# Farm Soil Health: assessment across a forestry to pasture chronosequence

## Healthy soil, healthy plants, healthy people

Nicole Schon and Ants Roberts

# Farm Soil Health

# Report prepared Ngai Tahu

# February 2020

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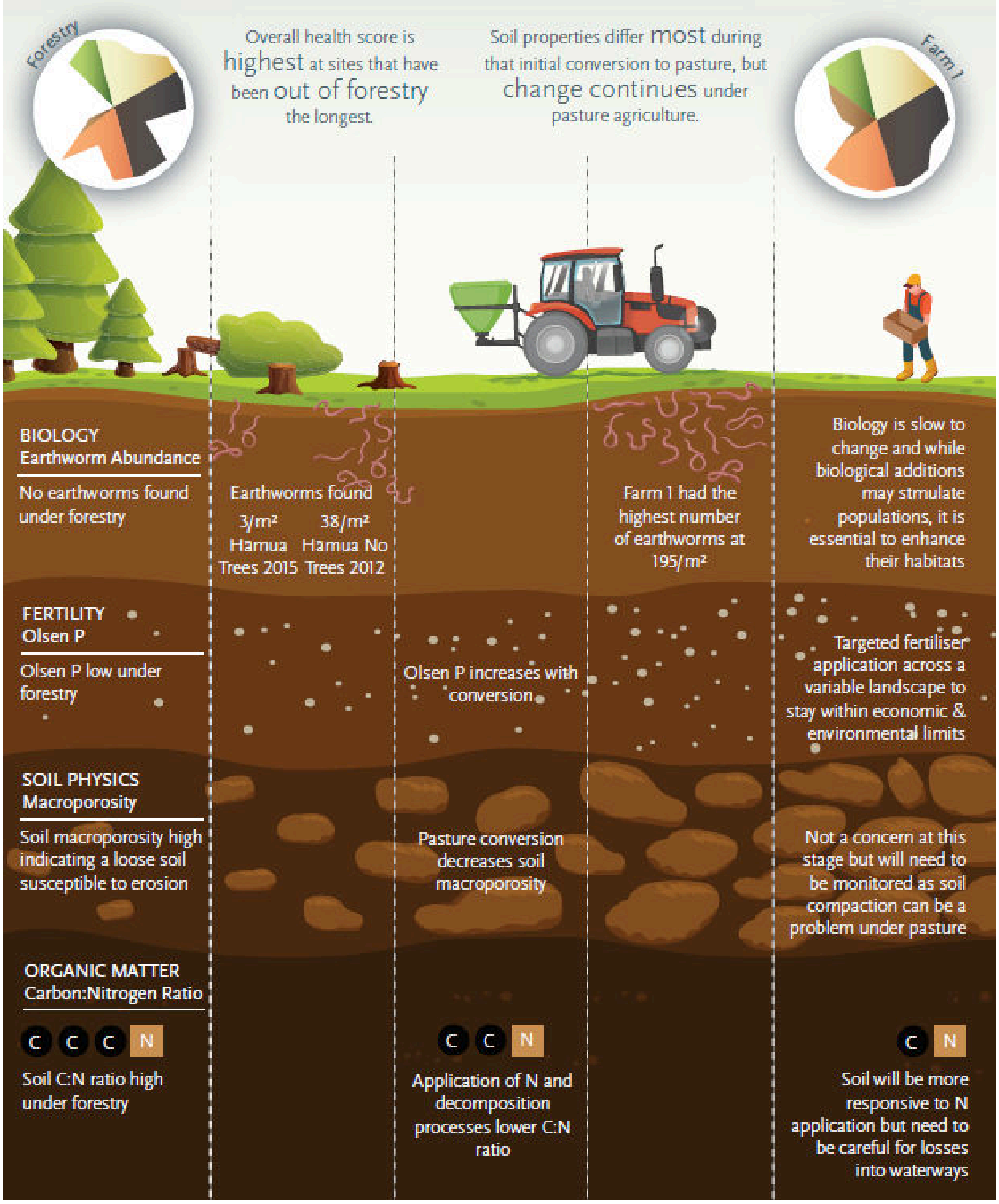
# 1. Executive Summary

Ngai Tahu farming have the goal to maintain the life sustaining capacity of soils during the change from forestry (*P. radiata*) to pasture agriculture. Sites were sampled across a chronosequence of five sites previously from Eyrewell forest, including a site still in forest and a site out of forestry for more than 10 years. Soil health was assessed through a combination of soil fertility and organic matter measures, as well as soil physical and biological properties in May 2019. These properties were assessed against target ranges suitable for high producing pasture agriculture, the closer to these targets, the better the soil health status.

The conversion of pine forest to irrigated dairy pasture tended to improve soil health. Factors limiting soil health under forestry at these sites included low fertility, high C:N ratio, high macroporosity, low microbial respiration and low earthworm abundance and functional diversity. Many of these variables that were not at their target levels were progressing in the right direction following conversion to pasture. Monitoring and managing the soils to ensure soil health continues in the right direction is essential. Management needs to ensure that nutrients are applied appropriately and the soil physical status is not degraded. Further, the soils rated poorly in soil biological indicators, even Farm 1 which had the highest soil health score; hence these soils may require action beyond standard best practice to accelerate soil health improvement.

## Report Summary



Overall health score is highest at sites that have been out of forestry the longest.

Soil properties differ most during that initial conversion to pasture, but change continues under pasture agriculture.

**BIOLOGY**
**Earthworm Abundance**

No earthworms found under forestry

Earthworms found

| 3/m² | 38/m² |
|---|---|
| Hamua Trees 2015 | Hamua No Trees 2012 |

Farm 1 had the highest number of earthworms at 195/m²

Biology is slow to change and while biological additions may stmulate populations, it is essential to enhance their habitats

**FERTILITY**
**Olsen P**

Olsen P low under forestry

Olsen P increases with conversion

Targeted fertiliser application across a variable landscape to stay within economic & environmental limits

**SOIL PHYSICS**
**Macroporosity**

Soil macroporosity high indicating a loose soil susceptible to erosion

Pasture conversion decreases soil macroporosity

Not a concern at this stage but will need to be monitored as soil compaction can be a problem under pasture

**ORGANIC MATTER**
**Carbon:Nitrogen Ratio**

C C C N

Soil C:N ratio high under forestry

C C N

Application of N and decomposition processes lower C:N ratio

C N

Soil will be more responsive to N application but need to be careful for losses into waterways

## 2. Introduction

Ngai Tahu farming have the objective of maintaining the life sustaining capacity of soil under changed landuse. The life sustaining capacity of the soil is based on a healthy soil, with a good structure, appropriate water storage and drainage, readily available nutrients, and populations of a diversity of beneficial organisms. Maintaining the underlying soil physical, chemical and biological elements enables the soil to continue to function and provide ecosystem services to sustain living things and be resilient to degradation and other unfavourable perturbations.

Literature on soil health (including soil quality) is vast, and although there are many approaches which can be taken to assess soil health, there is no universally accepted methodology, due to a diversity of landscapes and landuses in which they need to be applied (Bünemann *et al*., 2018). Soil health often refers to the dynamic properties of the soil which can change with management; however this is governed by their inherent soil properties (land suitability). In New Zealand soil quality is often described using a basic suite of indicators developed from a project spanning 500 soils (Lilburne *et al*., 2004; Sparling *et al*., 2008). This approach has been employed through regional councils for monitoring soil quality and State of Environment reporting (Drewry *et al*., 2017). The suite of indicators includes a measure of acidity (pH), fertility (Olsen P), organic resources (total carbon, total nitrogen and mineralizable nitrogen) and physical quality (bulk density and macroporosity) (sindi.landcaresearch.co.nz). All are considered dynamic or manageable properties of soil (Dominati *et al*., 2014). We added indicators used to assess soil health overseas (e.g. commercially available Cornell Soil Health Test) to this basic suite of indicators (Table 2.1), in order to gain further insights into the response of soil health under changing landuse.

We used the expanded indicator set to assess how conversion from forestry (*Pinus radiata*) to irrigated pasture agriculture (dairy production) influenced soil health in comparison to targets set for high producing grazed pasture soils. The investigation included how soil health changed during the process of conversion to irrigated pasture by sampling an existing forest site (*Pinus radiata*, dryland), dairy pasture soils 2, 4 and 10+ years post conversion (with irrigation introduced between 2 and 7 years post conversion) and soils converted to irrigated dairy support 3 years ago.

**Table 2.1: Full list of indicators used to access soil health at selected Ngai Tahu sites in May 2019. Indicators with asterix (*) form the current basic suite of indicators used in New Zealand.**

| Indicator | Description |
|---|---|
| **Soil fertility** | |
| Soil acidity (pH) * | Acidity of soil. Acidity influences availability of plant nutrients and soil biological activity. |
| Phosphorus availability (Olsen P) * | Plant available phosphorus (P). Essential plant nutrient. |
| Potassium availability (K) | Plant available potassium (K). Essential plant nutrient. High K can influence uptake of other cations and cause hypomagnesaemia. |
| **Soil organic matter properties** | |
| Soil total carbon * | Amount of carbon (C)/organic matter, benefiting soil structure, biology and nutrient availability. |
| Soil total nitrogen * | Amount of nitrogen (N) in soil. Organic forms mineralised to become plant available. Essential for plant growth. |
| Organic matter quality (C:N ratio) | Amount of C available for every unit of N. High C:N ratio typically associated with lower quality organic matter and net immobilisation of N. |
| Readily available carbon (HWEC) | Carbon readily available for carbon decomposition. |
| Mineralizable N (AMN) * | Quantity of N potentially available for plant uptake through mineralisation. |
| **Soil physical properties** | |
| Soil density (BD) * | Soil bulk density measures how tightly packed the soil is. Dense soils restrict water and air movement. |
| Soil macroporosity * | Number of large pores in soil, improving water and air movement through the soil. Macropores decrease with compaction. |
| Available water capacity (AWC) | Amount of plant available water the soil can potentially store. |
| **Soil biological indicators** | |
| Soil microbial respiration (MicroResp) | Activity of soil microbes. |
| Earthworm abundance | Abundance of earthworms, their activity in the soil benefits soil structure and nutrient availability. |
| Earthworm diversity | Range of earthworm functional roles represented. |
| **Pasture pests and diseases** | |
| Pasture insect pest abundance | Damage to pasture caused by feeding from a pests. |
| [*Pasture disease risk (AMN:TN)*] | [*This indicator is still being tested but appears to indicate risk of soil-borne disease to pasture plants*]. |

# 3. Method

## 3.1 Site Selection

We sampled an existing forest site (*Pinus radiata*, dryland); dairy pasture soils 2, 4 and 10+ years post conversion (with irrigation introduced between 2 and 7 years post conversion) and soils converted to irrigated dairy support 3 years ago (Table 3.1). Sites were selected from land that was previously in Eyrewell Forest, north of the Waimakariri River near Christchurch, New Zealand (Figure 3.1). All sites were located on a Pallic Firm Brown, Lismore silty loam soil, these soils are characterised as shallow, well drained and moderately stony (www.smap.landcareresearch.co.nz). Average annual temperature was 11.5ºC with average rainfall of 650 mm at these sites. All GPS coordinates for sampled sites are given in Appendix 1.

