Soil Quality of Plantation Forestry Sites in the Auckland Region 2011

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Soil Quality of Plantation Forestry Sites in the Auckland Region 2011

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Executive summary

The land and soil in Auckland are important and valuable resources. They support the growing population by providing food, a place to live and work, and recreational and tourism opportunities. Some soil and landform combinations also have cultural and/ or historical significance to different groups of people.

The Resource Management Act 1991 section 35 requires councils to carry out 'State of the Environment' reporting every five years whether it is for marine, freshwater, groundwater, terrestrial, air or soil quality monitoring. Soil quality monitoring within the Auckland region was instigated in 1995 as part of a national '500 Soils Project'. Soil quality refers to the ability of the soil to sustain biological production, maintain environmental quality, and promote plant and animal health. Land uses sampled within Auckland in recent years include horticulture, dairy and drystock sites in 2008, 2009 and 2010, respectively. Fifteen plantation forestry sites were the focus of soil sampling in 2011 representing three dominant soil orders for the Auckland region namely Brown, Ultic and Recent. These correspond to seven soil series.

Key soil quality properties of interest include soil acidity (pH), organic carbon (OC), total nitrogen (TN), Olsen P (plant available phosphorus), anaerobic mineralisable nitrogen (AMN- plant available nitrogen), bulk density and macroporosity (at -10kPa). Trace element concentrations measured in the current report include arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc; however, the majority of the report will focus and report on key soil quality results.

The key soil quality indicator outside target ranges on most occurrences was Olsen P. However, when put into perspective only one site would be considered seriously over these guidelines. Five sites had both TN and OC contents below guidelines, three of which included all Pinaki sand sites. Two sites fell within the very low guideline range for concentrations of AMN and these two sites had correspondingly low (0.1 %) TN contents. Macroporosities (-10kPa) were above guidelines for all three Pinaki sand sites sampled. Although low macroporosity is less desirable, indicating soil compaction, soils with high macroporosity are prone to soil erosion, hydrophobicity and excessive draining. In contrast, bulk density increased for the re-sampled Pinaki sand sites which likely influenced the significant increase in bulk density that was observed when 2011 results were compared to those sampled between 1996-2000. These changes are discussed in detail in the report.

Overall, the three Pinaki sand sites had a major affect on results with more than three indicators failing to meet recommended guidelines. These three sites aside, soil quality was generally better under plantation forestry than that for the recently sampled horticultural, dairy and drystock sites in Auckland. In contrast, to the majority of horticultural, dairy and drystock reported sites which record low macroporosity, the indicator outside target ranges on most occurrences, soil macroporosity was less of an issue under plantation forestry. Pastoral and horticultural sites also tend to have Olsen P concentrations higher than the recommended requirements for these land uses. While four sites in the current study had Olsen P concentrations higher than the recommended range, it is less of an extensive issue for plantation forestry.

It is suggested that more sampling sites are identified in the future that represent a broader range of soil types to ensure one soil type alone does not have such a dominating impact on results. It is also recommended that all these sites are re-sampled several more times at five-yearly intervals to determine long-term temporal trends in soil quality properties for plantation forestry.

Contents

1.0 Introduction

The land and soil in Auckland are important and valuable resources. They support the growing population by providing food, a place to live and work, and recreational and tourism opportunities. Some soil and landform combinations also have cultural and/ or historical significance to different groups of people (Dominati et al., 2010).

Soil forms into many different types, depending on the parent material and the environment that it has come from. The dominant soil types in Auckland are the Ultic soils, representing about 38-40% land area which are located predominantly in north Auckland (NZLRI, 2010, Curran Cournane and Taylor, 2013). Granular soils, representing about 17% of land area, are dominant in south Auckland. Some of these Granular soils are some of the best soils in New Zealand. Other soil orders in Auckland include Brown, Recent, Allophanic, Gley, Raw, Organic, Anthropic, Melanic, Oxidic and Podzol (Hewitt, 1998).

The Resource Management Act 1991 section 35 requires councils to carry out 'State of the Environment' reporting every five years whether it is for marine, freshwater, groundwater, terrestrial, air or soil quality monitoring. Soil quality monitoring within the Auckland region was instigated in 1995 as part of a national '500 Soils Project' (Hill et al., 2003) and continued until 2000 after which time it was not again established until 2008. Annual soil sampling events contribute to 'State of the Environment' reporting. Land uses sampled in recent years include horticulture, dairy and drystock sites in 2008 (Sparling, 2009), 2009 (Stevenson, 2010) and 2010 (Fraser and Stevenson, 2011), respectively. Plantation forestry sites were the focus of soil sampling in 2011.

Key soil quality properties of interest include soil pH, organic carbon (OC), total nitrogen (TN), Olsen P, anaerobic mineralisable nitrogen (AMN), bulk density and macroporosity (at -10kPa). The following trace element concentrations were also measured in the current report, arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc. However, the majority of the report will focus on the key soil quality parameters listed above.

Study objectives included:

- Soil sampling for those sites referred to as plantation forestry sites between 1996 and 2000, and currently under this land use, to determine changes in soil quality over time;
- Selecting new sampling sites that represent broad geographical coverage and representative soil types in the Auckland region;
- Identify which key soil quality indicators are of most concern;
- Determining trace element concentrations for all sites;

- Reporting findings from the study and providing results to landowners, for not only educational and feedback purposes, but to establish better trust relationships between Council and landowners and to ensure access to sites in the future.

2.0 Materials and methods

2.1 Sample sites and soil sampling

Fifteen plantation forestry sites were sampled (Figure 1) between 01-05 August, 2011, for a suite of soil parameters which included soil acidity (pH), organic C (OC)[A], total N (TN), anaerobic mineralisable N (AMN- plant available nitrogen), Olsen P (plant available phosphorus), bulk density, macroporosity[B] at -5 and -10 kPa (which includes pore sizes greater than 60 and 30 microns, respectively) and the C/N ratio. All but the C/N ratio are known as key soil quality indicators (Sparling et al., 2003).

Note on definitions:

- [A] Total carbon (TC) will now be described as organic carbon (OC) given soil pH was <7 for all sampled sites. Soil pH >7 suggests insignificant or nil presence of carbonate carbon (Hill L, pers comm., Landcare Research).

- [B] The term used to describe pores sizes >30microns will now be termed macroporosity -10kPa, as opposed to its previous ‘air-filled porosity’ referral, to ensure consistency between various regional councils. Furthermore, although macroporosity at -5kPa data will be presented only macroporosity at -10kPa will be included in the determination of meeting the soil quality guideline procedure. C/N ratio data will also be presented but will not be included in the determination of meeting the soil quality guideline procedure.

All results for chemical attributes will be discussed on a gravimetric basis because guidelines are presented in such a manner (Table 1). Target ranges for these indicators are listed in Table 1 and are specific for forestry sites. For each site, the number of occurrences a value fails to meet the target ranges were recorded and the proportion of sites meeting the suggested target ranges for the seven indicators were calculated. Furthermore, a suite of trace elements were also analysed and analytes reported in the study include arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc. Nitrate, ammonium, initial water content, particle density and total porosity were also analysed and are presented in the appendices 7.1 and 7.2.

