration of water quality in ground and surface waters.

Diffuse contamination of surface waters with P and N could be reduced by applying no more than the amount of fertiliser needed for production, managing critical source areas, reducing surface runoff and riparian planting.

Loss of SOM is considered a key soil attribute as it affects many physical, chemical and biological properties that control soil services such as productivity, the adsorption of water and nutrients, and resistance to degradation. Low SOC is associated with reduced aggregate stability, infiltration, drainage, airflow, microbial biomass, microbial activity, and nutrient mineralisation due to a shortage of energy sources and loss of habitat. Scarce SOC results in less diversity in soil biota with a risk of the food chain equilibrium being disrupted, which can cause increases in accumulation of toxic substances, plant pests and diseases. Of particular significance to the Waikato catchment is SOM's role in retaining nitrogen in the soil.

In arable systems, adding manures, adequate fertilisation, the return of plant material and crop rotation can all help reduce the decline in SOM. However, re-establishment of pasture appears the most practical method of recovering SOM for these systems.

Considerable conversion of land from pine plantations to pasture has taken place on Pumice soils. Pumice soils are very light with weak structure and erode easily when disturbed. Impacts of this intensification can include loss of soil carbon and SOM, increased surface compaction, decreased aggregate stability and crusting with the associated issues of low water infiltration and storage, overland flow, causing soil erosion, and carrying nutrients, sediment, pathogens, organic matter and other contaminants to waterways. The impact of intensification on the biological, physical, and chemical condition of pumice soils is likely to be greater than on Allophanic or Granular soils both of which are weathered volcanic soils and more traditionally used for pastoral land use.

Acidification of soils is not an issue in the Waikato region.

Results for 2015

Soils in 2015 under native vegetation were on average acidic (pH 5.4), high in total C (mineral soils 15.3%), low in Olsen P (7 mg/L), low in bulk density (0.56 t/m3) and had high macroporosity (25% v/v). Soils under forestry had generally similar characteristics to soils under native but had lower total C 8.6%). Soils under pasture were on average less acidic (pH 6.0) than forest soils, but with more Olsen P (49 mg/L), and lower macroporosity (9%). Soils under horticulture were similar to pasture. Soil under arable were most different from soils under native vegetation. These had low total C (5.0%), indicating loss of SOM, very high Olsen P (91 mg/L) indicating excessive fertility, and bulk density (0.94 t/m3), indicating compaction. Arable soils also had high pH (6.4).

Representativeness

Compared to land area in each land use and soil type category in 2015, land under native vegetation, Podzols, Pumice soils, Recent soils and Ultic soils were underrepresented. Ideally, the representativeness of the dataset can be improved by increasing the numbers of native sites by 33 to 45 site; Recent soil sites by 9 to 15 sites; Podzol sites by 9 to 14 sites; Pumice sites by 12 to 38 and Ultic soil sites by 5 to 7 sites. The total number of soil quality monitoring sites would need to increase to about 190-200 for the sampling programme to be representative of all the major land uses and soil orders in the Waikato region.

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Appendix I: Determining the number of nationally representative samples[1]

The design of a sampling programme will depend on the soil quality information that is required. It is therefore important to define the objectives of the monitoring, and also the level of precision required. The variability of items in the minimum data set differs (a combination of spatial and temporal variability, plus laboratory error). Variability of items in the recommended minimum data set is given in Table 1. Experience suggests that variance in soil properties can be as high within a relatively short distance as at larger distances.

Soil properties that show large changes in response to land use can have large CV but still show significant differences. Macroporosity remains a useful measure even though it has a high CV because there are correspondingly large changes in the means in response to land use pressures.

Table 1. Overall coefficients of variation of physical, chemical and biological properties used to measure soil quality. The variance is the sum of any systematic, spatial and land use effects.

Physical characteristics	Co-efficient of Variance (%)	Chemical and biological characteristics	Co-efficient of Variance (%)
Bulk density	7.2	pH	2.3
Particle density	1.2	Total C	9.4
Total porosity	3.5	Total N	8.6
Macroporosity	29.4	Olsen P	15.6
Aggregate stability	14.7		

It is important to define the level of precision required before rejecting a soil property because the CV may appear high. A high CV can be lowered by increased replication.

Sampling and analytical work is time consuming and expensive, so it is important only to take as many samples as needed. The number of samples is determined by the variability and the degree of precision needed. The number of samples needed to give an answer within the required margin of error can be estimated from the variance (assuming a normal distribution around the mean). If the variance is not known, it can be estimated from the formula s2 = (R/4)2, where R is the estimated range in measurements. The sample size (N), is then given by N = t2s2/D2 where t is Students t value at desired level of confidence, s2 is the variance and D is size of the difference to be detected.

Example
Suppose we measure bulk density on 15 soil samples. We get a mean (Mg/m2) and standard deviation of 0.8±0.05. The variance (s2) is thus 0.0025 (square of the standard deviation). If we want to detect a difference (D) of 0.02 between samples at a 90% probability of being correct, how many samples are needed? We apply the formula N = t2s2/D2. For 90% probability, t = 1.64, thus:

N = (1.64 x 1.64 x 0.0025)/(0.02 x 0.02) = 16.8
We need to collect 17 samples to detect a difference of 0.02.
That seems a lot; perhaps a difference of 0.05 Mg/m2 would be acceptable. So reapplying the formula

1 Hill RB, Sparling GP 2009. Soil quality monitoring. In: Land Monitoring Forum. Land and soil monitoring: a guide for SoE and regional council reporting. Hamilton: Land Monitoring Forum. pp 27–88.

N = (1.64 x 1.64 x 0.0025)/(0.05 x 0.05) = 2.7
Three samples would be adequate to detect a difference of 0.05 Mg/m2

As shown above, the number of samples will depend on the degree of stratification, the level of certainty required, and the soil property being measured (some properties such as Olsen P are more variable than others such as soil pH). There are potentially more than 150 land-use and soil order combinations; but the reality is that some combinations will have no representatives, because that particular land use does not occur on that soil order. Also many of the soil orders and some land uses can be grouped for some characteristics. Of the combinations that are represented in a region, a sampling programme should endeavour to have at least 5 representatives in that cell.

The ideal of having the frequency of sampling proportional to the area of land use, and of having a minimum of 5 representatives per cell category, may not be attainable when resources are limited. A defensible regional strategy is to sample sites that are thought to be "at risk" of soil deterioration – known as "targeted" sampling. Included within that strategy should be some low-risk and undisturbed sites to provide a basis for comparison.

An advantage of using standardised sampling and analyses, and nationally consistent soil and land use categories, is that individual examples can be combined across regions, so that on a national basis the target of 5 representatives per cell can be obtained. Analyses of the 500 Soils data showed that for combined soil orders and 6 or 8 land use categories, for most soil properties a total of 500 sites was sufficient to detect a 20% change in the mean with a 95% level of confidence. Sample numbers should be sufficient to detect at least 20% change in the mean at the 95% confidence level.

If the variance is known, calculate the number of samples using the formula shown above. As a general rule, have a minimum of 5 representatives in each category/cell.

Appendix II: Required laboratory methods for soil quality monitoring[2]

Sample preparation for analysis

Soil preparation

Chemical analyses - the 25 individual cores are bulked and mixed before analyses. Discard any adhering vegetation. Sieve through <6 mm or 2 mm mesh, and discard roots, macrofauna, and stones remaining on the sieve.

If soil needs to be dried (e.g. from waterlogged sites) to permit handling, then a cold air fan with continual mixing of the soil is recommended, or by spreading the soils on trays in a cold-room with frequent mixing. In either case, the intention is to avoid any heating or localised rapid drying of the soil.

Storage of moist soils for extended periods is not recommended as there will be change in soil properties. If absolutely necessary, moist soils should be stored in loosely-sealed polyethylene bags at 5°C.

Moist soils are used for the mineralisable N test; dried soils are used for the other chemical measurements. Once air-dried the soils can be stored in sealed containers at room temperature.

Drying and grinding

Samples are dried as soon as they arrive at the laboratory to minimise biological transformations and other chemical reactions. If the sample size is too large, reduce it by coning and quartering. Only complete this step after the sample has been dried and homogenised. Plant and root material are removed by hand then the samples are dried in a forced-air convection drier at 35 °C for approximately 5 days. The actual time depends on factors such as sample size, moisture content, texture and organic matter content. Large rock fragments are removed before the sample is ground in a roller grinder to pass a 2-mm sieve. The ground soil is mixed and a subsample taken for analysis. For methods which require a small sample weight (< 1.0 g) a subsample is taken from the < 2-mm portion and further ground in a ring mill to < 0.25-mm. In some cases, air-drying changes soil properties to such an extent that field-moist samples is used instead e.g. anaerobic mineralisable nitrogen.

Moisture content method

Most results of soil chemical and biochemical analyses are reported on an oven-dry (105^{o}C) basis, but as oven drying causes irreversible changes analyses are carried out on field moist samples, those wetted up to a particular moisture tension or in the cases of some analyses on air-dried samples (dried at a temperature of no more than 35^{o}C). All final results must be converted to an oven dry weight basis.

[2] Hill RB, Sparling GP 2009. Soil quality monitoring. In: Land Monitoring Forum. Land and soil monitoring: a guide for SoE and regional council reporting. Hamilton: Land Monitoring Forum. pp 27–88.

Drying procedure

1. Make all weighings to 3 decimal places.
2. Weigh a labelled aluminium or glass dish with lid and record the weight (w_1).
3. Accurately weigh approximately 5g of soil sample into the dish and record weight (w_2).
4. Dry at 105^{o}C for 8-24 hours (overnight) to a constant weight.
5. Remove from oven, fit lid, cool and reweigh (w_3).