**Table 3.1: Site information, including years since forestry and irrigation, at selected Ngai Tahu sites, arranged left to right by years since forestry ceased.**

| | **Forestry** | **Farm 16** | **Hāmua Trees** | **Farm 1** | **Hāmua No trees** |
|---|---|---|---|---|---|
| Landuse | *Pinus radiata* | Dairy support | Dairy production | Dairy production | Dairy production |
| Number of sites sampled | 5 | 8 | 5 | 5 | 5 |
| Years since forestry ceased | 0 | 3 | 4 | 7 | 10+ |
| Years since irrigation commenced | 0 | 3 | 2 | 7 | 2 |

**Figure 3.1: Location of all sampling sites**

An existing dryland forest that was dominated by *Pinus radiata* was sampled. Five sites south of Hunter Road were sampled (Figure 3.2).

Farm 16 had previously been involved in a trial that added some soil biology at time of conversion from forestry to irrigated pasture in 2016. Control plots as well as plots which had received applications of a combination of earthworms (endogeic and anecic) and rhizobia (commercially coated seed containing TA1 as control and seed plus laboratory strain S3N2 as rhizobia treatment) and mycorrhizae were sampled (Figure 3.3, off Murray Road). Each treatment was replicated 4 times.

**Figure 3.2: Location of Forestry sampling points (●).**

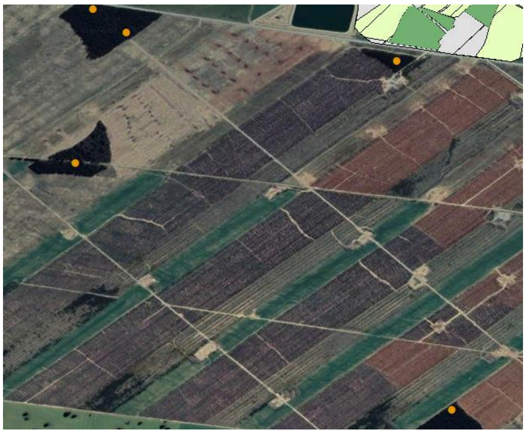
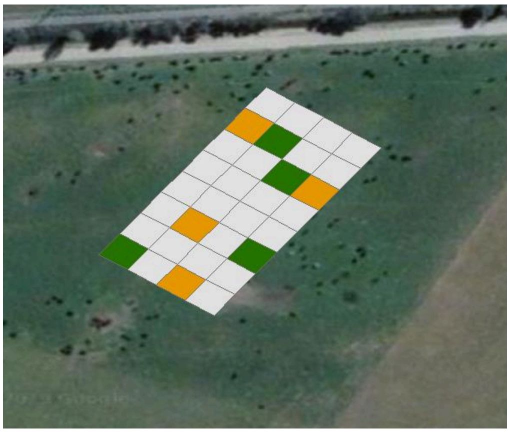
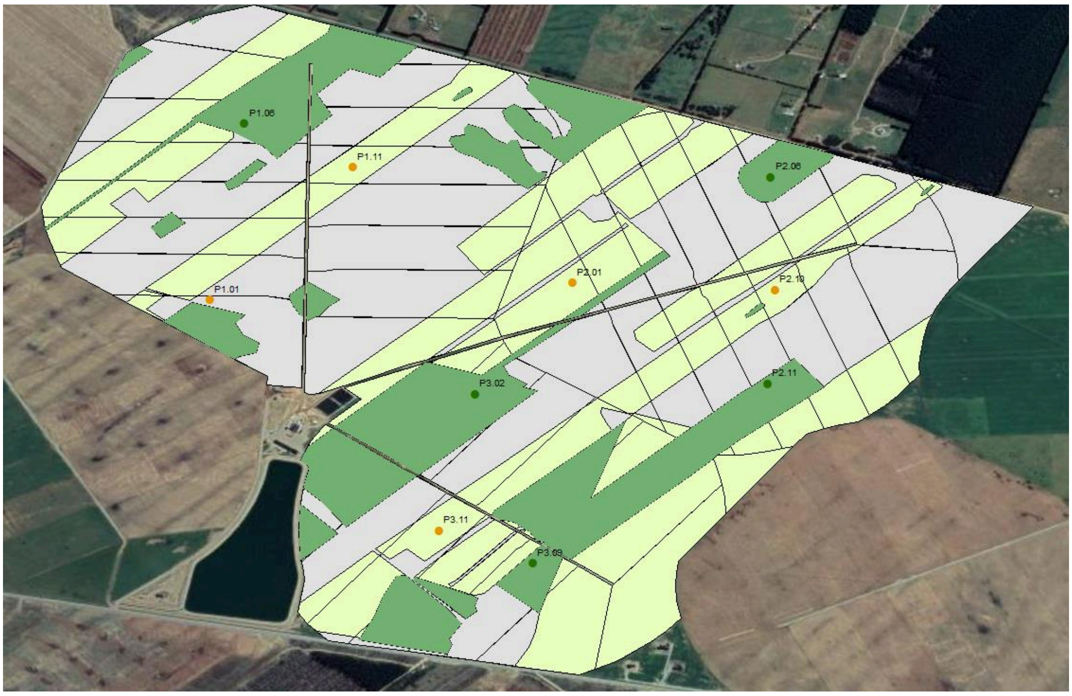


**Figure 3.3: Location of Farm 16 sampling points (● control, ● biological additions).**



Farm Hāmua is located north of Hunter Road and 10 sites were chosen for sampling (Figure 3.4). This farm was in its second year of irrigation and first year of dairy production, milking 1020 cows on 330 hectares. Five of these sites had no *P. radiata* since at least 2009 (10+ years post forestry, 2 years irrigated) and another five of these sites had *P. radiata* before 2015, (4 years post forestry, 2 years irrigated).

**Figure 3.4: Location of Hāmua sampling points (● no trees, ● trees 2015).**



Farm 1 had been in dairy production the longest, being converted to irrigation in 2012. Farm 1 is located off Carleton Road. Five sites were selected for sampling (Figure 3.5).

**Figure 3.5: Location of Farm 1 sampling points (●).**

## 3.2 Sampling

A number of samples were collected in May 2019 to determine soil fertility, soil organic matter, physical properties, biological indicators and pasture pests and diseases.

### 3.2.1 Soil fertility

Thirty soil fertility cores (25 mm diameter × 75 mm deep) were collected for each sampling point and bulked together. Soil was air dried, sieved to 2 mm and analysed. Samples were analysed for soil pH (1:2.5 soil:water), Olsen P (Olsen *et al.*, 1954), potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) (Rayment and Higginson, 1992). Samples were analysed at ARL.

### 3.2.2 Soil organic matter properties

Soil total nitrogen (N) and carbon (C) were analysed using the Dumas combustion method using an Elementar Vario Max Cube Analyser at ARL. Anaerobically mineralizable nitrogen was determined over a 7 day incubation (Keeney and Bremner, 1966) at ARL. Hot water carbon was determined using an overnight extraction in hot water and analysed using a total organic carbon analyser (Ghani *et al.*, 2003) at RJ Hill Laboratories.

### 3.2.3 Soil physical properties

Triplicate samples for measuring bulk density and soil hydraulic properties were collected (100 mm diameter, 75 mm deep). Due to the stone content of the soil some samples could not be collected first time and so results may not be representative of the site. Tension tables were used to determine macroporosity (0-10 kPa), field capacity (10 kPa) and wilting point (1500 kPa) (Gradwell, 1960) at the Soil Physics Lab at Landcare Research. Total available water capacity was the difference between field capacity and wilting point. Bulk density was determined by oven-drying at 105°C for 48 h and weighing. Stone content in each sample was determined and accounted for.

### 3.2.4 Biological indicators

Sub samples of the soil fertility cores were used to determine rhizobia effectiveness and microbial respiration.

Microbial respiration was determined using a MicroResp assay (Campbell *et al.*, 2003) by S. Young (AgResearch). Colorimetric $CO_2$-traps, consisting of 96-well microplates of a cresol red based pH indicator, were sealed to the deep-well plate filled with soil and incubated at 22°C for 5 h. Absorbance of the $CO_2$-traps was measured at 590 nm (Biolog microplate spectrophotometer) immediately prior to sealing to the soil and following incubation. Change in absorbance was calculated against the $CO_2$ concentration to give $CO_2$ evolution. Basal respiration was measured as well as respiration with the addition of glucose, galactose, arginine, alanine, glucosamine, citric acid and succinic acid.

The symbiotic performance of rhizobia populations was compared against the commercial standard *Rhizobium leguminosarum bv. trifolii* TA1 (Wakelin *et al.*,

2018) by E. Gerard (AgResearch). The symbiotic potential of rhizobia from the soil samples was determined using growth of *T. repens cv.* Tribute under N-limited conditions. Sterilised and germinated seeds were planted into vermiculite (Grade 2, Exfoliaters (Aust) Pty Ltd). Plants were inoculated 3 days after sowing with a suspension of soil from each site. Plants were grown in a growth room (16 h light at 22°C; 8 h dark at ambient temperature) for 42 days and watered with sterile water as required. Plant shoots were harvested 42 days after inoculation, dried at 60°C for 48 hours, and dry weights recorded.

Five soil turves (200 × 200 × 200 mm) were collected and hand-sorted for soil invertebrates from each site. Earthworms were identified by species and counted by N. Schon (AgResearch).

### 3.2.5 Pasture pests and diseases

Insect pasture pests were identified and counted from the soil turves collected for soil invertebrates.

The risk of root pathogen pressure was determined using the ratio of anaerobically mineralizable nitrogen to total nitrogen (B. Dignam pers. comm). Early results from New Zealand-wide sampling of dairy soils has shown this ratio to be an indicator of soil-borne plant disease pressure but more testing is required to confirm this. The indicator is included here to show the range of possible risks to soil functioning.

## 3.3 Statistical Analysis

For Na, OM, soil C, soil N, soil C:N ratio and macroporosity their change since forestry and irrigation (in years, Table 3.1) was examined with linear regression. For HWEC its change was examined with a linear spline model, and for pH, Olsen P, Ca, Mg, K, CEC, AMN, bulk density and AWC their change was examined with quadratic regression. Years since irrigation did not necessarily correspond to years since forestry (Table 3.1).

A comparison between invertebrates was made using average values with an analysis of variance (ANOVA) to determine the influence of years since forestry and irrigation. The ANOVA was applied to each invertebrate variable separately from other variables. In all invertebrate variable analyses, Years was used as a factor. This is because invertebrate abundance did not exhibit continuous changes during the study period. In addition, total earthworm abundance, *L. rubellus* abundance and clover root weevil abundance was $\log_e(x+1)$-transformed prior to the ANOVAs, to stabilise variation. All ANOVAs were carried out with statistical software SAS version 9.3.

There were no significant differences in soil properties between the control and biological additions at Farm 16 so data from all sample points are pooled in the results Tables and Figures for this farm.