Nine plantation forestry sites had previously been sampled, 1996-2000 (Appendix 7.3 and 7.4), during the early development of the national ‘500 Soils Project’ (Hill et al., 2003). Eight of the nine sites were re-sampled; one site had undergone a significant amount of disturbance and was not re-sampled. Furthermore, of the eight re-sampled sites two sites had also experienced a degree of soil disturbance; site number 24 (Table 2) had been converted to pasture and site number 72 had been harvested in 2008. As such, site 24 was not included in the report and 2011 site data are presented in appendix 7.3 for this site. Site number 72 data is included in the report. Eight newly selected sites were also sampled that represented a broad geographical coverage of the Auckland region in predominant forests (Figure 1). The eight new sites also consisted of three new soil types representative of the Auckland region from the Ultic soil order. The three new soil types were namely Hukerenui, Rangiora and Mahurangi [Albic, Mottled and Albic Ultics, respectively, as defined by the New Zealand Soil Classification- NZSC (Hewitt, 1998)] and all 15 soil types sampled include the three soil orders namely Ultic, Brown and Recent (Appendix 7.4). The status of the seven re-sampled sites will be compared with archive data from previous soil samples collected between 1996 and 2000 (Appendix 7.3). The soil classification, soil series name and year that the site was established are listed in Table 2.

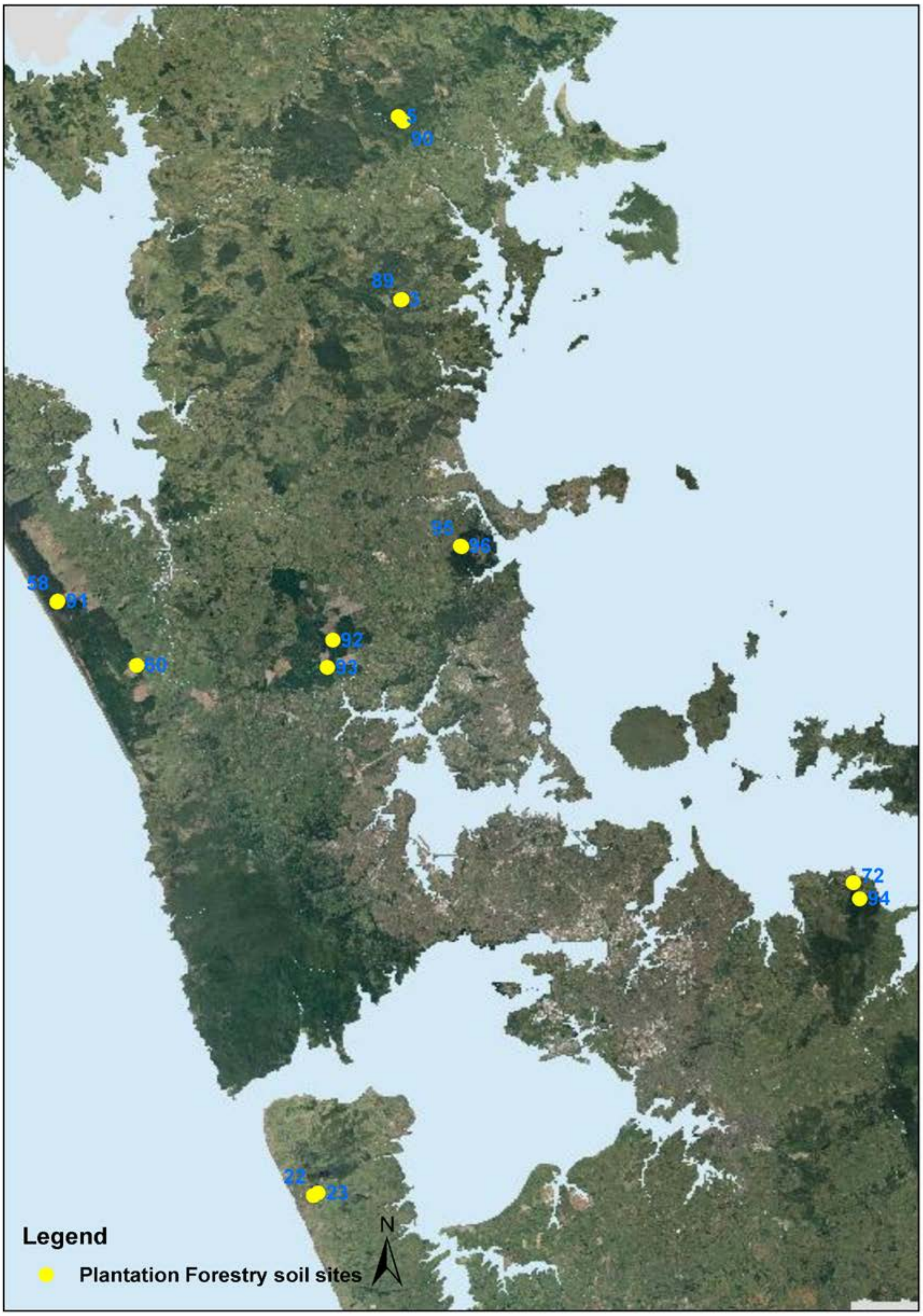

Figure 1. Location of the fifteen plantation forestry sites sampled in 2011.

Note: no plantation forest sites exist on the Hauraki Islands.

The soil sampling methodology was comparable to previous year's soil sampling whereby samples were collected every 2m along a 50m transect at a 0-10cm soil depth, for chemistry samples, using a

2.5cm diameter corer; 25 individual samples were bulked and this was repeated twice, for both chemical and trace elements analysis. For soil physical analysis, three stainless steel rings (10cm in diameter and 7.5cm in depth) were pressed into the soil to excavate intact soil cores. The intact soil cores were collected at the 15, 30 and 45m intervals along the 50m transect (Figure 2).

Figure 2. An intact soil core used to establish the soil physical quality of the soil.

2.2 Laboratory analysis

Methods for determination of all soil physical, chemical and biological analysis were those outlined in Hill *et al.* (2003). Briefly, the composite samples were well mixed, air-dried and sieved (<2mm) for Olsen P (Olsen et al., 1954). High temperature combustion methods were used for organic carbon (OC) and total nitrogen (TN) analyses (Blakemore et al., 1987). Soil pH was measured in deionised water at a 2.5:1 water to soil ratio (Blakemore et al., 1987) and AMN was determined under the anaerobic (waterlogged) incubation method from field moist conditions (Keeney and Bremner, 1966).

Back in the physics laboratory, smaller stainless steel rings (5.5cm width and 3cm depth) were used to sub-sample the larger rings by pressing into the larger core using a bench mounted drill press. The sub-sampling of the larger rings is to correct for any sampling error or bias between field staff and to ensure the measurement of a fully intact soil core. The smaller cores were saturated and equilibrated at both -5 and -10kPa on ceramic tension plates to determine macroporosities. Dry bulk densities and total porosities were calculated from oven (105°C) dry weights.

Soil samples for trace element concentrations were mixed air dried and sieved to <2mm before chemical analysis. Total recoverable arsenic, cadmium, chromium, copper, mercury, nickel, lead and zinc were determined by digestion of soil in nitric/hydrochloric acid and trace elements were analysed in digest by inductively coupled plasma mass spectrometry (ICPMS) (USEPA 200.8).