Note: Because oven-dry soil rapidly picks up water vapour from the atmosphere (even in some desiccators), it is necessary to reweigh as soon as the dish is cool enough to handle, but before it cools to room temperature. If large numbers of samples are being weighed it is necessary to remove only about 10 dishes from the oven at one weighing.

Calculation of results

Moisture Content (%MC) = $(w_2 - w_3) / (w_3 - w_1) \times 100$

where: w_1 = weight of tin, w_2 = tin + fresh weight of soil, w_3 = tin + oven dried weight of soil

Moisture Factor (MF) = 1+ (%MC/100)

Converting analyses to an oven-dry weight basis when results are presented on a fresh or air-dried weight basis: Oven-dry weight = Result * MF

Total C method

Recommended methods for determining total C and N are by high temperature combustion. High temperature combustion causes less potential pollution than dichromate oxidation as there is no toxic Cr salts produced, nor boiling highly concentrated acids. If high temperature instruments such as the Leco FP-2000 CNS Analyser are not available, then dichromate oxidation and titration should be used for total C, and Kjeldahl digestion for total N (see Blakemore et al 1987).

LECO FP-2000 CNS ANALYSER

The Leco FP-2000 is a microcomputer based instrument used to measure carbon, nitrogen and sulphur in a wide range of solid and liquid samples.

The sample is weighed into a ceramic boat and loaded into the furnace where it is combusted in a stream of oxygen. The combustion process produces CO2, N2, NOx and SO2. Passing through a heated catalyst further reduces the NOx to N2. The CO2 and SO2 are measured by infrared detection while the N2 is measured by thermal conductivity. Further details are available in the instrument instruction manual (Leco Corporation, 1994).

Note that high temperature combustion methods are usually more efficient than the wet oxidation for organic C and Kjeldahl digestion for total N. Conversion factors will need to be derived in order to compare the different methods.

Total N method

High temperature combustion is the preferred methodology for total N determination. It is normally analysed in conjunction with total C (see Total C method above). Kjeldahl digestion should be used if high temperature combustion methods are not available (see Blakemore et al 1987). The efficiency of the two methods needs to be compared and conversion factors derived to make conversions between the two methods.

Refer to the manufacturer's manual for operation of the instruments.

Mineralisable N method

This method provides an index of the amount of N that is potentially mineralisable over time. The method is that of Keeney (1982) based on Bremner (1965). Their approach is based on the mineralisation of soil organic N by soil microbes, but is carried out under waterlogged conditions. Microbial immobilisation of N is very much less under the anaerobic conditions that develop in waterlogged soils. The method is therefore particularly suitable for soils with high C:N ratio such as forest litter layers, unimproved soils and peats, where microbial immobilisation under normal aerobic incubation can result in no net mineralisation of N.

Reagents

POTASSIUM CHLORIDE, 2.5 M. Dissolve 186.4 g in water and make up to 1 litre.
STOCK AMMONIUM STANDARD (100 µg NH4-N/mL). Weigh 0.4720 g ammonium sulphate, (NH4)2SO4, dried at 110oC, dissolve and make up to 1 litre in a volumetric flask with deionised water.
WORKING AMMONIUM STANDARDS (KCl). Pipette 0, 2, 4, 6, 8, and 10 mL stock ammonium standard into 100 mL volumetric flasks. To all add 20 mL deionised water then make to volume with 2.5 M KCl. These standards contain 0, 2, 4, 6, 8, and 10 µg NH4-N/mL in 2 M KCl. Solutions are stable for about 6 months.

Procedure

1. Weigh out 5 g (oven dry equivalent) of soil into 30 mL Universal bottle and add 10 mL of water. For low density peat soils use 1-2 g oven dry equivalent of soil or use 5 g moist soil. Cap tightly and incubate at 40oC for 7 days.

2. Weigh a second 5 g sample directly into a 150 mL extraction bottle, add 10 mL water and 40 mL 2.5 I KCL. Cap and extract on a reciprocal shaker, at 200rpm, for 1 hour. Include two blanks with no soil. After extraction, filter the solutions through Toyo 5C filter paper and collect in a Universal bottle. Store at 4oC or frozen until analysis.

3. After 7 days remove the incubated samples, shake briefly to mix the contents, and quantitatively transfer the soil-water mixture to a 150 mL extraction bottle using the 40 mL of 2.5 M KCl extractant to wash out universal. Shake and filter as above.

4. Measure ammonium concentrations in the extracts using an Auto-Analyzer as described in Method 4A.II by Blakemore et al (1987) or an equivalent method. Present results as µgN/g oven-dry soil.

5. Anaerobic mineralised nitrogen is calculated from the increase in ammonium-N between day 7 and day 0. Results are expressed as µgN/g soil.

Soil pH in water method

Soil pH is a measure of the activity of ionised H (H+) in the soil solution. This is one measure of the acidity or alkalinity of the soil. Soil acidity or alkalinity can greatly influence plant growth. Generally, within New Zealand, soil tend towards acidity (low pH). For optimal pasture and crop production, pH values of 5.5-6.5 are often recommended. Soil acidity is usually controlled by the application of lime. Some types of fertilisers (e.g. ammonium sulphate) will normally reduce soil pH. Many soil chemical and biological reactions are controlled by the pH of the soil solution: solubility of various compounds, relative bonding of ions to exchange sites, and the activity of various microrganisms. Measurements of whole soil pH using fresh soil as opposed to air-dried soil have been found to equate better to the pH of soil solution, particularly for soils with low electrical conductivity and for soils that are not fertilised.

The following conditions are important for reproducible pH measurements (Blakemore et al 1987): moistness of soil, suspension medium, ratio of soil to suspension medium, degree of stirring, and the positioning of electrodes. Results obtained using water will be about 0.5-1.0 units higher than those obtained with salt suspensions.

pH 7 BUFFER: Using commercially available tablets or sachets make up fresh solution monthly and store at 4^{o}C.

pH 4 BUFFER: 0.05 *M* POTASSIUM HYDROGEN PHTHALATE. Dissolve 1.021g KOOC. C_6H_4.COOH in deionised water and make up to mark in 100-mL volumetric flask. Note buffer is pH 4.0 at 20 C and pH 4.1 at 25 C. Make up fresh monthly and store at 4^{o}C.

Procedure

1. Weigh 4 g of soil (field moist, <4mm) in to a Universal bottle (2 replicates).

2. Add 10 mL distilled water. This final ratio of soil to suspension medium is the standard international ratio of 1:2.5. For soils very high in organic matter content (peats) a wider ratio (1:5 or 1:20) should be used to obtain workable slurries.

3. Homogenise mixture thoroughly with glass rod until all soil crumbs are dispersed.

4. Cover and leave overnight.

5. Immediately prior to pH measurement calibrate the pH meter using pH 4 and pH 7 buffers. Buffers should be held at room temperature for at least 2 hours prior to measurement. Thoroughly rinse electrode with water, and dab dry with tissue, between all measurements.

6. Measure pH of the samples by carefully placing the bulb of the combined electrode halfway between the soil/water interface (so as not to disturb soil interface). Wait for the reading to equilibrate and remain steady for 30 s. Replicate measurements should give results within 0.1 pH unit.

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Olsen P method

The determination of available P (Pi) follows the procedure of Brookes et al (1982). It is based on the method of Olsen et al (1954) which uses an extraction with bicarbonate to estimate plant-available phosphorus in soil (it is commonly referred to as Olsen P). Sodium bicarbonate acts through a pH and ion effect to remove solution phosphorus plus some labile exchangeable P. Many extraction techniques for "plant available" phosphate have been developed. The bicarbonate extraction method is suitable over a wide range of soil types and pH values (Kamprath and Watson 1980). Phosphate in solution is determined colourimetrically using the Murphy Riley method (Murphy and Riley, 1962) as described by Blakemore et al. (1987). Interference from organic matter dissolved in solution can be decreased by decolourising with activated, acid-washed, charcoal added to the extract. Polyacrylamide is an alternative (less messy!) decolourising agent provided the colour in the extracts is not excessive. Polyacrylamide also flocculates colloids and speeds filtration of clay soils.

The sodium ions in the bicarbonate extract also displace K+ ions from negatively charged sites on the soil colloids. Thus, the extract includes soil solution K plus “exchangeable” K and together they constitute the readily available K pool in soils (McLean and Watson 1985).

Preparation of reagents

EXTRACTING REAGENT (0.5 *M* $NaHCO_3$). Dissolve 42.0 g sodium hydrogen carbonate in distilled water and dilute in about 980 ml. Adjust pH to 8.5 by adding approximately 50% sodium hydroxide drop by drop and make up to 1 litre. To prevent pH changes in the reagent, make up fresh and adjust pH immediately before use (Cowling *et al*. 1986).
SUPERFLOC, 0.2%. Dissolve 0.6 g A2100 polyacrylamide in 300 ml distilled water.
HYDROCHLORIC ACID, 43% v/v. Add 43 ml conc. HCl for every 57 ml deionised water.
ACTIVATED CHARCOAL, DARCO G80. This brand of charcoal is sufficiently pure to use as supplied but other propriety brand can contain large amounts of Pi. The Pi can be removed by heating charcoal to >60°C in a beaker with the 43% HCl, allow to cool, rinse firstly with water, then $NaHCO_3$ and then again with water. Place the activated charcoal on a Buchner funnel to extract residual water and dry the charcoal in a oven.
MURPHY-RILEY REAGENT A (DOUBLE STRENGTH), 1.2% AMMONIUM MOLYBDATE, 0.1mg/ml ANTIMONY, 2.5 *M* SULPHURIC ACID. Dissolve 60 g $(NH_4)_6Mo_7O_{24}.4H_2O$ in 1 litre water. The rate of solution may be increased by warming, *but do not heat above 60°C*. Cool the solution. Dissolve 1.3343 g antimony potassium tartrate in 250 ml water. Add both of the dissolved reagents to 2500 ml of 5 *M* H_2SO_4 (705 ml conc. H_2SO_4 made to 2500 ml with water). Mix thoroughly, make to 5 litres. This solution is stable at room temperature if stored in dark bottles.
MURPHY - RILEY REAGENT B. In each 100 ml of reagent A dissolve 1.056 g ascorbic acid and mix. This reagent must be made as required as it does not keep for more than 24 hours.