## 3.4 Soil Health Score

Soil health scores were determined in comparison to target ranges. Optimal ranges have been defined by experts as reported in the literature. Some targets are used for State of the Environment reporting. We used these targets in combination with targets specific to productive deep, free draining friable soils formed from volcanic tephra (e.g, Egmont black loam). Values at or within their optimal range were given a value of 1. If values were below their target range their score was calculated using Equation 1, and if the value was above their target range their score was calculated using Equation 2. Scores were plotted to represent proximity to target ranges. Changing landuse will result in different targets needing to be met. When values dropped below suboptimal values (not presented in this report) an extra weighting (1.5x) was given in the equation, with a minimum value of 0 possible.

**Equation 1**

$$\text{Score} = 1 - \frac{\text{target - measured value}}{\text{target – theoretical minimum}}$$

**Equation 2**

$$\text{Score} = 1 - \frac{\text{measured value - target}}{\text{theoretical maximum – target}}$$

# 4. Results

Soils from the Ngai Tahu sites had 8-15% stone content (Table 4.1). Soil moisture was >22% under irrigation, but the dryland forest soils had 11.1% soil moisture at the time of sampling and were noted as being hydrophobic during soil hydraulic analyses. Soil moisture at Farm 16 was also 5% lower in comparison to the other pasture sites. Soil colour was obviously different at the Forestry site at the time of sampling and these differences remained once the soils were dried (Figure 4.1).

**Figure 4.1: Soil colour from sample sites after oven drying**

**a) Forestry**

**b) Farm 1**

It is important to understand differences in soil types across New Zealand. Soils located at Eyrewell forest (Lismore silty loam) have a Land Use Capability rating of Class 4 (ourenvironment.scinfo.org.nz). This means that it has significant limitations for arable use or cultivation, is suitable for occasional cropping, pastoralism, tree crops and forestry. Some Class 4 is also suitable for viticulture and berry fruit. Figure 4.2 shows the profile of this soil. Under long term pasture there is an A horizon (topsoil) which is 15-20 cm deep, with an overlying B horizon (subsoil) of around 20 cm deep which sits on gravels and stones (C horizon). In contrast a soil which has a Land Use Capability rating of Class 1 has the most versatile multiple landuse, with minimal limitations, being highly suitable for cropping, viticulture, berry fruit, pastoralism, tree crops and forestry. An example of soils on Class 1 land is the Egmont black loam (Figure 4.2) a volcanic soil in South Taranaki. Typically, these soils consist of topsoils 20-25 cm deep overlying subsoils up to a meter deep which sit on the parent material (airfall tephra). It is the deep, fine textured nature of the A and B horizons which allow these soils to retain around 150 mm of plant available water, while the high allophane content allows the soil to sequester and protect large amounts of soil C. It is important to note that the Lismore soil, no matter how well developed (under grazed pastoral agriculture) will continue to have limitations and never reach the status of a Class 1 land. The soil health targets we have set for this report are for highly productive pastures on deep, free draining friable soil formed from allophanic tephra (Table 4.1). These targets are narrower than the target ranges used in the State of Environment reporting and while it is recognised that the soils of Eyrewell forest may never reach these targets due to the inherent properties of the soil, it allows us to recognise the limitations that influence, and will continue to influence the Ngai Tahu farms.

**Figure 4.2: Soil profiles of two contrasting soils**

a) **Lismore shallow silty loam soil**

b) **Egmont black loam**

**Table 4.1 (continued over page): Mean soil properties in soils sampled at Ngai Tahu May 2019 (shown along gradient of time since forestry ceased).**

| | Optimal range[1] | Target high producing pasture[2] | Forestry | Farm 16 | Hāmua Trees | Farm 1 | Hāmua No trees |
|---|---|---|---|---|---|---|---|
| Soil fertility | | | | | | | |
| pH[2] | 5.5-6.3 | 5.8-6.0 | 5.2 | 6.2 | 6.3 | 5.7 | 6.6 |
| Olsen P (µg/ml) | 20-30 | 30-35 | 7.6 | 51.0 | 18.2 | 29.0 | 22.8 |
| Potassium (QT) | 7-10 | | 9.4 | 14.1 | 10.2 | 11.8 | 13.0 |
| Calcium (QT) | >1 | | 3.2 | 13.3 | 11.4 | 7.8 | 11.0 |
| Magnesium (QT)[3] | 8-30 | | 23.4 | 26.4 | 25.8 | 26.6 | 25.2 |
| Sodium (QT) | >3 | | 9.8 | 8.9 | 9.8 | 10.2 | 10.8 |
| Cation exchange capacity (me/100g) | >12 | | 17.6 | 24.0 | 22.0 | 20.0 | 19.8 |
| Organic matter properties | | | | | | | |
| Total nitrogen (%) | 0.25-0.70 | 0.6-0.7 | 0.31 | 0.40 | 0.36 | 0.53 | 0.42 |
| Total carbon (%) | >2.5 | >6 | 8.6 | 8.3 | 8.6 | 8.9 | 7.4 |
| Carbon to nitrogen ratio | 8-12:1 | 9-11:1 | 27.0 | 20.5 | 23.5 | 16.5 | 17.7 |
| Hot water carbon (mg/kg) | >1400 | | 4034 | 3271 | 2708 | 2796 | 2586 |
| Anaerobically mineralizable nitrogen (kg/ha) | 50-250 | 180-200 | 78 | 158 | 165 | 209 | 244 |
| Soil physical properties | | | | | | | |
| Bulk density ($g/cm^3$) | 0.7-1.4 | 0.7-0.9 | 0.91 | 0.80 | 0.86 | 0.99 | 1.01 |
| Macroporosity (%) | 8-30 | 10-15 | 41.7 | 40.3 | 34.7 | 26.9 | 32.0 |
| Available water capacity (mm/100mm) | >6 | >20 | 8.8 | 11.6 | 14.2 | 15.5 | 11.1 |
| Stones (%) | | | 11.5 | 9.8 | 13.2 | 14.3 | 15.2 |
| Soil moisture (%) | | | 11.1 | 22.7 | 33.7 | 31.5 | 27.7 |

**Table 4.1 continued: Mean soil properties in soils sampled at Ngai Tahu May 2019 (shown along gradient of time since forestry ceased).**

| | Optimal range[1] | Target high producing pasture[2] | Forestry | Farm 16 | Hāmua Trees | Farm 1 | Hāmua No trees |
|---|---|---|---|---|---|---|---|
| Biological indicators | | | | | | | |
| Microbial respiration (µg/g/h $CO_2$-C) | 1.25-5 | | 1 | 1.18 | 1.32 | 1.08 | 0.95 |
| Total earthworm abundance (m$^{-2}$) | >400 | | 0 | 5 | 3 | 195 | 38 |
| Epigeic earthworm (m$^{-2}$)$^{\#}$ | >25 | | 0 | 0 | 3 | 41 | 1 |
| Endogeic earthworm (m$^{-2}$)$^{\#}$ | >350 | | 0 | 4 | 0 | 122 | 29 |
| Anecic earthworm (m$^{-2}$)$^{\#}$ | >25 | | 0 | 1 | 0 | 0 | 0 |
| Pasture pests and diseases | | | | | | | |
| Pasture disease risk (AMN:TN) | >2 | | 1.7 | 3.9 | 3.1 | 2.7 | 3.9 |
| Porina (m$^{-2}$) | <20 | | 1 | 0 | 2 | 2 | 0 |
| Grassgrub (m$^{-2}$) | <150 | | 0 | 0 | 0 | 2 | 0 |
| Clover root weevil larvae (m$^{-2}$) | <130 | | 0 | 2 | 87 | 32 | 76 |

Below (orange), at (green) and above (yellow) either optimal range or target range for high producing pasture.

1 Optimal ranges from Sparling et al. (2008), Roberts and Morton (2016), Drewry et al. (2017), van Groenigen et al. (2014) and Schon et al. (2012), Ferguson et al. (2019), Doran et al. (1997), Houlbrooke et al. (2011), www.smap.landcareresearch.co.nz, www.hilllaboratories.co.nz and www.dairynz.co.nz. Please note some target ranges are provisional and may change as science and understanding improve.

2 Target ranges for a deep, free draining friable soil formed from allophanic tephra under highly productive dairy farm conditions where information available. Information from Roberts (pers. comm) and (Roberts and Morton 2016).

3 8-10 optimal for pasture, 25-30 optimal for animal health.

4 Epigiec species include *Lumbricus rubellus, Dendrodrilus rubidus.* Endogeic species include *Aporrectodea caliginosa, Aporrectodea trapezoides, Octolasion cyaneum.* Anecic species include *Aporrectodea longa*.

## 4.1 Soil fertility

Soil pH is a measure of acidity (pH<7) or alkalinity (pH>7). Acidity (low pH) can affect availability of plant nutrients but can be remedied through lime application (Roberts and Morton, 2016). The forest soil had the lowest pH with an average of 5.2 across sites (Figure 4.2, Table 4.1). Not many sites fell within the target ranges for soil pH, either being above or below targets (Roberts and Morton, 2016). Lime application during the conversion process has helped to remedy low soil pH. Too high soil pH i.e., pH 6.5 + can decrease availability of some trace elements (e.g., Zn, Cu, Mn, Fe), while increasing availability of others (e.g., Mo, B).

**Figure 4.2: Soil pH across Ngai Tahu sites May 2019.** Dashed lines represent target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

Olsen P, a measure of plant available phosphorus, was lowest at the Forestry site (Figure 4.3, Table 4.1). As pastures were established Olsen P levels increased through fertiliser application. Olsen P was above economic optimum levels at Farm 16 (although these results appear to be specific to this site and do not refelct farm fertility testing). Increases in nutrient status above target ranges will only result in very small increases in pasture production and can have negative environmental outcomes (Roberts and Morton, 2016; Taylor *et al*., 2016). Some sites at Hāmua and Farm 1 also fall above target ranges (e.g. Farm 1 paddock 2.13 and Hāmua paddock 2.01), while others fall below (e.g. Hāmua paddock 1.01, 1.06, 2.11 and 3.11).

