Impacts of conversion from forestry to pasture on soil physical properties of Vitrands (Pumice Soils) in the Central North Island, New Zealand

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Djuro Paripovic

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Abstract

At least 30 000 hectares of land has been converted from plantation forest to pasture in the central North Island of New Zealand between 2000 and 2010. When forests are cleared for pasture the soil may undergo changes in soil structure affecting physical properties. The overall objective of this study was to investigate changes in soil physical properties in Pumice Soils following land use change from forest to pasture.

Two study areas were identified; one near Tokoroa (Maxwell Farms), and one near Taupo (Wairakei Estate). At each study area a series of sites including: plantation pine forest, pasture converted from pine forest 2,3,4 and 5 years ago, and long term (>50 years) dairy, and sheep and beef pasture, were identified, all on Taupo Pumice Soil. Field and laboratory methods included measurement of; penetration resistance, degree of packing, soil dry bulk density, soil hydrophobicity, unsaturated and saturated hydraulic conductivity, soil moisture retention, aggregate stability, particle size distribution, and soil pH.

There was increased soil compaction in the A horizon on recently converted sites compared to pine forest sites as evidenced by higher soil dry bulk density, increased penetration resistance, and degree of packing. At the Tokoroa study area the pine forest soil A horizon had a significantly lower dry bulk density (mean 0.58 g/cm^3) ($P < 0.05$) than any of the pasture sites (mean 0.65 - 0.72 g/cm^3). At the Taupo study area only long term dairy (mean 0.78 g/cm^3) and the youngest pasture site (3 years since conversion from pine forest) (mean 0.74 g/cm^3) had higher ($P < 0.05$) bulk density than the plantation pine forest soil. At the Tokoroa study area, the penetration resistance and degree of packing in the A horizon of the pine forest site was lower ($P< 0.01$) than any other site. The degree of packing and penetration resistance at the Taupo study area in the A horizon of the pine forest site was lower ($P< 0.05$) compared to 3 years old conversion and long term dairy pasture but was not significantly different from pastures converted 4 and 5 years ago.

The water repellency of recently converted pastures was higher ($P < 0.05$) than pine forest at both study areas. Two of the three long-term pasture sites investigated had very low water repellency.

The long term pasture sites had markedly higher total available water holding capacity than either the recently converted pastures or the pine forest sites. The pine forest soil water content at 10 kPa (field capacity) and 100 kPa (readily available water) was generally lower than pasture sites. At the Tokoroa study area there was no significant difference in unsaturated hydraulic conductivity between the pine forest soil and any other site. At Taupo the pine forest soil unsaturated hydraulic conductivity was higher ($P < 0.05$) than the most recent conversion site (3 years old) but not significantly different from other sites. At the Taupo study area none of the land uses had significantly different saturated infiltration rate compared to the pine forest. At the Tokoroa study area the pine forest saturated hydraulic conductivity was higher ($P < 0.05$) than the 5 years old conversion or the long term sheep and beef farm.

The A horizon, at both study areas, was observed to be deepest under long term dairy farm followed by forest and shallowest on sites recently converted from pine plantation. There was no clear pattern of changes in soil colour, pedality or boundary distinctiveness and shape, between different sites. Aggregate stability of the Ap horizon was noticeably lower in recently converted pastures than in the pine forest or long term pasture sites. Soil pH values were generally in 4.5 to 5.9 ranges across all land uses in all horizons. The exception was the most recent conversions to pasture (2 and 3 years ago converted) at the Tokoroa study area which exceeded pH 6, presumably due to high rates (3.5 T/ha) of lime application during the conversion process.

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Table of Contents

Chapter 1 Introduction

Chapter 2 Literature Review

Chapter 3 The study areas and sampling sites

Chapter 4 Materials and Methods

Chapter 5 Results: Field methods results

Chapter 6 Results: Laboratory Methods

Chapter 7 Discussion and conclusions

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

This chapter provides a brief introduction on the background and objectives of this research project.

1.2 Project background

1.2.1 Land use change

There are several interacting drivers for land use change but the exponential growth of human population is fundamental. In the 20th century, the world saw the biggest increase in human population in history due to lessening of the mortality rate and massive increase in agricultural productivity (ISRIC, 2009). Increasing agricultural production required more new, previously untilled soils. Land use change resulted with important consequences, affecting soil, water and the atmosphere (Davidson *et al*, 2000).

Most studies that assess land use changes at the global scale are focused on: deforestation, cropland expansion, dry land degradation, urbanisation, pasture expansion, and agricultural intensification (Hartemink *et al*, 2006).

1.2.2 Land use change from forestry to pasture in New Zealand

Land use has been changing through the history of settlement in New Zealand (Ward *et al*, 2009). Between 1992 and 2002, afforestation with pine tree (*Pinus radiata)* in New Zealand has led to the establishment of over 600 000 ha of new pine plantation forests, about 85% of which were on fertile pastures used previously for grazing sheep and cattle (MAF 2009). This trend has been reversed lately by decline of profitability of forestry industry and has shifted land conversion towards pastoral production.

When forests are cleared for pasture the soil may undergo changes in soil structure affecting physical properties including the water infiltration rate and moisture holding capacity. Soil physical characteristics influence plant growth rates, soil erosion, infiltration, water runoff, and therefore flood occurrence in the catchment. There is growing concern regarding the impacts of the latest land use change from plantation forest to pasture on the soil and water quality in the vulnerable area which include waterways.

Soil organic matter (SOM) content is widely recognised as a factor that influences a number of soil physical properties (Bauer *et al.*, 1992). De Oliviera *et al.* (2008) found that forest to pasture conversion caused lower soil organic carbon content (SOM). Steffens *et al.* (2008) similarly suggested that organic carbon, total N and total S concentrations decreased with increasing grazing intensity. However, recent findings from New Zealand showed a significant increase in soil organic matter in the first 5 years after conversion from plantation forest to dairy pasture on Pumice Soils (Hedley *et al.*, 2009).

1.2.3 Land use change in central North Island (CNI)

There has been increasing pressure lately for conversion of pine plantation forest to agricultural land within the upper Waikato Catchment. Tens of thousands of hectares of land have been converted from plantation forest to pasture in the central North Island of New Zealand between 2000 and 2010 (Figure 1).

The land use change was driven by the perceived better long term returns from dairy farming compared with forestry.

Figure 1.1 Land conversion from pine plantation forest to dairy pasture, Wairakei Estate near Taupo

1.2.4 Soils of central North Island

Pumice Soils (NZ Soil Classification, equivalent to Vitrands in *Soil Taxonomy*) is the dominant soil order of the central North Island, formed on pumice deposited mainly from the AD 232 ± 5 Taupo volcanic eruptions (Hogg *et al*., 2009). Pumice Soils are sandy or gravelly dominated by pumice, or pumice sand with a high content of natural glass, low clay contents (generally less than 10%), they have weak structure and erode easily when disturbed, but are generally resistant to livestock treading damage. Drainage of excess water is rapid but the soils are capable of storing large amounts of water for plants, thanks to high pumice material content. The water holding capacity of Pumice Soils increases as the organic matter content of the topsoil is built up (Landcare Research 2009).

Pasture production on Pumice Soils in summer is often limited by moisture availability. Because of increasing pressure on water resource use in the area an enhanced understanding of soil moisture holding capacity will contribute to our ability to manage plant available moisture. The plant root depth of much of the pasture on farms recently converted from forest was relatively shallow (about 10 cm), thus making pasture especially prone to moisture stress during dry periods. It is suggested that if we can identify causes of the shallow root depths and find a means to counteract the problem, root depth could be doubled from 10 to 20 cm, which would increase the moisture available to plants during dry periods and could lead to an overall increase in pasture production.

1.3 Objectives

The overall objective of this study was to investigate changes in soil physical properties in Pumice Soils following land use change from forest to pasture. Specific objectives were: To investigate the consequences of conversion from forest to pasture on the soil moisture retention, aggregate stability, soil dry bulk density, and hydrophobicity.

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Chapter 2

Literature review

2.1 Introduction

Land use is critical factor for water and soil quality as well as an important driver of rural economies (Hillel, 2003). Changes in land use and land cover impact on water quality and soil properties. There is extensive peer-reviewed literature covering land use and specifically change from plantation forest to pasture and impacts on soil properties including soil physical properties. Ward (2009) stated that effects of deforestation and pasture conversions, as well as agricultural intensification, have been fairly well documented. Many studies on the effect of conversion from forest to pasture quantified impacts on physical soil properties through increased compaction (Geissen *et al*, 2009), decreased infiltration rate (Taylor *et a.l*, 2009) and lower soil water holding capacity (Singleton *et al*, 1999; Bormann *et al*, 2008).

This review outlines the importance of soil structure and soil physical properties such as soil dry bulk density, aggregate stability, soil water storage, water infiltration rate, and water hydrophobicity for pasture production and how soil physical properties are affected by land use and land use change particularly from forest to pasture.

2.1.1 Soil organic matter (SOM) content and land conversion

Soil organic matter (SOM) content is widely recognized as a factor that influences a number of soil physical properties (Bauer *et al.*, 1992). There are numerous studies covering the influence of SOM content and quality change through land conversion on soil physical properties. Many findings suggest that conversion from forest to pasture is followed by decreased SOM in the soil (Parfitt *et al.,* 2003; DeOliviera *et al.,* 2008; Steffens *et al.,* 2008).

Goh *et al.,* (1987) suggest that there are different SOM dynamics in native forest and pine plantation forest. They measured the quantity of accumulated organic matter in the topsoil (0-20 cm) of indigenous (beech or podocarp) forests and nearby *Pinus radiata* plantations in five widely separated forest sites in the South Island of New Zealand. The findings suggest that conversion from native forest to plantation forestry is followed by lower SOM content. Total SOM mass of forest topsoil in native and *Pinus radiata* plantation stands ranged from 25 to 464 and 9 to 79 t/ha, respectively (Goh *et al.,* 1987).

In research by DeOliviera *et al.,* (2008) in the watershed Agua Fria (Brazil) has been found that forest to pasture change has caused lower organic carbon content (SOM) and hence reduced soil aggregate stability and an increased proportion of small-sized aggregates. Steffens *et al.,* (2008) reported that in a semiarid steppe of Inner Mongolia (PR China) organic carbon, total N and total S concentrations decreased significantly with increasing grazing intensity which was followed by significant soil bulk density increase. During long-term laboratory incubations of New Zealand soil from pasture and forest, Parfitt *et al.,* (2003) confirmed, loss of SOM caused by land use change from indigenous forest to pasture, by means of increased gross nitrification, net nitrification, and hence leaching of NO^3-N. However, recent findings from New Zealand showed a significant increase in soil organic matter in the first 5 years after conversion from plantation forest to dairy pasture on Pumice Soils (Hedley *et al.*, 2009).

2.2 Soil Dry Bulk Density

2.2.1 Soil dry bulk density definition

Soil dry bulk density is the oven-dry (105ºC) mass of soil in an undisturbed state per given volume (Equation 2.1). The dry bulk density (ρ_b) is usually expressed in g/cm^3 or t/m^3 which are numerically equivalent (McLaren and Cameron, 1993).

$$\rho_b = \frac{mass\ of\ dry\ soil\ g}{total\ volume\ of\ soil\ cm^3} \qquad \text{(Equation 2.1)}$$

Dry soil comprises two main components, soil which makes up the weight and air which makes up part of the volume but does not contribute to the weight (Smith and Mullins, 1991). The soil dry bulk density is in an inverse relationship with soil porosity, soil dry bulk density increases with decreasing soil porosity (McLaren and Cameron, 1996).

2.2.2 Soil dry bulk density: relationship to land use

Human activities such as agricultural practices (ploughing, sowing, grazing), changes in land use related to deforestation or reforestation of land, can significantly affect soil, especially top soil horizons bulk density (Table 2.1) and therefore hydraulic properties.

Gonzalez-Sosa *et al.*, 2010 studied soil physical properties in a suburban catchment in France. Their results showed a high impact of land use on soil physical properties especially soil dry bulk density. The lowest dry bulk density values were obtained in forested soils with the highest organic matter content. Permanent pasture soils showed intermediate values, whereas the highest values were encountered in cultivated lands.

Soil dry bulk density generally increases (Figure. 2.1), upon conversion from forest to agricultural land (Murty *et al., 2002)*. However, in other soils bulk density was lower in agricultural than forest soils. The average increase in bulk density following change from forest to pasture was statistically significant at 12.9 ± 1.6% (*n* = 78) (Murty *et al., 2002)*, with changes following conversion to cultivated land use and pasture being (16.9 ± 2.2%; *n* = 36) and (9.5 ± 2.1%; *n* = 42), respectively.

Table 2.1 Changes in soil dry bulk density in topsoil reported in literature for specific land use changes

Land use change	**Change in SBD**	**Authors**
Grass to crops	5–20% increase	Bauer and Black (1992)
Forest to crops	13% increase	Bewket and Stroosnijder (2003)
Crops to grass	No signif. differences	Breuer *et al.,* (2006)
Grass to crops	3–21% increase	Bronson *et al.,* (2004)
Grass to crops	3–17% increase	Franzluebbers *et al.,* (2000)
Forest to grass	9.5% (±2%) increase	Murty *et al*., (2002)
Forest to crops	17% (±2%) increase	Murty *et al*., (2002)
Forest to grass	0–27% increase	Neill *et al.,* (1997)

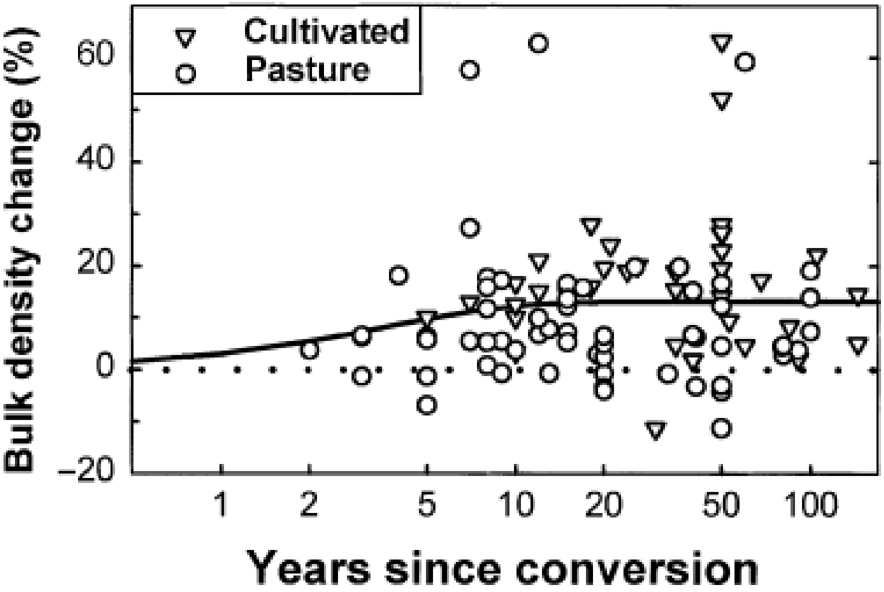

Figure 2.1 Bulk density change after land conversion from forest to pasture or cultivated soils. Adopted from Murty *et al., 2002.*

2.2.3 Increased bulk density and soil compaction impact on plants

Compaction modifies the pore volume and pore structure of the soil (Soane *et al.,* 1980). Most agricultural land that has been compacted to some degree by livestock trampling is expected to influence the success of plant seedlings. Skinner *et al.,* (2009) investigated the impact of soil compaction on seedlings of a woodland eucalypt (*Eucalyptus albens*) and an annual grass (*Vulpia myuros*) in a laboratory experiment. The depth of root penetration declined linearly with increasing bulk density, resulting in a decrease in root depth of around 75% in the most compacted soil compared with the least compacted soil for the grass and the eucalypt. Shoot length and primary root length did not vary between soil bulk density levels for either species. However seedlings responded to increasing levels of compaction with oblique (non-vertical) root growth. Results suggested that seedlings of both E*. albens* and *V. myuros* will be more susceptible to surface drying in compacted than uncompacted soils and therefore face a greater risk of desiccation during the critical early phase after germination.

2.2.4 How severe and permanent is soil compaction caused by land use?

There is some controversy about the magnitude of land use change impact on soil physical properties, irreversibility of soil compaction, and time of recovery after use or intensity of land use has changed. It has been suggested by Greenwood *et al.,* (2001) that most soils under grazed permanent pastures at Kyabram Dairy (Victoria, Australia) compacted to some extent (even those managed to minimise soil physical degradation). However, the magnitude of compaction was usually small, and limited to the upper 50-150 mm of the soil. Zimmermann *et al.,* (2008) presented results from a 2 km² large research area in southern Ecuador showing that cattle grazing strongly reduced soil saturated hydraulic conductivity on newly established pasture converted from pine plantation compared to plantation pine forest. Results showed a permeability decrease of two orders of magnitude after forest conversion to pasture at shallow soil depths, and a slow regeneration after pasture abandonment that required a recovery time of at least one decade.

A decline in values for soil properties from never trodden to previously pugged was observed in the Waikato Region by Singleton *et al.,* (1999). The study of the physical condition of 3 soils used for intensive dairy farming showed that pugging was having a long-term effect on soil physical properties of all 3 soils, including the well-drained Allophanic Soil that rarely pugged. The greatest changes were in hydraulic conductivity which had decreased by 80%, proportion of pores decreased by 46%, and proportion of small aggregate size (<20 mm) increased 4 times on expense of macro aggregates (>60 mm).

2.3 Aggregate stability

2.3.1 Soil structure and aggregate stability

“Soil structure is defined as the size and arrangement of particles and pores in soils” (Oades, 1984). Factors which influence soil structure are soil mineralogy, soil water content, exchangeable cations, organic matter, flora and fauna, and non-soil factors like human activities. Soil properties are dynamic and often change, especially under human influence. Pores occur within and between particles or aggregates, soil pores provide living space for soil organisms which include roots. For vigorous plant growth soil structure can be defined in terms of the presence of pores for the storage of water available to plants, pores for the transmission of water and air, and pores in which roots can grow (Oades, 1984).

The common shapes of aggregates can be granular or blocky, tablet like, prism-like, platy, or wedge-like (Milne *et al.*, 1995). Soil aggregates are groups of soil particles that are bound to each other more strongly than to adjacent particles (United States Department of Agriculture, 2004). Two categories of aggregates macro- (> 250/µm) and micro- (< 250µm) depend on organic matter for stability against disruptive forces caused by rapid wetting or soil tillage. Microscopic aggregates are the building blocks of larger aggregates. The macro-aggregates and the arrangement of them, along with chemical attraction between particles, determine soil structure.

Organic matter produced by soil biota, decomposing dead roots and litter hold the particles together. Tisdall and Oades (1982) stated that primarily, mineral particles are bound together by persistent binding agents like biotic debris while these micro aggregates, in turn, are bound together to macro aggregates by transient and temporal binding agents (polysaccharides, roots, and fungal hyphae). The aggregate hierarchy theory has been used by many authors to explain correlations between a reduction of aggregation and a loss of SOM (Six *et al.,* 2000 and Six *et al.,* 2004).