Preparation of standards

STOCK SOLUTION (100 µg P/ml). Dissolve 0.1968 g potassium dihydrogen phosphate, KH_2PO_4, in deionised water and make up to 500 ml in a volumetric flask.
WORKING STANDARDS (0-10 µg P/ml). Pipette 0, 0.5, 1, 1.5, 2, and 2.5 ml of stock solution into 25 ml volumetric flasks and make up to mark with deionised water. These standards contain 0, 2, 4, 6, 8 and 10 g P/ml respectively.

Procedure

1. Prior to analysis all glassware must be acid washed - soak for several hours in 10% HCl and rinse thoroughly with distilled water.

2. Also prior to analysis it is necessary to determine whether a decolourising step is necessary. With extracts from high organic matter soils with low inorganic phosphorus organic matter will precipitate on addition of the acidic Murphy-Riley Reagent and may cause colour interference at 882 nm. Perform an extraction to determine the extractable P conc. in the soil. If the P conc. is high, i.e only a small aliquot of filtrate (1-2ml) is required for analysis, organic matter in this solution is unlikely to interfere.

3. Weigh out 4 g oven dry equiv. wt. of soil (3 reps) in 250 ml plastic centrifuge bottles.

4. To all bottles add 80 ml $NaHCO^3$. Temperature of the extractant is a source of variability. Olsen et al (1954) found that extractable P increased by 0.43µg P/g for each degree rise in temperature between 20°C and 30°C for soils containing 5-40 µg P/g. Include 2 reagent blanks. As the amount of phosphorus extracted is time dependent, it is important that the addition of reagents and later filtering is done without delay.

5. Cap bottles and shake end-over-end at ca. 60 rpm for 2 hours. Note: both shaking time and speed can affect the amount of element extracted. This is particularly true in the case of P (Olsen and Sommers 1982).

6. Add approx.. 1ml superfloc to each bottle, swirl and filter through Whatman 42 (or equivalent) filter paper into Universal bottles, collecting approximately 20 ml filtrate.

7. Cap and store in at 4°C if not analysed immediately.

8. The decolourising step, if necessary, must be carried out quickly as organic P hydrolyses under acid conditions. Transfer 10 ml filtrate to 100 ml plastic specimen bottle (remaining filtrate kept at 4^{o}C may be used for Total P analysis). Add 1ml 43% HCl (carefully so foam does not escape) and swirl several times.

9. Add 2 scoops of activated charcoal, then a further 1 ml of HCl. Swirl and filter immediately through GF/C into universal bottles.

10. Treat standards and blanks similarly.

11. Pipette 5 ml sample filtrate or standard solution into a 25 ml volumetric flask. Add 2 ml double strength Murphy Riley Reagent B, make up to 25 ml with distilled water and mix.

12. Leave for 30 min for colour to develop. (With ascorbic acid reductant maximum colour is produced in 10 minutes and is stable for 24 hours).

13. Read absorbance at 882nm. (Another less sensitive peak at 660nm can also be used).

NB: When cleaning the volumetric flasks afterwards use acetone first to remove any traces of the colour reagent.

Calculation of results

Prepare a standard curve of g P/ml against absorbance to calculate unknowns.

$g\ P/ml = mX + c$

where: X = sample peak height (mm), m = regression slope coefficient, c = regression constant

Bicarbonate Pi (μgPg^{-1} soil) = (S-B)*(V+v)/w

where: S = sample (µgP/ml), B = blank (µgP/ml), V = extracting volume (ml), v = soil water (ml), w = soil oven-dry weight (g)

References

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Bulk density method

Dry bulk density gives an indication of whether a soil is loose or compacted, and provides a factor to convert any soil properties measured on a weight basis to a volume equivalent. Intact cores or soil blocks are needed and bulk density measurements can be conveniently combined with moisture release characteristics to measure porosity and available water.

Procedure

1. Inspect the top and bottom of each core sample to check that the surfaces are level with the ends of the brass liner. If necessary, trim the soil surfaces with a razor until they are level with the ends of the liner. The brass liner rings used by Landcare Research are 30 mm high and hold a volume of 68.6 cm^3 of soil; other similar liners are acceptable. All the liners are numbered and weighed prior to use. The procedure described here allows the soil in the liner to be subsampled in case it is needed for other analyses.

2. Weigh the soil core + liner to 3 decimal places and record on the worksheet as Mass of Liner + Soil at sampling. (Subtract the liner weight to get the mass of soil at sampling).

3. Remove the core from its liner by pushing it out with fingers. Place the extruded soil sample into its weighed water content dish. If desired take subsamples at that point.

4. Weigh the water content dish and soil to 3 decimal places, and record on the worksheet as Mass of Dish + Wet Soil.

5. Place the water content dishes of soil into an oven and dry overnight at 105 - 110°C with the lids of the water content dishes open.

6. Remove the water content dishes of soil from the oven and replace the lids. When cool, weigh the dishes of dry soil to 3 decimal places and record on the worksheet as Mass of Dish + Dry Soil. Calculate weight of water (dish plus wet soil, minus dish plus dry soil), and the weight of dry soil (dish plus dry soil minus weight of dish).

7. Calculate the gravimetric water content
   Water content (%) = weight of water /weight of dry soil x 100

8. Apply that water content figure to the original weight of moist soil in the liner when to get the soil dry weight when sampled. Dry weight = (Weight of moist soil x 100)/(100 + % water content)

9. Calculate the dry bulk density by dividing the dry mass (g weight) of soil by the volume (cm^3) of the liner. Bulk density = Soil dry weight/Volume of liner

10. Acceptable S.I. units are g cm^{-3} or the equivalent Mg m^{-3} Bulk densities for mineral soils typically range between 0.8–1.3 Mg m^{-3}, and for organic soils (peats) 0.1–0.5 Mg m^{-3}.

Macroporosity method

Macropores are the larger pores that are the main route by which air enters soil. They are the first pores to be lost when soil is compacted. In the literature the size range for defining macropores varies between 30 and 3000 µm. The Regional Council Land Management Forum decided that a tension of –10 kPa would be used to calculate macroporosity (explained below) which corresponds to a pore size of around 30 µm. Other organisations routinely use –5 kPa tensions to calculate macroporosity and care should be taken to make sure the desired tension has been used.

Method

To calculate macroporosity it is necessary to know the **bulk density, particle density,** and **volumetric water content at –10 kPa.**

Bulk density and particle density are first used to calculate **total porosity**

Total Porosity (%) = (1 - (Bulk density / Particle density)) x 100

Then to calculate macroporosity

Macro Porosity (%) = Total Porosity - (Volumetric water content at -10 kPa)

The method to calculate bulk density is given in section 9 of this report. Methods to measure these particle density and volumetric water content are given below. Intact soil cores are required for these measurements (See section 5.2.4 for the method to take intact soil cores for soil physical samples).

Particle density

Particle density is the ratio of mass of dry solids (particles) to the volume those solids occupy. This volume excludes pore spaces between and within particles. The units are Mg/m3. In this method the mass is determined by weighing. The volume is calculated from the mass (and density) of water displaced by the soil particles when placed into a density bottle.

Calibration of density bottles

Clean, dry 50 ml density bottles are weighed to 3 decimal places. The density bottles are filled with de-aired water and then placed in a circulating waterbath (25°C) to come to constant temperature. The bottle stoppers are inserted and the outside of the bottles thoroughly dried with a towel. The bottles of water are weighed to 3 decimal places.

Note: The mass of the density bottle always includes its stopper. Care must be taken to ensure each bottle is always weighed with its own stopper.

This calibration procedure need only be carried out periodically provided the same bottles and stoppers are used each time.

Calibration procedure

1. Open the vacuum desiccator inlet and outlet valves.
2. Open the gas ballast valve on the vacuum pump.
3. Turn on the vacuum pump and leave it running for 10 minutes to warm-up.
4. While the vacuum pump is warming up, weigh each density bottle to 3 decimal
5. places, and record as Mass of Bottle on a calibration worksheet.
6. Remove the density bottle stopper.
7. Half fill the density bottles with distilled water.

8. After the vacuum pump has had at least 10 minutes to warm up, close the vacuum desiccator inlet valve.
9. Place the density bottles into the vacuum desiccator.
10. Close the gas ballast valve on the vacuum pump.
11. Close the vacuum desiccator inlet and outlet valves.
12. Vacuum has now been applied to the density bottles. After a few minutes, the water in the density bottles should begin to bubble.
13. Leave the bottles in the desiccator with the pump running and the desiccator inlet tap open for approximately 30 minutes.
14. Close desiccator inlet valve.
15. Gradually open the desiccator outlet valve. Care must be taken to ensure this valve is opened slowly. If the outlet valve is opened too quickly, the rapid intake of air is capable of knocking the density bottles over.
16. Completely fill the density bottles with distilled water.
17. Repeat evacuation procedure

Note: When the bottles are full, some water may be lost from the bottles when bubbling occurs. This is not a problem during the calibration procedure, as this water can be replaced at the end of the process. However, care must be taken during the actual particle density measurement to ensure this does not happen.