2.3 Statistical analysis

Soil physical properties, OC, TN, AMN, Olsen P and C:N were tested for normality and transformed if necessary before being subjected ANOVA to determine changes in soil quality attributes for years sampled between 1996-2000 and 2011. Organic C, TN, AMN and Olsen P are expressed on a gravimetric. All statistical analyses were carried out using the statistical package Genstat 14 (GenStat, 2011) and graphics using Sigmaplot 11 (SigmaPlot, 2008). Summary data for trace elements concentrations for 8 analytes are presented as Box and Whisker plots. The boxes represent the inter-quartile range (25^{th} to 75^{th} percentile) and the whiskers show the range of values that fall within the inner fences. Outliers are illustrated with black circles. The median is shown as a line in each box.

3.0 **Results and discussion**

Fifteen sites representing a broad geographical coverage of the Auckland region and covering three soil orders (Brown, Ultic and Recent), corresponding to five soil subgroups and seven soil series, were sampled to determine the soil quality of plantation forestry sites in 2011 (Table 2). Seven of these sites were originally sampled between 1996-2000. The target ranges for seven key soil quality indicators for forestry sites for different soil orders are listed in Table 1 (Sparling et al., 2003, Mackay et al., 2006, Workshop, 2011, SINDI, 2011). Note that the ranges presented in Table 1 are a modification of those presented in a report by Sparling *et al.* (2003), Mackay *et al.* (2006) and following a more recent 'Key Soil Quality Review Workshop' held in May 2011, (Taylor, 2011). The site code, soil classification, soil series name and the year that the site was established are listed in Table 2.

Results for soil physical, chemical and biochemical indictors and C/N ratio are presented in Table 3. Items highlighted in bold represent values outside the recommended guideline target range. In colour print copies, the bold numbers in red are values below the recommended target range and those bold colours in blue exceed the recommended target range. Twenty-seven % of sites met all targets (Figure 3a). and 27%, 20%, 23%, and 13% of sites had one, two, three and >four indicators outside target guidelines, respectively (Figure 3a). Olsen P was the indicator failing to meet recommended guidelines on the most occurrences (Figure 3b).

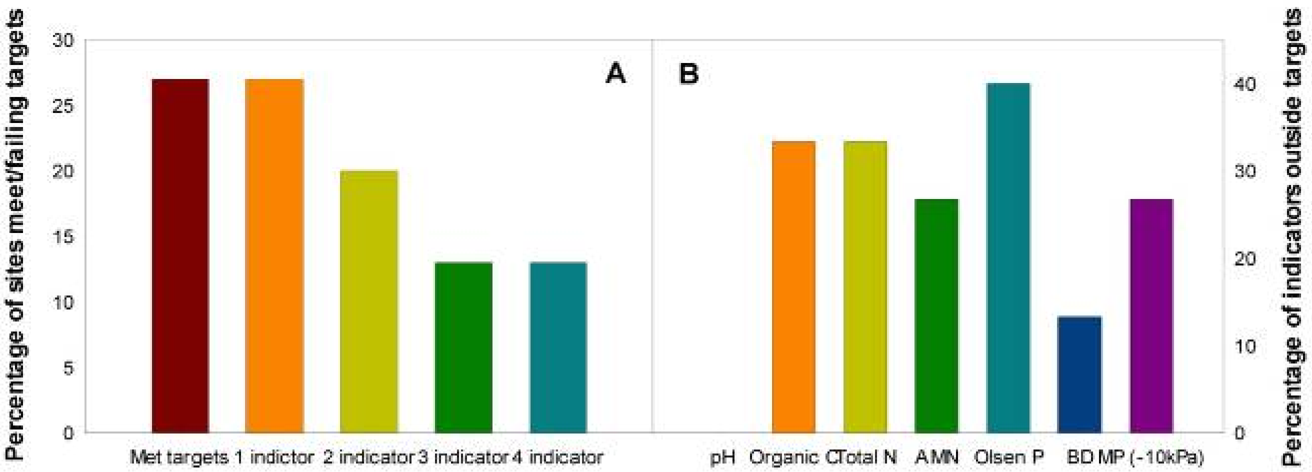

Figure 3. Percentage of plantation forestry sites outside targets for (A) a number of key soil quality indicators and for (B) key soil quality parameters.

Six of the 15 sites (40%) were outside the recommended range for Olsen P concentrations; four of which exceeded the target range (Figure 3b and Table 3). Only one of the sites (site 3 - 68 mg/kg).

would be considered to be extremely high for forestry and could be attributed to fertiliser drift from adjacent pastoral grazed land.

Five sites sampled had % TN and % OC contents below guidelines and this included all three Pinaki sand sites sampled. Pinaki sand soils are very young soils formed within the last 20,000 years on very recent sand dunes and as a result have been reported to be too young to develop significant amounts of organic material (Claridge, 1961). Furthermore, OC content at one sampled site for a Red Hill sand decreased drastically since sampled in 1998 but when all site data was pooled together no significant decline in OC was recorded. Particular attention in future sampling events should be focused at this site to determine if OC contents continue to decline.

Four of the 15 sites (27%) fell below the AMN target range (Figure 3b). Anaerobic mineralisable N is an estimate of N available for plant uptake through decomposition of soil organic matter. Greater organic N contents have been observed on pastoral based systems through contributions of fertiliser and N fixation. For forestry soils, very low AMN values are considered to be within the range 5-20 mg/kg and two sites fell within that particular range. These latter two sites also have TN contents at the lower limit (< 0.1%).

The C/N ratio considered optimal for all land uses and soils from an environmental perspective is within the range 7-30 (Sparling et al., 2003). Only one site fell outside this guideline measuring at 35 and this was also a Pinaki sand site. Two sites with very low AMN concentrations were also Pinaki sand sites. A high C/N ratio indicates N deficiency and this would also correspond to the sites with low TN and AMN contents (Table 3).

Table 1. Provisional target ranges for soil pH, organic carbon (%), total nitrogen (%), anaerobic mineralisable nitrogen (AMN mg/kg), C/N ratio, bulk density (g/cm^3) (Sparling et al., 2003, SINDI, 2011), Olsen P (mg/kg) (Taylor, 2011) and macroporosity (-10kPa) (% v/v) (Mackay et al., 2006) for various soil orders under plantation forestry.

Soil type	Soil pH	OC	TN	Olsen P	AMN	Bulk density	Macroporosity	C/N[1]
Recent	4-7	>3	0.2-0.7	5-30	40-175	0.8-1.3	8-30	7-30
Brown	4-7	>3.5	0.2-0.7	5-30	40-175	0.7-1.3	8-30	7-30
Ultic	4-7	>3.5	0.2-0.7	5-30	40-175	0.7-1.3	8-30	7-30

[1] C/N ratio is not considered a key soil quality indicator but a guideline range for all soil orders and land uses is provided

In contrast to many findings from pastoral and arable based systems, the majority of macroporosity (-10kPa) values outside target ranges were high rather than low (Table 2). Greacan and Sands (1980) attributed the compaction of forest soils to the pressure tree roots apply to the soil as they increase in size as well as the direct effect of heavy harvesting machinery. Mackay *et al.* (2006) reported that timing of sampling is important in relation to harvest rotation of 25-30 years because over this period biological activity can encourage topsoil development or enough time has passed to ameliorate compacted topsoil. Three of the four sites that exceeded macroporosity (-10kPa) guidelines are located in the same forest and represent Pinaki sand and values for the three sites ranged from 37-40 % v/v (at -10kPa). Low macroporosity (-10kPa) is less desirable than high macroporosity and indicates soil compaction (Curran Cournane et al., 2011). High macroporosity (-10kPa) can encourage wind and water erosion as the soil becomes more loose and the soil can become more susceptible to climate extremes, particularly drought (Mackay et al., 2006). Soils with high macroporosity also have the tendency to become hydrophobic. Macroporosities (-10kPa) of 40% v/v are uncommon and are usually the case for excessively draining soil (Mackay et al., 2006) as is the case for this soil type (Hicks D, pers comm.)[A].