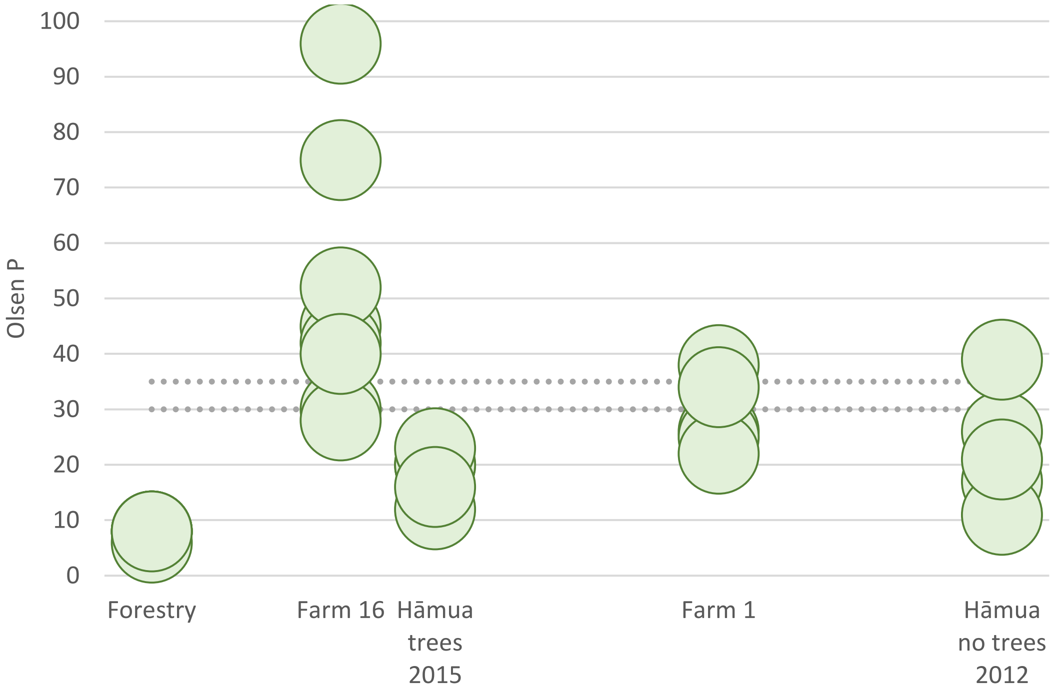
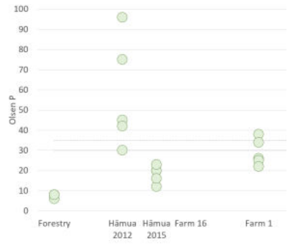


**Figure 4.3: Olsen P across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



The cation exchange capacity (CEC) was not limiting in this study, increasing during conversion to pasture through the addition of lime which increases soil negative charge. Among the cations, calcium (Ca) was lower at the forestry site, reflecting the application of lime during conversion to pasture and an increase in soil pH (Table 4.1). Potassium (K), magnesium (Mg) and sodium (Na) were similar at all sites. All cations were within recommended ranges except K. Soil K is naturally high in these soils and was above optimum at several of the pasture sites (Figure 4.4). High pasture K levels can reduce the dietary adsorption of Mg and induce a magnesium (Mg) deficiency (often called grass staggers), especially pre and post calving.

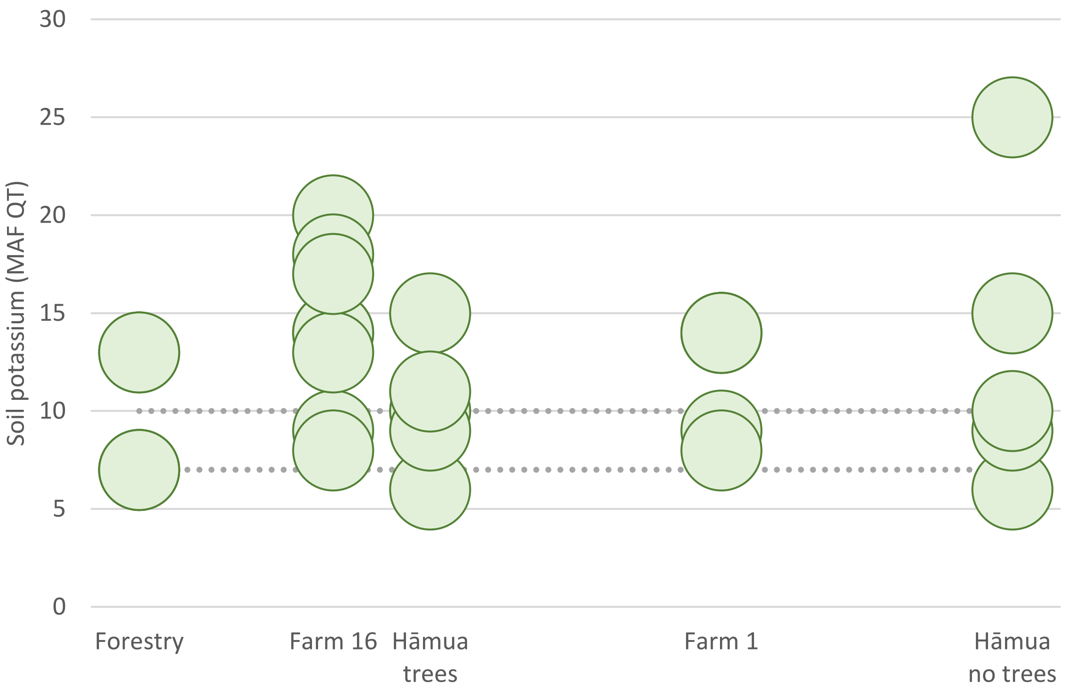
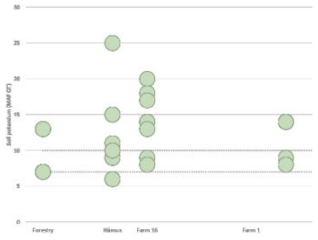


**Figure 4.4: Soil potassium across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts and Morton, 2016). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



## 4.2 Soil organic matter properties

Soil total carbon (C) is a good indication of the amount of organic matter, which is important for retaining soil moisture and nutrients and is food for soil biology. Soil carbon was above 7.4% at all farms (Figure 4.5, Table 4.1), with more carbon being better and values over 2.5% recommended for pallic soils (Sparling *et al.*, 2008) and greater than 6% for high producing soils. Soil organic matter is easily lost and can take a long time to replace.

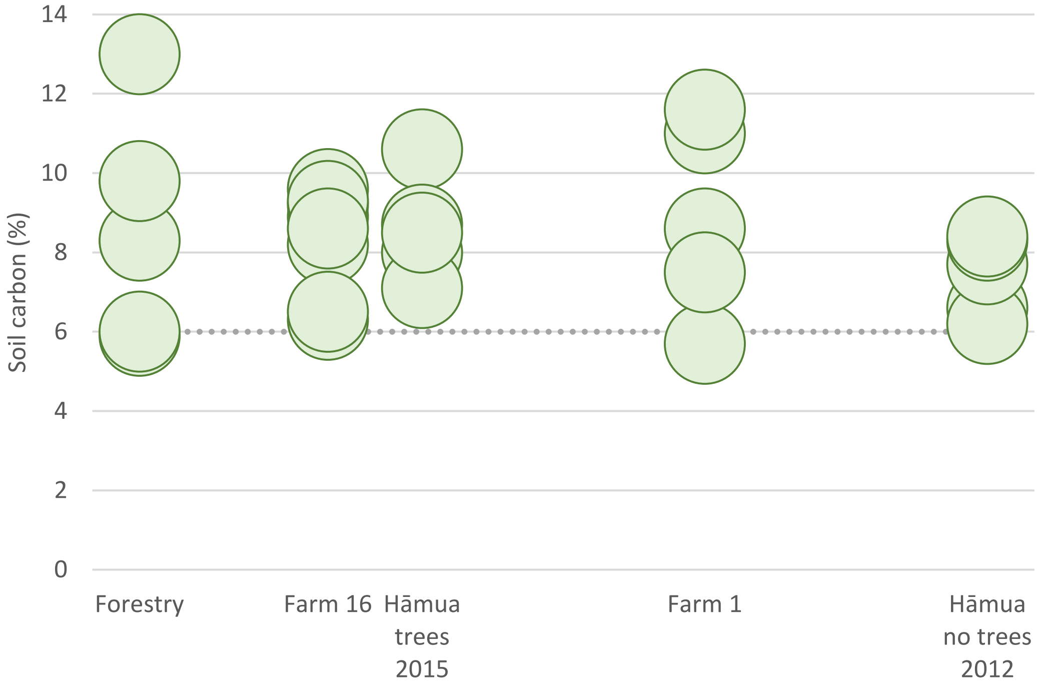
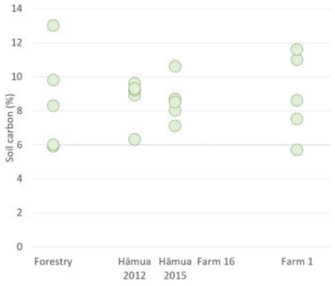
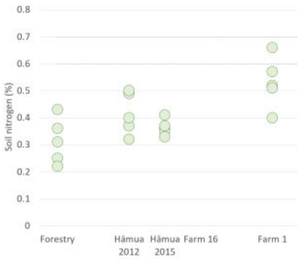


**Figure 4.5: Soil total carbon across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



Soil total nitrogen (N) was lower than the target range for high producing soils across most sites, with the exception of some paddocks at Farm 1 (Figure 4.6, Table 4.1). Soil total N includes organic N which needs to be mineralised to become plant available, values exceeding 0.7% can cause environmental problems.

**Figure 4.6: Soil total nitrogen across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



The soil C:N ratio was higher than the target range for the forestry site (Figure 4.7, Table 4.1). The C:N ratio decreased after conversion to pasture, but it remains above the target range. A high C:N ratio indicates that there is reduced availability of N to plants, with net immobilisation. Once the C:N ratio drops below 25, N will start to become more available to plants through mineralisation. In high producing pastures a C:N ratio of 9-11 is desirable to ensure more N is available to plants during decomposition than is required by microbes for growth and reproduction.

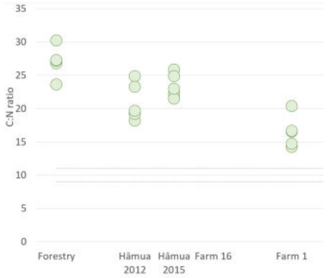


**Figure 4.7: Soil C:N ratio across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

Anaerobically mineralised nitrogen (AMN) is an estimate of the nitrogen that can be supplied to plants through the decomposition of soil organic matter. Low values (below 50 kg/ha) in pastures will limit N availability and pasture growth. Even with AMN values of greater than 50 kg N/ha pasture can still be limited by insufficient N to reach potential yields. AMN was lowest under forestry but on average was within target range across all sites (Figure 4.8, Table 4.1). Individual sites were above the target range at Farm 16 and Hāmua no trees (2.01 and 2.10).

**Figure 4.8: Anaerobically mineralisable nitrogen across Ngai Tahu sites May 2019.** Dashed line represents target value range (Sparling *et al.*, 2008). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

Hot water carbon (HWEC) was above the target of 1400 mg/kg at all sites (Figure 4.9, Table 4.1), with a decline occurring during conversion to pasture. Hot water carbon is a measure of carbon readily available for microbial decomposition and is often correlated with microbial biomass and associated soil functions. The target given here is a provisional target and more research needs to be conducted to refine this (Drewry *et al.*, 2017).