2.3.2 Aggregate stability and land use

The stability of pores and particles is essential for optimum growth of plants. Aggregate stability is generally strongly correlated with soil organic matter content (Chaney and Swift, 1984; Mashum *et al.,* 1988), or plant litter debris. Upon cultivation the organic matter of soils typically decreases with a corresponding decrease in aggregate stability (Angers *et al.*, 1997; Li *et al*., 2007).

Aggregation is influenced by land use and land use change in the way that the proportion of water stable macro aggregates is reduced in the order forest > pasture/grassland > arable land and is further diminished with the duration of arable use (Ashagrie *et al*., 2007, Haynes a*t al*., 1991, Jastrow, 1996 and John *et al*., 2005). Microaggregates, however, seem to be less influenced by land use (Oades, 1984, Besnard *et al*., 1996 and Puget *et al*., 2000).

2.4. Water infiltration rate (hydraulic conductivity)

2.4.1 Water infiltration rate definition and importance

Water supplied from above (by rain or irrigation) to the soil surface penetrates in the soil surface and is absorbed into the soil profile is the process of infiltration (Hillel, 2003). The process of infiltration can occur both under unsaturated and saturated conditions. During a high intensity rainfall when soil becomes saturated by water, the infiltration rate is called saturated hydraulic conductivity. If water supply intensity is greater than soils potential infiltration rate, water will accumulate on the soil surface causing overland flow or water runoff. Surface runoff can cause soil erosion, and carry nutrients, sediment, organic matter and other contaminants to waterways. "The hydraulic properties of the topsoil control the partition of rainfall into infiltration and runoff at the soil surface" (Hubbard *et al.,* 2000).

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2.4.2 Forest to pasture conversion impact on water infiltration rate

Water infiltration rate under grazed pasture was generally an order of magnitude less than that under pine forest, at 5 paired sites in the Central North Island under pine forest and agriculture (Taylor, 2009). Sharrow (2007) investigated physical conditions of soils near Corvallis (Oregon, USA) under never grazed forest and silvopasture and pasture grazed for 11 years. Results showed change of soil infiltration rates, soil bulk density, and soil porosity. Soil in the silvopasture and pasture had 13% higher bulk density and 7% lower total porosity than those in adjacent forests, average water infiltration rate was 38% less in silvo-pastures than in forests, however water holding capacity of the top 6 cm of soil was similar.

Compaction can reduce infiltration capacity by decreasing soil hydraulic conductivity, but the effect of compaction on soil water repellency decrease and hence leading to improved infiltration rate. Although there may be a reduction in soil conductivity upon compaction, in some circumstances the more rapid infiltration may lead to an overall increase in the proportion of rain or irrigation water infiltrating water repellent soil, rather than contributing to surface run-off or evaporation (Bryant *et al.,* 2007). The study, conducted by Bryant *et al.,* 2007, explored the effect of compaction on the wettability of water repellent soil by means of decrease of surface roughness. They suggested that an increase in compaction coincided with a significant reduction in soil surface water repellency by soil surface roughness decrease. Reduced soil surface roughness provided an increase in the contact area between sessile water drops and soil surfaces providing increased opportunities for surface wetting mechanisms, which in turn increased the soil's initial infiltration capacity.

2.5 Soil water repellency or hydrophobicity

2.5.1 Soil’s hydrophobicity or water repellency definition

Soil water hydrophobicity is more present in soils worldwide than formerly thought (Dekker *et al.,* 2005). During the last 20 years soil water repellency has been a topic of study in more than 20 countries including Europe, USA, Australia and New Zealand.

“A hydrophilic surface allows water to spread over it in a continuous film whereas water on a hydrophobic surface water ‘balls up’ (Fig.2.2) into individual droplets” (Doerr *et al.,* 2000). Water hydrophobicity is the most common in sandy soil with pasture cover, but has been also observed on soils with high clay content, peat and very often on volcanic tephra soils (Dekker *et al.,* 2005).

Many studies performed worldwide, described negative impacts of soil repellency. Water flow in preferential pathways has been found to cause accelerated leaching of surface-applied agrochemicals and naturally existing water soluble salts, resulting in increased risk to the underlying groundwater (Hendrickx et al., 1993; Ritsema and Dekker, 1994; Blackwell, 2000; Graber et al., 2001). The main characteristics of water-repellent soils are reduced infiltration capacity, increased overland flow and hence soil erosion, development of fingered flow in structural or textural preferential flow paths, and creation of unstable, uneven (Figure 2.3), irregular (Figure 2.4) wetting fronts (Hendrickx *et al*., 1993; Dekker and Ritsema, 1994; Ritsema and Dekker, 1994, 1998). Fingered flow induced by hydrophobicity can lead to considerable variations in water content in a water repellent soil, which can lead to poor seed germination and plant growth (Wallis *et al*., 1993).

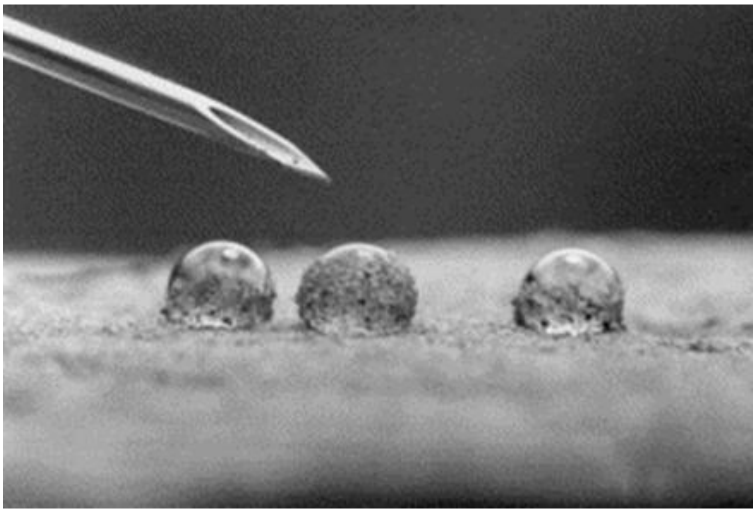

Figure 2.2 Water droplets resisting infiltration into soil due to water repellency. Hypodermic needle for scale (Doerr *et al.*2000)

Figure 2.3 Uneven wetting patterns caused by water repellency in sandy soil near Geraldton, Western Australia, following a large rainfall event (75 mm in 3–4 h in March 1999), (from Doerr *et al.*2000).

Figure 2.4 Irregular wetting front following 30 mm rain, Tokoroa, 2008 conversion forest to pasture,

2.5.2 Origin of hydrophobicity in soils

In most soil repellency studies it is accepted that soil water repellency is caused by organic compounds derived from living or decomposing plants or microorganisms.

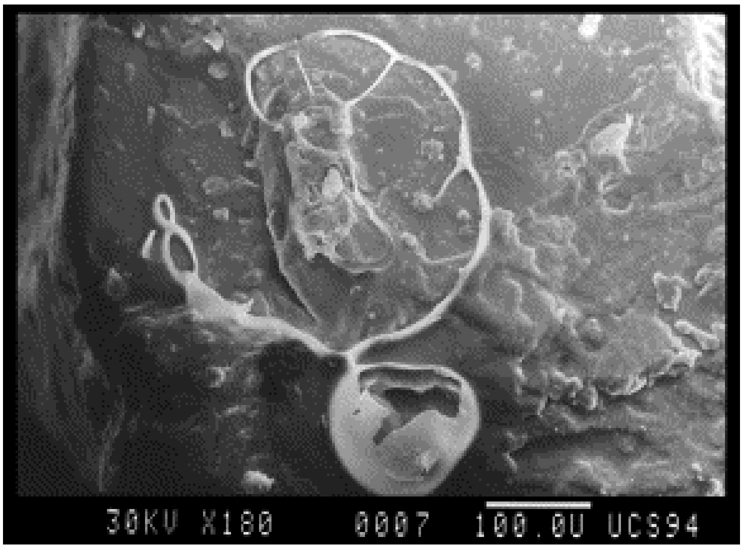

Figure 2.5 Hydrophobic organic coating on a previously hydrophilic sand grain formed during an experimental burn of *Eucalyptus globulus* litter over dry, washed sand (SEM image, 180 × magnification)(from Doerr *et al.* 2000).

Hydrophobicity has been attributed to the presence of an organic coating on the soil particles (Fig.2.5), which consists mainly of waxes and oils (Mashum *et al*., 1988).

Plants most commonly associated with water repellency seem to be certain evergreen tree types. In particular, trees with a considerable amount of resins, waxes or aromatic oils such as eucalyptus and pines (Doerr *et al.,* 2000). In many studies, the occurrence of water repellency has been associated with particular vegetation types but cannot be assumed that these species always induce water repellency under natural conditions. However there is strong evidence of spatial variability within a small area ($1m^2$) and seasonal variability of soil water repellency (Dekker *et al.,* 2009). Study in Germany by Buczko *et al.,* 2006, confirmed that the water repellent character of a forest soil changed throughout course of the year. The forest soil hydrophobicity was strongest in summer and weakest in late autumn after a prolonged wet period.

In some studies, fire has been a ‘triggering’ factor (Nyman *et al.,* 2010; Varela *et al.,* 2010). However, high levels of soil water repellency have also been reported under pine forest vegetation types not affected by fire. Findings by Doerr *et al.,* 2009 from north-western USA clearly demonstrate that the soil water repellency commonly observed in pine forests following burning is not necessarily the result of recent fire but can instead be a natural characteristic.

In other studies based on laboratory experiments, soil water repellency has been linked to fresh plant material, so natural decomposition and incorporation into the soil have been excluded as a factor (DeBano *et al* 2000). The mechanism of input of hydrophobic substances into the soil is not always clear (Doerr *et al.,* 2007). Decaying plant litter has been shown to be a source of water repellent substances in some studies (DeBano *et al* 2000); other studies have found water repellency to be more closely associated with the root activity of plants (Dekker *et al* 2005).

2.6 Soil water content and potential

The amount of water contained in the soil and the energy state of the water present in the soil are important factors affecting plants and soil physical properties. Soil water content is important for soil consistency, plasticity, strength, compactibility, penetrability and stickiness. The air/water ratio (content) and gas exchange of the soil which affects roots respiration, the activity of microorganisms and the chemical state of the soil are affected by soil water content (Hillel, 2003).

2.6.1 Soil water content

Water can be present in the soil as liquid and vapour. Water molecules can also be incorporated on the surface of colloidal materials (clay) or within clay lattice structure (structural water). Structural water is immobile and is released upon mineral decomposition which requires heating to 400 ˚C or higher (some exceptions exist, for example structural water from gypsum or allophone can be evaporated by heating to 80 ˚C) (Smith and Mullins, 1991).

Soil water content is a widely accepted term and refers to the water that can be evaporated from soil by heating to 100 - 110˚C until there is no further weight loss. The process of evaporation normally takes 24 hours at 105 ˚C. Water evaporated in the process is called gravimetric soil water content (Smith and Mullins, 1991). The content of water in the soil can be expressed in terms of mass or volume ratio (Equation 2.2).

$$\theta_m = \frac{Mw}{Ms} = \frac{mass\ of\ wet\ soil - mass\ of\ dry\ soil\ g}{mass\ of\ dry\ soil\ \ g} \quad \text{(Equation 2.2)}$$

Where:

θ_m is gravimetric moisture content
Mw is mass of water
Ms is mass of solids

Gravimetric moisture is the ratio between water and soil mass multiplied by 100 and expressed in percentage. The volumetric soil water content is the ratio of water volume to total (bulk) soil volume also expressed in a percentage.

2.6.2 Soil water potential

Soil water dynamics are determined by water potential (Ψ), differences in potential energy between one point and another control water flow within the soil until equilibrium is reached. Water moves in the soil constantly in the direction of decreasing potential energy (Hillel, 2003). The rate of decrease of water potential and distance are moving forces determining water flow. The formal definition by International Soil Science Society (Hillel, 2003) describes total soil water potential as “the amount of work that must be done per unit quantity of pure water to transfer reversibly and isothermally to the soil water an infinitesimally small quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water and is at the elevation of the point under consideration”.

Total of soil water potential is made from sum of three components (Smith and Mullins, 1991); it can be expressed by Equation (2.1).

$$\Psi_t = \Psi_p + \Psi_g + \Psi_o \qquad \text{(Eq. 2.1)}$$

Where:
Ψ_t = Total potential
Ψ_p = Pressure (or matric) potential
Ψ_g = Gravitational
Ψ_o = Osmotic

Matric potential (Ψ_p) is amount of energy which holds water by forces of adhesion to the soil particles and by capillarity in soil pores of the soil matrix. To access soil water held by matric potential plants need to do suction work to overcome this potential energy. This means that matric potential is always negative; most commonly expressed in kPa (McLaren and Cameron, 1996). Osmotic potential (Ψ_o) is energy which holds water attached to ions or molecules by hydrating attractions. Process of osmosis also is used by plants to overcome soil water potential to absorb water in plant roots and for water and solute movement through plant tissue. Gravitational potential (Ψ_g) is energy induced by Earth’s gravitational force and is adequate to elevation of soil water, this component of water potential is always 0 or positive (Hillel, 2003).

2.6.3 Soil water release characteristic (SWRC)

The soil water characteristic or water release characteristic is the relation between soil water content and water matric potential, terms like water retention curve or pF curve referring also to water release characteristic (McKenzie *at al*., 2002).

The amount of water held by soil in a range of potentials can be measured by a number of field and laboratory methods. A typical measurement method is applying suction or pressure to neutralize water potential energy. Undisturbed soil core samples are saturated by water placed inside a pressure chamber on a ceramic porous plate and are exposed to a range of pressures between 1 and 1500 kPa (Fig. 2.6). Part of the pressure chamber, separated by porous ceramic plate and rubber membrane, under atmospheric pressure provide escape for surplus of water. The loss of water from the soil core is measured at each pressure gravimetrically (McLaren and Cameron, 1996). The soil water content measured at different pressures is adequate to water potential for a given pressure. The range of results can be plotted as a curve called water release characteristic (McKenzie *at al*., 2002).

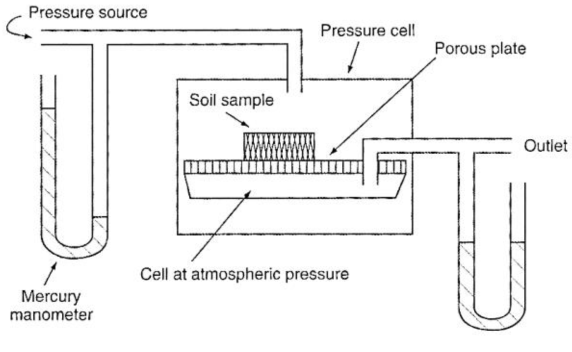

Figure 2.6 Pressure plate apparatus for water release characteristic measurements (Hillel, 2004).

2.6.4 Water holding capacity importance

The efficiency of the use of rain and irrigation water by plants is of great importance especially in dry periods (Andry *at al*., 2009). Plants with shallow rooting may be more affected by a soil's low water-holding capacity. It has been widely reported that water and mineral uptake, and hence growth of shallowly-rooted crops and grasses, decline as ψ declines (Dean-Knox *et al*., 1998). Poor water and fertilizer use efficiency by plants is common on soils characterized by low water-holding capacity and excessive drainage of rain or irrigation water from the root zone. Because of low water holding capacity and hence low soil moisture content, seed germination plant development and growth may be critically restricted (Warren.*et al*., 2005).

2.7 Penetration resistance and Degree of Packing

2.7.1 Principals and definition

Penetration resistance is not a particular property of a soil than rather sum of effects of several properties (Bourke *et al.,* 1986). Penetration resistance is measurement of force required to penetrate soil, usually expressed in pressure units (Bar, Pa). A variety of instruments, called penetrometers are used for penetration resistance measurement. Most of them consist of a probe which is driven into the soil by applied force. The resistance is recorded as the amount of force required to penetrate the probe to certain depth (marked on the probe). Griffiths (1999) adopted the term "degree of packing" to identify consistence of the soil in situ. Degree of packing is a measure of how closely or densely the particles or peds are packed together within a horizon and reflects the ease with which particles or peds may be removed from the horizon. The degree of packing can be used as an indicator of soil rooting depth and infiltration rate and water movement in general.

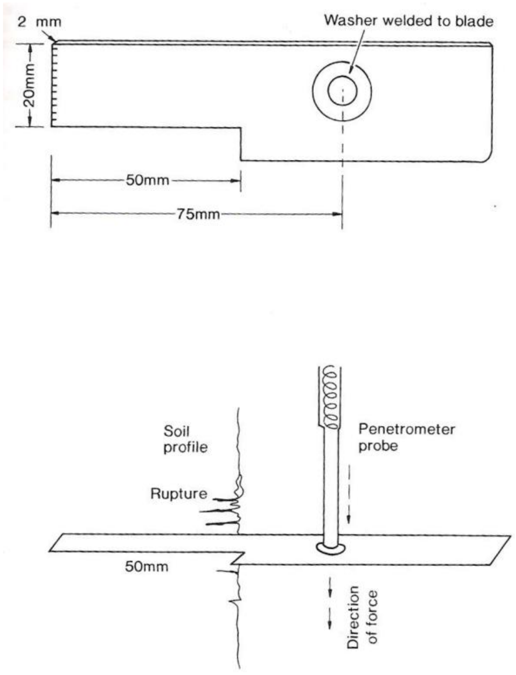

Figure 2.7 Singleton blade and pocket penetrometer, for degree of packing measurement (adopted from Milne *et al.*, 1995)

The single-vane shear is a method to measure the degree of packing using a Singleton blade and hand-held penetrometer (Figure 2.7) (Milne *et al.*, 1995; Griffiths, *et al., 1999).* Readings for the degree of packing have been found to be sensitive to soil water content. The readings are only indicative for measurements taken from soils at or near field capacity (soil water held at -10 to -30 kPa) (Griffiths, *et al.,* 1999).

A low degree of packing and fine soil peds with rough surfaces is an indication of soils with rapid hydraulic conductivity, whereas a high degree of packing and coarse peds with smooth/shiny ped surfaces indicates a soil of slow hydraulic conductivity.

2.7.2 Soil properties controlling Soil Strength

Soil strength (penetration resistance and degree of packing) is influenced by bulk density (Fig. 2.8) soil moisture (Milne *et al.*, 1995; Sojka *et al.,* 2001) and soil texture (Soane *et al.,* 1980; Bourke *et al.,* 1986; Lhotsky *et al.* 1991; da Silva *et al.,* 2002).

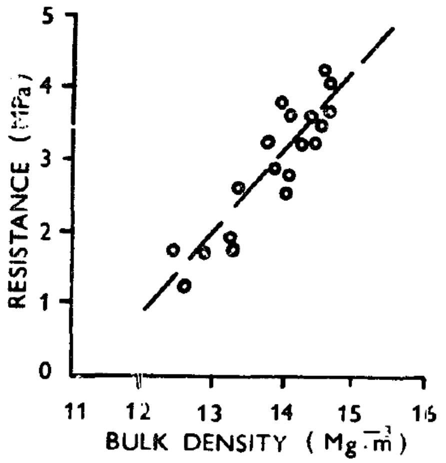

Figure 2.8 Relationship between penetration resistance and soil dry bulk (adopted from Lhotsky *et al.* 1991)

The relationship between soil degree of packing and penetration resistance varies widely with soil moisture and texture. Field measurement under homogeneous soil moisture conditions is of fundamental importance to reduce dispersion of the results and to obtain a significant relationship between soil dry bulk density and penetration resistance (Blanco-Sepulveda, 2009).