1. Remove the density bottles from the vacuum desiccator.
2. Place a 300 mL beaker of distilled water into the vacuum desiccator.
3. Repeat evacuation, applying a vacuum to the beaker of distilled water for approximately 30 minutes.
4. While the beaker is in the vacuum desiccator, place the density bottles into a circulating water bath running at a temperature of 25° C for approximately 30 minutes. Check, and if necessary adjust, the water level in the water bath to slightly below the neck of the density bottle.
5. Close the vacuum desiccator inlet and outlet valves.
6. Remove the beaker from the vacuum desiccator.
7. Open the vacuum desiccator inlet valve.
8. Open the gas ballast valve on the vacuum pump, and leave the vacuum pump running for at least 10 minutes.
9. Use the water in the beaker to top up the density bottles, until they are completely full of water.
10. Leave the bottles for a further 10 minutes in the waterbath.
11. Remove the density bottles from the water bath.
12. Turn off the water bath heater.
13. Replace the bottles stoppers, taking care to ensure that each bottle has its own stopper inserted.
14. Thoroughly dry the density bottles with a towel.
15. Weigh the density bottles to 3 decimal places, and record the weight as Mass of Bottle +Water on the calibration worksheet.
16. Turn off the vacuum pump.
17. Empty the density bottles and allow to dry.

Measuring particle density

10 - 15 g of < 2 mm ground oven dried soil is placed into a 50 mL density bottle. The bottle is weighed to 3 decimal places and recorded as Mass of Bottle + Soil on a worksheet. A small amount of distilled water is added to the bottle until the sample appears saturated. The bottle is then placed into a vacuum desiccator and a vacuum is gradually applied to the sample. Care must be taken as the sample will bubble vigorously and it is important not to lose any material from within the bottle. The bubbling can be controlled by regularly decreasing and increasing the vacuum inside the desiccator. Over a period of 2 - 3 hours distilled water is gradually added

to the bottle, applying the vacuum to the sample following each incremental addition of water, until the bottle has been filled to the base of the neck. Once the bubbling has ceased and the sample has been under full vacuum for at least 1 hour, the bottle is transferred to a circulating water bath set at 25 °C to come to constant temperature. After about 30 minutes, the bottle is removed from the water bath and the bottle stopper is inserted. The outside of the bottle is then dried thoroughly with a towel and the bottle weighed to 3 decimal places, the mass recorded as Mass of Bottle+Water+Soil on the worksheet. The results can then be calculated.

Apparatus

Mortar and pestle, small funnel, 50 mL glass density bottles, vacuum desiccator connected to a vacuum pump capable of reaching 1 x 10^{-3} Mb, circulating water bath set to 25 ° C, 300 mL beaker, distilled water, balance (400 g capacity, 0.001 g readability), worksheet.

Note: The mass of the density bottle always includes its stopper. Care must be taken to ensure each bottle is always weighed with its own stopper.

Procedure

Open the vacuum desiccator inlet and outlet valves.
Open the gas ballast valve on the vacuum pump.
Turn on the vacuum pump and leave it running for 10 minutes to warm-up.
While the vacuum pump is warming up, using a mortar and pestle, grind the oven dry soil to approximately < 2 mm, or use 2 mm mesh sample.
Using a small funnel, place approximately 10 - 15 g of oven-dry soil into a clean, dry, 50 mL density bottle.
Weigh the bottle and soil to 3 decimal places, and record as Mass of Bottle + Soil, on the worksheet.
Add a small amount of distilled water to the density bottle until the sample appears saturated.
After the vacuum pump has had at least 10 minutes to warm up, close the vacuum desiccator inlet valve.
Place the density bottles into the vacuum desiccator.
Close the gas ballast valve on the vacuum pump.
Close the vacuum desiccator outlet valve.
Slowly open the vacuum desiccator inlet valve.

Vacuum has now been applied to the density bottles. After a few seconds bubbling will occur. It is important to take care that material is not ejected from the density bottle due to this bubbling. It may be necessary to close the desiccator inlet valve, and gradually open the desiccator outlet valve, to reduce the vacuum, in order to control the bubbling. Once the bubbling has died down the inlet and outlet valves can be closed again. This decreasing and increasing of the vacuum will need to be carried out several times.

The above steps should be carried out over a period of 2 - 3 hours.
Once the initial vigorous bubbling has ceased, close the vacuum desiccator inlet valve.
Gradually open the vacuum desiccator outlet valve.
Add distilled water to the density bottles, until they are approximately 1/3rd full.
Repeat evacuation and open
Add distilled water to the density bottles, until they are approximately 2/3rd full.
Repeat evacuation and open
Add distilled water to the density bottles, until they are filled to the base of the neck.
Repeat evacuation and open, taking extra care to ensure material is not ejected from the bottle due to bubbling.
Once all the bubbling has ceased, leave the bottles for a further 1 hour, under full vacuum.
Close the vacuum desiccator inlet valve
Gradually open the vacuum desiccator outlet valve.
Remove the density bottles from the vacuum desiccator.

Place a 300 mL beaker of distilled water into the vacuum desiccator.
Repeat evacuation applying a vacuum to the beaker of distilled water for approximately 30 minutes.
While the beaker is in the vacuum desiccator, place the density bottles into a circulating water bath running at a temperature of 25°C for approximately 30 minutes. Check, and if necessary adjust, the water level in the water bath to slightly below the neck of the density bottle.
Close the vacuum desiccator inlet valve.
Gradually open the vacuum desiccator outlet valve.
Remove the beaker from the vacuum desiccator.
Open the vacuum desiccator inlet valve.
Open the gas ballast valve on the vacuum pump, and leave the vacuum pump running for at least 10 minutes.
Use the water in the beaker to top up the density bottles, until they are completely full of water.
Leave the bottles for a further 10 minutes in the waterbath.
Remove the density bottles from the water bath.
Turn off the water bath heater.
Replace the bottles stoppers, taking care to ensure that each bottle has its own stopper inserted.
Thoroughly dry the density bottles with a towel.
Weigh the density bottles to 3 decimal places, and record the as Mass of Bottle+Water-f Soil on the worksheet.

Calculations
Particle Density (t/m3)= (0.99707 x (BS - B)) / (BW - (BWS - (BS - B)))

Where:

BS	=	Mass of Bottle + Soil (g)
B	=	Mass of Bottle (g)
BW	=	Mass of Bottle + Water (g)
BWS	=	Mass of Bottle + Water + Soil (g)
0.99707	=	Density of water at 25 ° C (t/m3)

Total porosity

Total porosity is the proportion of the volume of a soil, that is occupied by air or water (i.e. the voids). It is calculated from the bulk density and particle density using the relationship:

Total Porosity (%) = (1 - (Bulk density / Particle density)) x 100

Volumetric water content at –10 kPa

Method

1. Prepare the core
   Inspect the top and bottom of each core sample to check that the surfaces are level with the ends of the brass liner. If necessary, trim the soil surfaces with a razor until they are level with the ends of the liner.
   Weigh the soil core + liner to 3 decimal places and record on the worksheet as Mass of Liner + Soil at sampling.
   Place the core onto the ceramic plate, on top of a piece of filter paper. Place a plastic disc on top of the core. It is good practice to keep the cores in order by placing the cores clockwise from the brass inlet on the ceramic plate.
   Place the plate of cores into an empty plastic tray.
   Taking care not to splash the cores, add water to the tray until the plate surface is covered by 3 - 5 mm of water.
   Allow the plate of cores to sit for approximately 1 hour and then add another 10 mm of water.

Repeat until the water level is just below the top of the cores. Do not submerge the cores. This gradual wetting from the base of the cores will ensure the soil structure is not damaged during the saturation process.
Leave the plate of cores to saturate overnight. Most soils will reach saturation in 16 hours, however some may require more time.
When the cores are fully saturated the plate of cores is ready for a tension to be applied.

2. Prepare the ceramic plate
A ceramic extraction plate consists of a ceramic plate approximately 28 cm in diameter which is sealed on one side by a thin rubber diaphragm. An internal screen between the diaphragm and the plate provides a passage for water to flow. An outlet stem running through the ceramic plate connects the passage to the outlet tube. The ceramic plates are quite strong, however they can break if dropped or struck. If after a period of time the flow rate of an extraction plate drops due to calcium carbonate deposits on the plate surface, these can be removed by careful sanding with a fine sandpaper. Deposits in the pores of the plate can be removed by flooding the plate surface with a 10% solution of hydrochloric acid then applying pressure to the plate to flush the solution through. The plate will then require a similar flush with distilled water.

Prior to using the ceramic plates, they must be fully saturated with water. This is achieved by fully submerging the plate in water and soaking for several days prior to using the plate. The process can be sped up considerably if a length of plastic tubing is attached to the plate and water drawn through the plate by a simple water vacuum pump.