Given the unusually low initial water contents and volumetric water content at -10kPa, a typical measurement of field capacity (Table 4), for the Pinaki sand sites compared to the other sampled sites, suggests that hydrophobic conditions could be a factor in the observed high macroporosities. If the soil experienced hydrophobic conditions and did not wet up completely in the laboratory the volume of micropores will be underestimated and therefore overestimate the volume of macropores. This is discussed further below in relation to these sites' correspondingly high bulk densities.

[A]Douglas Hicks- Soil Scientist contractor

Table 2. Soils and land use classes in the Auckland region sampled in 2011 for soil quality attributes.

ARC code	Site code	Year established	Current land use	NZSC subgroup	Soil series
ARC96_03	2011-05-02	1996	Plantation forestry	Mottled Yellow Ultic	Whangaripo clay loam
ARC96_01	2011-03-02	1996	Plantation forestry	Mottled Yellow Ultic	Whangaripo clay loam
ARC98_10	2011-22-02	1998	Plantation forestry	Typic Sandy Brown	Red Hill sand
ARC98_11	2011-23-02	1998	Plantation forestry	Typic Sandy Brown	Red Hill sand
ARC98_12	2011-24-02[1]	1998	Pastoral farming	Typic Sandy Brown	Red Hill sand
ARC99_21	2011-58-02	1999	Plantation forestry	Typic Sandy Recent	Pinaki sand
ARC99_23	2011-60-02	1999	Plantation forestry	Typic Sandy Recent	Pinaki sand
ARC00_10	2011-72-02	2000	Plantation forestry	Albic Ultic	Marua clay
ARC11_89	2011-89-01	2011	Plantation forestry	Mottled Yellow Ultic[2]	Whangaripo clay loam
ARC11_90	2011-90-01	2011	Plantation forestry	Mottled Yellow Ultic[2]	Whangaripo clay loam
ARC11_91	2011-91-01	2011	Plantation forestry	Typic Sandy Recent	Pinaki sand
ARC11_92	2011-92-01	2011	Plantation forestry	Albic Ultic[2]	Hukerenui
ARC11_93	2011-93-01	2011	Plantation forestry	Albic Ultic[2]	Hukerenui
ARC11_94	2011-94-01	2011	Plantation forestry	Mottled Ultic[2]	Rangiora
ARC11_95	2011-95-01	2011	Plantation forestry	Albic Ultic[2]	Mahurangi
ARC11_96	2011-96-01	2011	Plantation forestry	Albic Ultic[2]	Mahurangi

[1]See appendix 7.1 and 7.2 for 2011 site 24 soil measurements. Site number 24 has converted to pasture.

[2]Soil classification subject to a comprehensive pedological assessment

Table 3. Soil chemical, physical and biological characteristics for 2011 plantation forestry sampled sites within Auckland. Results for macroporosity (-5kPa) and C/N ratio in the shaded column are presented but excluded from the determination of meeting the soil quality guideline procedure.

Site number	Soil series	pH	Organic C %	Total N %	AMN mg/kg	Olsen P mg/kg	Bulk density g/cm^3	Macroporosity (-10kPa). (%v/v)	Macroporosity (-5kPa). (%v/v)	C/N ratio
3	Whangaripo clay loam	4.75	6.7	0.39	94	68	0.95	15	12	17
5	Whangaripo clay loam	4.73	7.22	0.44	133	6	0.83	13	11	16
22	Red Hill sand	6.3	4	0.35	141	32	1.18	22	16	11
23	Red Hill sand	5.69	3.2	0.24	59	25	0.95	32	25	14
58	Pinaki sand	5.66	1.8	0.06	19	5	1.48	39	30	29
60	Pinaki sand	5.18	1.6	0.05	12	16	1.52	37	30	35
72	Marua clay	5.32	3	0.18	97	4	1.1	8	6	17
89	Whangaripo clay loam	4.48	6	0.37	49	42	1.1	10	8	16
90	Whangaripo clay loam	4.75	7.6	0.4	107	5	0.82	22	19	19
91	Pinaki sand	5.84	2.7	0.11	51	5	1.3	40	33	24
92	Hukerenui	4.65	6.8	0.24	42	5	1.19	12	10	28
93	Hukerenui	4.92	5.2	0.2	31	4	1.23	14	12	26
94	Rangiora	4.66	5.3	0.19	38	5	1.07	17	15	28
95	Mahurangi	5.05	6.2	0.31	69	43	1.11	14	12	20
96	Mahurangi	5.34	4.6	0.26	70	19	1.06	14	12	18

Two sites, both Pinaki sand (58 and 60), exceeded bulk density guidelines (Table 2), indicating compaction; this contrasts with the high macroporosity values observed at these sites and will be discussed further below. There were large increases in bulk density when samples collected in 1999 and 2011 were compared for these two sites, and also for site 22 (Red Hill sand) sampled in 1998 and 2011 (Table 5). Bulk density significantly increased from 0.93 g/cm^3 sampled during 1996-2000 to 1.15g/cm^3 sampled in 2011 equating to a percentage mean change increase of 24% that was largely influenced by these three sites (Table 5). For repeat sites, absolute soil quality changes and percentage mean change comparisons (mean ([2011 value – original value)]/original value x100)), for sampling periods 1996-2000 and 2011, are presented in Table 5.

Table 4. Initial water content, volume water content -10kPa, macroporosity -10kPa, bulk density, particle density and total porosity for the 15 plantation forest sites.

Site number	Initial water content (% w/w)	Volume water content 10kPa (% v/v)	Macroporosity -10kpa (% v/v)	Bulk density (g/cm^3)	Particle density (g/cm^3)	Total porosity (% v/v)
3	53.47	47.53	14.73	0.95	2.51	62.27
5	64.73	52.60	13.43	0.83	2.45	66.03
22	28.33	35.27	22.43	1.18	2.79	57.70
23	40.07	33.23	31.50	0.95	2.68	64.73
58	8.67	7.77	39.43	1.48	2.81	47.20
60	7.80	10.10	37.00	1.52	2.87	47.10
72	47.17	48.90	8.20	1.10	2.57	57.10
89	44.17	47.03	9.83	1.10	2.55	56.87
90	55.53	44.73	21.83	0.82	2.46	66.57
91	12.60	12.00	39.50	1.30	2.68	51.50
92	37.30	42.73	11.50	1.19	2.60	54.23
93	32.57	38.80	14.13	1.23	2.60	52.93
94	40.10	39.60	17.40	1.07	2.49	57.00
95	37.93	42.13	13.73	1.11	2.52	55.87
96	42.27	44.17	13.63	1.06	2.49	57.80

Note high particle densities for sites 22, 23, 58, 60 and 91 corresponding to soils derived from iron sands.