To and Kay, (2005) gave examples obtained by several workers in which the relationship between soil dry bulk density and penetration resistance varied from almost linear, measured at same moisture content, to strongly curved when soil moisture varied. He stressed the importance that cone resistance should be measured when the whole profile is at field capacity in order to reduce the variation attributable to water content. Lapen *et al.,* (2004) also demonstrated the numerous ways in which changes in water content may influence penetration resistance.

In research by Blanco-Sepulveda 2009, soil strength measurement has been done with soil moisture at field capacity and a constant depth of 1.5 cm. Soil dry bulk density results correlated significantly with soil penetration resistance (R=0.69; p≤0.01) Sojka *et al.,* (2001) (Figure 2.9).

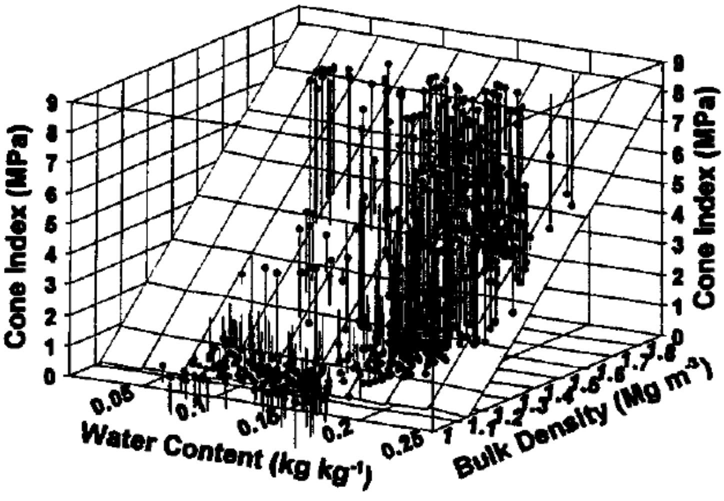

Figure 2.9 Relationship between Soil dry bulk density, Soil moisture content and penetration resistance (Cone Index in MPa) (adopted from Sojka *et al.,* 2001)

2.7.3 Land use effects on Soil Strength

There is increasing evidence that soil compaction and structural degradation resulting from livestock treading or heavy machinery is a problem in New Zealand (Singleton *et al.*, 1999; Burgess, *et al*., 2000, Houlbrooke *et al.*, 2008); and worldwide (Greenwood and Mckanzie 2001; Greenwood *et al.* 1997; Geissen *et al*, 2009; Bormann *et al.*, 2008 Pérez *et al.*, 2010). Compaction caused by livestock treading under intensive farming systems can be detrimental to soil structure by causing compaction, which adversely influences air, water, and nutrient movement and hence chemical and biological processes in soils.

2.8 Particle size distribution

2.8.1 Soil particle size

A particle is any coherent body bounded by a clearly recognizable surface (Smith and Mullins, 1991). Soil contains organic and mineral particles of different shape and size and hence different physical properties. Aggregates in the mineral soil fraction are classified according to size. Clay is the smallest mineral soil particle (> 0.002 mm), medium fraction is silt (0.06-0.002 mm), sand is the largest (>0.06 mm) (Table 2.2). The proportion of sand, silt and clay in a soil is determining of soil texture and most physical properties (McLaren and Cameron, 1993).

Table 2.2 Particle size classification for soil particle size distribution (Standards Association of New Zealand (1986), standard adopted from ISSS (The International Society of Soil Science).

	Sand			Silt	Clay
	Coarse	Medium	Fine		
Size	2.0 mm	0.6-0.2 mm	0.2-0.06 mm	0.06-0.002 mm	0.002 mm

2.8.2 Soil texture

The proportion of sand, silt and clay is an important soil physical characteristic determining hydrological and many other soil properties and can be used, along with soil bulk density, to predict soil hydrological properties as an infiltration rate and water retention. Traditional methods for characterizing soil physical properties, especially hydrological, are often time consuming and expensive. There are numerous research attempts to establish simple, reliable, cost effective and faster methods to predict or determine soil hydrological properties. Most of new methods rely on particle-size analysis, soil dry bulk density and simple infiltration tests in cylinders (Braud *et al.*, 2005). In the study by Minasny *et al.*, 2007 they developed an alternative way of estimating water retention characteristic and soil's infiltration hydraulic conductivity from sand and clay content. They established mathematical function which estimates the water retention shape parameter and infiltration rate by fitting particle-size distribution data (more than five fractions) and a measurement of bulk density (Fig. 2.10).

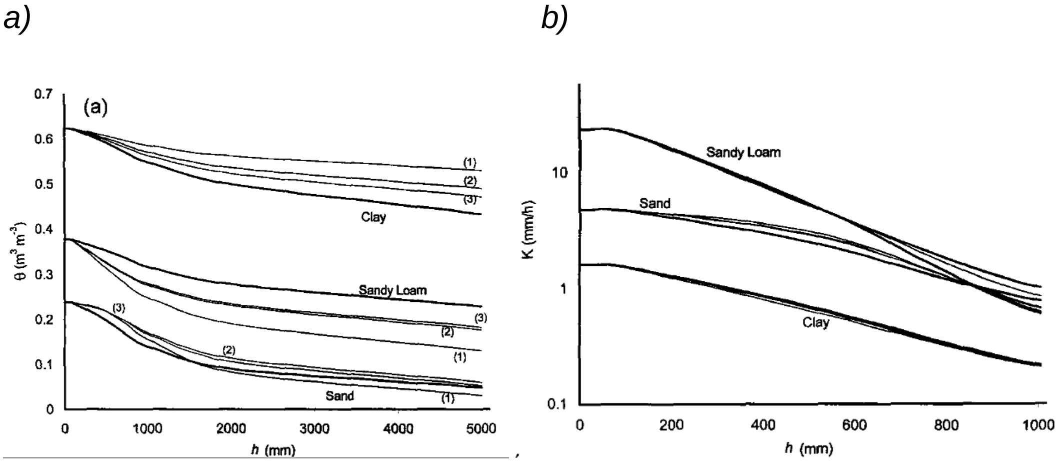

Figure 2.10 Predictability of hydraulic conductivity (a) and water retention (b) curves for three soil types: sand, sandy loam, and clay. Water retention can be predicted reasonably well for sand, while for sandy loam and clay the prediction deviates with increasing suction. Meanwhile, all three methods predicted hydraulic conductivity very well (Minasny *et al.*, 2007).

2.9 Pine plantation forest impact on soil properties

Plantation forest of exotic conifer species such as Radiata pine (*Pinus radiata*) and Douglas fir (*Pseudotsuga menzieii*), covers approximately 1.7 million ha (ca. 7% of total land area) in New Zealand (MAF, 2009). Between 1992 and 1997, 50–90 000 ha of new forest have been planted each year (Glass, 1997).

Studies of soil properties under pine plantations forests in temperate regions indicate alterations in a number of soil properties including lower pH and altered nutrient availability (Turner and Kelly, 1985; Davis and Lang, 1991; Hawke and O'Connor, 1993; Alfredsson, *et al.*, 1998)

2.9.1 Soil acidification by pine plantation forest

In research located at Drummond (northwest of Invercargill, New Zealand) by Alfredsson, *et al.*, 1998 soil pH was lower under pine than grassland in the 0–5 cm depth increment. The change from grassland to conifers decreased levels of organic carbon, total nitrogen and exchangeable cations and increased exchangeable acidity in the upper 20–30 cm of soil.

Results from research by Farley and Kelly (2004) demonstrate that the change of land use from pasture to plantation forest can affect soil pH on a decadal time scale, with implications for long-term site productivity. A decline in pH occurred between the time of pine forest establishment and 10 years of age. Soil pH was higher in the grassland soils (mean pH 5.5) compared to pine forest which had a mean pH of 5.2. However, the lower pH only affected the upper tier of the A horizon (0–10 cm depth), indicating that pH decrease is being driven by soil processes that predominate in the near-surface environment.

2.9.2 Soil acidity, lime application and soil physical properties

Soil acidification is a process that can either be accelerated by certain plants and human activities or slowed down by management practices. Liming is the most common management practice used to neutralize soil acidity. Most plants grow well in the pH range 5.5–6.5, and the objective of liming applications is to maintain pH in the optimum range. Liming enhances the physical, chemical, and biological soil properties through its direct effect in ameliorating soil acidity (Bolan, *et al.*, 2005). Haling, *et al.*, 2010 in their research examined root growth of five perennial grasses in three acid soils treated with lime and without lime. The results suggested a significant effect of soil acidity on root growth of acid-soil sensitive genotypes by restricting lateral root length and root-hair density. The soil adhering to the root system was significantly greater in soils with lime treatment. Better root growth and higher root-hair density of the plant root system in the soil with closer to optimum acidity results in an enhanced soil adherence to root hairs and has positive implication for soil physical properties.

Changes in the physical properties of soil have often been attributed to liming practices in an indirect way, due to greater root growth and biological activity. Lime incorporated in the soil, can promote micro-aggregate stability by altering soil electrochemistry, e.g. cation exchange capacity, pH, base saturation (Rheinheimer *et al.,* 2002; Kaminski *et al.,* 2005; Bortoluzzi *et al.,* 2009). Hydrophilic/hydrophobic character and cohesion forces between the soil particles are determined by the soil chemical properties (Ciotta *et al.,* 2004).

In a study using laser diffraction to determine soil aggregation stability Bortoluzzi *et al.*, (2010) found a positive relationship between soil aggregation and changes in electrochemical properties due to soil liming (Fig 2.11).

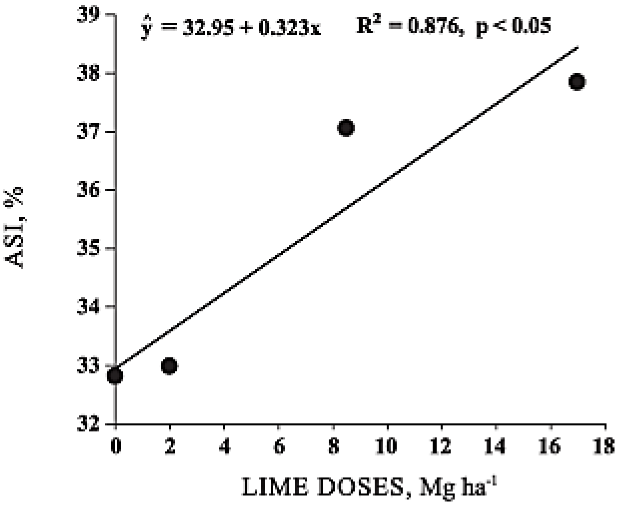

Figure 2.11 Aggregate stability Index (ASI %) linear increase with lime application increase (from Bortoluzzi *et al.*, 2010).

2.10 Summary and conclusion

New Zealand pastoral agriculture and forestry are important sectors in the national economy. There has been considerable afforestation with pine tree in New Zealand since 1990 (0.56 million hectares) mainly on expense of pastures used previously for sheep and cattle grazing. This trend has been reversed lately (afforestation has declined to lowest level of around 1000 hectares in 2008, MAF, 2010) towards pastoral production, mainly because of dairy farming profitability. The process of conversion from pine plantation forest to pasture has attracted environmental concerns. Sustainable management of land and water resources requires understanding of the soil properties, and soil's resilience to negative impacts, so that soil's health and fertility can be sustained even enhanced during the conversion.

Soil organic matter (SOM) content has been recognized by many authors as a factor influencing a number of soil physical properties. Many studies suggest that conversion from forest to pasture is followed by decreased SOM in the soil. However Goh *et al.,* (1987), suggest different, mainly slower, SOM accumulation in pine plantation compare to native forest in New Zealand.

A number of studies suggest that decrease of SOM content in the converted land correlates with decreased soil porosity and lower aggregate stability. Increase of soil dry bulk density upon land conversion, indicates increased soil compaction. Many works recognize that soil compaction has been caused by livestock trampling. Increased soil compaction can lead to reduced soil infiltration capacity and leads to decreased soil hydraulic conductivity. Taylor (2009) suggested that water infiltration was an order of magnitude less under converted pasture compared to pine forest in the Central North Island (NZ). Soil texture and SOM content are essential in determining soil water dynamics. The efficiency of the use of rain or irrigation water by plants is of great importance to successful pasture management. Water holding capacity and soil water release characteristic of managed soil is essential knowledge when planning irrigation quantities and dynamics or water conservation measures. Cropping programme, crop rotation, pasture composition should be planned according to soil hydraulic characteristics.

Soil water repellency may be present in sandy soils, particularly when land is occupied with plants producing aromatic oils (such as pine tree). Many authors recognize sudden exposition to sunlight as a triggering factor for increased soil hydrophobicity. Soil's water repellent character can be variable within a very small area (1 m^2) and can change in a short period of time especially after prolonged wet weather.

There is substantial research focused on land use change from forest to pasture driven by concerns related to carbon stock changes locally and globally.

Although research has focused on land use change impacts on soil properties, more investigation is necessary to recognize and understand changes of soil physical properties for specific central North Island conditions and to help sustainable management of land and water resources under newly established dairy pastures converted from pine plantation forest providing better understanding of effects of land use on soil water holding capacity, infiltration rate, soil dry bulk density, soil aggregate stability.

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Chapter 3

The study area and sampling sites

3.1 Background of the study area

3.1.1 Location

The study area for this research was the Volcanic Plateau in the North Island of New Zealand, which stretches about 180 km south-west from the Bay of Plenty coast to Mt Ruapehu. The plateau is bounded to the east by the North Island main ranges and to the west by the Mamaku Plateau and the Hauhungaroa Range (McKinnon, 2009 a). Rotorua, Taupo and Tokoroa are the main urban centres on the plateau, the highest-altitude towns in the North Island, at 279, 369 and 326 metres altitude, respectively.

Soil samples were collected from two study areas: Wairakei Estate north-east from Taupo town and Maxwell Farms west from Tokoroa, both large plantation forests to pasture conversion sites (Figure 3.1). The following background information describes the climate, geology, soils, and land use of the study areas.

Figure 3.1 Locations of the Tokoroa and Taupo study areas

3.1.2 Climate

The Volcanic Plateau has a temperate climate (udic and mesic in terms of Soil Taxonomy, 1999). The Plateau mean annual rainfall is 1102 - 1401 mm and mean air temperature is 11.9 - 12.8°C (1971-2008 period). Taupo has 69 ground frost days a year (the most of any North Island town) and a July mean temperature of less than 8°C. The mean annual rainfall is 1100mm in Taupo and 1300 mm in Tokoroa (NIWA, 2010).

3.1.3 Geology and geomorphology

The Volcanic Plateau is the product of volcanic eruptions from the Taupo Volcanic Zone (Figure 3.2). Past volcanic activity on the plateau created many lakes. Lake Taupo (357 m above sea level, ~620 km^2 in area) is New Zealand's biggest lake and occupies its largest volcano, the rhyolitic Taupo caldera volcano (Wilson *et al.* 1995). The lake was formed after caldera collapse following the voluminous Oruanui/Kawakawa eruption about 27,000 years ago, and the volcano has erupted 28 times since then generating widespread tephra fall deposits over much of the North Island. The most recent explosive eruption was the Taupo eruption that occurred in late summer or early autumn in AD 232 ± 5 (Hogg et al., 2009) that generated both a non-welded pyroclastic flow deposit (Taupo Ignimbrite) and tephra fallout deposits (Walker, 1980). The pumice deposits form the surface parent materials for much of the Volcanic Plateau area within a radius of about 80 km of Lake Taupo (Lowe and Palmer, 2005) and are highly siliceous. A second recently active rhyolite caldera volcano, Okataina, lies to the east of Rotorua. Other volcanoes were active in the recent past including the andesitic stratovolcanoes of the Tongariro Volcanic Centre and Mt Taranaki/Egmont, and relatively frequent eruptions from these have dusted andesitic tephras over much of the central North Island (most recently from Mt Ruapehu 1995-1996).

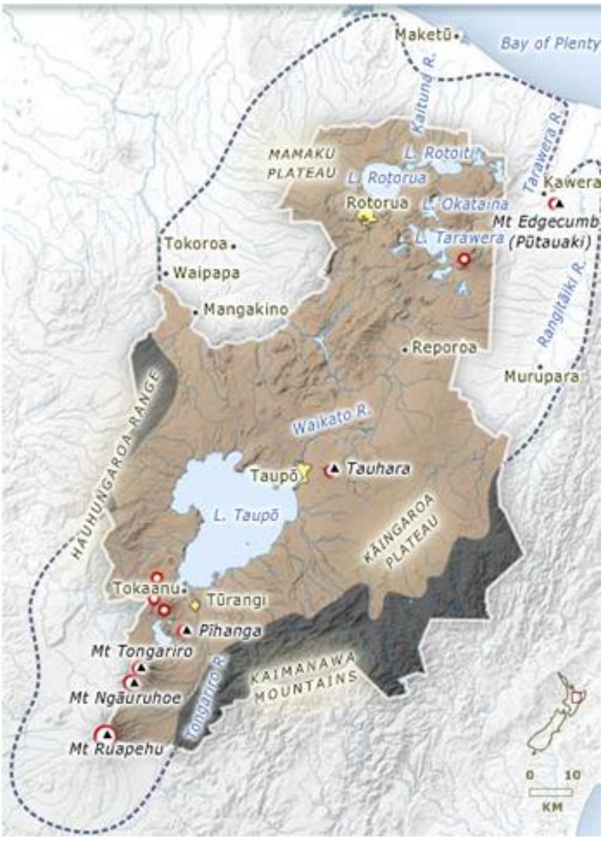


Figure 3.2 The Volcanic Plateau stretches from the Bay of Plenty coast to south of Ruapehu, red marks indicate volcanic cones (McGlone, 2009).

The tephra deposits are younger and generally less weathered from north-west to south-east, the youngest area being closest to the centre of the most recently active volcanic centres in the Taupo volcanic zone. The general soil pattern mirrors this trend (Frogatt, *et al.,* 1990).

3.1.4 Soils

The dominant soils in central North Island are the Pumice Soils (NZ Soil Classification (Hewitt, 1998), equivalent to Vitrands in *Soil Taxonomy*) (Lowe and Palmer, 2005) formed on pumice deposited mainly from the AD 232 ± 5 Taupo eruption (Figure 3.3) (Hogg *et al.* 2009). In many places the Taupo eruption deposits overlie buried soils on successions of earlier tephra deposits (Molloy, 1988; Lowe and Palmer, 2005).