3. Procedure for saturation of a ceramic extraction plate
Fill a large plastic tray with water.
Attach a short extraction tube fitting to the brass outlet on the plate.
Fit a 5 cm long x 3 mm dia. steel tube to the short extraction tube.
Fit a 1.5 m x 5 mm plastic tube to the steel tube.
Place the plate into the plastic tray of water and fully submerge.
Attach the free end of the plastic tubing to an inlet of a water vacuum pump. Check that if the pump has more than one inlet, that the unused inlets are clamped shut.
Turn on the vacuum water pump. This will draw water through the plate and along the plastic tube.
Leave the water vacuum pump running until large amounts of air no longer appear inside the plastic tube. This will take approximately 2-3 hours.
Clamp the plastic tube shut, and detach it from the water vacuum pump.
Turn off the water vacuum pump. ;
Submerge the free end of the plastic tubing in the water and remove the clamp from the tubing. Water will be drawn back into the plate for a few seconds.
Remove the free end of the plastic tubing from the water, hang it down to the floor and place it over a large beaker. Water should now begin to slowly drip from the end of the plastic tubing.
Remove any trapped bubbles of air from the tubing by gently tapping the tubing. Guide the air towards the free end of the tubing. It may be necessary to bend the tubing slightly to achieve this.
Leave the plate submerged, with the plastic tubing hanging down, and the water slowly dripping out the end of the tube until there are no more air bubbles appearing in the tube. This will probably take approximately an hour.
Clamp the plastic tubing shut. The plate is now ready for use.

Note: If the plate is to be used at tensions >10 kPa a clamp should be applied to the short extraction tube fitting just above the brass outlet on the plate. The plastic tubing and 5 cm long x 3 mm dia. steel tube must then be removed as they are no longer required at tensions > 10 kPa.

4. Volumetric water content at –10 kPa

   Place the plate of prepared cores, inside a large plastic bag on the appropriate shelf of the tension table, to apply the desired tension. Allow the long plastic tube to protrude out of the plastic bag.

   Put the free end of the long plastic tube attached to the extraction plate, into the tension table water container. Check that the water level in the container is at the level marked, and that the water level line is exactly the correct distance below the surface of the ceramic plate, to apply the desired tension. To apply a tension of –10 kPa there must be 100 cm difference in height from ceramic plate surface to the water level marker.

   Remove the clamp from the plastic tube and check the tube is free of air bubbles. If necessary, move any bubbles along the tube towards the water container, by bending and tapping the tube. Take care to keep the end of the tube submerged in the water container. If there are a large number of air bubbles, it may be necessary to remove the core samples, and re-saturate the plate.

   Cover the plastic bag containing the plate of cores with a sheet of plastic and a towel to minimise evaporation.

   Maintain the water level in the water container at the mark by removing any excess water with a syringe.

   Leave the cores to drain to equilibrium. Equilibrium is reached when the water level in the container has remained static for at least 24 hours. At a tension of -10 kPa, this should approximately take 5-7 days.

   The core samples are weighed, then extruded into a tared water content dish. The dishes of soil are weighed and then dried overnight at 105 - 110 °C. The dishes of dry soil are then weighed and the weight of soil and weight of water calculated. Section 9

   Weigh the soil core + liner to 3 decimal places and record on the worksheet as Mass of Liner + Moist Soil.

   Remove the core from its liner by pushing it out with fingers. Place the extruded soil sample into a weighed (tared) water content dish.

   Weigh the water content dish and soil to 3 decimal places, and record on the worksheet as Mass of Dish + Moist Soil in the Water Content measurement after final tension section.

   Place the water content dishes of soil into an oven and dry overnight at 105 - 110°C with the lids of the water content dishes open.

   Remove the water content dishes of soil from the oven and replace the lids. When cool, weigh the dishes of dry soil to 3 decimal places and record on the worksheet as Mass of Dish + Dry Soil in the Water Content measurement after final tension section.

   From the measurements taken calculate the soil dry weight and the weight of water as described in section 9.

   Convert the soil mass to volume using the bulk density measure (Volume of soil = Mass of soil/ Bulk density). The volume of water can be considered equivalent to the volume with an assumed mass of 1. Calculate the volumetric water content

   Volumetric water content (%)= (Vol of water) / (Mass of Dry Soil/Dry Bulk Density) x 100

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Aggregate stability method

Aggregate stability by wet sieving indicates the resistance of soil aggregates to stress imposed by rapid wetting and mechanical abrasion.

Soil sampling

Samples should be collected when the soil is moderately moist, avoiding sampling under very dry or very wet conditions. Sample size is generally approx. 15 cm x 15 cm (spade width x spade width) to a depth of 10 cm. Samples should always be handled with care to avoid any compaction of aggregates (i.e. don't drop or stack samples). Chill samples until analysis.

Sample processing

Sieve field moist samples through a 4 mm sieve by very gently breaking up clods and shaking through the sieve. Avoid forcing aggregates through sieve as this can create artificial 'aggregates'. Sieve the <4 mm sample through a 2 mm sieve by shaking only. When all <2 mm soil has fallen through sieve retain the sample remaining on the sieve (i.e. retain the aggregates between 2 and 4 mm in diameter) for analysis. Place this sample on a tray in the drying cupboard until air dry. If air dried samples are to be stored or transported ensure they are placed in pottles (rather than bags) as they are very vulnerable to disintegration in this state. Extreme care should be taken with samples once air dried.

Analysis (using wet sieve)

Ensure wet siever is on level ground
Place the sieve nests in the mechanical siever, ensuring the sieves in each nest are in the descending order of 2, 1 and 0.5 mm
Fill wet siever with water so that water will just cover a soil sample on the top sieve at all times (i.e. the point where water just starts to lap up the side of the wet siever when the siever is on, but before water laps up the side of the sieve nests - to avoid potentially losing soil).
From each sample of air dried 2-4 mm aggregates weigh out a 50 g sample for wet sieving and a 10 g sample to determine moisture content. These weights can vary but the actual weight used must be recorded (to 2 decimal places). Aggregate stability should not be determined if the usable soil sample is less than about 25 g as the accuracy of results below this is unknown. When using a sample of this size, moisture can be determined by only using 4 g of soil (minimum) .
Place the 50 g soil sample carefully onto the top sieve (spread out to cover most of the sieve surface).
After wet sieving for the 20 minutes carefully remove each nest of sieves from the water.
Using a white, plastic photo developing tray and a low pressure hose wash out the sample remaining on each sieve into a pottle (each pottle should be previously weighed - to 2 decimal places).
Pour off most excess water from each pottle after settling for a few minutes (be careful to not lose unsettled soil).
Place pottles and moisture content samples in oven at 105^{o}C overnight. Depending on how much water is initially poured off they may require more time than this to dry.
Weigh all oven dry samples (to 2 decimal places). As the pottle weight has already been determined, weigh the total weight of pottle and soil. Make up 5 g/l Sodium Hexametaphosphate ((NaPO3)6) solution. This is a dispersing agent to allow soil minerals to pass through a sieve, leaving stones on the surface.

To the 2, 1 and 0.5 mm aggregate fractions in the pottles, add 100, 50 and 25ml of $(NaPO_3)_6$, respectively.
Place a top on each pottle and shake on an orbital shaker for at least 6 hours.
For each pottle, wash the contents onto a 0.5 mm sieve and rinse through the soil minerals, leaving the stones on the surface.
Using the photo developing tray and a low pressure hose wash out the stone sample remaining on the sieve back into the original pottle.
Pour off excess water from each pottle after settling for about a minute.

Appendix III: Soil quality target ranges[3]

Figures in bold show the suggested target range (or critical limit) for each soil property, to be used in "by exception" reporting.

Total Carbon (% w/w)

Allophanic	0.5	**3**	4	9	12
Semiarid, Pumice and Recent	0	**2**	3	5	12
Organic	Exclusion (> 15% total C, so always ample)				
All other soil orders	0.5	**2.5**	3.5	7	12
	Very Depleted	Depleted	Normal	Ample	

Notes: Applicable to all land uses. 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 (% w/w)

Pasture	0	**0.25**	0.35	0.65	**0.7**	1.0
Forestry	0	**0.10**	0.2	0.6	**0.7**	1.0
Cropping and Horticulture	low target 0.25 and high target of 0.7 used					
	Very depleted	Depleted	Adequate	Ample	High	

Notes: Applicable to all soil orders. Target ranges for cropping and horticulture are poorly defined.

Mineralisable N (ug/g) [AMN]

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
	Very Low	Low	Adequate	Ample	High		

[3] Sparling G.P., Lilburne L., Vojvodic-Vukovic M. 2003. Provisional targets for soil quality indicators in New Zealand. Lincoln, Landcare Research updated from Mackay AD, Dominati E, Taylor MD 2013. Soil Quality Indicators: The Next Generation. Client report number: RE500/2012/05. Hamilton, AgResearch and the LMF.

Notes: Applicable to all soil orders. Targets for cropping and horticulture are poorly defined. Targets as reviewed by Mackay AD, Dominati E, Taylor MD 2013. Soil Quality Indicators: The Next Generation. Client report number: RE500/2012/05. Hamilton, AgResearch and the LMF.

pH

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 & horticulture on all soils except Organic	4	**5**	5.5	7.2	**7.6**	8.5
Cropping & 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					
	Very Acid	Slightly Acid	Optimal	Sub-optimal	Very alkaline	

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 in real life because of windthrow.

Olsen P target ranges

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**	50	**50**	200
Forestry on all soil orders	0	**5**	10	**50**	200
	Very Low	Low	Adequate	High	

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

Note: Targets as reviewed by Mackay AD, Dominati E, Taylor MD 2013. Soil Quality Indicators: The Next Generation. Client report number: RE500/2012/05. Hamilton, AgResearch and the LMF.