Note sites numbers 58, 60 and 91 with very low initial water content possibly suggesting hydrophobicity.

The bulk density of the three Pinaki sand sites averaged at 1.43 g/cm^3, an unexpected value given the high macroporosities observed at these sites. A possible explanation for such high bulk densities for the Pinaki sand can be attributed to the soil's inherent properties. In New Zealand, iron sands have been reported to be highest on the western inner-middle shelves between Auckland and Taranaki (Carter, 1980). Pinaki sands on these western shelves of Auckland have been identified to contain heavy minerals such as augtite and hornblendes, and some magnetite, the latter being a component of ironsands (Claridge, 1961). These heavy minerals can originate by the sea in suspension that disperse inland once dried out. Prevailing winds blow these materials and sand inland from sand dunes and beaches assisting in the formation of the Pinaki sand (Claridge, 1961). High bulk densities have also been observed for Pinaki sand sites under pastoral based systems in conjunction with high macroporosity measurements. For example, samples taken underneath well established fence lines (>5 years) in pasture for two Pinaki sand sites averaged at 1.04 g/cm3 and 30% v/v for bulk density and macroporosity, respectively (Curran-Cournane et al., 2013). Such high macroporosities are typically linked with low bulk densities and vice versa (Curran Cournane et al., 2010a, Curran Cournane et al., 2010b), but for the Pinaki sand soils the heavy minerals likely contribute to an increase in bulk density and is not necessarily indicative of soil compaction but is a distinctive characteristic of these soil types. Although there were occasional signs of cattle defecation and deer grazing between sites, this was more likely to be associated with roaming stock under low intensive grazing as it was not picked up in macroporosity, a more sensitive indicator of soil compaction (Curran Cournane et al., 2011).

As previously mentioned, the high macroporosity could also be related to errors associated with hydrophobicity at the Pinaki sand sites which exhibited very low volumetric water contents (Table 4). If the soil experienced hydrophobic conditions and did not wet up completely in the laboratory the volume of micropores will be underestimated and therefore overestimates the volume of macropores (Fraser S pers. comm., Landcare Research). It is difficult to identify the lack of complete wetting up of cores in the laboratory without disturbing an intact soil core. In future, additional cores should be sampled at these sites to test for hydrobophicity by cutting the extra cores after the cores had presumably reached saturation point. The latter would confirm or rule out the hydrophobic possibility.

Another possible explanation for the reported increase in bulk density regards the influence changes in OC contents have on both bulk density and particle density at these Pinaki sand sites. When first sampled in 1999 the particle density at Pinaki site numbers 58 and 60 were 2.57 and 2.71 g/cm^3, respectively (Sparling et al., 2000), versus 2.81 and 2.87 g/cm^3, respectively, when re-sampled in 2011. In contrast to the seven key soil quality indicators, particle density generally remains constant in soil and does not change. However, OC soil contents are not as stable in soil. Mean OC contents at these two Pinaki sand sites in 1999 measured 2.6% versus 1.7% in 2011. During the 1999 sampling period the increase in OC reflected a mean bulk density of 0.96 g/cm^3 and mean particle density for 2.6 g/cm^3 for these two sites. In comparison, the mean 1.7% OC content recorded at these sites in 2011 reflected a mean bulk density of 1.5 g/cm^3 and mean particle density of 2.84 g/cm^3. Therefore, a decrease in OC contents reflects an increase in bulk density and particle density as was observed at these sites sampled in 2011.

Alternatively, it is not possible to rule out the possibility of spatial variability as an enduing factor. The hand held GPS equipment, Garmin GPSmap 78 model, used to locate these sites generally has an accuracy of up to 3 metres, which can increase under canopy. It is therefore possible that spatial variability played a factor in the soil quality changes observed at the Pinkai sand sites.

Overall, the three Pinaki sand sites had a major influence on results with more than three indicators failing to meet recommended guidelines. It is suggested that more sampling sites are identified in the future that represent a broader range of soil orders to ensure one soil type alone does not have such a dominating impact on results.

There were no significant differences for the remaining soil quality indicators between the two sampling periods (Table 5) and suggests that the site that had been harvested prior to the 2011 soil sampling event did not skew the results.

In contrast, to the majority of horticultural, dairy and drystock reported sites which record low macroporosity (Sparling, 2009, Fraser and Stevenson, 2011, Stevenson, 2010, Curran-Cournane et al., 2013), the indicator outside target ranges on most occurrences, soil macroporosity was less of an issue under plantation forestry. Pastoral and horticultural sites also tend to have Olsen P concentrations higher than the recommended requirements for these land uses. While four sites in the current study had Olsen P concentrations higher than the recommended range, it is less of an extensive issue for plantation forestry.

Table 5. Changes in soil quality attributes for plantation forestry sites in the Auckland Region sampled 1996-2000 and repeated in 2011.

Site number	First sampled	Second sampled	Soil type	Soil pH	Organic C %	Total N %	C/N	Olsen P mg/kg	AMN mg/kg	Macroporosity -5kPa (%v/v)	Bulk density g/cm^3
3	1996	2011	Whangaripo clay loam	0.08	2.08	0.09	1.69	34.11	54.2	-0.27	-0.10
5	1996	2011	Whangaripo clay loam	-0.20	1.62	0.14	-2.26	-6.55	67.7	3.91	-0.01
22	1998	2011	Red Hill sand	1.03	-1.37	-0.13	0.27	9.84	62.1	-18.56	0.42
23	1998	2011	Red Hill sand	0.79	-7.76	-0.52	-0.90	-51.74	-30.0	6.97	0.04
58	1999	2011	Pinaki sand	-0.06	-2.38	-0.20	12.93	-0.24	-42.8	2.30	0.59
60	1999	2011	Pinaki sand	-0.71	0.70	0.01	12.43	9.68	3.18	-13.30	0.50
72	2000	2011	Marua clay	0.24	-1.72	-0.01	-8.43	-0.98	40.59	-12.33	0.06
		Mean change		0.17	-1.26	-0.09	2.25	-0.84	22.14	-4.47	0.21
		SED		0.27	1.41	0.11	3.76	13.04	15.26	5.97	0.11
		F-statistic		ns	ns	ns	ns	ns	ns	ns	0.05
		Mean change (%)		3.56	-5.69	-12.37	14.09	24.27	46.2	-7.56	24.30

Trace element concentrations were within target ranges for soil health for all analytes (Figure 3). It is recommended that these sites are re-sampled in 5-10 years' time.