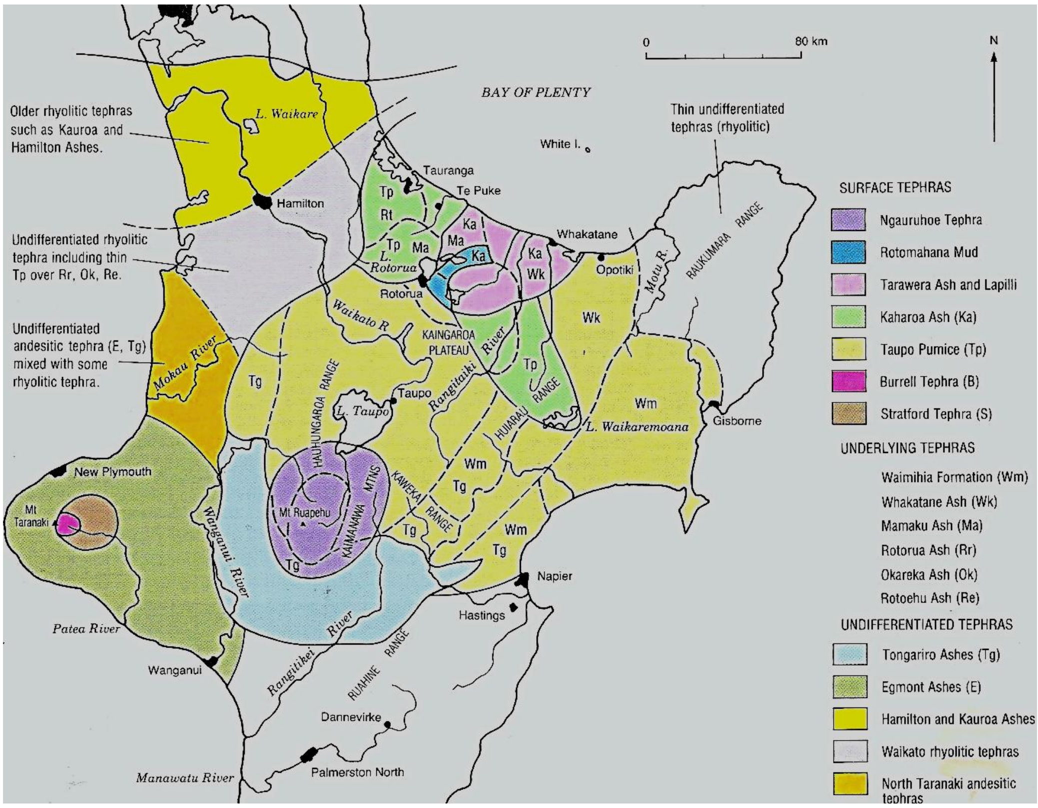


Figure 3.3 Map of soils formed on volcanic deposits in Central North Island (Molloy, 1988)

A suite of soils, called the Taupo suite and including the Taupo soil series, has formed on the AD 232 ± 5 Taupo pumice deposits. All are of the same age and young (only about 1800 years old), weakly weathered, coarse textured and susceptible to erosion. The A horizon colour is related to vegetation cover: deep and black under bracken fern or shallow and grey under manuka scrub, or brown under podocarp/hardwood forest (Rijkse and Vucetich, 1980). Clay content is generally less than 10% and typically comprises the clay mineral allophane (Lowe and Palmer, 2005). The soil structure is weakly developed, and aggregates are mainly crumb or granular in shape. Because of a lack of weathering material (like iron oxides), soil consistence appears to be friable. Bulk density is generally low (0.6 - 0.8 T/m3). The Pumice Soils are very porous and have good drainage (Molloy, 1988). Pumice has a vesicular nature, retaining moisture, and thus compensating for the soil's free-draining properties. The Pumice Soil properties favour deep rooted plants, providing sufficient moisture and nutrients in deeper soil horizons (Molloy, 1988). Pumice Soil derived from rhyolitic tephra tends to be low in trace elements (for example copper, selenium and cobalt).

3.1.5 Agricultural and forestry land use

3.1.5.1 Historical background

The first known human settlement on the Volcanic Plateau was around the early 1300s by Polynesians from eastern Polynesia (Hogg et al., 2003). Early settlers burned the forest to clear land for cultivation, and by the 19th century the vegetation was mostly tussock, fern, manuka and similar plants (McKinnon, 2009b).

Early sheep and cattle farming attempts in the Central North Island were unprofitable because of a stock wasting disease called "bush sickness", discovered in the mid-1930s to be caused by cobalt deficiency. Cobaltised superphosphate fertilizer (includes cobalt sulphate) topdressing was applied as a remedy for the deficiency. When cobalt was added to the soil on an annual basis, the land became productive pasture (NZSSS, 1974).

However, the pumice land was also suitable for exotic forestry. Radiata pine (*Pinus radiata*) seed had been imported to New Zealand from California in the 1840s to grow shelter for farms. The first experimental plantings of selected exotic *Pinus radiata* as a large scale plantation forest were made from 1913 in the Broadlands area near Taupo town, which is included in Wairakei Estate. The experimental plantations were successful and the radiata pine cultivars had been showing faster growth rates in New Zealand than anywhere else in the world and became the dominant species for forest plantings in New Zealand (NZ Forest Owners Association, 2010).

Tree planting was accelerated from the late 1920s and early 1930s, stimulated by low land values, caused by low land demand for agricultural production (Vucetich *et al.* 1978). In 1925 the Government introduced financial incentives to create plantations of imported species and to reduce the pressure on native forests.

From 1925 New Zealand Perpetual Forests started planting radiata pine forests near Tokoroa (area close to Maxwell Farms) (NZ Forest Owners Association, 2010).

3.1.5.2 Changes in land use

Afforestation with pine trees (*Pinus radiata)* in New Zealand has led to the establishment of over 1.158 million hectares of plantation forestry (MAF 2009). Trend of increasing planting has been reversed in the early 2000's, with conversion of pine plantation forest to pastoral farming. There has been increasing pressure for conversion of pine plantation forest to agricultural land on the Volcanic Plateau. The land use change was driven by the perceived better long term returns from dairy farming compared with those from plantation forestry.

3.2 Study areas

3.2.1 Tokoroa

The landscape in the Tokoroa study area consists of gently rolling to steep hilly land and flattish plateaux (underlain by old, welded ignimbrites) and terraces (Lowe *et al.,* 2005). Flat lands are mainly on terraces, with micro depressions and small hills. Outcrops of welded ignimbrite are visible on steeper parts of the study area. The surface soils are developed in about

50 cm of fine-grained, non-welded, Taupo Ignimbrite overlying a succession of buried, more weathered soil material developed from older tephras that in turn overlie welded ignimbrites at depth (Appendix 1: Soil profile description).

3.2.1.1 Maxwell Farms

Maxwell Farms is a privately owned (Richard Maxwell and family) dairy farming enterprise located 10 km west from Tokoroa (Jack Henry Rd). Maxwell Farms are divided into 6 dairy units, each with modern milking facilities (Figure 3.4). Each unit has approximately 1000 dairy cows on 330-400 Ha of clover-grass mixture pasture (2.9 cows/Ha; cumulative for the enterprise).

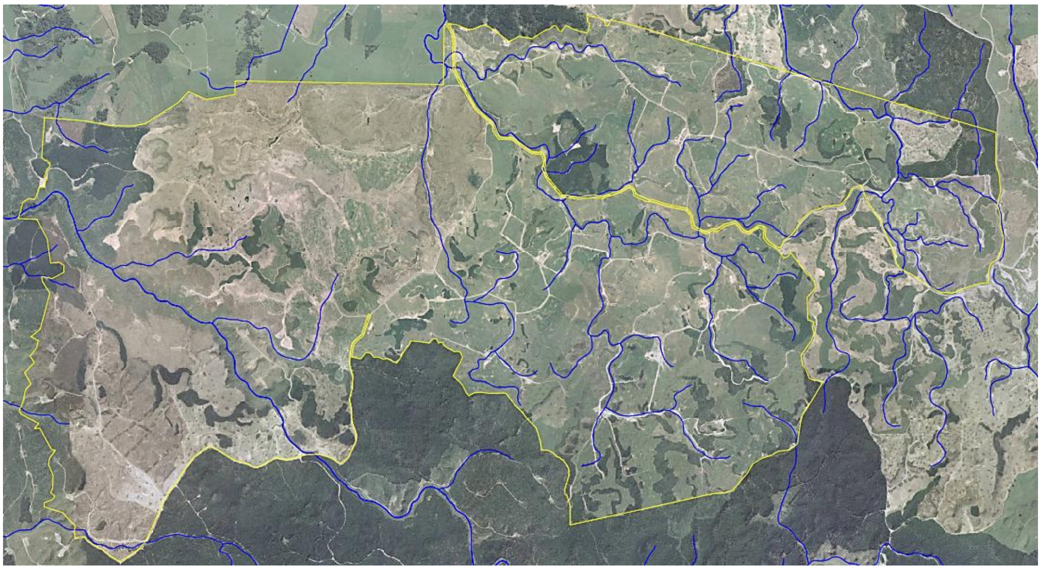


Figure 3.4 Map of Maxwell farm, yellow line marks the farm boundary, dark green areas represent pine plantation forest

Conversion of land from pine forestry (after 2nd or third pine rotation) to pasture started at the end of 2004. Forest was harvested in stages, from each proposed farming unit's central part (to provide space for the main infrastructure like the milking shed, housing, and communication), progressing towards peripheral boundaries of the unit.

Mature trees were harvested in the conventional way but smaller trees were removed by bulldozing. Bulldozers were used for landscaping, to flatten terrain which on same places caused substantial replacing and mixing of a soil's A horizon. Pine tree stumps were uprooted and left in heaps on paddocks (Fig. 3.5). The heaps were removed or spread systematically when paddocks were more established and heaps smaller. After landscaping, dolomitic lime (5T/ha) and sulphur superphosphate (12.8 % P_2O_5, 14.6% S and 17% $CaCO_3$) (1 T/ha) was applied (Tuck, personal communication 2010).

Land was prepared by disking and heavy harrow. Planting of clover/rye grass mix was generally by roller drill or broadcasting on less accessible sites. The conversion process from forest to dairy pasture took on average 2-3 months. As soon as pasture was productive dairy cows grazing followed.

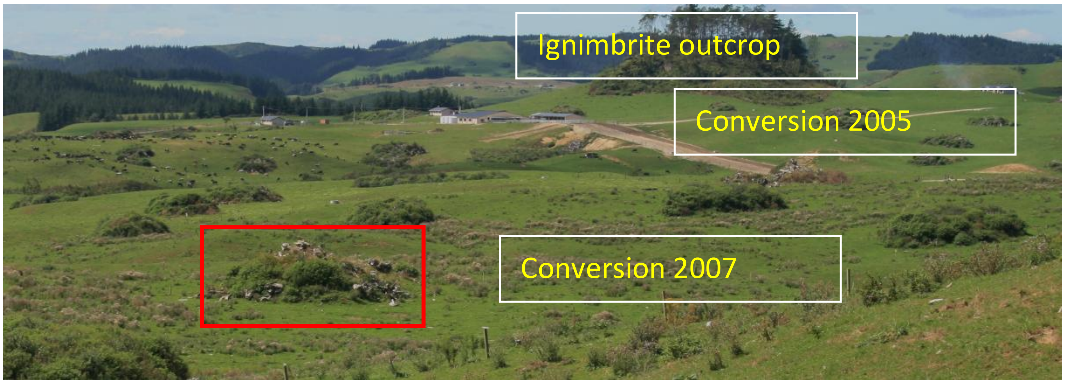


Figure 3.5 Tokoroa landscape (Maxwell farm, Unit 5): two conversion ages 2005 and 2007, red rectangle pointing piled pine trees residues

3.2.1.2 Long term dairy and sheep pasture

Maxwell Farms are on land that has been recently converted from forest to pasture. Long term sheep and dairy land was identified on next door neighbour's farms on the same soil and landscape. North from Maxwell Farms Unit 6, two farms which were converted from native bush about 50 years ago were sampled. Hunt Farm (owned by Mervin Hunt) initially a sheep farm and later converted to a dairy farm and Ranger Farm which has remained a sheep-beef farm since establishment.

3.2.2 Taupo

Flat to easy rolling discontinuous terraces (Rijkse and Vucetich 1980) are the main topographic character of the Taupo study area (Wairakei Estate and Nui Frisian Farm). The paddocks we sampled in the Taupo study area were flat with small humps and depressions (scale of ~1 m). The soil parent materials comprise nonwelded Taupo Ignimbrite and fallout tephra from the AD 232 ± 5 Taupo eruption, amounting to about 1.5 m in thickness (Lowe *et al.,* 2005). The Taupo study area is closer to the eruption source, so pumice material is coarser with large pumice clasts found in soil profiles. Ignimbrite material was not visible in soil profiles in the Taupo study area since the pumice layer is thicker compared to Tokoroa.

3.2.2.1 Wairakei Estate

The Wairakei Estate is an area of approximately 25, 000 ha between Taupo and Reporoa, in the angle formed by SH5 and SH1 (Figure 3.6).

Project development (includes planning and conversion) and management after conversion has been done by different companies. Landcorp Farming (a NZ government owned, “state owned enterprise”) has signed a lease agreement with a group of private owners of the land. Landcorp Developments Ltd (subsidy of Landcorp Farming) is a company established to convert 25,000 hectares from forestry into farming (the Wairakei Estate Pastoral project) (Marshall, 2007). Landcorp Pastoral Ltd (Shareholding Company) has been formed to farm the land following its conversion by Landcorp Developments. The Wairakei Estate Pastoral project is planned over 20 years and started in 2004, with 15,000 ha identified for dairying and 8000 ha for sheep and beef farming. The remaining 2000 ha are riparian strips or are unsuitable for farming. A high proportion of land is still under forestry (Marshall, 2007). Mainly flat land has been converted to pasture from 2004 to 2008 at Wairakei Estate

(Figure 3.7). Conversion involved mature trees harvest and removing smaller trees by bulldozer.

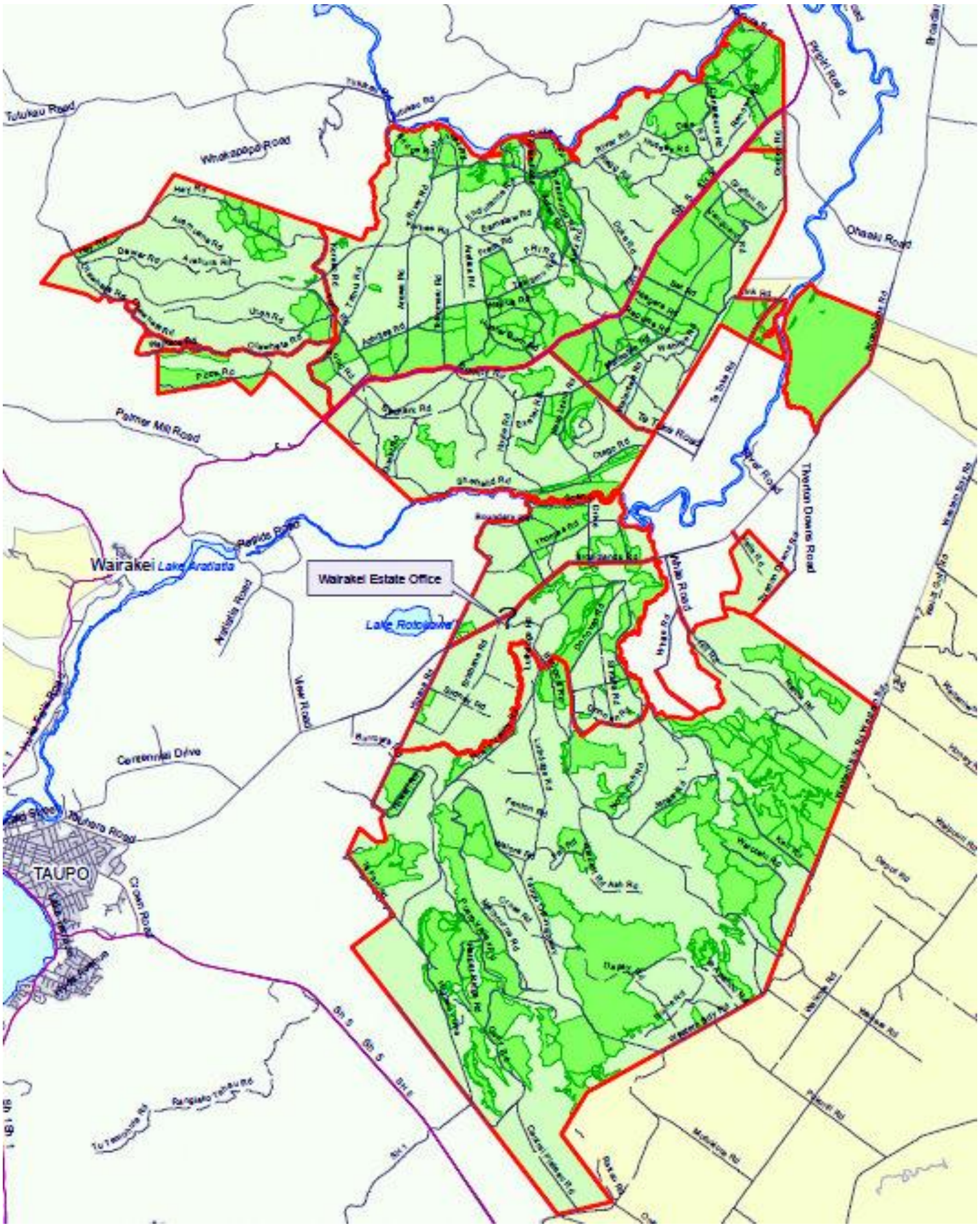


Figure 3.6 Map of Wairakei Estate, red line marks the farm boundary, dark green areas represent converted pasture, light green areas are pine plantation forest

Figure 3.7 Wairakei Estate, established pasture planted in rye grass and recently converted paddock

Harvest residues and small trees were collected in heaps or wind rows, which were burnt and buried in a convenient place (big trenches or gullies). Ameliorative lime (3.5 T/ha) and single superphosphate (1.7 T/ha) applications followed (Bullick, personal communication 2010).

Approximately 60% of each farm was planted in ryegrass, and the remaining 40%, closer to milking sheds, was planted in a fescue based mix which included chicory, plantain, white and red clovers.

Wairakei Estate is divided into 6 dairy farms which are subdivided into 6 ha paddocks with three-wire fences. Their dairy production target is 850 kg to 900 kg milk solids per ha with a stocking rate at 2.4 cows per ha (Bullick, personal communication 2010).

3.2.1.2 Long term dairy pasture

Long term dairy land has been identified on the next door neighbour's farm on the same soil and landscape, 4 km north-west from Wairakei Estate.

Nui Frisian Farm (owned by Robin Brodison) was initially a sheep farm and was converted to a dairy farm in about 1950.

3.3 Sampling sites criteria and list

At each of the study areas the land under different use: pine plantation forest, pasture conversions where land use has changed 2-6 years ago, long term (more than 20 years) dairy pasture, and long term sheep pasture was identified.

The eleven study sites were chosen on the following criteria:
(1) Land use – we required as even a spread of time since conversion from forest to pasture as possible, along with sites still in forest and sites that had been in pasture for over 20 years.
(2) All sites were located, as far as possible, on the same landscape unit (a widespread terrace) with the same soil type (Taupo Pumice Soil).
(3) Avoiding places, where soil physical properties might be influenced by factors other than land use change. Areas adjacent to roads, fence lines, troughs, and gateways were avoided, as were areas of obvious bulldozing.

Six sites were identified at Tokoroa and five at Taupo (Table 3.1) . Each location (Tokoroa (Figure 3.8) and Taupo (Figure 3.9)) included pine plantation forest, 3 conversion sites and long term dairy pasture. We did not identify a suitable long term sheep pasture at the Taupo study area but we did sample a long-term sheep/beef pasture at the Tokoroa study site.