Bulk Density (t/m³) or Mg/m3

Semiarid, 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
		Very Loose	Loose	Adequate	Compact	Very compact

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

Macroporosity(-10 kPa) (%)

Pastures, cropping and horticulture	0	**10**		**30**	40
Forestry	0	**8**		**30**	40
		Very Low	Low	Adequate	High

Note: As reviewed by Mackay AD, Dominati E, Taylor MD 2013. Soil Quality Indicators: The Next Generation. Client report number: RE500/2012/05. Hamilton, AgResearch and endorsed by the LMF.

Appendix IV Statistical analysis

Spline regression often represents a less biased and more efficient alternative to standard linear, curvilinear, or categorical analyses of continuous exposures and confounders. A model was fitted to each response variable that included:

- Linear and non-linear (spline) trends over time
  - Overall
  - Varying by land use
  - Varying by soil order
- Average levels that varied for each combination of land use and soil order
- Random terms to account for average differences between sites and their linear and non-linear trends over time; the last of these accounts for serial correlation within sites.

This model estimated the true trend when the sites sampled change from year to year. The model was simplified for each variable (indicator) to remove unnecessary spline terms but retaining the overall spline and the site splines. The separate splines for land use and soil order were not required for the models for all variables except macroporosity, which required different splines for each land use.

The models were used to

- describe the trends over time
- estimate the true values at 2015 (the last year)
- estimate the site to site and random within site variation

Each indicator was assessed for statistical trends using linear mixed modelling with random splines overall, by soil order and by land use. Four of the variables required log transforming to get approximate constancy and normality of the residual variation (Table 1). The back-transformed estimates were "bias-corrected" to make this the same as the overall arithmetic mean of all the original values in the data. Data calculated by this method are presented in the results section for 1995-2015.

Table 1: The sum of the between site and residual (within site and lack of fit of the model) variances expressed as a standard deviation.

	Site + residual SD
Bulk Density	0.1269
pH	0.3260
Macroporosity	5.3047
Total C% (log)	0.3415
Total N% (log)	0.3452
Olsen P (log)	0.7388
AMN (log)	0.4044

The probability that sites will violate the lower and upper limits for each variable was calculated using these models and the predicted 2015 values (shown in the tables in the following sections).

As a check on the model validity, we calculated the observed and expected violations for the sites present in 2015. These showed a good match (Table 2).

Table 2: Observed and expected violations for each indicator for 2015 sites.

	Number	Bulk Density	pH	Macroporosity	Total C%	Total N%	Olsen P	AMN	Total
Below lower limit	Expected	2.8	0.1	12.8	0.1	0.0	2.8	0.0	18.6
	Observed	1	0	15	0	0	5	0	21
Above upper limit	Expected	0.0	0.9	0.3	0.0	12.8	9.9	0.0	23.9
	Observed	0	1	1	0	13	9	0	24

The accuracy of estimated values in any one year was improved by utilising the information from sites before and after each time period, thus increasing the effective sample size. The size of the improvement was shown by calculating the effective sample size, e.g. for the 2015 estimated values the effective sample size was calculated as the square of the ratio of the site + residual standard deviation over the standard error of the estimates (Table 3).

Table 3: The overall effective sample size over all soil and land use combinations for each indicator present in the data showing improvement over the 29 sites sampled in 2015.

	Overall effective sample size
Bulk Density	189
pH	106
Macroporosity	77
Total C% (log)	203
Total N% (log)	201
Olsen P (log)	153
AMN (log)	160

Effective sample size for any particular soil or land use (or combination of these) were calculated for each variable; they are roughly in proportion to the number of sites in each (Tables 4-10).

Table 4: The effective sample size for soil and land use combinations for bulk density for the 29 sites sampled in 2015.

	Effective sample size Bulk density t/m3						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	12.5	6.8	9.1	3.3		30.4	62.1
Brown	3.8	4.4		2.2		14.7	25.1
Gley	6.0		1.2	1.1	1.1	14.0	23.4
Granular	7.8		1.8	1.2		8.0	18.7
Organic	1.3		0.7	1.1		3.3	6.4
Podzol		2.5		1.0	3.0	1.2	7.6
Pumice	1.7	7.7	0.8		2.8	24.2	37.3
Recent		1.0		1.1		4.5	6.5
Ultic		1.0				1.0	1.9
Total	33.0	23.3	13.5	11.0	6.8	101.2	188.9

Table 5: The effective sample size for soil and land use combinations for macroporosity @ -10 kPa for the 29 sites sampled in 2015.

	Effective sample size Macroporosity_at_10_kPa						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	3.5	2.9	2.2	1.5		10.8	20.8
Brown	2.1	2.3		1.3		6.9	12.6
Gley	1.9		0.4	0.8	0.8	5.9	9.8
Granular	3.0		1.0	0.9		4.6	9.5
Organic	0.4		0.3	0.8		1.8	3.4
Podzol		1.1		0.6	1.2	0.4	3.3
Pumice	0.8	2.3	0.3		1.2	8.1	12.7
Recent		0.6		0.7		2.2	3.5
Ultic		0.6				0.6	1.2
Total	11.7	9.7	4.1	6.7	3.2	41.4	76.8

Table 6: The effective sample size for soil and land use combinations for Olsen P for the 29 sites sampled in 2015.

	Effective sample size Olsen P (µg/cm3) (log scale)						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	10.2	5.5	7.7	2.8		22.2	48.4
Brown	3.5	3.8		2.0		12.1	21.3
Gley	5.5		1.2	1.0	1.0	11.2	19.8
Granular	6.5		1.6	1.0		6.7	15.9
Organic	1.1		0.6	1.0		2.8	5.4
Podzol		2.3		0.9	2.5	1.0	6.8
Pumice	1.4	6.2	0.7		2.6	16.7	27.5
Recent		0.9		1.0		3.9	5.7
Ultic		0.9				0.9	1.8
Total	28.2	19.5	11.7	9.7	6.0	77.4	152.6

Table 7: The effective sample size for soil and land use combinations for Total N for the 29 sites sampled in 2015.

	Effective sample size Total N (%) (log scale)						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	14.6	6.8	9.9	3.2		32.4	67.0
Brown	4.2	4.3		2.2		14.9	25.5
Gley	7.1		1.5	1.1	1.1	14.5	25.3
Granular	8.2		1.8	1.1		8.2	19.4
Organic	1.5		0.7	1.1		3.6	6.9
Podzol		2.7		1.0	3.1	1.4	8.2
Pumice	1.9	8.8	1.0		3.2	25.3	40.3
Recent		1.0		1.1		4.6	6.6
Ultic		1.0				1.0	1.9
Total	37.6	24.6	15.0	10.7	7.4	106.0	201.2

Table 8: The effective sample size for soil and land use combinations for AMN for the 29 sites sampled in 2015.

	Effective sample size AMN (mg/kg) (log scale)						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	9.2	6.4	7.5	3.2		25.3	51.6
Brown	3.3	4.4		2.3		13.1	23.1
Gley	4.2		0.7	1.2	1.1	11.8	19.0
Granular	6.8		1.6	1.3		7.2	17.0
Organic	0.9		0.5	1.2		2.8	5.4
Podzol		2.0		0.9	2.5	0.8	6.2
Pumice	1.4	6.0	0.6		2.2	19.8	29.9
Recent		0.9		1.1		3.8	5.8
Ultic		0.9				0.9	1.8
Total	25.8	20.6	10.9	11.2	5.8	85.5	159.8

Table 9: The effective sample size for soil and land use combinations for Total C for the 29 sites sampled in 2015.

	Effective sample size Total C (%) (log scale)						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	15.2	6.8	10.1	3.2		32.3	67.6
Brown	4.4	4.2		2.1		14.9	25.6
Gley	7.5		1.7	1.1	1.0	14.5	25.8
Granular	8.3		1.8	1.1		8.3	19.5
Organic	1.6		0.7	1.1		3.7	7.0
Podzol		2.8		1.0	3.2	1.5	8.4
Pumice	2.0	9.1	1.1		3.4	25.1	40.7
Recent		1.0		1.0		4.6	6.6
Ultic		1.0				1.0	1.9
Total	38.9	24.9	15.5	10.6	7.6	105.8	203.2

Table 10: The effective sample size for soil and land use combinations for soil pH for the 29 sites sampled in 2015.