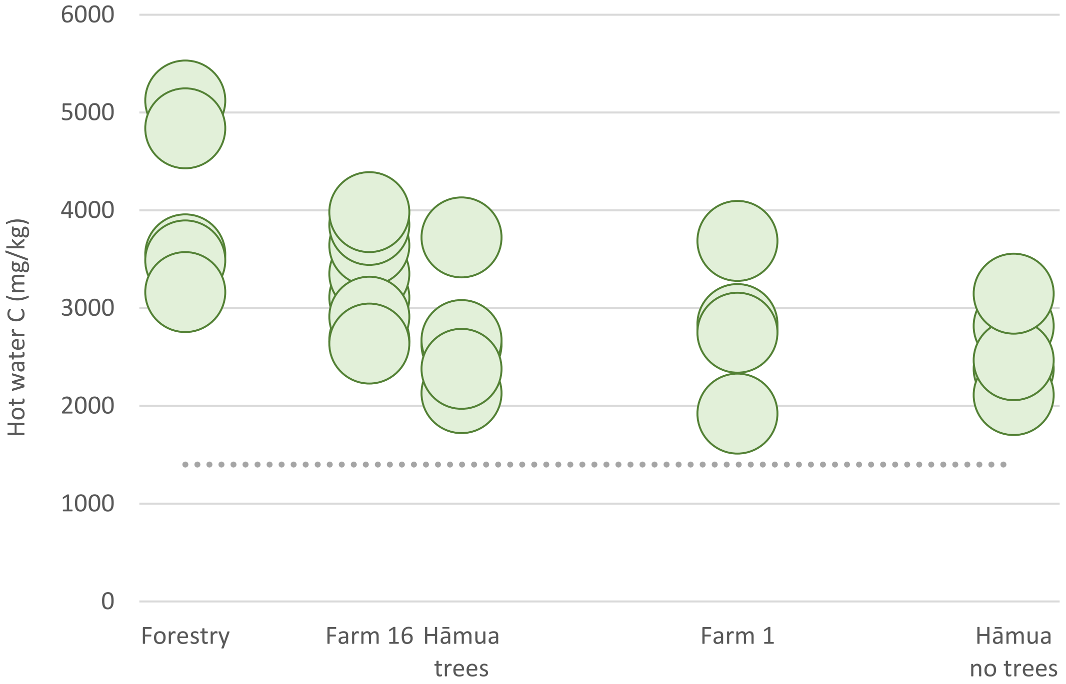
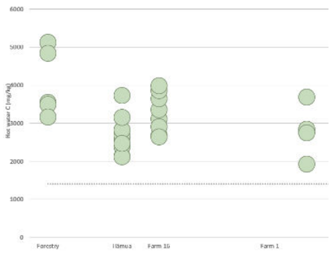


**Figure 4.9: Hot water carbon across Ngai Tahu sites May 2019.** Dashed line represents the provisional target value (Drewry *et al.*, 2017). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



## 4.3 Soil physical properties

Soil bulk density defines the soil structural condition determined on a mass to volume basis. An excessive bulk density (i.e. >1.4) is indicative of a soil in a compacted state. Compacted soils decrease pasture yield potential while increasing the risk of surface runoff. Average soil bulk density was increasing as time since forestry increased (Figure 4.10, Table 4.1).

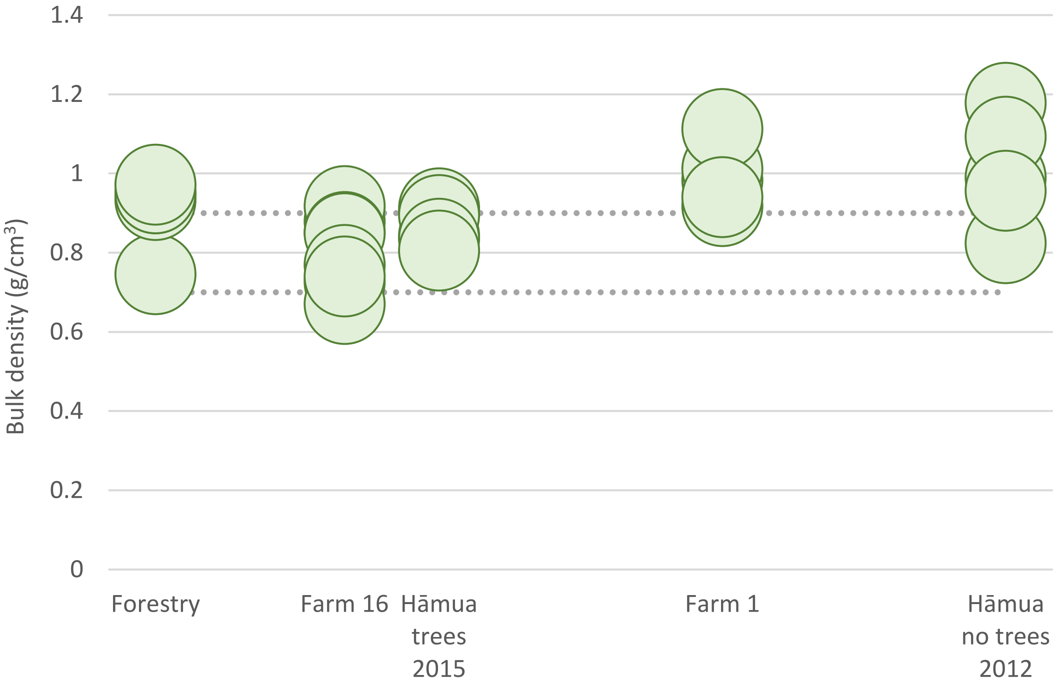
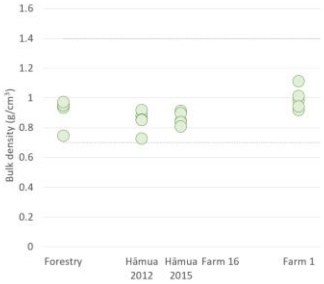
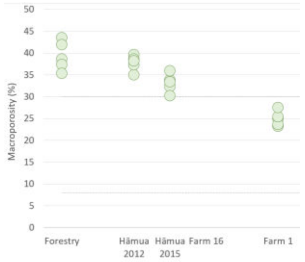


**Figure 4.10: Bulk density across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



Soil macroporosity is a measure of large pores and is another measure of soil density and compaction status. Macropores are required to transport water and air through the soil while providing a habitat for macrofauna (i.e., earthworms and insects). Soil macroporosity was above the optimal range at most of the sites (Figure 4.11, Table 4.1) and higher than is typical of pasture soils. The high macroporosity indicates a loose soil, more susceptible to erosion. As time since conversion from forestry increased, macroporosity decreased, reflecting the increasing impact that grazing animals have on soil structure.

**Figure 4.11: Macroporosity across Ngai Tahu sites May 2019.** Dashed line represents target value range (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.



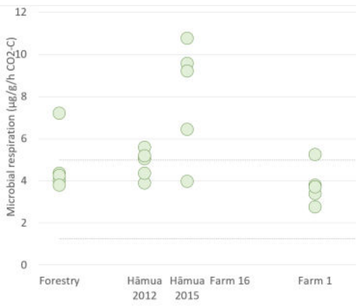
Available water holding capacity (AWC) is the difference between field capacity (i.e., the amount of water in soil after 2–3 days draining from a saturated state) and permanent wilting point, giving an indication of the amount of plant available water the soil can store. AWC reflects the soil texture and organic matter content of the soil. Conversion to pasture improved the water holding capacity of the soil (Figure 4.12, Table 4.1). The AWC was measured in the surface soil and as soil depth increases AWC per unit depth also decreases.

**Figure 4.12: Available water capacity across Ngai Tahu sites May 2019.** Dashed line represents target value to be above (Roberts pers. comm). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

## 4.4 Biological Indicators

Microbial respiration is an indication of bacterial activity and the rate of decomposition. Across all sites respiration rates were close to the low end of the target levels and there was no statistically significant difference in basal respiration between forestry and pasture sites (Figure 4.13, Table 4.1). Mean microbial respiration rates using the same methodology for agricultural soils in Ireland was 1.87 µg/g/h $CO_2$-C (Richter *et al.*, 2018) and were higher than results from the Winchmore fertiliser trial (Horne, 2016). Target ranges of respiration through the $CO_2$ burst test are 2.4 times greater than basal respiration (McGowen *et al.*, 2018), the target levels here reflect those for basal respiration, but it may be that these targets may need further refining. Improving microbial respiration will take time and require improvements in the soil environment (e.g. organic matter and soil moisture). When respiration was induced through the addition of different carbon substrates there was an indication that as the years since forestry increased the microbial community was able to better utilise simple carbon sources and less adapted to utilise more complex carbon sources, although this was not significant (data not shown).

**Figure 4.13: Microbial respiration across Ngai Tahu sites May 2019.** Dashed line represents target value to be above from (Doran *et al.*, 1997). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced



The symbiotic performance of rhizobia populations was compared against the commercial standard. Rhizobia performance was similar to the commercial standard at the Forestry site (103%) and Farm 1 (102%) but was lower at Hāmua (60%). At Farm 16 the application of seed coated with a laboratory strain of Rhizobia did not show improvement in rhizobia effectiveness in comparison to application of commercially coated seed (49%vs 68%, respectively). The commercially coated seed plots were not as effective as they could have been, which may have been due to the lack of viability of the inoculum if the coated seed used was not coated within two weeks prior to sowing (Villamizar, L. *pers. comm.*).

Total earthworm abundance across all farms was low (Figure 4.14, Table 4.1) and below target levels of over 400 m$^{-2}$ which have shown to increase pasture production by 20% (van Groenigen *et al.*, 2014; Schon *et al.*, 2016). Although earthworms are typically sampled during winter/early spring, their abundance in Canterbury in May under irrigation should not be much lower (Fraser *et al.*, 2012). No earthworms were observed in the forestry soil. Earthworms can passively disperse into an area through soil on machinery, livestock movements and birds (Marinissen and Van den Bosch, 1992). Deliberate earthworm introductions at 10 m spacings takes 6-7 years until full establishment (Stockdill, 1979). At Hāmua there were more earthworms at sites that had been out of forestry for longer (38 vs 3 m$^{-2}$, respectively). Farm 1 had the highest abundance of earthworms but with an overall average abundance of 195 m$^{-2}$ was still well below the optimal range, although paddock P2.13 reached abundances of nearly 600 m$^{-2}$. Earthworms are important within the soil to improve soil structure, water infiltration and enhance nutrient availability to plants. To increase earthworm populations their environment needs to contain enough food and have a suitable habitat (including adequate soil moisture). Earthworm additions may be a way to stimulate their populations, particularly at sites such as these that have no natural populations. The biological additions at Farm 16 resulted in some earthworms being detected compared to the control (0 vs 10 m$^{-2}$, respectively), although this was not statistically significant (data not shown).