Conversion sites at Tokoroa were: 2, 3, and 5 years since conversion from pine forest to dairy pasture. At Taupo conversion sites were: 3, 4, and 5 years since conversion from pine forest to dairy pasture.

Table 3.1 List of sampling sites

		Tokoroa study area	Taupo study area
Long term	Pine forest	**PF** Maxwell Farms Forest, next to fertilizer storage E:175º44”34.9” S:38º12’56.3” Elevation: 300 m	**PF** Wairakei Estate Forest opposite Pinto F. E:176º15’44.0” S:38º32’06.3” Elevation: 386 m
Conversion year	2008	**C 2** Maxwell Farms, Unit 6 paddock 23 E:176º42’38.5” S:38º12’36.6” Elevation: 324 m	
	2007	**C 3** Maxwell Farms, Unit 6 paddock 15 E:176º43’15.5” S:38º13’02.7” Elevation: 327 m	**C 3** Wairakei Estate Pinto F, paddock 521 E:176º16’03.3” S:38º31’59.6” Elevation: 364 m
	2006		**C 4** Wairakei Estate Renown F. paddock 413 E:176º17’00.9” S:38º30’49.7” Elevation: 354 m
	2005	**C 5** Maxwell Farms, Unit 6 paddock 49 E:176º44’06.4” S:38º12’37.4” Elevation: 312 m	**C 5** Wairakei Estate Renown F. paddock 308 E:176º17’20.1” S:38º29’53.0” Elevation: 356
Long term	Dairy farm	**D F** Hunt Farm E:175º42’17.9” S:38º12’32.6” Elevation: 333 m	**D F** Nui Frisian F. paddock 31 E:176º15’01.4” S:38º29’13.7” Elevation: 376 m
	Sheep and beef farm	**SB F** Ranger Farm E:175º43’19.4” S:38º12’31.2” Elevation: 314 m	

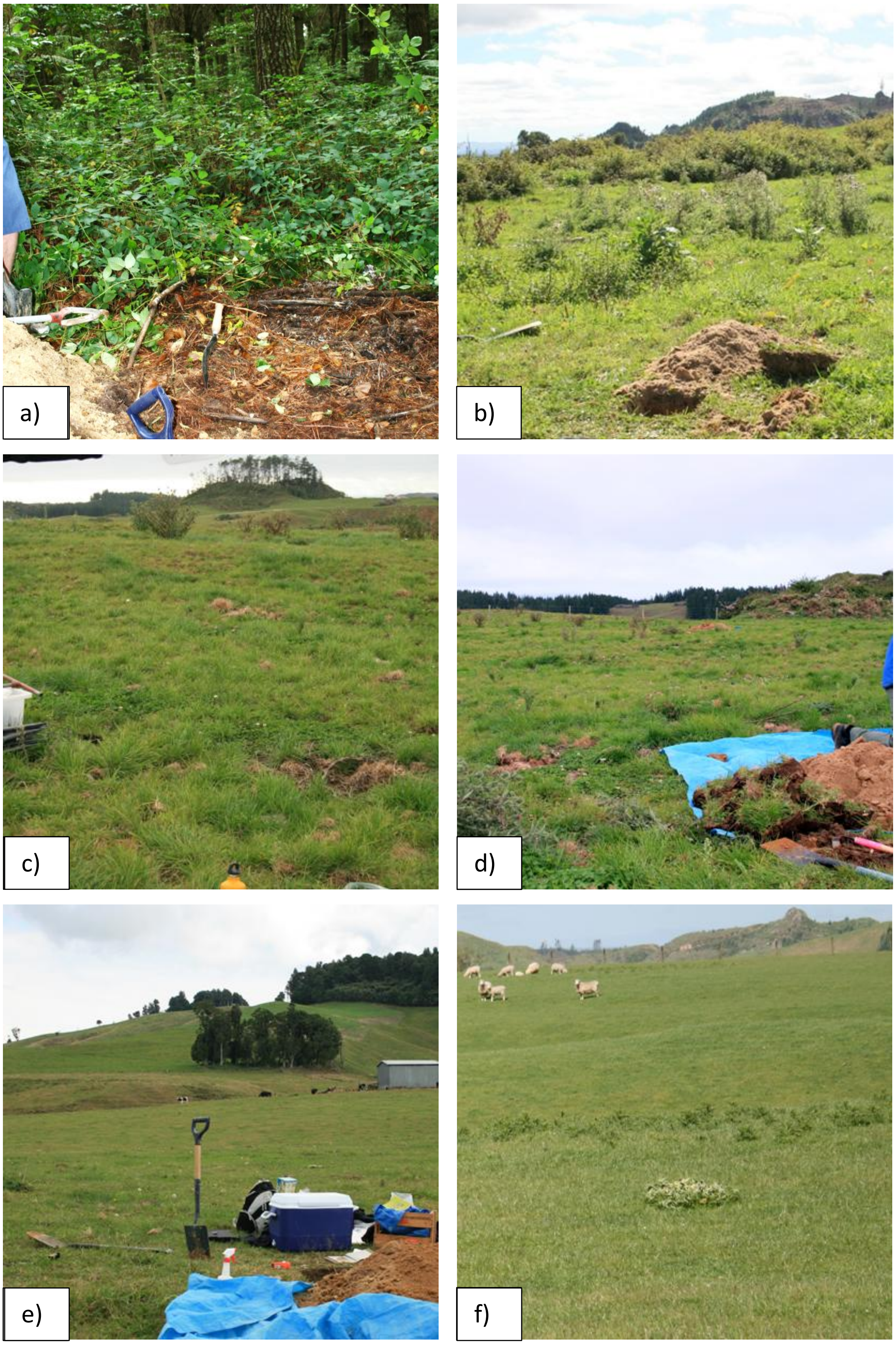


Figure 3.8 The Tokoroa study area sampling sites:

a) plantation pine forest, b) pasture converted from pine forest 2 years ago, c) pasture converted from pine forest 3 years ago, d) pasture converted from pine forest 5 years ago, e) long term dairy pasture, f) sheep and beef long term pasture.

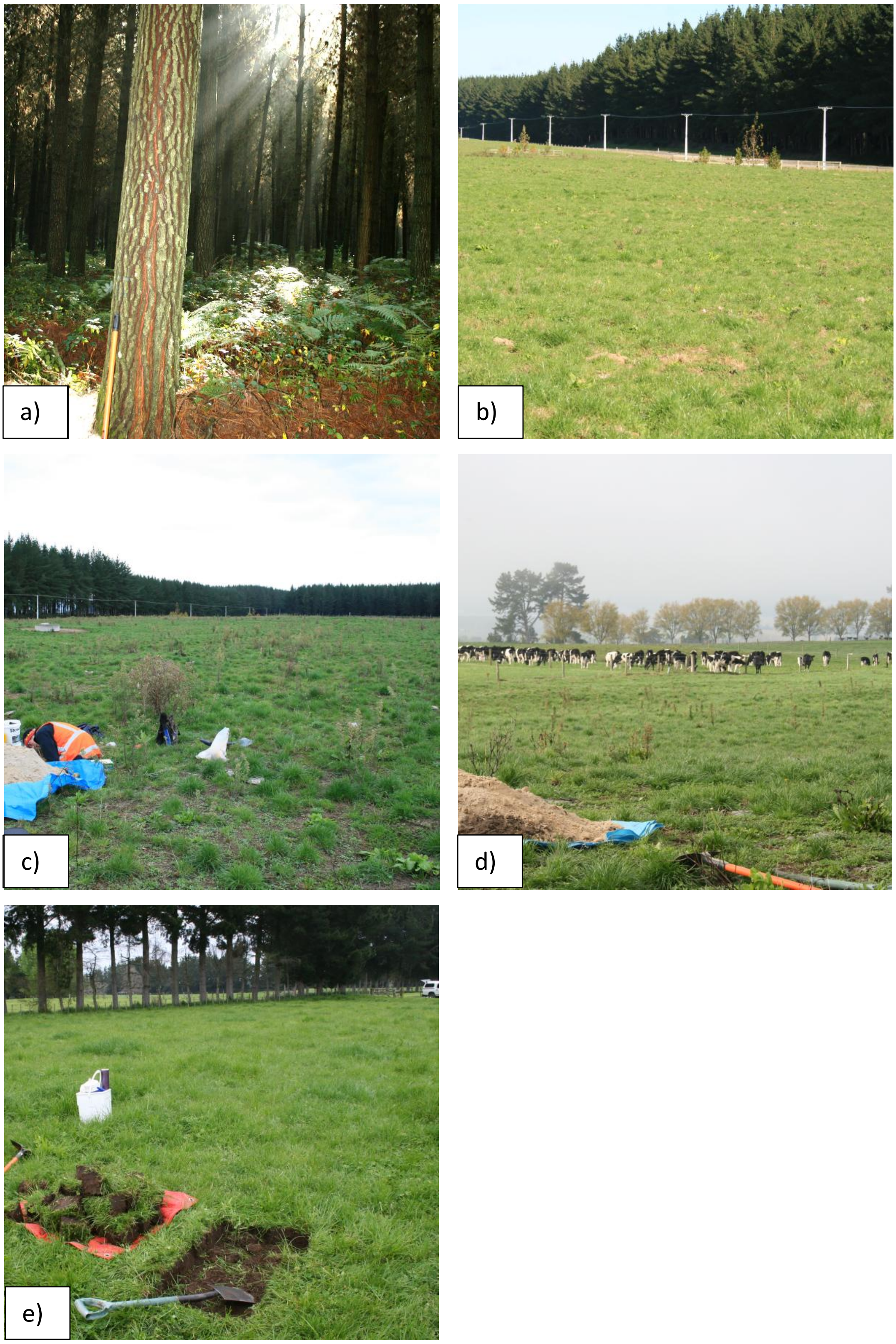


Figure 3.9 The Taupo study area sampling sites:

a) plantation pine forest, b) pasture converted from pine forest 3 years ago, c) pasture converted from pine forest 4 years ago, d) pasture converted from pine forest 5 years ago, e) long term dairy pasture.

Chapter 4

Materials and Methods

4.1 Introduction

This chapter describes field methods including soil sampling protocol and the laboratory measurement methods used in the study.

4.2 Field Methods

4.2.1 Soil profile descriptions

All soil profile description sites were located as much as possible on the same landscape with the same soil type (Taupo Pumice Soil), elevation, terrain configuration (terrace or the shoulder of a hill). Areas adjacent to roads, fence lines, troughs and gateways were avoided, as were areas of obvious bulldozing.

At each sampling site three pits (Figure 4.1a) were excavated, by hand using a spade and a shovel, up to 0.7m depth for soil description and soil sampling. Turf was saved, intact, on the side for later replacement, after pits were refilled with soil.

Soil profile descriptions were recorded following New Zealand’s Soil Description Handbook (Milne *et al.,* 1995). Horizon descriptions included; soil moisture state, horizon boundary description, colour, texture, macro fabric, roots, consistence, parent material, mottles and an allophone test (NaF test) (Figure 4.1b). Horizon notation was recorded following Clayden and Hewitt, (1994), and soil classification followed Hewitt's, (1998) New Zealand Soil Classification.

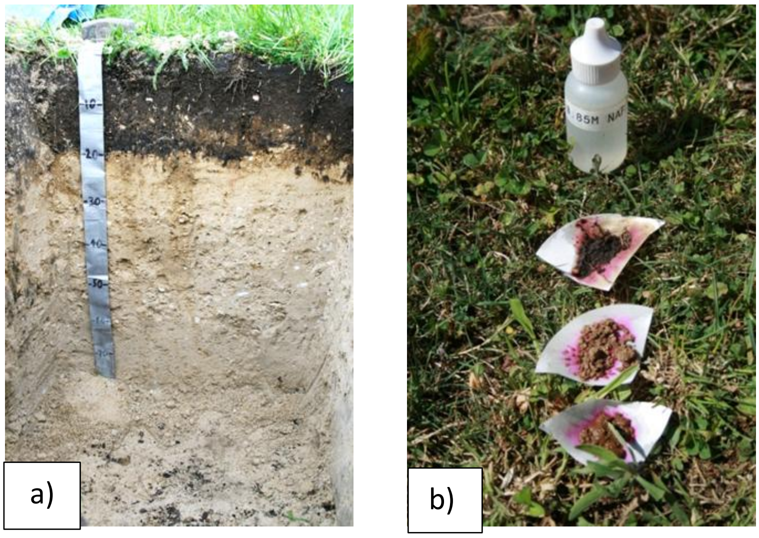


Figure 4.1 Field investigation a: Soil pit for soil profile description, long term dairy farm, Taupo, b: allophone test (NaF test)

4.2.2 Penetration resistance (hand-held penetrometer)

A hand-held penetrometer was used to measure penetration resistance in the excavated soil pits. The indicator marker was set to zero, and then the penetrometer was pushed into the soil at a constant rate until the engraved line, 6 mm from the tip, was even with the soil surface (Gee and Bauder, 1986). The penetrometer was then removed from the soil and the scale read. Ten replicates were made for each soil horizon. The force required to push the tip of the penetrometer into the soil was recorded, penetration resistance (in bars) 0.67 was calculated by scale reading multiplied by 0.67 (spring factor) and then converted to mega Pascals (1bar = 0.1 MPa) (Gee and Bauder, 1986).

4.2.3 Degree of packing

The single-vane shear method described by Griffiths *et al.,* (1999) was used to measure the degree of packing using a Singleton blade and hand-held penetrometer. The Singleton blade was pushed firmly into the vertical face of the soil profile and the hand held penetrometer was placed on the washer of the blade and a force applied. The force applied by the penetrometer, caused the blade to move sideways, breaking the soil away from the horizon; this force was used as a measure for the degree of packing (Griffiths *et al., 1999).* The calculation, conversion and number of replicates were the same as for penetration resistance.

4.2.4 Soil sampling procedure for laboratory analyses

4.2.4.1 Undisturbed soil cores, PVC and stainless steel cylinders

Undisturbed soil cores from the Ap horizon (Figure 4.2) were carved and extracted by using a knife, 5 cores from each main pit on each landscape unit were collected. Prior to carving petroleum jelly was smeared on the inside surface of the rings to ensure that edge flow was prevented during laboratory measurement of hydraulic conductivity. The PVC or stainless steel rings were placed on an even soil surface and soil was carved vertically into a cone shape around the core using a knife.

Figure 4.2 Undisturbed soil cores sampling

Pressure was applied to the core using a block of wood to slide the ring down the soil core as carving took place, until a full depth of 10 cm was reached. Cores were removed from the profile using a sharp knife, and an excess of several centimetres at the base and about 2 mm on the top, of the cores was left, to prevent damage during transportation.

All soil cores were labelled, wrapped by cling-wrap and placed in labelled plastic bags, sealed, transported to the laboratory, and stored at 4°C until analysed.

The Cores were used in the soils laboratory to determine:

1. saturated hydraulic conductivity (Ksat)
2. Unsaturated hydraulic conductivity K-40
3. Big cores were subsampled using smaller cores to determine soil bulk density and some soil was spared to determine moisture content
4. Bulk density cores were subsampled for the moisture release-subsample cores.

4.2.4.2 Bulk samples

Bulk soil samples were taken from individual horizons, using a sharp kitchen knife and spade, for laboratory analyses of soil moisture content, hydrophobicity, particle size analyses, and aggregate stability. Samples were between 0.8 and 1 kg of weight, taken in a manner to minimise aggregate disturbance.

Part of the sample was air-dried for determination of soil water repellency and particle size distribution. The remainder of the bulk samples were kept in a fridge for gravimetric soil moisture content and aggregate stability determination.

4.3 Laboratory Methods

4.3.1 Bulk density

The undisturbed cores for infiltration rate were subsampled after infiltration rate measurement was completed, using smaller stainless steel cores (60mm diameter, 50 mm high and 144 cm^3 volume). The cylinders were placed on top of the infiltration cores (Figure 4.3), and a small block of wood was placed over the core and a mallet was used to hammer the core into the soil (Gradwell, 1979; Burke *et al*., 1986).

Figure 4.3 Undisturbed soil core subsampling

The subsampled cores were trimmed back with a sharp knife until flush with the core. If some soil had been lost from rings, the gaps were replaced with clover seed (measured in a 10 ml measuring cylinder). The volume of clover seed was subtracted from the total volume of the ring to determine the volume of soil. The mass of moist soil that was contained in the rings was then weighed using a digital laboratory scale (+/- 0.01 g). Soil dry bulk density was calculated (Equation 4.1) (Gradwell and Birrell 1979; McLaren and Cameron, 1996).

Moisture adjustment was a separate process, soil left after subsampling was homogenized by mixing, using a spatula. Approximately 30 g of soil was placed in a labelled pre-weighed aluminium tray. Aluminium containers were then placed in a 105°C oven for 24 hours. After drying, containers were placed in a desiccator until cooled to room temperature. Aluminium trays were reweighed with oven dry soil. Soil moisture content percentage was calculated (Equation 4.2 and equation 4.3) (Burke *et al*., 1986):

$$soil\ dry\ bulk\ density\ g/cm^3 = \frac{Owen\ dry\ mass\ of\ soil\ in\ g}{volume\ of\ soil\ in\ cm^3} \quad \text{(Equation 4.1)}$$

Oven dry soil gravimetric moisture percentage was calculated following equation 4.2.

$$Moisture\ \% = \frac{mass\ of\ wet\ soil - mass\ of\ dry\ soil\ g}{mass\ of\ dry\ soil\ \ g} \times 100 \quad \text{(Equation 4.2)}$$

The water content on volume basis was calculated following equation 4.3.

(Equation 4.3)

$$Moisture\ vol\ \% =\ gravimetric\ moisture\ \% \times soil\ dry\ bulk\ density\ g/cm^3$$

4.3.2 Hydraulic conductivity

4.3.2.1 Unsaturated hydraulic conductivity

Unsaturated hydraulic conductivity was determined in the laboratory (Figure 4.4) at a tension of -0.4 kPa (K_{-40}) (unsaturated hydraulic conductivity at a suction of 40 mm), using a method adapted from McKenzie *et al.,* (2002).

The soil cores were pre-treated before unsaturated hydraulic conductivity was determined. The soil on each core was trimmed with a sharp knife until the soil was flush with the core holder (cylinder); any "smeared" soil surfaces were removed with a tip of a knife.