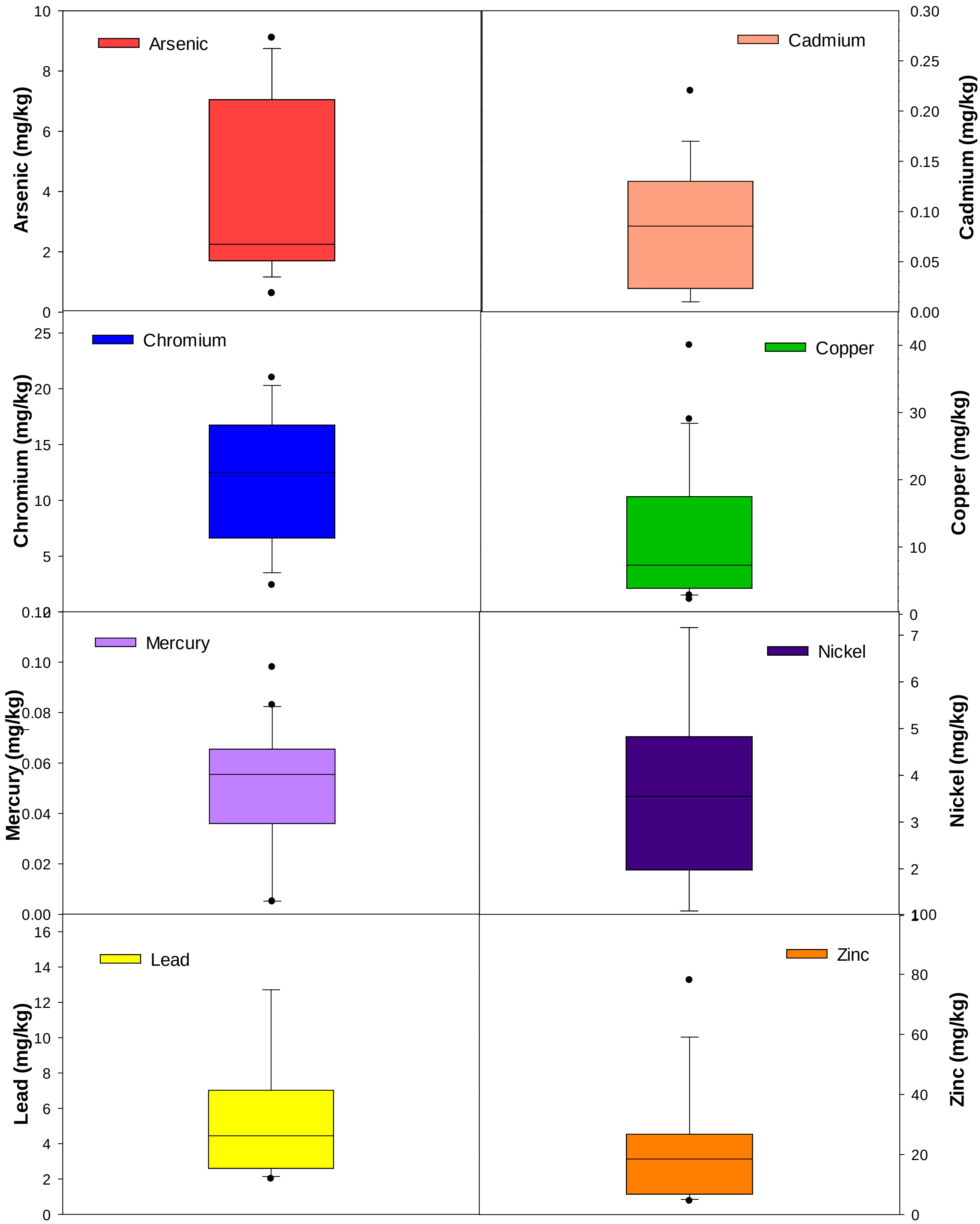

Figure 3. Trace element concentrations (mg/kg) at the 15 soil quality monitoring sites. The dashed grey lines illustrate where an analyte is approaching the upper limit for soil health. The boxes represent the inter-quartile range (25th to 75th percentile) and the whiskers show the range of values that fall within the inner fences. Outliers are illustrated with black circles. The median is shown as a line in each box.

4.0 **Conclusions and recommendations**

The key soil quality indicator outside target ranges on most occurrences was Olsen P. However, this should be interpreted with caution because only one site would be considered seriously over guidelines and was possibly associated with fertiliser drift from adjacent pastureland. Five sites had both TN and OC contents below guidelines, three of which included all Pinaki sand sites. Pinaki sand soils are very young, recently formed soils and have been reported to be too young to develop significant amounts of organic material (Claridge, 1961). Organic C content at one sampled site for Red Hill sand decreased drastically but when all site data was pooled together no significant decline in OC was recorded. Particular attention in future sampling events should be focused at this site to determine if OC contents continually decline. Two sites fell within the very low guideline range for concentrations of AMN and these two sites had correspondingly low (< 0.1 %) TN contents.

Macroporosities (-10kPa) were above guidelines for all three Pinaki sand sites sampled. Although low macroporosity is less desirable, indicating soil compaction, soils with high macroporosity are prone to soil erosion, hydrophobicity and excessive draining. In contrast, bulk density increased for the re-sampled Pinaki sand sites which likely influenced the significant increase in bulk density that was observed when 2011 results were compared to those sampled between 1996-2000.

Overall, the three Pinaki sand sites had a major affect on results with more than three indicators failing to meet recommended guidelines. These three sites aside, soil quality was generally better under plantation forestry than that for the recently sampled horticultural, dairy and drystock sites in Auckland. In contrast, to the majority of horticultural, dairy and drystock reported sites which record low macroporosity, the indicator outside target ranges on most occurrences, soil macroporosity was less of an issue under plantation forestry. Pastoral and horticultural sites also tend to have Olsen P concentrations higher than the recommended requirements for these land uses. While four sites in the current study had Olsen P concentrations higher than the recommended range, it is less of an extensive issue for plantation forestry.

It is suggested that more sampling sites are identified in the future that represent a broader range of soil types to ensure one soil type alone does not have such a dominating impact on results. It is also recommended that all these sites are re-sampled several more times at five-yearly intervals to determine long-term temporal trends in soil quality properties for plantation forestry.

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7.0 **Appendices**

7.1 2011 Soil Chemistry data

Site #	Water content (method 104(ii)) (%dry weight)	pH (2:5 Water) (method 106 (i))	Organic C (method 114) (%)	Total N (method 114) (%)	C/N ratio (calculation)	NO3-N (method 118) (mg/kg) KCL-extractable	NH4-N (method 118) (mg/kg) KCL-extractable	Anaerobic mineralisable-N (method 120) (mg/kg)	Olsen P (method 124) (mg/kg)
3	63.9	4.8	6.7	0.39	17.0	8.9	19.5	94	68
5	73.9	4.7	7.2	0.44	16.4	4.4	8.2	133	6
22	36.0	6.3	4.0	0.35	11.3	21.6	2.0	141	32
23	28.2	5.7	3.2	0.24	13.6	5.7	0.3	59	25
24	43.4	5.8	3.8	0.40	9.6	10.7	0.6	129	35
58	14.0	5.7	1.8	0.06	28.9	<0.1	0.1	19	5
60	13.7	5.2	1.6	0.05	34.8	<0.1	0.2	12	15
72	49.2	5.3	3.0	0.18	16.9	3.1	11.7	97	4
89	63.0	4.5	6.0	0.37	16.4	16.4	17.9	49	42
90	72.8	4.8	7.6	0.40	18.8	2.6	7.2	107	5
91	21.5	5.8	2.7	0.11	23.7	<0.1	3.4	51	5
92	55.6	4.7	6.8	0.24	28.2	<0.1	4.2	42	4
93	47.3	4.9	5.2	0.20	25.9	<0.1	3.4	31	4
94	45.1	4.7	5.3	0.19	27.9	<0.1	7.2	38	5
95	47.5	5.1	6.2	0.31	20.2	<0.1	3.8	69	43
96	46.0	5.3	4.6	0.26	17.6	0.1	9.3	70	18