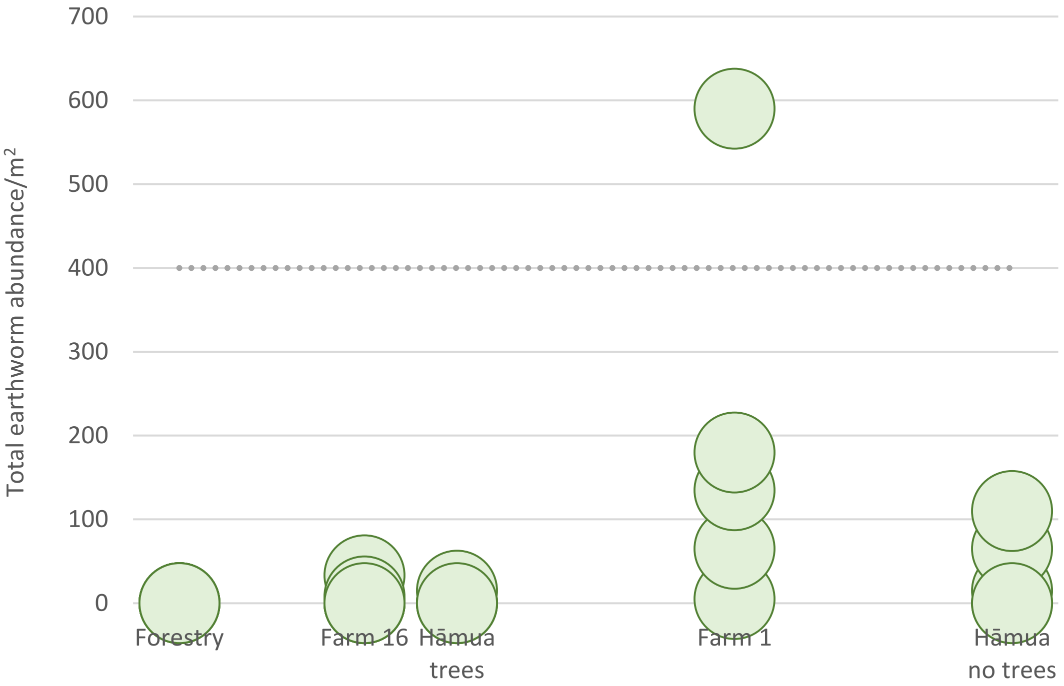


**Figure 4.14: Total earthworm abundance across Ngai Tahu sites May 2019.** Dashed line represents target value to be above (van Groenigen *et al*., 2014). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

It is also important to ensure earthworm functional diversity is represented within the soil (Schon *et al*., 2012). Among earthworms three main earthworm functional groups are recognised *viz.* epigeic, endogeic and anecic (Bouché, 1977). Their differing feeding strategies and activity in the soil (Figure 4.15) have differing influences on soil services. Anecic earthworms were only observed at Farm 16 where biological introductions occurred, the absence of this deeper burrowing earthworm can have, for example, implications for organic matter incorporation as they feed on twice as much organic matter than epigeics and move this to greater depths (Edwards and Bohlen, 1996). Just like total earthworm abundance, the abundance of earthworms in each earthworm functional group was below target levels, with the exception of epigeic earthworms at Farm 1 (Table 4.1).

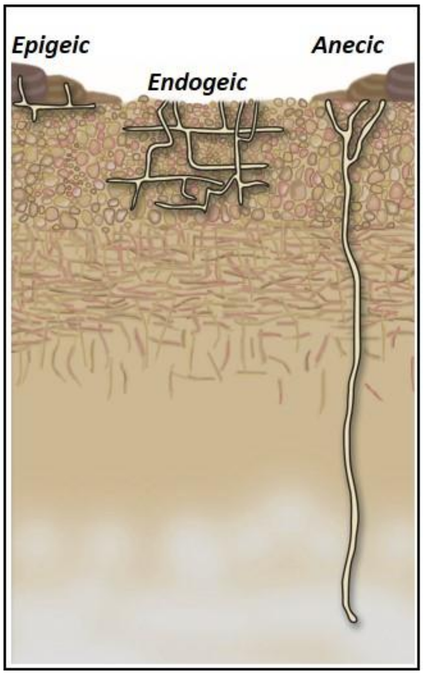


**Figure 4.15. Earthworm functional groups activity through the soil profile**. Epigeic earthworms feed on organic matter on the soil surface and do not form permanent burrows. Endogeic earthworms burrow through the topsoil improving soil structure and feeding on the organic matter here. Anecic earthworms feed on organic matter on the soil surface and take this into their burrows which open to the soil surface improve water infiltration.

## 4.5 Pasture pests and diseases

The risk of pasture disease was assessed using the ratio of AMN:TN. This ratio has been used to determine the active fraction of organic matter in the soil, being a sensitive measure to changes in organic matter quality and low ratios have also been associated with greater risk of pasture disease (Dignam, B., *pers. comm.*). This ratio is still being tested before we can ascertain with certainty of the relationship between this ratio and pasture disease pressure. The AMN:TN ratio was less than the target value under forestry, but increased at or above the target value for all pasture soils (Figure 4.16, Table 4.1).

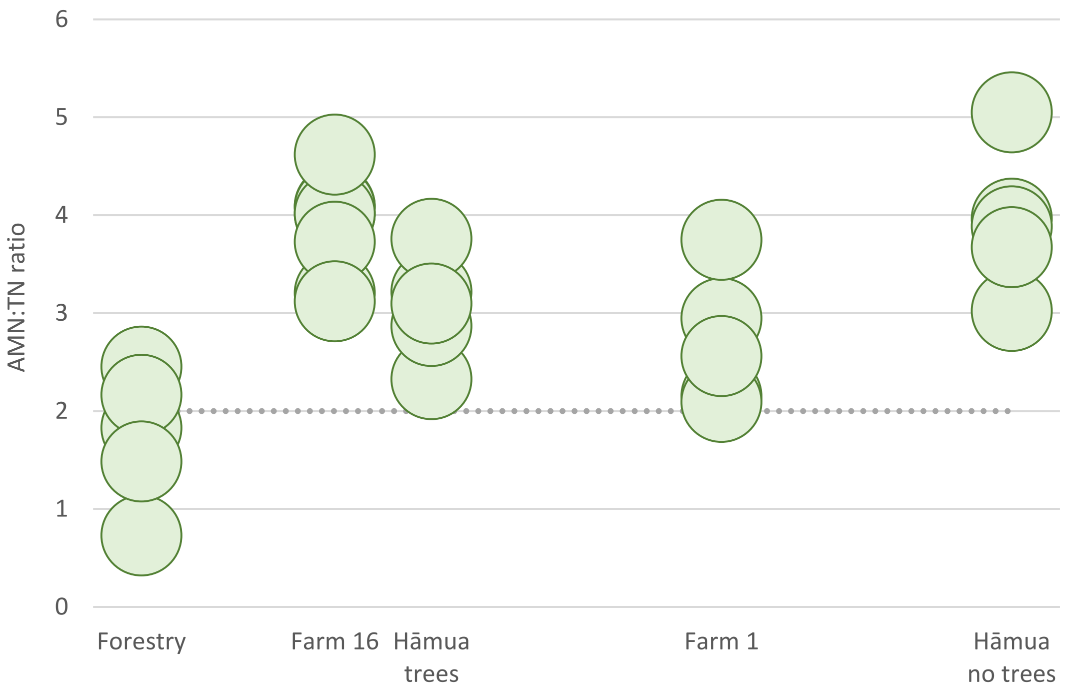


**Figure 4.16: AMN:TN ratio across Ngai Tahu sites May 2019.** Dashed line represents target value to be below (www.hilllaboratories.co.nz.) Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

Among the insect pests the clover root weevil larvae (*Sitona obsoletus*) was most abundant, reaching average populations across Hāmua of 87 m$^{-2}$ (Figure 4.17, Table 4.1). Abundances in paddock P1.06 was 200, and has reached pest status. In other paddocks their abundances may also be reaching densities of economic significance under stressful environmental conditions (e.g., drought). Clover root weevil larvae feed on the nodules and roots of clover plants while adults feed on the leaves, reducing production and atmospheric nitrogen fixation by these legumes (Ferguson *et al.*, 2019). Biological control of the clover root weevil is established over nearly all of New Zealand through the parasitic wasp (*Microctonus aethiopoides*). However, clover root weevil populations in new pasture may be high initially and damage can be minimised by avoiding overgrazing.

**Figure 4.17: Clover root weevil larvae abundance across Ngai Tahu sites May 2019.** Dashed line represents target value to be below (Ferguson *et al.*, 2019). Graph shown along gradient of time since forestry ceased, inset shows gradient of time since irrigation commenced.

Porina (*Wiseana spp.*) and grass grub (*Costelytra giveni,* formerly *C. zealandica*) were present at some sites in low numbers and are not considered a problem at the time of sampling. Porina feed on plant leaves and grass grub larvae feed on plant roots. In older pastures grass grub and porina generally occur at low densities and are constrained by naturally occurring pathogens. After cultivation grass grub and porina populations can build up and can be particularly damaging 2–5 years after cultivation (Ferguson *et al.*, 2019).

## 4.6 Overall soil health

Overall soil health scores were determined, with the lowest scores found under forestry (49.8%). Farm 1 had the highest score (84.5%) (Figure 4.18, Table 4.2). Although Hāmua no trees had been out of forestry for longer, it is likely that the longer period of irrigation at Farm 1 has had a positive influence on the abundance of earthworms, increasing the total soil health score. The main factors contributing to a lower score across all sites was suboptimal soil fertility, high C:N ratios, high macroporosity, low microbial respiration and low earthworm abundance and functional diversity. Many of these variables that were not at their target levels were a result of suboptimal levels under forestry and were still in the process of reaching target levels, which will take many years under good pastoral management. Some properties were being actively managed (e.g., soil fertility and soil nitrogen), while others were not (e.g., soil macroporosity and microbial respiration). Soil fertility is easier to manipulate than some of the other measures of soil health, and although these were low under forestry, excessive application of nutrients during the conversion process had resulted in these exceeding their optimal range.

*Although there are well defined optimal ranges for soil fertility required for pasture agriculture, target ranges for some of the other indicators are not as well understood and calibrated. For example, both AMN and HWEC are reported to be related to microbial biomass (Hart et al., 1986; Ghani et al., 2003) but we observed these to have a differing response under forestry. It may be that under forestry there is plenty of C but microbial activity is limited by other factors (e.g., soil N supply). Further research is required to determine what these target values need to be for optimal soil performance in order to gain a more accurate representation of soil health.*

**Table 4.2: Soil health scores at selected Ngai Tahu sites May 2019.** Each variable contributing to the total soil health score can have maximum value of 1. The higher the total soil health score the better.