Filter paper and small amount of sand was placed on top of the soil core stand to provide good contact between the soil core and the water column in the stand. A small dome of sand was created above the soil core to fill any remaining space, and provide a good surface contact between the permeameter and the soil (McKenzie *et al., 2002).*

The soil cores were equilibrated for 24 hours to a potential of -0.4 kPa, with a hanging column of water by setting the outlet on the stands at a potential of -0.4 kPa. Permeameters were calibrated by adjusting the tube on the bubbling tower to give a tension of -40 mm and then placed on the sand above the soil core (McKenzie *et al*., 2002). Once unsaturated flow was occurring, unsaturated hydraulic conductivity was determined; by measuring the change in the water level in the permeameter in 30 minutes.The change of water level height was converted to a volume of water in ml by multiplying the cross section area of the bubbling tower and loss of height of water column in mm.Level height was converted to a volume using calculation: $r^2\pi = 11^2$ mm x 3.14 = 380 mm^2, for every mm of height, water discharge equals 380 mm^3 or 0.38 cm^3 which is 0.38 mL, so every mm discharge from bubbling tower equals 0.38 ml. K_{unsat} was calculated using Darcy's law (Equation 4.3)

$$q = \frac{Q}{AT} = -K\frac{\Delta H}{L} \qquad \text{(Equation 4.3)}$$

Where:

Q = volume passing through core (cm^3)
A = cross section area of the core (cm^2)
T = time
K = unsaturated hydraulic conductivity (cm/min)
Δ H = pressure head gradient (cm)
L= thickness of the soil

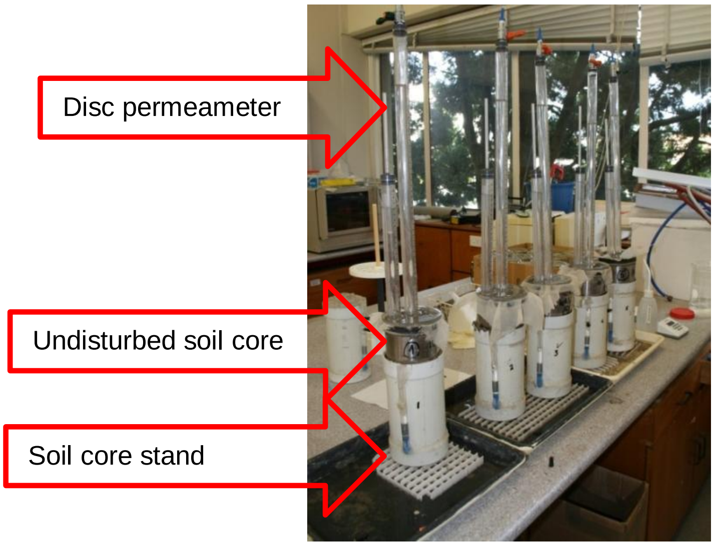


Figure 4.4 Unsaturated infiltration rate (K_{-40}) determination using disc permeameter and stand providing water tension

4.3.2.2 Saturated hydraulic conductivity (K_{sat})

The same soil cores used for K_{-40} were also used to determine K_{sat}. A cutting blade was used to trim cores evenly; 2.5 cm below the top at the core edge to a groove at 5 cm depth lined the inner part of the K_{-40} core. Soil cores were submerged in water and kept overnight to become fully water saturated.

Soil cores were placed on a PVC grill in a tray (Figure 4.5). A nail (coloured black at the tip) was placed in the middle of the core top surface, exposed 1 cm above the soil surface to indicate the level at which water should fill the soil core cylinder. Saturated hydraulic conductivity was determined by filling water by measuring cylinder and starting the clock from when the first amount of water reached the meniscus formed from the nail. Water was added to maintain a constant level during measurement. The time (s), and volume (ml) used was recorded continuously until a constant infiltration rate was achieved.

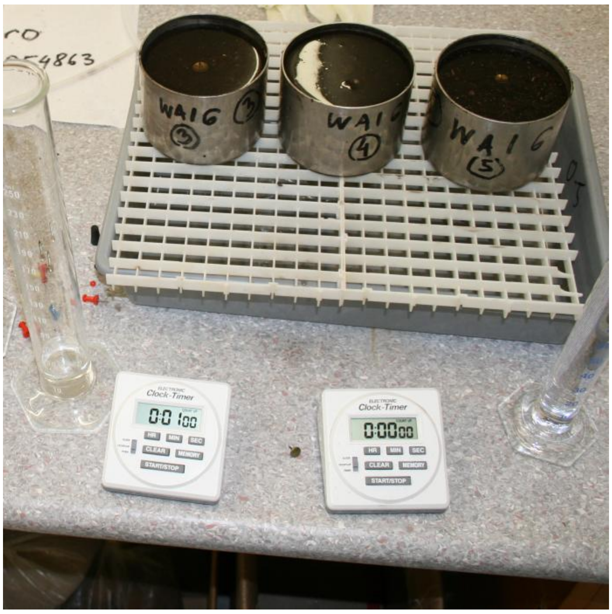


Figure 4.5 Saturated infiltration rate (K_{sat}) determination in the laboratory

A series of five readings were recorded and the infiltration rate was calculated. The flow per unit area of soil was determined using the Darcy's Law rearranged equation (Equation 4.4) (Burke *et al*., 1986).

$$K_{sat} = \frac{Q}{AT} X \frac{L}{\Delta H} \qquad \text{(Equation 4.4)}$$

Where:

K_{sat} = saturated hydraulic conductivity (cm/min)
Q = volume passing through core (cm^3)
A = cross section area of the core (cm^2)
T = time
L= thickness of the soil
ΔH = pressure head gradient (cm)

4.3.3 Particle size distribution

Particle size distribution was measured using the Malvern MasterSizer Laser Sizer. Particle size distribution was determined for one representative soil profile, for each field site. Three replicate, 0.3 g soil samples were weighed and placed into beakers, then 10 mls of 10% hydrogen peroxide (H_20_2) solution was added to each sample, to remove cementing agents, such as organic matter (Buurman *et al.,* 1997). Samples were then left overnight in the fume cupboard. After oxidation, beakers were gently heated on a hot plate to boil off excess peroxide. Samples were then cooled and 10 ml of 10% calgon dispersing agent solutions was added and samples were left to stand for a further 24 hours. Samples were then placed in an ultrasonic bath for 10 minutes to break up the aggregates mechanically by the transmission of vibrating sound waves (Buurman *et al.,* 1997). After dispersion, a small sub-sample of about 3 ml was placed in the Sample Presentation Unit of the Malvern MasterSizer Laser Sizer using a dropper. Results were automatically collated on a computer displaying the particle size distribution and values were later converted to particle size textural classes (clay, silt, sand). Soil texture was then determined using the soil texture triangle of Milne *et al., (1995).*

4.3.4 Soil water repellency

Soil water repellency was determined using the WDPT test (water drop penetration test) (Dekker *et al.*, 2009). Two 200-µL drops of distilled water were placed on the surface of the air-dried soil samples (Fig 4.6), and the time that elapsed before the drops were absorbed was determined. The average time for water drops is reported as the WDPT. In general, a soil is considered to be water repellent if WDPT exceeds 5 s (DeBano, 2000; Dekker *et al.,* 1996).

Figure 4.6 Air dried soil samples from Tokoroa prepared for water repellency determination in the laboratory

On each sample 10 readings were taken and 3 classes of repellency were recognized:

- Class I, wettable, not water repellent (infiltration within 5 s);
- Class II, slightly water repellent ($5 < \text{WDPT} \leq 60$ s);
- Class III, strongly water repellent ($60 < \text{WDPT} \geq 900$ s).

Test time was extended to a maximum of ¼ of hour (900 s), after which time, if the drops still had not penetrated, a reading of 900 s was recorded.

4.3.5 Soil aggregate stability

Aggregate stability was measured using the method described by Gradwell (1979). Approximately 50g of air dried soil aggregates, sieved to between 2 and 4 mm, were saturated overnight by capillary action, and then rinsed onto a column of sieves (2 mm, 1 mm and 0.5 mm). The nest of sieves was then placed in a water bath (Fig. 4.7) and oscillated at a rate of 30 oscillations per minute for 30 minutes, making sure the aggregates stayed submerged throughout each stroke. The low electrical conductivity of the water was maintained by the changing water after each batch.

Figure 4.7 Equipment used for the aggregate stability determination in the laboratory

Upon completion of oscillations aggregates were washed into aluminium containers, then dried (45˚C overnight) and weighed. To determine the ratio between soil aggregates and sand, the dried soil from each sieve was dispersed and poured over the sieve from which it was removed. Any material retained was dried and weight subtracted (representing sand fraction) from the weight of aggregates in that size category. Water stable aggregates (WSA) were calculated using Equation 4.5.

$$WSA = \frac{Ww - Wd}{\left(\frac{Ws}{mf}\right) - (\sum sd)} \times 100 \qquad \text{(Equation 4.5)}$$

Where:

WSA = Water stable aggregates percentage
Ww = Aggregates remaining on each sieve after wet sieving
Ws = Initial soil weight
mf = moisture factor
Σsd = total amount of sand

4.3.6 Soil pH

Soil pH was measured according to standard method (U.S. Department of Agriculture (USDA), 2010). Before any measurements were taken the pH meter was calibrated at pH 4.0 and 7.0 with a standard buffer solution. 10 g of air-dried sieved soil was weighed into a 100 ml beaker and 25 ml of distilled water was added. The mixture was then stirred vigorously with a high speed stirrer for 15 seconds and left to stand for 30 minutes. The electrodes of the pH meter were washed in distilled water. The supernatant pH was measured and recorded with the bulb of the pH meter electrode submerged in the solution.

4.3.7 Water release characteristic

An air pressure (pressure plate) method was used to determine the soil water release characteristic in a range of pressure from 1kPa-1500kPa (9 different pressure measurements). Pressure apparatus equipment from the “Soil moisture Equipment Corporation” (Santa Barbara, USA) was used.

4.3.7.1 Soil samples

A steel ring (10x60 mm) with a piece of filter paper attached to the bottom by a rubber band was pre-weighed (ring + rubber band + filter paper). Undisturbed soil core (used for soil dry bulk density, described in section 4.3.1), was placed over the steel ring, pushed down using flat surface jar top (56 mm in diameter) and sliced across by sharp blade, creating a subsample 10 mm high (Figure 4.8a). Initial weight (ring + rubber band + filter paper + soil) and soil moisture were determined. The samples were used to determine soil water retention in a range of pressure from 1 - 500 kPa.

For the 1500 kPa pressure extractor disturbed soil samples were used, retained by PVC rings, without filter paper between the soil sample and the 1500 kPa porous plate.

Figure 4.8 Samples for moisture retention measurement on pressure plate apparatus a: Individual sample; b: set of samples water saturated sitting on porous ceramic plate inside extraction vessel

4.3.7.1 Procedure

The measurement procedure started with soaking ceramic pressure plate overnight in a mild solution of water and bleach (to prevent build-up of micro-organisms). The saturated pressure plate was placed in the extractor on metal stands designed to hold them horizontally. Soil samples were placed on the ceramic plate (Fig.4.8b) (1 ceramic plate can accommodate a maximum of 13 undisturbed soil samples). Water was poured gently onto the plate and left to soak overnight to saturate the soil sample. Next morning the outflow tube connecting between the ceramic plate and rubber membrane, was attached to the outflow pipe on the extraction vessel. The lid was placed over top and tightened by bolts ensuring that the vessel was sealed. A measuring cylinder was placed next to the pressure apparatus and end of outflow pipes were placed in the cylinder to collect water flowing out of soil samples. Compressed air was released into the chamber at the required pressure, causing water to flow from the soil through the ceramic plate until equilibrium was reached. The measuring cylinder indicated flow, once the flow ceased meant that soil moisture and air pressure reached equilibrium.

When equilibrium was reached, pressure was released; ensuring water back-flow from measuring cylinder or connection pipes was prevented. The vessel was open and soil samples were taken for gravimetric water content determination (Equation 4.2). The procedure was repeated from lowest towards highest pressure. After 500 kPa equilibrium has been reached, soil samples were oven dried (105˚C, for 24 hours) and gravimetric soil moisture content determined. The time necessary to reach equilibrium was 3 days or longer for the low pressure test, up to 14 days for 500 kPa pressure. In one batch 2 pressure plates were used per pressure apparatus with 12 individual samples on each plate. The procedure was calibrated by running test samples on 3 pressure settings.

The total available water capacity (TAW) was calculated by deducting amount of water held at -1500 kPa (permanent wilting point (PWP)) from amount of water held at field capacity (FC) assuming that field capacity is amount of water held at -10 kPa (McLaren and Cameron, 1996). TAW (total available water) was calculated following equation 4.6.

$TAW\%\ vol = FC(\%, vol) - PWP(\%vol)$ (Equation 4.6)

Readily available water (RAW) was calculated by deducting amount of water held at PWP (% vol) from amount of water held at 100 kPa.

Chapter 5

Results of field investigations

5.1 Introduction

This chapter presents the results of observations and measurements undertaken directly in the field. Full data is included in Appendix 1 (Soil profile descriptions) and Appendix 2 (Penetration resistance).

5.2 Soil Profile Descriptions

Soil profile descriptions were made for each land use (Appendix 1) from two study areas: 6 from Tokoroa (Pine forest, 2008 Conversion, 2007 Conversion, 2005 Conversion, long term dairy farm and long term sheep and beef farm) (Figure 5.1a), and 5 from Taupo (Pine forest, 2007 Conversion, 2006 Conversion, 2005 Conversion, and long term dairy farm) (Figure 5.1b).

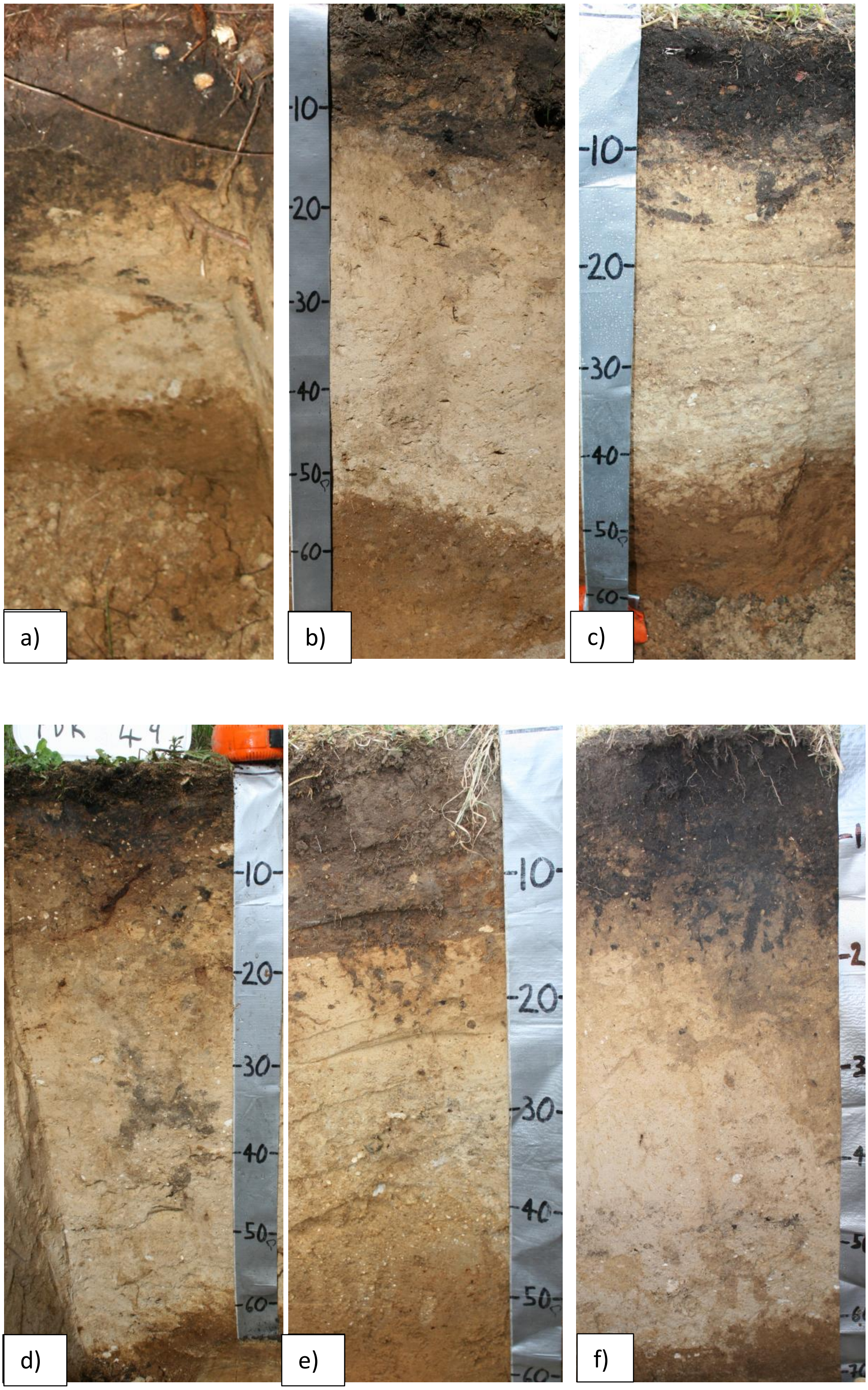


Figure 5.1a Soil profiles from the Tokoroa study area: a) plantation pine forest, b) pasture converted from pine forest 2 years ago, c) pasture converted from pine forest 3 years ago, d) pasture converted from pine forest 5 years ago, e) long term dairy pasture, f) sheep and beef long term pasture.

Figure 5.1b Soil profiles from the Taupo study area: a) plantation pine forest, b) pasture converted from pine forest 3 years ago, c) pasture converted from pine forest 4 years ago, d) pasture converted from pine forest 5 years ago, e) long term dairy pasture.

5.2.1 Tokoroa and Taupo typical soil profile compared

The Pumice Soil at both study areas (Tokoroa and Taupo) is of same age and on same parent material formed on pumice deposited mainly from the AD 232 ± 5 Taupo eruptions (Hogg et al., 2009). The main difference between the soils from Tokoroa and Taupo was the thickness and texture of the C horizon. The Taupo study area is closer to the source of air fall tephra than the Tokoroa. C horizons in all Taupo soil description pits were deeper than the pits in Tokoroa (Figure 5.2). C horizon pumice material in Taupo was coarser and lighter in colour (yellow-grey) compared to Tokoroa (yellow-orange) pumice in C horizon.

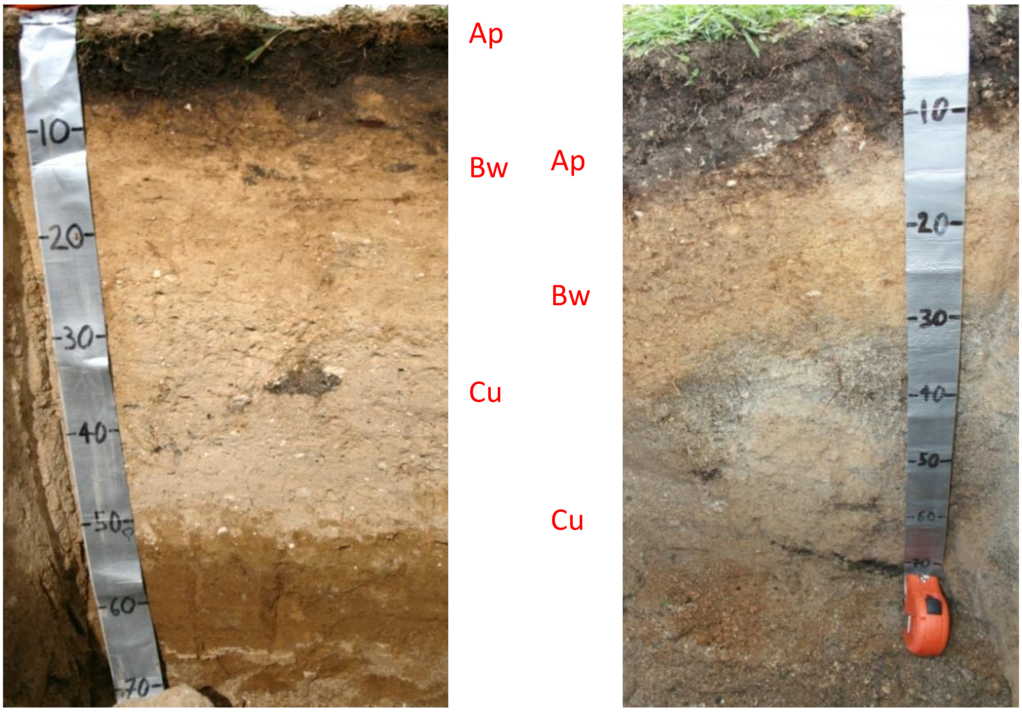


Figure 5.2 Typical soil profile Tokoroa left, Taupo right

5.2.2 A horizon thickness under different land uses

The selected sampling sites and conversion ages had similar soil profile description at both study areas. The main difference observed was the depth of the A horizon (Table 5.1). Depths of A horizon (observed on both study sites) were deepest under long term dairy land use (Tokoroa 15 cm, Taupo 20 cm), followed by forest (Tokoroa 13 cm, Taupo 19 cm) and shallowest on sites converted from pine plantation forest to pasture (Tokoroa 10-12 cm, Taupo 8-13 cm). However with one-off measurements and a variable environment, no clear trends can be elucidated.