	Effective sample size pH						
Soil_Order	Arable	Forestry	Horticultu	Native	Other	Pasture	Total
Allophanic	6.3	4.4	5.0	2.7		13.1	31.6
Brown	2.8	3.5		2.0		9.4	17.7
Gley	3.1		0.6	1.1	1.0	7.6	13.3
Granular	4.4		1.3	1.1		5.3	12.2
Organic	0.7		0.4	1.0		2.1	4.3
Podzol		1.7		0.8	2.0	0.6	5.1
Pumice	1.1	3.8	0.4		1.7	8.7	15.7
Recent		0.8		0.9		2.9	4.6
Ultic		0.8				0.8	1.5
Total	18.5	14.8	7.8	9.7	4.6	50.5	106.0

Appendix V Results of 2015-16 soil quality monitoring

Site No.	Soil Order	Land system	Land use detail	pH	Total C (%)	Total N (%)	Olsen P (mg/L)	AMN (mg/kg)	Bulk Density (t/m^3)	% Macropores @ -10 kPa
20	Gley	Pasture	Dairy	5.9	6.4	0.66	65	207	1.08	26
23	Brown	Forestry	Plantation forest	6.0	5.0	0.28	4	110	0.95	7
24	Brown	Pasture	Dry stock beef sheep	5.6	8.4	0.66	11	231	0.76	27
25	Brown	Native	Indigenous forest	5.2	7.3	0.38	2	120	0.82	16
29	Podzol	Drystock	Beef	6.9	7.9	0.51	31	170	0.51	22
30	Podzol	Pasture	Dairy	6.1	6.8	0.53	39	126	0.77	4
31	Allophanic	Pasture	Dairy	6.7	13.0	1.40	38	340	0.67	43
36	Allophanic	Arable	Cropping onions	6.2	5.2	0.54	100	60	0.95	11
37	Allophanic	Arable	Cropping potatoes	6.2	5.9	0.59	30	72	0.73	6
68	Allophanic	Arable	Cropping potatoes/onions/oats	6.9	6.5	0.57	84	38	0.79	16
71	Allophanic	Arable	Cropping potatoes/onions/oats	7.2	5.5	0.48	134	37	0.84	12
72	Allophanic	Pasture	Dry stock beef	5.8	11.1	1.06	37	293	0.83	3
90	Allophanic	Pasture	Dry stock sheep	5.9	8.2	0.84	6	181	0.73	22
91	Allophanic	Pasture	Dairy	6.6	5.8	0.57	46	112	0.99	7
92	Allophanic	Pasture	Dairy	6.2	9.2	0.87	20	169	0.73	10
94	Allophanic	Arable	Cropping onions/maize/ potatoes	6.2	5.2	0.53	81	53	0.86	6
95	Brown	Pasture	Dairy	6.5	6.4	0.57	70	201	0.94	9
96	Gley	Pasture	Dairy	5.6	5.4	0.60	25	90	0.81	14
97	Gley	Pasture	Dairy	6.3	3.9	0.41	81	131	1.04	10
100	Gley	Pasture	Dairy	6.0	9.0	0.70	41	180	0.91	5
101	Granular	Pasture	sheep/lightly forested	5.3	11.8	1.03	17	239	0.82	3
102	Granular	Pasture	dry stock Sheep	6.3	14.7	1.42	13	362	0.68	10
103	Brown	Pasture	dry stock - techno beef	5.5	7.9	0.71	81	213	0.99	4
104	Granular	Pasture	dry stock - techno beef	5.5	8.2	0.72	60	264	0.92	4
107	Brown	Pasture	Dairy	6.2	4.3	0.41	96	120	1.03	9
108	Brown	Pasture	Dairy	6.5	9.8	0.92	134	207	0.86	8
109	Brown	Pasture	Dairy	6.2	9.1	0.79	69	170	0.80	6
145	Allophanic	Native	Senic reserve	5.6	23.4	1.35	2	416	0.27	24
147	Allophanic	Horticulture	kiwifruit	6.9	7.6	0.73	67	144	0.76	10

Appendix VI Results for all 150 soil quality monitoring sites

Site No.	Soil Order	Land system	Land use detail	pH	Total C (%)	Total N (%)	Olsen P (mg/L)	AMN (mg/kg)	Bulk Density (t/m^3)	% Macropores @ -10 kPa
1	Allophanic	Pasture	Dairy	6.3	10.4	1.07	42	391	0.73	6
2	Allophanic	Pasture	Dairy	6.1	8.8	0.87	98	349	0.77	5
3	Allophanic	Forestry	Woodlot	5.3	9.1	0.62	19	174	0.75	11
4	Allophanic	Forestry	Pine plantation	4.8	8.5	0.71	-	53	0.81	13
5	Allophanic	Pasture	Dairy	6.4	9.2	0.91	43	186	0.79	6
6	Allophanic	Pasture	Dairy	5.8	10.2	1.08	27	281	0.73	8
7	Organic	Pasture	Dairy	5.9	23.1	1.7	-	190	0.53	9
8	Organic	Pasture	Dairy	6.1	36.5	1.7	-	263	0.39	6
9	Pumice	Pasture	Forest to Pasture	5.8	7.0	0.45	40	185	0.69	12
10	Pumice	Forestry	Plantation forestry	5.5	7.5	0.38	3	122	0.5	43
11	Pumice	Pasture	Dairy	5.6	10.2	0.93	31	330	0.58	13
12	Pumice	Pasture	Forest to Pasture	5.8	5.4	0.36	50	142	0.81	9
13	Pumice	Pasture	Forest to Pasture	6.0	7.9	0.58	47	240	0.67	14
14	Pumice	Pasture	Dairy	5.8	7.2	0.7	80	271	0.71	3
15	Pumice	Pasture	Dairy	5.8	6.0	0.52	101	146	0.69	18
16	Pumice	Pasture	Dairy	5.9	7.6	0.64	63	197	0.8	10
17	Pumice	Pasture	Dairy	5.8	8.6	0.75	126	289	0.83	5
18	Brown	Pasture	Dry Stock Dairy runoff	6.1	8.0	0.72	10	318	0.81	6
19	Brown	Forestry	Plantation forestry	6.3	6.2	0.48	14	195	0.87	5
20	Gley	Pasture	Dairy	5.9	6.4	0.66	65	207	1.08	26
21	Organic	Pasture	Dairy	6.7	47.8	2.52	26	288	0.36	16
22	Organic	Native	Indigenous forest	4.7	50.5	1.28	2	261	0.1	58
23	Brown	Forestry	Plantation forest	6.0	5.0	0.28	4	110	0.95	7
24	Brown	Pasture	Dry stock beef sheep	5.6	8.4	0.66	11	231	0.76	27
25	Brown	Native	Indigenous forest	5.2	7.3	0.38	2	120	0.82	16
26	Pumice	Pasture	Forest to Pasture	5.6	6.6	0.43	106	193	0.7	16
27	Pumice	Pastore	Forest to Pasture	5.2	6.2	0.54	125	156	0.72	23
28	Podzol	Native	Indigenous forest	4.4	18.2	0.88	11	196	0.57	25
29	Podzol	Drystock	Beef	6.9	7.9	0.51	31	170	0.51	22
30	Podzol	Pasture	Dairy	6.1	6.8	0.53	39	126	0.77	4

Site No.	Soil Order	Land system	Land use detail	pH	Total C (%)	Total N (%)	Olsen P (mg/L)	AMN (mg/kg)	Bulk density t/m^{-3}	% Macropores @-10 kPa
31	Allophanic	Pasture	Dairy	6.7	13.0	1.40	38	340	0.67	43
32	Recent	Pasture	Dairy	6.2	6.9	0.7	89	351	0.81	5
33	Recent	Pasture	Dairy	5.6	7.3	0.74	62	322	0.81	7
34	Allophanic	Forestry	Plantation forest	5.6	18.2	1.39	6	268	0.54	7
35	Allophanic	Pasture	Dairy	5.6	18.2	1.56	8	475	0.58	17
36	Allophanic	Arable	Cropping onions	6.2	5.2	0.54	100	60	0.95	11
37	Allophanic	Arable	Cropping potatoes	6.2	5.9	0.59	30	72	0.73	6
38	Allophanic	Native	Indigenous forest	5.8	18.2	1.01	2	333	0.46	21
39	Allophanic	Pasture	Dry stock	6.2	13.8	1.03	4	194	0.55	3
40	Allophanic	Arable	Maize	7.0	5.4	0.53	28	86	0.73	17
41	Brown	Native	Indigenous forest	5.2	6.5	0.34	3	111	0.59	19
42	Brown	Forestry	Pine was drystock	5.4	7.2	0.5	15	101	0.94	17
43	Brown	Forestry	Pinus radiata (~8 yrs)	5.3	5.2	0.28	7	89	0.87	28
44	Recent	Native	Indigenous forest	5.9	5.8	0.36	4	133	0.76	23
45	Recent	Pasture	Dry stock b&s was deer	5.4	4.7	0.43	34	138	1.08	4
46	Gley	Pasture	Dairy was market garden	6.9	4.3	0.4	99	120	0.92	7
47	Gley	Pasture	Dairy	6.3	5.7	0.55	87	160	0.76	8
48	Ultic	Forestry	Forestry	5.4	4.5	0.21	7	83	1.09	15
49	Ultic	Pasture	Dry stock (beef)	5.9	5.4	0.48	19	154	0.97	8
50	Granular	Pasture	Dairy	6.0	6.9	0.6	81	138	0.84	5
51	Granular	Pasture	Dry stock Beef & sheep	5.8	8.0	0.71	12	182	0.82	7
52	Pumice	Native	Indigenous forest	6.2	13.6	0.88	9	226	0.43	33
53	Gley	Arable	Maize Cut & Carry	6.8	8.0	0.76	49	216	0.81	3
54	Allophanic	Arable	Maize Cut & Carry	7.1	8.1	0.74	52	213	0.74	2
55	Brown	Pasture	Dry stock	6.4	5.4	0.49	50	145	0.93	5
56	Podzol	Forestry	Forestry	4.3	11.5	0.4	2	58	0.4	50
57	Podzol	Forestry	Forestry	5.6	6.6	0.32	2	76	0.64	27
60	Allophanic	Horticulture	Orchard	6.3	6.9	0.62	33	159	0.76	10
61	Granular	Arable	Cropping	6.2	2.7	0.24	76	18	1.15	16
62	Granular	Arable	Cropping	6.5	2.3	0.19	279	19	1.23	12