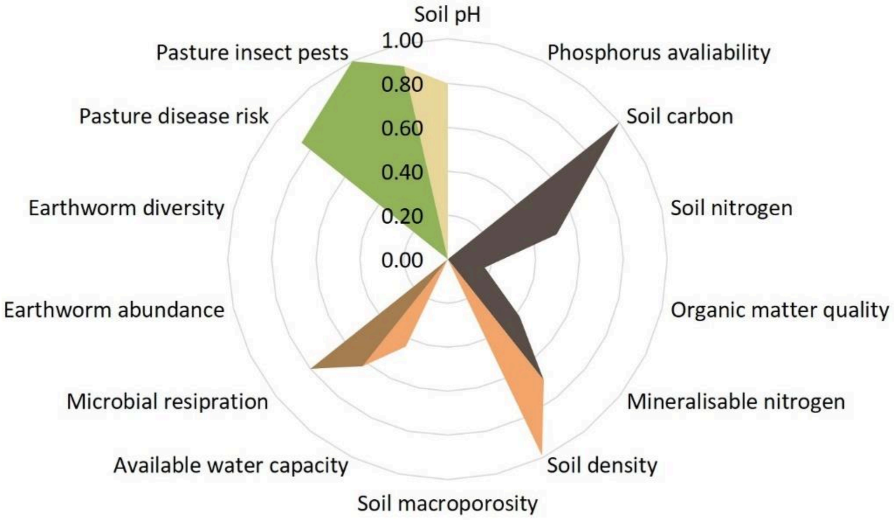
| | | **Forestry** | **Farm 16** | **Hāmua Trees** | **Farm 1** | **Hāmua No trees** |
|---|---|---|---|---|---|---|
| Soil fertility | Soil acidity | 0.8 | 0.92 | 0.88 | 0.97 | 0.76 |
| | Phosphorus availability | 0 | 0.89 | 0.61 | 0.97 | 0.76 |
| Soil organic matter properties | Total carbon | 1 | 1 | 1 | 1 | 1 |
| | Total nitrogen | 0.51 | 0.66 | 0.59 | 0.88 | 0.69 |
| | Organic matter quality | 0.17 | 0.51 | 0.35 | 0.81 | 0.77 |
| | Mineralisable N | 0.42 | 0.87 | 0.91 | 0.96 | 0.78 |
| Soil physical properties | Soil density | 0.99 | 1 | 1 | 0.90 | 0.88 |
| | Soil macroporosity | 0 | 0 | 0.16 | 0.66 | 0.27 |
| | Available water capacity | 0.44 | 0.58 | 0.71 | 0.78 | 0.56 |
| Biological indicators | Soil microbial respiration | 0.80 | 0.94 | 1 | 0.76 | 0.86 |
| | Earthworm abundance | 0 | 0.01 | 0.01 | 0.49 | 0.10 |
| | Earthworm diversity | 0 | 0.67 | 0.33 | 0.67 | 0.67 |
| Pasture pests and disease | Pasture disease risk | 0.85 | 1 | 1 | 1 | 1 |
| | Pasture insect pests | 1 | 1 | 1 | 1 | 1 |
| ***Total soil health score (%)*** | | **49.8** | **71.8** | **68.2** | **84.5** | **72.1** |

**Figure 4.18. Overall soil health (continued over page)** Showing distance from optimal ranges (represented by 1.0) for Ngai Tahu sites in May 2019 along gradient of increasing time since forestry.

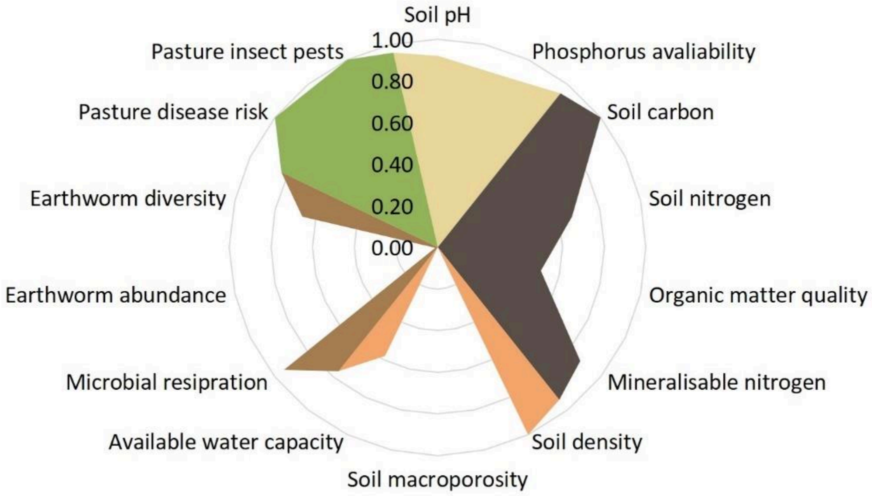
■ soil fertility ■ organic matter properties ■ soil physical properties

■ biological indicators ■ pasture pests and disease

**Forestry**

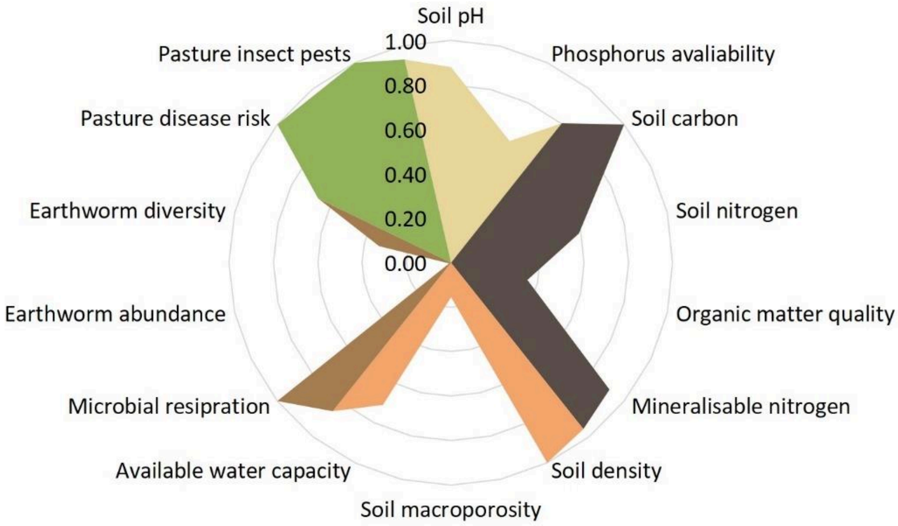


**Farm 16**

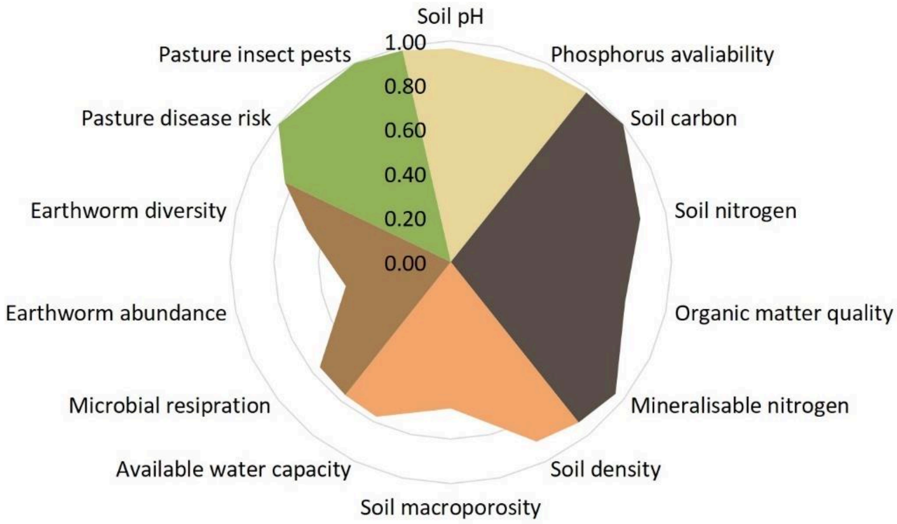


## Figure 4.18 continued. Overall soil health

### Hāmua trees

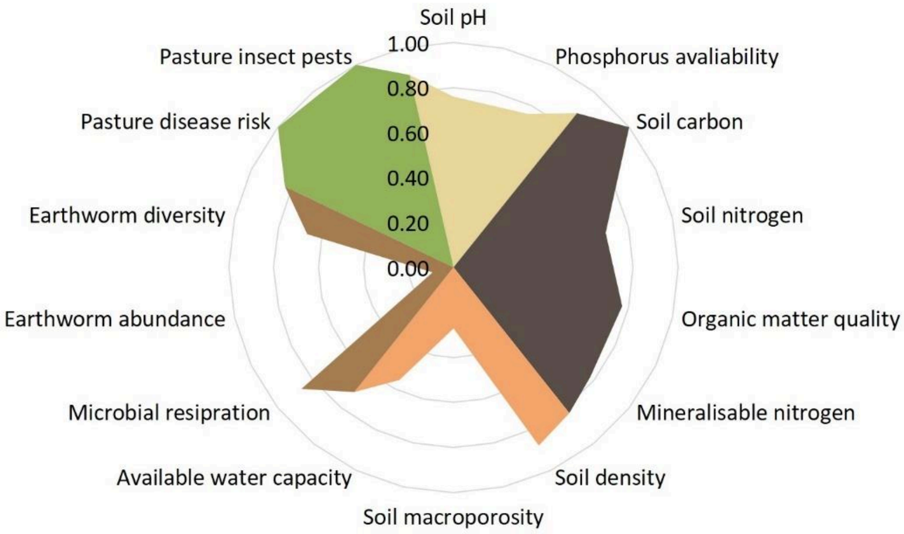


### Farm 1



## Figure 4.18 continued. Overall soil health

### Hāmua No Trees



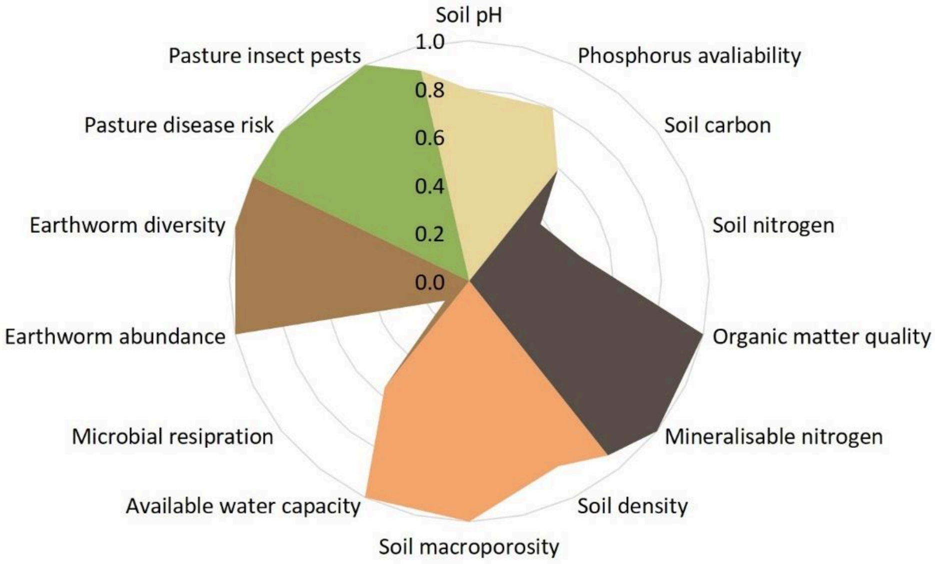
Comparison of the overall soil health at the Ngai Tahu farms with soils under long-term sheep production at Winchmore (producing 12 T/DM/ha (McBride, 1994)) on the same Lismore soils, shows that it remains difficult to reach optimal soil health for a high producing soil (Figure 4.19). At Winchmore there has been an improvement in the soil physical and biological properties, however soil carbon and nitrogen levels are lower (and C:N ratio of 10.5:1) than those measured in the Ngai Tahu samples. The Winchmore results are typical of what might be expected for Lismore soils, and highlight that even after long-term land development inherent soil properties will limit soil health and target ranges specific to individual soil types may be required.

**Figure 4.19. Soil health comparison at Winchmore.** Showing distance from optimal ranges (represented by 1.0) for Ngai Tahu sites in May 2019 along gradient of increasing time since forestry.