Table 5.1 Horizon thickness (cm) in soil description pits

	Land use	*Ap*	*Bw*	*Cu*	*bB*
Tokoroa	**P F**	13.0	15.0	40.0	>16
	C 2	12.0	6.0	34.0	>18
	C 3	10.0	13.0	38.0	>24
	C 5	10.0	10.0	24.0	>36
	D F	15.0	9.0	19.0	>27
	SB F	12.0	19.0	32.0	>13
Taupo	**P F**	19.0	18.0	>58	
	C 3	11.0	15.0	>44	
	C 4	13.0	18.0	>45	
	C 5	8.0	28.0	>34	
	D F	20.0	16.0	>45	

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, D F = long term (50+ years) dairy farm, SB F= long term (50+ years) sheep and beef farm.

5.2.3 A horizon colour, boundary and pedality

Ap horizon’s colour, pedality and boundary shape showed variability under different land use (Table 5.2). The moist colour of the Ap horizon varied from black to brownish black and dark reddish brown with no apparent pattern to land use. However when air dried (Figure 5.3) the soil from the pine forest was apparently darker in colour than the other soils.

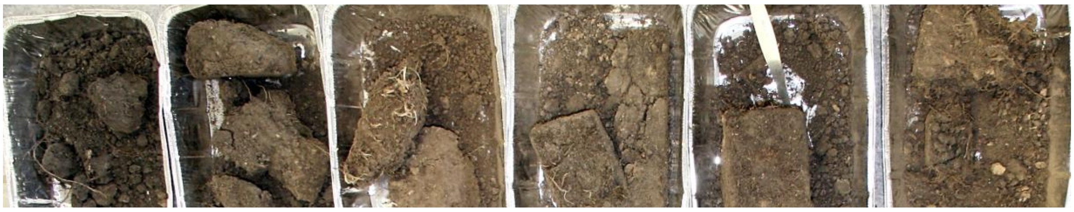


Figure 5.3 Air dried A horizon samples from the Tokoroa study area in the laboratory.

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 5 = pasture converted from pine forest 5 years ago, D F = long term (50+ years) dairy farm, SB F= long term (50+ years) sheep and beef farm.

Table 5.2 Ap Horizon colour, pedality and boundary shape

Site		Colour	Degree and type of pedality	A/B boundary distinctness and shape
Tokoroa	P F	Black (10YR 1.7/1)	apedal earthy	distinct smooth
	C 2	Brownish black (7.5YR 2/2)	moderate platy	abrupt convolute
	C 3	Black (10YR 1.7/1)	moderate blocky	distinct smooth
	C 5	Black (10YR 1.7/1)	moderate blocky	distinct occluded
	D F	Very dark brown (7.5YR 2/3)	moderate polyhedral	distinct smooth
	SB F	Black (7.5YR 2/1)	moderate polyhedral	distinct occluded
Taupo	PF	Black (7.5YR 2/1)	apedal earthy	distinct smooth
	C 3	Dark reddish brown (5YR 3/2)	moderate blocky	distinct smooth
	C 4	Brownish black (7.5YR 2/2)	apedal earthy	distinct smooth
	C 5	Brownish black (7.5YR 2/2)	moderate polyhedral	indistinct smooth
	D F	Black (7.5YR 2/1)	apedal earthy	distinct smooth

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, D F = long term (50+ years) dairy farm, SB F= long term (50+ years) sheep and beef farm.

Soil structure (Macrofabric) in the Ap horizon varied under different land use and conversion age. The most common pedality type was block-like (polyhedral and blocky) recorded at 6 sites. The next most common pedality type was apedal earthy (4 sites including both pine forest sites).

Only 2 years since converted pasture at the Tokoroa study area had platy pedality type in the Ap horizon (Figure 5.4).

No clear pattern of changes in colour, pedality or boundary distinctiveness and shape between different land use histories was recognized.

Figure 5.4 Soil's Ap horizon macrofabric: platy pedality type at pasture converted 2 years ago (C 2), Tokoroa study area.

5.3 Soil consistence

5.3.1 Introduction

Penetration resistance and degree of packing measurements were read in "units" but results were converted to Mega Pascal. Readings were undertaken in dry parts of the year 2010 (March-May (and early October for the long term Dairy farm in Taupo)) though moisture content varied between sampling sites (Chapter 6, Table 6.3). Data have to be interpreted with care when comparing different land use, because readings were under varying soil moisture content. However penetration resistance and degree of packing measurements are good indications to compare individual horizons in the same profile. Penetrometer and degree of packing results are classified from very low (< 0.5 MPa), low (0.5-1

MPa), medium (1-2.2 MPa), high (2.2-3.0 MPa) to very high (> 3.0 MPa) (Milne *et al.,* 1995).

5.3.2 Penetration Resistance and degree of packing

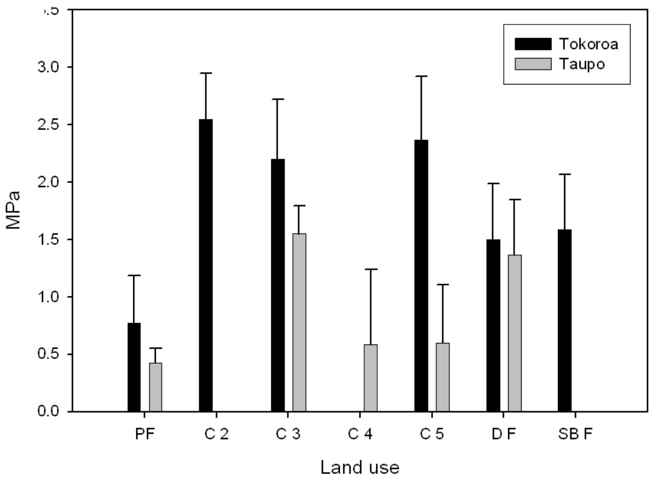
At the Tokoroa study area, the penetration resistance (Figure 5.5) and degree of packing (Figure 5.6) in the A horizon of the pine forest site was lower ($P < 0.01$) than any other site. The degree of packing and penetration resistance at the Taupo study area in the A horizon of pine forest site was lower ($P < 0.05$) compared to 3 years old conversion and long term dairy pasture but was not significantly different from pastures converted 4 and 5 years ago (highly variable sites). However there were no significant differences in Bw and Cu horizons between pine forest and the rest of the sites at both study areas or in the bB horizon at Tokoroa.

The penetration resistance and degree of packing were generally lower in the Ap horizon than deeper horizons at the Tokoroa and the Taupo study areas.

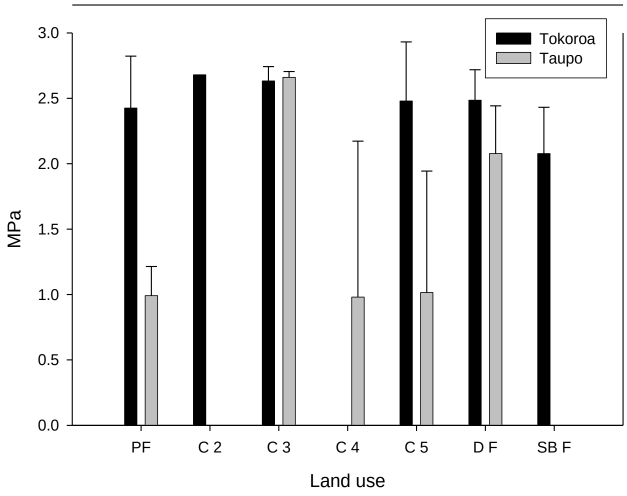
At both study areas the penetration resistance and degree of packing in the Bw and Cu horizons were classified as high, except Bw horizon in the Tokoroa sheep and beef farm which was moderate.

At the Tokoroa study area, penetration resistance and degree of packing of the bB horizon was classified as medium except 3 years since converted pasture which was high.

a. Ap horizon



b. Bw horizon



c. Cu horizon

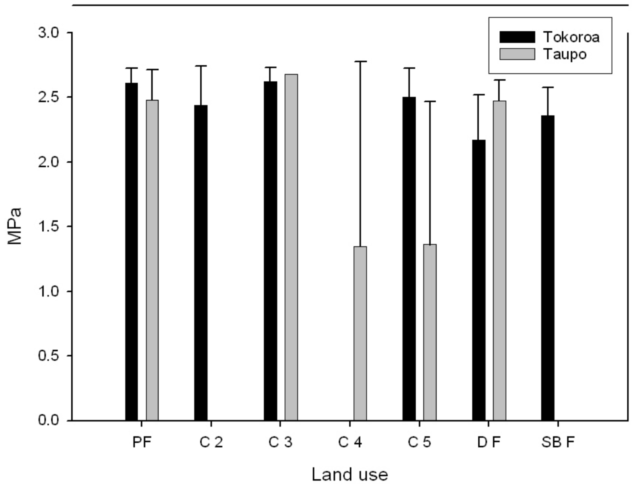
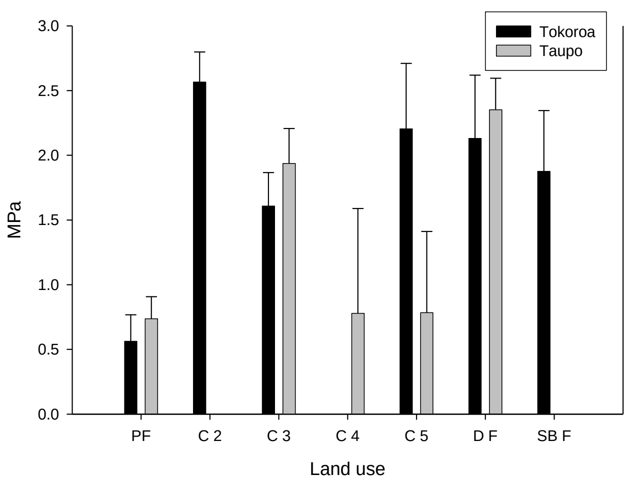


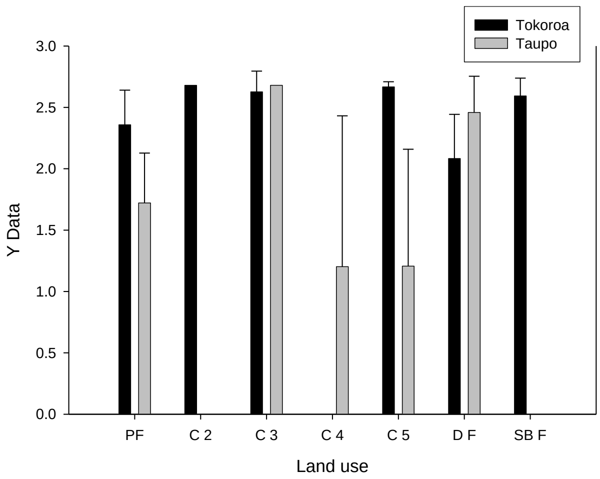
Figure 5.5 Penetration resistance for the different land use study sites: (a.)Ap, (b.) Bw, and (c.) Cu horizons

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, D F = long term (50+ years) dairy farm, SB F= long term (50+ years) sheep and beef farm.

a. Ap horizon



b. Bw horizon



c. Cu horizon

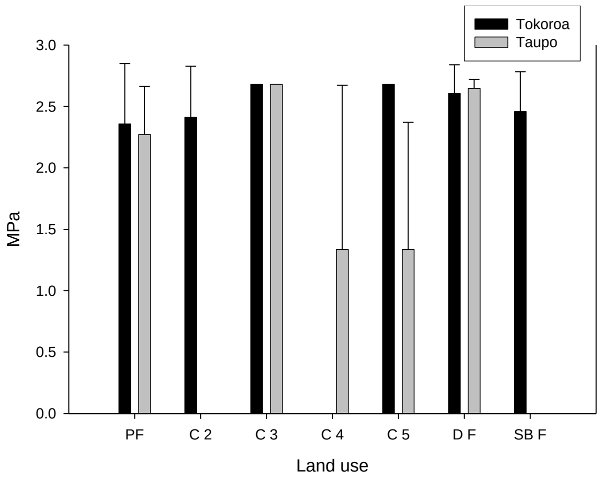


Figure 5.6 Degree of packing for the different land use study sites: (a.)Ap, (b.) Bw, and (c.) Cu horizons

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, D F = long term (50+ years) dairy farm, SB F= long term (50+ years) sheep and beef farm.

Chapter 6

Results: Laboratory investigations

6.1 Introduction

This chapter presents the results obtained in the laboratory; including soil dry bulk density, water repellency, unsaturated (K_{unsat}) and saturated (K_{sat}) hydraulic conductivity, aggregate stability, soil water release characteristic, soil pH, and particle size distribution.

6.2 Soil dry bulk density

The soil dry bulk density at both study areas (Tokoroa and Taupo) was low, ranging from 0.58 (Pine forest Tokoroa) to 0.78 g/cm^3 (Dairy farm Taupo). At the Tokoroa study area the pine forest soil had a significantly lower dry bulk density ($P < 0.05$) than any of the pasture sites (Figure 6.1).

However at the Taupo study area only long term dairy (mean 0.78 g/cm^3) and the youngest pasture site (3 years since converted from pine forest) (mean 0.74 g/cm^3) had higher ($P < 0.05$) bulk density compared to the plantation pine forest soil (Figure 6.2). Pastures converted from pine forest 4 and 5 years ago were not significantly different compared to the plantation pine forest.

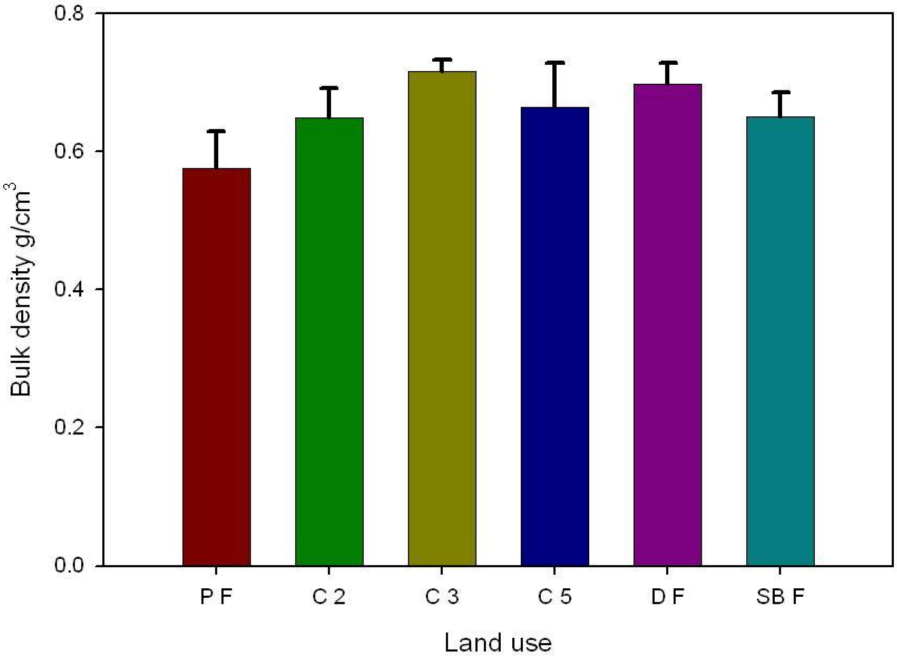


Figure 6.1 Tokoroa “A” horizon soil dry bulk density.

Each value is mean of 5 measurements. Error bars are one standard deviation. Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB F = long term (50+ years) sheep and beef farm.

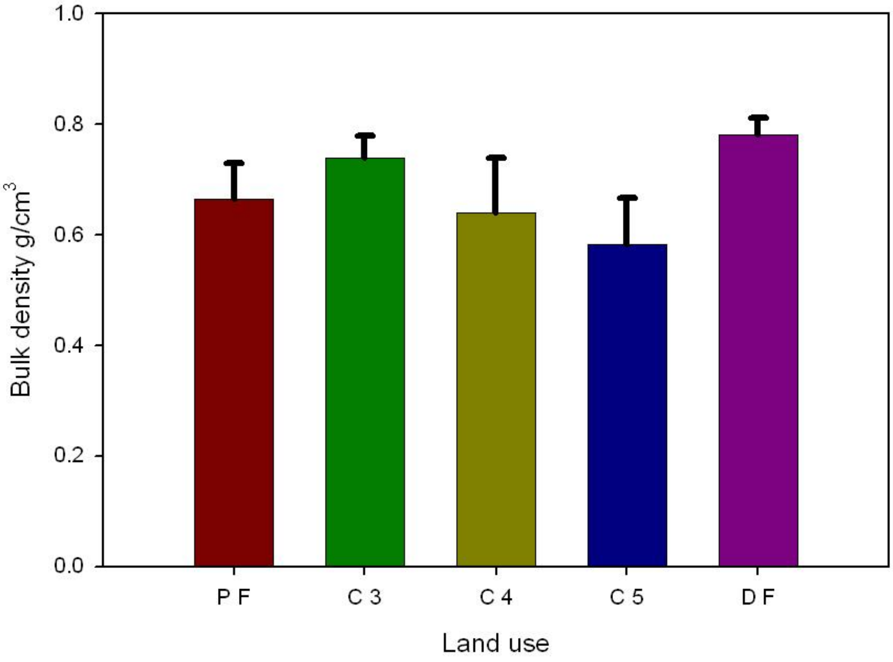


Figure 6.2 Taupo “A” horizon soil dry bulk density.

Each value is mean of 5 measurements. Error bars are one standard deviation. Where: PF = pine plantation forest, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm.

6.3 Soil repellency

Soil water repellency was measured on soil samples from 4 soil horizons in the Tokoroa study area (Ap, Bw, Cu and bB) and soil samples from 3 soil horizons in Taupo (Ap, Bw and Cu). Soil water repellency was evident only in the top horizon (Ap) from both areas (water drop penetration time > 5 seconds). The lowest water drop penetration time (WDPT) was measured on the pine forest samples (mean 11 seconds) (Figure 6.3) and the sheep farm (WDPT mean 12 seconds) at the Tokoroa study area. The sheep farm and the pine forest at Tokoroa were not significantly different. All 4 dairy pasture sites (pasture converted 2, 3 and 5 years ago and long term dairy farm) had significantly higher soil water repellency ($P < 0.05$) than the pine forest, and the long term sheep and beef farm. There was high variability between measurements, especially within those with high means. For example for 2 year old converted pasture WDPT mean was 222 seconds with a standard deviation of 312 seconds.