7.2 2011 Soil Physics data

	A	B	C	D	E	F	G	H	I	J	K	L
1	Lab number	Client ID	Site number	Liner number	Initial water	Dry bulk	Particle	Total	Macroporosity	Air filled	Vol. WC 5kPa	Vol. WC 10kPa
2					content (%w,w)	density (t/m3)	density (t/m3)	porosity (%v/v)	(%,v/v)	porsoity (%,v/v)	(%,v/v)	(%,v/v)
3	HP4761a	Site 3, 15m	3	1028	50.8	0.98	2.58	62.1	12.5	14.0	49.7	48.1
4	HP4761b	Site 3, 30m	3	1212	66.7	0.88	2.40	63.5	6.4	10.4	57.1	53.1
5	HP4761c	Site 3, 45m	3	1324	42.9	0.99	2.54	61.2	18.1	19.8	43.1	41.4
6	HP4759a	Site 1, 15m	5	1050	69.5	0.76	2.42	68.5	14.2	17.1	54.3	51.4
7	HP4759b	Site 1, 30m	5	1074	57.3	0.87	2.46	64.8	13.5	15.2	51.3	49.6
8	HP4759c	Site 1, 45m	5	1111	67.4	0.87	2.48	64.8	6.3	8.0	58.5	56.8
9	HP4772a	Site 14, 15r	22	1261	28.3	1.02	2.79	63.4	18.6	29.0	44.8	34.4
10	HP4772b	Site 14, 30r	22	1297	27.6	1.23	2.77	55.5	14.5	19.2	41.0	36.3
11	HP4772c	Site 14, 45r	22	1513	29.1	1.29	2.81	54.2	15.4	19.1	38.8	35.1
12	HP4773a	Site 15, 15r	23	1085	27.4	1.00	2.73	63.4	32.5	37.9	31.0	25.5
13	HP4773b	Site 15, 30r	23	1163	68.2	0.71	2.57	72.5	19.2	24.0	53.3	48.5
14	HP4773c	Site 15, 45r	23	1235	24.6	1.14	2.73	58.3	22.0	32.6	36.3	25.7
15	HP4774a	Site 16, 15r	24	1093	30.1	1.31	2.86	54.1	5.7	13.5	48.4	40.6
16	HP4774b	Site 16, 30r	24	1389	72.0	0.85	2.64	67.6	5.5	9.9	62.1	57.7
17	HP4774c	Site 16, 45r	24	1630	48.1	1.14	2.78	59.0	1.4	4.7	57.5	54.3
18	HP4763a	Site 5, 15m	58	248	7.0	1.50	2.84	47.2	34.5	39.8	12.8	7.4
19	HP4763b	Site 5, 30m	58	1015	10.8	1.33	2.80	52.5	25.5	43.1	27.0	9.4
20	HP4763c	Site 5, 45m	58	1027	8.2	1.63	2.80	41.9	29.7	35.4	12.3	6.5
21	HP4765a	Site 7, 15m	60	1014	6.2	1.61	2.90	44.6	29.4	36.5	15.2	8.1
22	HP4765b	Site 7, 30m	60	1354	8.6	1.52	2.86	46.8	28.4	36.2	18.4	10.6
23	HP4765c	Site 7, 45m	60	1503	8.6	1.43	2.85	49.9	31.1	38.3	18.8	11.6
24	HP4768a	Site 10, 15r	72	1067	49.8	1.09	2.53	57.1	4.9	7.3	52.2	49.8
25	HP4768b	Site 10, 30r	72	1323	44.2	1.09	2.62	58.5	10.1	11.9	48.4	46.6
26	HP4768c	Site 10, 45r	72	1385	47.5	1.13	2.56	55.7	3.2	5.4	52.5	50.3
27	HP4762a	Site 4, 15m	89	1351	52.2	1.03	2.52	59.0	6.1	8.2	52.9	50.8
28	HP4762b	Site 4, 30m	89	1624	40.5	1.12	2.59	56.7	10.9	12.7	45.8	44.0
29	HP4762c	Site 4, 45m	89	1657	39.8	1.15	2.55	54.9	7.3	8.6	47.6	46.3
30	HP4760a	Site 2, 15m	90	1131	55.0	0.88	2.48	64.6	13.5	16.7	51.1	47.9
31	HP4760b	Site 2, 30m	90	1187	48.2	0.93	2.51	63.1	16.2	18.1	46.9	45.0
32	HP4760c	Site 2, 45m	90	1195	63.4	0.67	2.39	72.0	28.4	30.7	43.6	41.3
33	HP4764a	Site 6, 15m	91	1183	14.5	1.29	2.70	52.1	29.3	37.4	22.8	14.7
34	HP4764b	Site 6, 30m	91	1358	16.4	1.13	2.64	57.3	36.9	43.4	20.3	13.9
35	HP4764c	Site 6, 45m	91	1378	6.9	1.48	2.69	45.1	31.3	37.7	13.7	7.4
36	HP4766a	Site 8, 15m	92	1009	36.2	1.26	2.62	51.9	5.8	6.9	46.1	45.0
37	HP4766b	Site 8, 30m	92	1059	35.7	1.23	2.62	52.9	7.1	8.4	45.7	44.5
38	HP4766c	Site 8, 45m	92	1511	40.0	1.08	2.57	57.9	16.4	19.2	41.5	38.7
39	HP4767a	Site 9, 15m	93	1002	28.4	1.15	2.59	55.6	21.2	24.4	34.4	31.2
40	HP4767b	Site 9, 30m	93	1502	32.9	1.38	2.65	47.8	1.2	1.7	46.7	46.1
41	HP4767c	Site 9, 45m	93	1643	36.4	1.15	2.57	55.4	14.6	16.3	40.8	39.1
42	HP4769a	Site 11, 15r	94	1110	32.3	1.29	2.53	49.0	7.2	8.9	41.8	40.1
43	HP4769b	Site 11, 30r	94	1340	37.3	1.02	2.53	59.9	21.5	23.4	38.3	36.5
44	HP4769c	Site 11, 45r	94	1651	50.7	0.92	2.42	62.1	16.7	19.9	45.4	42.2
45	HP4770a	Site 12, 15r	95	1271	31.7	1.27	2.56	50.4	7.6	9.0	42.8	41.4
46	HP4770b	Site 12, 30r	95	1301	46.2	0.96	2.48	61.4	14.9	16.6	46.5	44.8
47	HP4770c	Site 12, 45r	95	1367	35.9	1.11	2.52	55.8	14.1	15.6	41.7	40.2
48	HP4771a	Site 13, 15r	96	1076	37.8	1.21	2.54	52.5	5.7	7.3	46.9	45.2
49	HP4771b	Site 13, 30r	96	1237	35.4	1.16	2.53	54.1	9.8	11.3	44.4	42.8
50	HP4771c	Site 13, 45r	96	1397	53.6	0.80	2.41	66.8	20.5	22.3	46.3	44.5

7.3 Archived soil chemical and physical data 1996-2000 for plantation forestry

Table 5. Data compiled from 1996-2000 results used to assess changes in the soil quality of forestry sites