🟨 soil fertility 🟫 organic matter properties 🟧 soil physical properties

🟫 biological indicators 🟩 pasture pests and disease

### Irrigated and fertilised



# 5. Discussion

The change from forestry (*P. radiata*) to pasture agriculture causes large scale changes to soil. During the conversion process Ngai Tahu farming have the goal to maintain the life sustaining capacity of soils. Sampling across a chronosequence of sites previously from Eyrewell forest, including a site still in forest, showed that conversion to pasture changes soil health. The overall soil health score was higher at sites out of forestry for longer (Hāmua no trees and Farm 1). Farm 1 likely has a higher soil health score in comparison to Hāmua no trees, with a longer period of irrigation helping to increase earthworm abundance at this site. The main factors contributing to a lower score across all sites was suboptimal soil fertility, high C:N ratios, high macroporosity, low microbial respiration and low earthworm abundance and functional diversity. These factors encompass most aspects of the soil health spectrum, having implications for soil functioning. Many of the measured properties that had not reached their target levels were on the right trajectory, particularly those that are being actively managed (e.g., soil fertility). Despite this, the soil biological indicators rated poorly, even at Farm 1 which had the highest soil health score.

## 5.1 Soil fertility

Soil fertility targets for a pasture system are well defined. The nutrient status can be actively managed through both capital and maintenance applications of fertiliser to get parameters within their target range. Despite this Olsen P levels, which were low under forestry, were found to be above both the economic and environmental optimum at Farm 16. Some paddocks at Hāmua and Farm 1 were also found to be above optimum, while others remained below optimum. A low Olsen P will affect grass growth, while a high Olsen P has implications for P lost to surface water bodies. Soil potassium levels were found to be above optimum at certain sites across all farms, increasing the possible risk of hypomagnesaemia. Levels of soil K appear to be starting from high levels under forestry, with 2 out of 5 sites under forestry having K levels over 10. Many Canterbury soils have high levels of plant available K despite low or nil applications of K and may also have high reserve K status. These results highlight the importance of ensuring appropriate capital applications during the conversion process and careful management of nutrients to stay within target levels. Nutrient status varied across farms and this can be partially explained by previous history (e.g., Hāmua trees compared to no trees), and can be best managed through more comprehensive soil tests by all paddock testing. The correct type and rate of nutrient and /or lime can then be applied on a paddock by paddock basis.

## 5.2 Organic matter properties

Soil C was high for a Lismore soil with (Molloy and Ives, 1972) reporting C contents of 2.8% at the nearby Eyrewell Scientific Reserve. Soil C was high across all sites (>7.4%), and similar soil C contents under forestry and pasture has been reported by Murty *et al.* (2002). Nitrogen content was lower under forestry, although still within the target range. Higher soil N under pasture reflects greater N inputs through fertiliser and recycling in dung and urine of the grazing animals, and has also resulted in increasing readily available N. While the soil C:N ratio is reducing, the ratio remained above target levels for pasture. High C:N ratios indicates net immobilisation of N during the decomposition of organic matter, with N becoming unavailable to plants as microbes compete for more of the soil N for their own growth and reproduction. Once the C:N ratio drops below 25 more N will be mineralised during decomposition and become available to plants. As the C:N ratio drops and AMN increases we can expect to see a greater response of pasture to N fertiliser. Both Horrocks *et al.* (2016) and Hedley *et al.* (2009) suggest that a greater response to pasture fertiliser may be seen as soon as 3 years after conversion from forestry. Understanding the point when less N fertiliser is required for pasture response is critical in these soils which are vulnerable to leaching. Any excess fertiliser N may be easily lost to the environment, and although leaching may be low currently, this may change suddenly in the future. N leaching is highest under urine patches although total N loss will increase as the soil N pools increase under pasture management (Monaghan *et al.*, 2005).

## 5.3 Soil physical properties

Lismore soils are recognised as stony soils with good drainage. Although the stone content in the steel rings which were collected to assess soil physical properties was up to 15%, it is likely that stone content could have been higher than this in the bulk soil, as often samples were not collected in the first attempt. From the samples that were collected, the soil appeared friable and this was supported by their high macroporosity, with macroporosities being higher than expected under pasture. These results suggest that the forest soils are susceptible to erosion. Soil macroporosity declined with years under pasture, at this early stage the reduction in porosity is creating a soil with a better structure, being less friable and susceptible to erosion. However, a loss of macroporosity was highlighted as a key concern in New Zealand's State of Environment report (Ministry for the Environment & Stats NZ, 2018), and hence it is a property that needs to be managed to stay within target levels.

## 5.4 Biological indicators

Microbial respiration was low across all sites, being an indication of low microbial activity and rates of decomposition. The addition of a variety of C substrates suggest that as the years since forestry increased the microbial community was better able to utilise simple carbon sources and less adapted to utilise more complex carbon sources, although this was not significant. This observation would support the lowering of the C:N ratio as time from forestry increases, resulting in less recalcitrant material in the soil and decrease in less recalcitrant organic matter. Microbial respiration is enhanced by maintaining soil physical integrity (allowing the soil to breathe), having adequate soil moisture and organic matter inputs from the grazing animal (dung and urine), death and decay of plant material and application of effluent and/or composts.

Abundant earthworm populations are seen as a sign of healthy soils, with their activity in the soil promoting nutrient cycling and enhancement of soil structure. Earthworm abundance over 400 $m^{-2}$ improves soil condition and increases pasture production by 20% (van Groenigen *et al.*, 2014; Schon *et al.*, 2016). At the Ngai Tahu sites no earthworms were found under forestry, and average earthworm abundance and functional diversity remained low across all farms and below target levels of over 400 $m^{-2}$. Earthworm abundance was highest at Farm 1, which had been under permanent pasture and irrigation for the longest period of time, earthworm populations in paddock P2.13 reaching abundances of nearly 600 $m^{-2}$ but were less than 200 $m^{-2}$ in the other paddocks across the farm. Deliberate introductions of earthworms during conversion at Farm 16 did not result in a significant increase in earthworm populations (although there were more of the introduced endogeic and anecic earthworms found on sites that had received earthworms compared to the control sites 10 vs 0 m$^{-2}$, respectively). There may be a number of possible explanations for this including the application of earthworms at the time of conversion was in late spring when earthworms are no longer very active, it could be that soil moisture at the time of sampling was low (>7% lower than Farm 1 where earthworms were most abundant), or it may be that environmental conditions (e.g., organic matter quality) were not suitable to earthworms at the time of conversion from forestry and their deliberate addition at this time may have been ineffective. Further experiments will be required to determine this. Our results do show that over time earthworms will naturally establish, although this will take many years, with their abundance being 195 m$^{-2}$ seven years after conversion at Farm 1 and 38 m$^{-2}$ at Hāmua. Factors that stimulate microbial populations are the same that will stimulate earthworm populations (e.g., physical integrity, adequate soil moisture and organic matter inputs).

## 5.5 Pasture pests and disease

Pressure on pasture from pests and diseases appears to be limited at the sites sampled. The highest abundances of clover root weevil were found at Hāmua in paddock P1.06. Clover root weevil populations in new pasture may be high initially and damage can be minimised by avoiding overgrazing. It is important to be aware that populations of pasture pests change through time, for example grass grub and porina populations build up and can be particularly damaging 2–5 years after cultivation until the natural disease pathogens in the soil have built up to levels to match the pasture pests. It is important to be vigilant and understand pasture pest cycles to enable management of effects, given that traditional control chemicals are being increasingly banned from use.

# 6. Conclusions and recommendations

Although there is a general improvement in soil health as landuse has changed from forestry to pasture, there are still several aspects to soil health which can be improved across the pastoral sites at Ngai Tahu. These changes include longer-term improvement of soil C:N ratios, enhancing soil biological populations and monitoring soil physical status, as well as more immediate application of fertiliser to remain within economic and environmental limits.

These results highlight the importance of ensuring appropriate capital fertiliser applications during the conversion process and consequent management of nutrients to stay within target levels and maintain soil health. The variability in nutrient status across paddocks within each farm shows fertility levels that can be partially explained at least by previous history (e.g., Hāmua trees compared to no trees), and can be best managed through more comprehensive soil tests by all paddock testing on farms. The correct type and rate of nutrient and /or lime can then be applied on a paddock by paddock basis. With the changing status of the soil C:N ratio and N availability within the soil it is critical to continue to monitor this so we recognise when the soils are becoming more responsive to fertiliser application, and fertiliser applications may be able to be adapted and recommendations provided for future conversions.

Although soil macroporosity is currently above target levels, with this property known to be become degraded under grazed pastoral agriculture, in particular dairy, it is essential this soil property is monitored and managed so that macroporosity is maintained within the target range. Good soil management to avoid degradation of soil structure will be important, especially managing stock movement on the soils during wet periods when the soil is saturated and susceptible to pugging and compaction.

Pasture pests and disease have not been identified as being a problem at this point in time, but It will be important to be vigilant and understand pasture pest cycles to enable management of effects, with their populations causing the biggest problems 2-5 years after cultivation.

Soil biological indicators are low across all sites and remain low even at those sites which have been out of forestry the longest. In order to enhance this component of soil health it may require action beyond standard best management practice. In order to stimulate biology within the soil it is important to get conditions right: including maintaining soil physical integrity, having adequate soil moisture and good quality organic matter inputs. Biological additions may also help enhance the soil biology but further research into how soil biology can be maximised practically within a farm system is required.

The soil health status at the Ngai Tahu farms show an improvement towards targets to optimise pasture production. When compared to targets of high producing pastures on allophanic soils we recognise that the inherent characteristics of the Eyrewell soils will continue to have limitations, no matter how long they are developed. In comparison to the allophanic soils, the biggest inherent soil limitations will be soil profile depth (shallower B horizon), inability to sequester and protect as much soil carbon and inability to retain as much soil water, increasing risk to leaching. If moving towards different landuses different soil targets may need to be considered.

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# 9. Appendices

**Appendix 1.** Latitude and longitude for sampled sites

| Farm | Paddock | Latitude | Longitude |
|---|---|---|---|
| Dryland | | -43.4205 | 172.2854 |
| | | -43.4218 | 172.2873 |
| | | -43.4292 | 172.2844 |
| | | -43.4433 | 172.3059 |
| | | -43.4234 | 172.3027 |
| 8 | P2.06 | -43.4077 | 172.3153 |
| | P2.11 | -43.4143 | 172.3152 |
| | P3.02 | -43.4146 | 172.3059 |
| | P3.09 | -43.4199 | 172.3078 |
| | P3.11 | -43.4189 | 172.3048 |
| | P1.01 | -43.4116 | 172.2975 |
| | P1.06 | -43.4060 | 172.2986 |
| | P1.11 | -43.4074 | 172.3021 |
| | P2.01 | -43.4111 | 172.3090 |
| | P2.10 | -43.4113 | 172.3154 |
| 16 | Control | -43.4087 | 172.3629 |
| | Biological addition | -43.4088 | 172.3629 |
| | Biological addition | -43.4089 | 172.3630 |
| | Control | -43.4089 | 172.3631 |
| | Biological addition | -43.4092 | 172.3630 |
| | Control | -43.4091 | 172.3627 |
| | Biological addition | -43.4092 | 172.3625 |
| | Control | -43.4093 | 172.3627 |
| 1 | P2.11 | -43.3936 | 172.2163 |
| | P2.13 | -43.3963 | 172.2148 |
| | P1.2 | -43.3928 | 172.2040 |
| | P1.11 | -43.3889 | 172.2054 |
| | P3.3 | -43.4002 | 172.2007 |