Site No.	Soil Order	Land system	Land use detail	pH	Total C (%)	Total N (%)	Olsen P (mg/L)	AMN (mg/kg)	Bulk density t/m^{-3}	% Macropores @-10 kPa
63	Gley	Pasture	Dairy	6.1	7.9	0.67	42	200	0.68	5
64	Gley	Pasture	Dairy	5.6	5.9	0.51	81	171	0.89	4
65	Granular	Arable	Cropping	6.4	2.8	0.28	76	41	1.01	24
66	Granular	Arable	Cropping	5.7	3.3	0.32	141	88	1.27	6
67	Granular	Pasture	Dry stock Beef	6.0	4.4	0.35	50	135	1.24	6
68	Allophanic	Arable	Cropping potatoes/onions/oats	6.9	6.5	0.57	84	38	0.79	16
69	Granular	Pasture	Dry stock Beef	5.0	10.1	0.94	45	222	0.84	4
70	Gley	Arable	Maize Cropping	6.1	5.5	0.42	111	64	1.06	6
71	Allophanic	Arable	Cropping potatoes/onions/oats	7.2	5.5	0.48	134	37	0.84	12
72	Allophanic	Pasture	Dry stock beef	5.8	11.1	1.06	37	293	0.83	3
73	Granular	Native	Indigenous forest	5.6	8.0	0.48	4	165	0.76	18
74	Organic	Pasture	Dairy	5.7	27.2	1.19	22	109	0.57	1
75	Gley	Pasture	Dairy	5.6	5.9	0.54	29	105	0.94	6
76	Gley	Pasture	Dairy	6.0	9.4	0.78	31	187	0.94	8
77	Allophanic	Pasture	Dairy	6.1	7.7	0.74	40	125	0.82	7
78	Allophanic	Pasture	intensive calf raising	6.1	4.9	0.47	26	98	0.94	9
79	Gley	Pasture	Dry stock	6.1	2.7	0.27	58	94	1.17	4
80	Allophanic	Horticulture	Orchard	6.4	8.3	0.8	44	134	0.76	5
81	Allophanic	Horticulture	Orchard	6.6	5.6	0.58	22	119	0.82	14
82	Allophanic	Horticulture	Orchard	5.4	8.0	0.71	18	166	0.83	8
84	Gley	Native	Urban indigenous forest	4.2	14.7	0.83	42	140	0.52	29
85	Granular	Arable	Cropping	6.1	3.8	0.3	114	31	1.03	20
86	Granular	Arable	Cropping	5.7	3.4	0.3	99	25	1.11	13
88	Allophanic	Pasture	Drystock Sheep and beef	4.9	9.8	0.97	172	201	0.75	25
89	Organic	Pasture	Dairy	6.1	51.6	2.51	18	305	0.37	10
90	Allophanic	Pasture	Dry stock sheep	5.9	8.2	0.84	6	181	0.73	22
91	Allophanic	Pasture	Dairy	6.6	5.8	0.57	46	112	0.99	7
92	Allophanic	Pasture	Dairy	6.2	9.2	0.87	20	169	0.73	10
93	Allophanic	Arable	Maize	5.6	4.6	0.5	34	52	0.79	24
94	Allophanic	Arable	Cropping onions/maize/ potatoes	6.2	5.2	0.53	81	53	0.86	6

Site No.	Soil Order	Land system	Land use detail	pH	Total C (%)	Total N (%)	Olsen P (mg/L)	AMN (mg/kg)	Bulk density t/m^{-3}	% Macropores @-10 kPa
95	Brown	Pasture	Dairy	6.5	6.4	0.57	70	201	0.94	9
96	Gley	Pasture	Dairy	5.6	5.4	0.60	25	90	0.81	14
97	Gley	Pasture	Dairy	6.3	3.9	0.41	81	131	1.04	10
98	Brown	Pasture	Dairy	5.7	4.3	0.39	42	103	1.05	10
99	Brown	Pasture	Dairy	6.1	3.6	0.36	70	85	1.18	1
100	Gley	Pasture	Dairy	6.0	9.0	0.70	41	180	0.91	5
101	Granular	Pasture	sheep/lightly forested	5.3	11.8	1.03	17	239	0.82	3
102	Granular	Pasture	dry stock Sheep	6.3	14.7	1.42	13	362	0.68	10
103	Brown	Pasture	dry stock - techno beef	5.5	7.9	0.71	81	213	0.99	4
104	Granular	Pasture	dry stock - techno beef	5.5	8.2	0.72	60	264	0.92	4
105	Brown	Pasture	Dry stock Beef	6.2	11.0	1.11	48	205	0.67	5
106	Gley	Pasture	Dairy was maize	6.1	6.0	0.62	44	109	0.89	1
107	Brown	Pasture	Dairy	6.2	4.3	0.41	96	120	1.03	9
108	Brown	Pasture	Dairy	6.5	9.8	0.92	134	207	0.86	8
109	Brown	Pasture	Dairy	6.2	9.1	0.79	69	170	0.80	6
110	Allophanic	Pasture	Dry stock	6.3	10.1	0.9	7	208	0.66	6
111	Allophanic	Pasture	Dry stock	6.1	10.7	0.94	14	219	0.67	7
112	Allophanic	Native	Indigenous forest	5.5	13.4	0.74	2	130	0.53	29
113	Pumice	Pasture	Dairy	5.5	7.3	0.65	34	143	0.69	14
114	Pumice	Forestry	Forestry	4.9	7.1	0.53	47	97	0.6	36
115	Pumice	Forestry	Forestry	5.4	8.7	0.39	3	129	0.45	39
116	Pumice	Pasture	Dairy	6.7	8.0	0.67	46	184	0.7	8
117	Pumice	Pasture	Dairy	6.6	9.3	0.88	165	238	0.66	15
118	Pumice	Forestry	Forestry	5.9	2.2	0.09	5	32	0.84	26
119	Pumice	Pasture	Dairy	5.8	7.2	0.58	54	154	0.8	6
120	Pumice	Forestry	Forestry	5.4	6.8	0.35	18	89	0.87	24
121	Allophanic	Pasture	Dairy	6.2	13.6	1.26	24	235	0.65	2
122	Recent	Pasture	Dairy	6.0	5.8	0.59	28	179	0.88	3
123	Gley	Pasture	Dairy	5.9	10.7	0.93	28	169	0.68	8
124	Pumice	Pasture	Deer Farm	5.6	9.0	0.73	44	174	0.64	22
125	Pumice	Pasture	Deer Farm	6.2	7.4	0.63	43	123	0.76	7
126	Allophanic	Pasture	Deer Farm	5.8	12.3	1.22	40	243	0.66	9

Site No.	Soil Order	Land system	Land use detail	pH	Total C (%)	Total N (%)	Olsen P (mg/L)	AMN (mg/kg)	Bulk density t/m^{-3}	% Macropores @-10 kPa
127	Allophanic	Pasture	Deer Farm	6.1	13.3	1.3	36	262	0.63	6
128	Pumice	Pasture	Deer Farm	5.9	10.5	0.79	18	177	0.64	5
130	Brown	Pasture	Dairy	6.1	3.6	0.36	70	85	1.18	1
131	Allophanic	Forestry	Forestry	5.3	13.6	1.04	18	132	0.52	22
132	Allophanic	Pasture	Dry stock	5.7	15.0	1.35	14	232	0.6	10
133	Allophanic	Pasture	Dry stock Beef	5.8	9.1	0.92	30	223	0.86	8
134	Allophanic	Arable	Maize/Tama	5.9	6.6	0.67	55	105	0.85	7
135	Granular	Pasture	Dry stock Beef	5.8	8.6	0.84	62	176	0.86	4
136	Gley	Native	Indigenous forest	6.3	4.7	0.38	5	90	0.94	9
137	Gley	Pasture	Dairy	5.6	6.7	0.65	34	186	0.82	5
138	Granular	Horticulture	Kiwifruit Organic	6.6	7.8	0.7	92	398	0.87	6
139	Allophanic	Pasture	Drystock sheep	5.8	9.9	1.01	20	337	0.71	5
140	Allophanic	Horticulture	Kiwifruit Organic	6.5	11.3	1.04	28	361	0.71	9
141	Pumice	Pasture	Forest to Pasture	5.4	9.4	0.64	149	299	0.57	24
142	Pumice	Pasture	Forest to Pasture	5.4	8.7	0.49	63	161	0.67	23
143	Pumice	Pasture	Forest to Pasture	5.4	7.1	0.44	69	170	0.73	23
144	Allophanic	Forestry	Woodlot	5.0	7.1	0.49	36	100	0.84	30
145	Allophanic	Native	Senic reserve	5.6	23.4	1.35	2	416	0.27	24
146	Allophanic	Horticulture	kiwifruit	6.8	9.2	0.9	75	147	0.76	11
147	Allophanic	Horticulture	kiwifruit	6.9	7.6	0.73	67	144	0.76	10
148	Allophanic	Horticulture	kiwifruit	6.9	7.9	0.82	66	148	0.78	10
149	Allophanic	Horticulture	kiwifruit	7.0	7.2	0.68	122	127	0.88	15
150	Allophanic	Horticulture	kiwifruit	6.9	9.3	0.88	45	154	0.73	4
151	Allophanic	Horticulture	kiwifruit	7.1	6.9	0.71	93	111	0.81	9
152	Allophanic	Forestry	Plantation forestry	5.3	19.8	1.47	8	184	0.49	17
153	Brown	Forestry	Plantation forestry	4.7	6.7	0.44	8	72	0.88	16
154	Recent	Forestry	Plantation forestry	5.6	4.7	0.29	36	53	1.13	31
155	Allophanic	Forestry	Plantation forestry	5.2	14.3	0.67	1	186	0.46	43