Site number	Year sampled	pH	Organic C %	Total N%	AMN w/w	Olsen P (mg/kg)	Bulk Density (g/cm3)	Macroporosity-5kPa (%v/v)[3]
3	1996	4.67	4.60	0.30	40	33.8	1.05	12.6
5	1996	4.93	5.60	0.30	65	12.8	0.84	7.4
22	1998	5.27	5.34	0.49	79	22.0	0.76	34.7
23	1998	4.90	10.97	0.76	89	76.5	0.91	17.6
24	1998	5.53	9.37	0.86	170	13.8	0.64	23.4
24	2011[1]	5.81	3.82	0.4	86.1	34.8	1.1	4.2
58	1999	5.72	4.20	0.26	62	5.1	0.89	27.6
59[2]	1999	6.07	0.55	0.03	0	9.2	1.44	31.9
60	1999	5.89	0.92	0.04	9	5.8	1.02	42.9
72	2000	5.08	4.72	0.19	56	5.0	1.05	18.4

[1] Site converted to pasture in the 2011 sampling

[2] Site no longer existed in 2011 sampling year as a result of land use change

[3] Macroporosity -5kPa only analysed prior to 2008 soil sampling events

7.4 Site and soil type details for all 16 sites sampled

Site	5
Date sampled	01/08/2011
Landuse	Plantation forestry
NZSC	Mottled Yellow Ultic
Soil type	Whangaripo clay loam
Parent material	Strongly weathered fine sandstone

Sampling/field notes

The site is located in Mahurangi forest and was first sampled in 1996. This is the second rotation of Pinus radiata. It has been in pine >40 years and is due to be harvested in the next 12-13 years.

Site	90
Date sampled	01/08/2011
Landuse	Plantation forestry
NZSC	Mottled Yellow Ultic
Soil type	Whangaripo clay loam
Parent material	Strongly weathered fine sandstone

Sampling/field notes

The site is new and is located a few hundred metres from site 5. The soil type was identified as that from site 5 and the area is due to be harvested in 12-13 years.

Site	3
Date sampled	01/08/2011
Landuse	Woodlot
NZSC	Mottled Yellow Ultic
Soil type	Whangaripo clay loam
Parent material	Strongly weathered fine sandstone

Sampling/field notes

The site was first sampled in 1996 and is a Pinus radiata woodlot on a privately owned property.

Site	89
Date sampled	01/08/2011
Landuse	Woodlot
NZSC	Mottled Yellow Ultic
Soil type	Whangaripo clay loam
Parent material	Strongly weathered fine sandstone

Sampling/field notes

The site was first sampled during this study and is located about 100m uphill from site 3 on privately owned property.

Site	58
Date sampled	02/08/2011
Landuse	Pinus radiata forest
NZSC	Typic Sandy Recent
Soil type	Pinaki sand
Parent material	Wind-blown dune sand

Sampling/field notes

The site was first sampled in 1999 and is located at Woodhill forest. The site is adjacent to recreational tree climbing facilities and unlikely to be harvested in the near future. There was also some cattle excreta visible evidence of occasion cattle roaming.

Site	91
Date sampled	02/08/2011
Landuse	Plantation forestry
NZSC	Typic Sandy Recent
Soil type	Pinaki sand
Parent material	Wind-blown dune sand

Sampling/field notes

This is a new site at Woodhill forest to replace one that was converted into recreational landuse. Deer and bike tracks were visible whereby sampling was avoided.

Site	60
Date sampled	02/08/2011
Landuse	Plantation forestry
NZSC	Typic Sandy Recent
Soil type	Pinaki sand
Parent material	Wind-blown dune sand

Sampling/field notes

This site was first sampled in 1999. Deer and bike tracks were visible whereby sampling was avoided. Deer were also seen grazing alongside main roads in the forest. Pine leaf matter reached depths of 250mm.

Site	92
Date sampled	02/08/2011
Landuse	Plantation forestry
NZSC	Albic Ultic
Soil type	Hukerenui
Parent material	Strongly weathered sandstone

Sampling/field notes

This is a new site at Riverhead forest. Pine leaf matter reached depths of 500mm and decayed organic material depths of 290mm. The site is due to be harvested next year.

Site	93
Date sampled	02/08/2011
Landuse	Plantation forestry
NZSC	Albic Ultic
Soil type	Hukerenui
Parent material	Strongly weathered sandstone

Sampling/field notes

This is a new site at Riverhead forest and is about 500m from site 92. Pine leaf matter reached depths of 500mm and decayed organic material depths of 290mm. The site is due to be harvested next year.

Site	72
Date sampled	03/08/2011
Landuse	Harvested in 2008
NZSC	Acidic Orthic Brown
Soil type	Marua clay
Parent material	Greywacke

Sampling/field notes

This site was first sampled in 2000 at Whitford forest. It was harvested in 2008 and is due to be re-planted. It was sprayed in January 2011 to control the dense gorse and Pampas grass. Phosphate rock fertilser application terminated in the early 2000's.

Site	94
Date sampled	03/08/2011
Landuse	Plantation forestry
NZSC	Mottled Ultic
Soil type	Rangiora
Parent material	Greywacke

Sampling/field notes

This is a new site at Whitford forest and about 1km from site 72. There is occasional roaming of Belted Galloways. Pinus radiata is in its 3rd generation and the site is due to be harvested in 5years.

Site	95
Date sampled	04/08/2011
Landuse	Plantation forestry
NZSC	Albic Ultic
Soil type	Mahurangi
Parent material	Strongly weathered sandstone

Sampling/field notes

This is a new site at Weiti forest. The forest is predominantly Pinus radiata. Pine leaf matter depth was about 150-200mm and the depth of organic topsoil was shallow at about 100mm.

Site	96
Date sampled	04/08/2011
Landuse	Plantation forestry
NZSC	Albic Ultic
Soil type	Mahurangi
Parent material	Strongly weathered sandstone

Sampling/field notes

This is a new site at Weiti forest and is about 50m away from site 95, across a gravel road. The forest is predominantly Pinus radiata. Horse hoof prints were visible, likely to be the result of recreational horse riding and there were also occasional cattle excreta visible, indicative of roaming cattle.

Site	22
Date sampled	05/08/2011
Landuse	Woodlot
NZSC	Typic Sandy Brown
Soil type	Red Hill sand
Parent material	Dune sand on sandstone

Sampling/field notes

This site was first sampled in 1998 from a Pinus radiata woodlot in Awhitu Peninsula. The woodlot does not get harvested and is fenced off from surrounding drystock grazing.

Site	23
Date sampled	05/08/2011
Landuse	Woodlot
NZSC	Typic Sandy Brown
Soil type	Red Hill sand
Parent material	Dune sand on sandstone

Sampling/field notes

This site was first sampled in 1998 and is in the same location as site 22, about 500m distance away. The site is positioned on the valley floor in rolling country.

Site	24
Date sampled	05/08/2011
Landuse	Grazed pasture
NZSC	Typic Sandy Brown
Soil type	Red Hill sand
Parent material	Dune sand on sandstone

Sampling/field notes

This site was first sampled in 1998 that was then under woodlot. The site has now been converted to grazed pasture, predominantly by beef cattle.