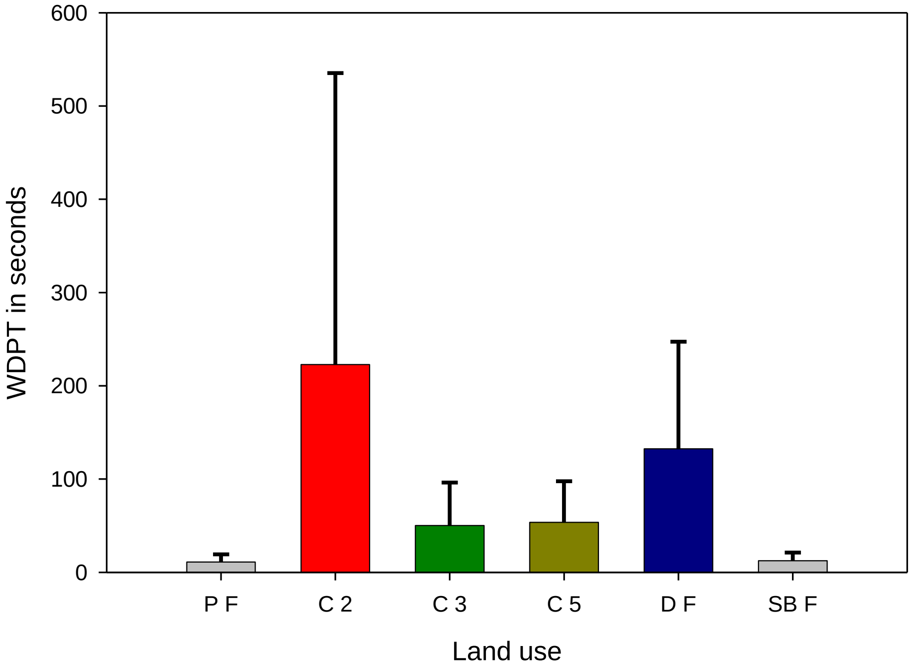


Figure 6.3 Tokoroa study area “A” horizon soil water repellency.

Each value is the mean of 10 readings. Error bars are one standard deviation.
Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

At the Taupo study area the lowest mean for water repellency (2 seconds WDPT) (Figure 6.4) was the long term dairy farm, which soil has been graded as not water repellent (WDPT < 5 seconds). The pine forest soil also had low water repellency (mean 5 sec., standard deviation 2 sec.). Pastures converted 3, 4 and 5 years ago had significantly higher WDPT (P < 0.05) compared to the pine forest or the long term dairy sites. The Taupo study area water repellency data were generally highly variable.

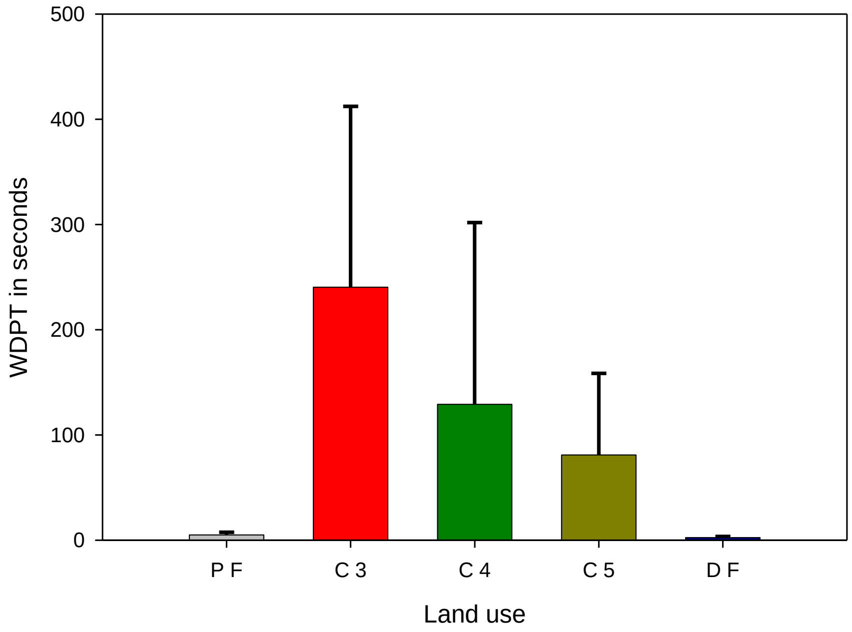


Figure 6.4 Taupo study area A horizon soil water repellency.

Each value is the mean of 10 readings. Error bars are one standard deviation.
Where: PF = pine plantation forest, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm.

6.4 Hydraulic conductivity

6.4.2 Unsaturated hydraulic conductivity (K_{unsat})

At the Tokoroa study area there was no significant difference in unsaturated hydraulic conductivity (K_{-40}) between the pine forest, and pastures converted from pine forest or long term dairy farm (Figure 6.5). The highest mean (8.7 mm/hour) K_{-40} was for the long term sheep and beef farm which was significantly higher than pine plantation forest (mean 4.8 mm/hour) ($P < 0.05$).

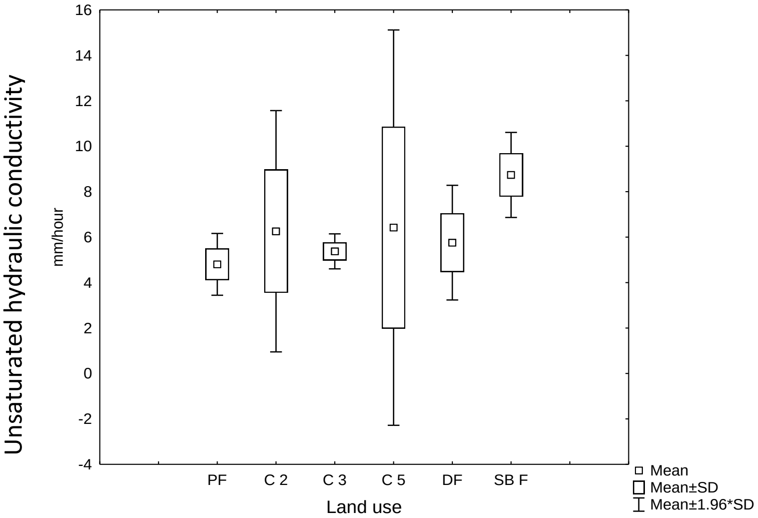


Figure 6.5 Tokoroa study area A horizon Unsaturated ($K_{-40unsat}$) hydraulic conductivity.
Each value is the mean of 5 readings.
Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB F = long term (50+ years) sheep and beef farm.

At the Taupo study area the unsaturated hydraulic conductivity (K_{-40}) measured on the pine forest samples (mean 7.6 mm/hour) was significantly higher ($P < 0.05$) than the pasture converted from pine forest 3 years ago (mean 2.69 mm/hour). Pastures converted from pine forest 4 and 5 years ago and long term dairy farm did not differ significantly from the pine plantation forest or each other.

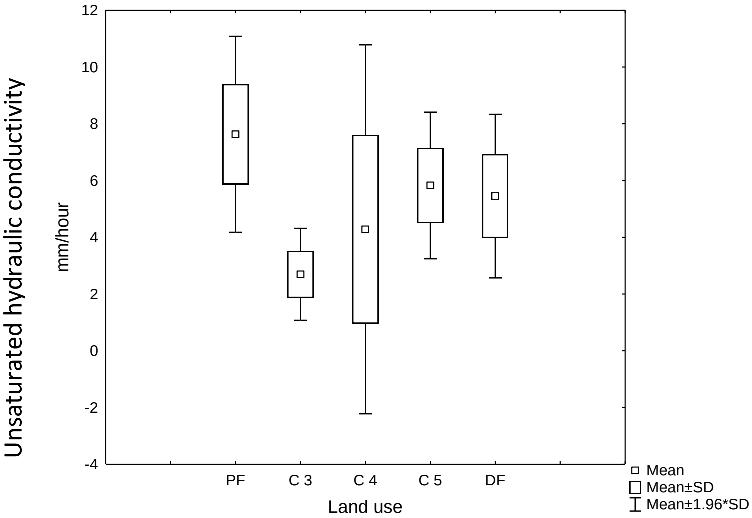


Figure 6.6 Taupo study area A horizon unsaturated (K_{unsat}) hydraulic conductivity.

Each value is the mean of 5 readings.Where: PF = pine plantation forest, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm.

6.4.3 Saturated hydraulic conductivity (K_{sat})

At the Tokoroa study area the saturated hydraulic conductivity (K_{sat}) in the pine forest samples was the highest. However only pastures converted from pine forest 5 years ago (C 5) and the long term sheep and beef farm had a significantly lower saturated infiltration rate ($P < 0.05$) than the pine forest (Figure 6.7).

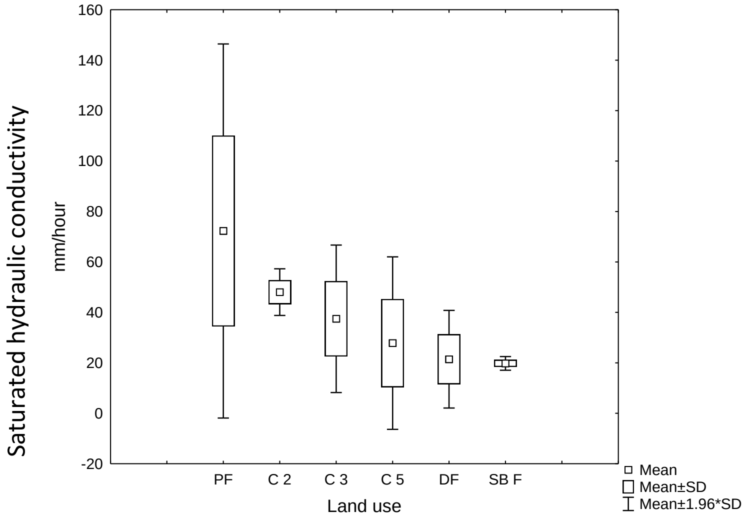


Figure 6.7 Tokoroa study area A horizon Saturated (K_{sat}) hydraulic conductivity.

Each value is the mean of 5 readings.Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

At the Taupo study area the saturated hydraulic conductivity (K_{sat}) values measured on the dairy farm samples (mean 91.32 mm/hour) were the highest and the pine forest second highest (mean 52.3 mm/hour) (Figure 6.8). However none of the land uses had significantly different infiltration rate compared to the pine forest.

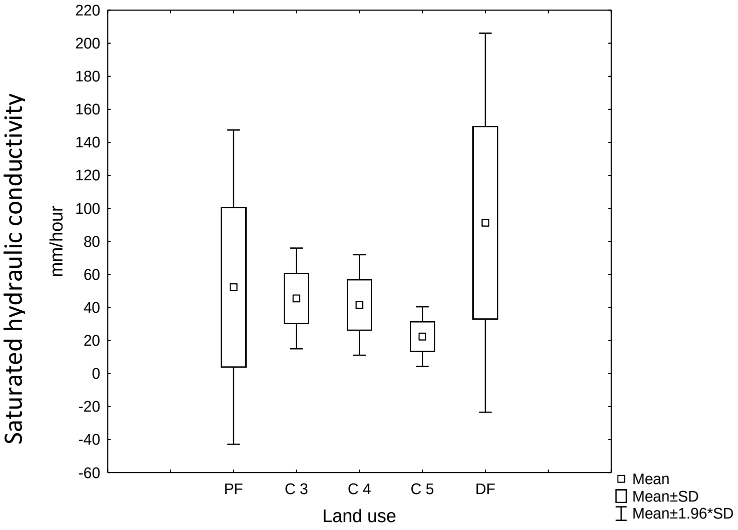


Figure 6.8 Taupo study area A horizon saturated (K_{sat}) hydraulic conductivity. Each value is the mean of 5 readings.Where: PF = pine plantation forest, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm.

6.5 Aggregate stability

Aggregate stability of the Ap horizon was noticeably lower in pastures converted from pine forest than in the pine forest and long term pasture sites (Table 6.1). The Bw horizon had slightly higher means than the Cu horizon (27% at Tokoroa and 22.7% at the Taupo study area) but similar low levels in all land uses. The Cu horizon aggregate stability was generally below 12% in the Tokoroa and the Taupo study area.

Table 6.1 Aggregate stability of soil aggregates (between 2 – 4 mm Ø) in % for the Tokoroa and Taupo study areas

Aggregate % > 2 mm						
TOKOROA	PF	C 2	C 3	C 5	D F	SB F
Ap	64.4	35.8	28.6	57.5	70.5	70.7
Bw	14.4	27.7	16.3	43.4	24.2	36.2
Cu	10.0	0.7	15.8	14.4	17.2	8.4
bB	59.2	51.7	55.6	73.4	69.5	65.5
TAUPO	PF	C 3	C 4	C 5	D F	
Ap	75.0	37.8	42.6	52.3	74.7	
Bw	19.9	27.3	17.0	41.9	7.7	
Cu	11.3	5.5	13.3	16.8	7.6	

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

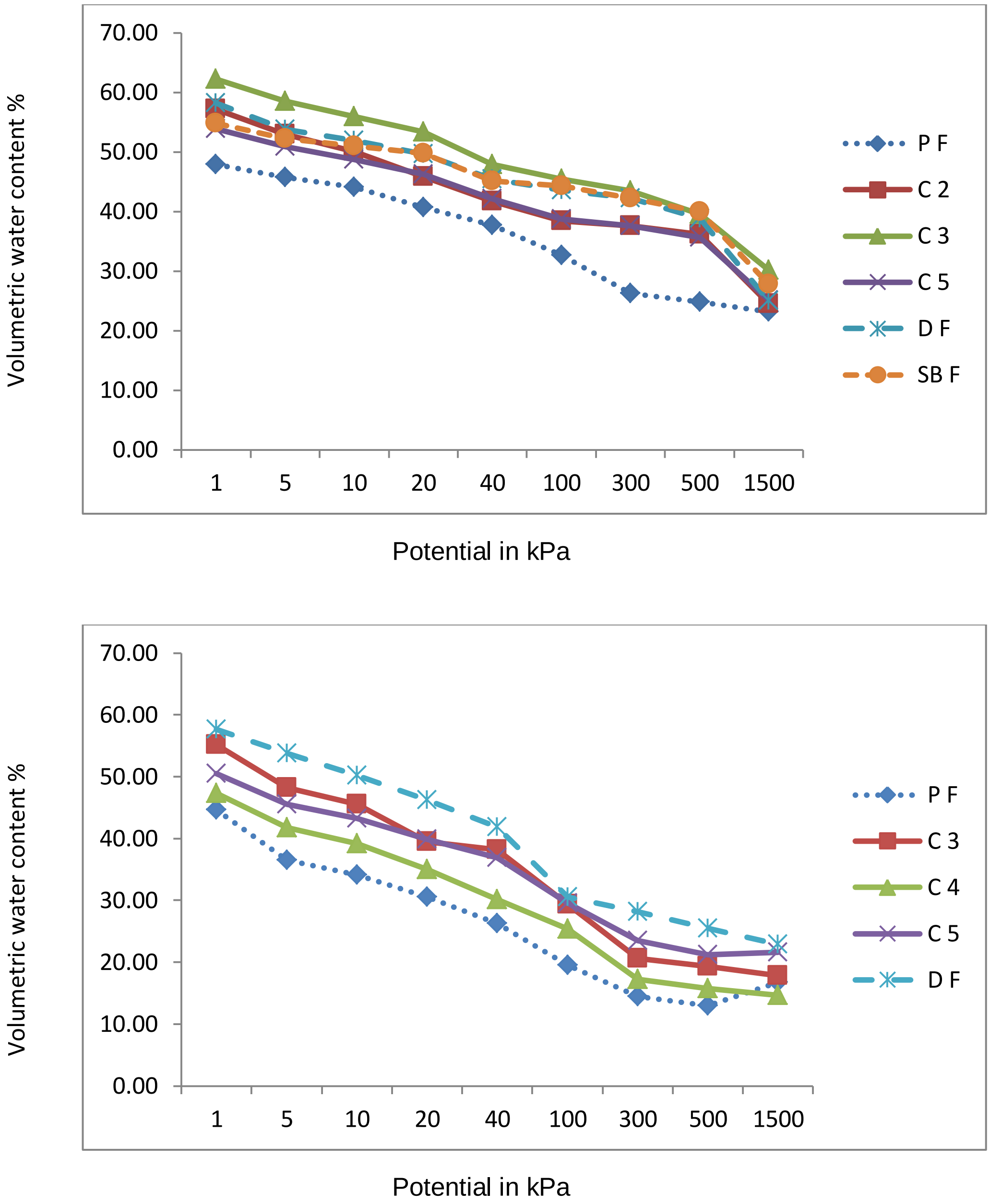
All pastures converted from pine forest had a lot of organic material from the pine trees in the Ap horizon (Figure 6.9a). Bw and Cu horizons across all land uses at both areas contained pumice (Figure 6.9b).

a **b**

Figure 6.9 Dried material (pine remnants and pumice clasts) on the 2 mm sieve after soil was dispersed

6.6 Water release characteristic

The main characteristic of the Pumice Soil (samples from the Ap horizon, approximately 7.5 cm deep) at both study areas is that change of water content was greatest at low potentials (Figure 6.10a, 6.10b). Most of water has been extracted between potentials 1 kPa to 100 kPa. In general water content at 1 kPa capacity was 45 – 60% dropping to 20 – 45% (volumetric moisture content) at 100 kPa and reaching between 15% and 25% (Sheep and beef farm Tokoroa) at 1500 kPa. The main difference between the two study areas is that at the Taupo study area the water content drop was higher between 100 and 500 kPa compared to the Tokoroa study area.



a)

b)

Figure 6.10 Soil moisture release characteristic curve for A horizon soils (7.5 cm depth) from the a) Tokoroa, b) Taupo study area

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

Data are generally means of 5 repetitions except 1500 kPa which are generally means of 3 replications.

At the Taupo study area the pine plantation forest soil had a significantly lower ($P<0.05$) water potential at 10 kPa compared to the 3 and 4 years old conversion or the dairy farm. There were no significant differences of soil water potential at 10 kPa between sites at the Tokoroa study area.

Pine forest soil water potential at 100 kPa was significantly lower ($P<0.05$) compared to 3 and 4 years old conversion or dairy farm soil at the Taupo study area. Pine forest soil at Tokoroa study area had significantly lower ($P< 0.05$) water potential compared to long term sheep and beef farm at 100kPa.

At 500 kPa, the pine forest soil at the Tokoroa study area had lower ($P<0.05$) water potential compared to any other Tokoroa site. At the Taupo study area pine forest soil had lower ($P<0.05$) water potential compared to 3 years old conversion or long term dairy farm.

The pine forest soil had the lowest total available water capacity mean at the Tokoroa and Taupo study area.The long term dairy farm at the Tokoroa and Taupo study area and 3 years old conversion at the Taupo study area had the highest total available water mean (Table 6.2).

Table 6.2 Moisture contents, readily and total available water (% v/v) in the Ap horizon for the Tokoroa and Taupo study areas

Study area	Land use	*10 kPa	100 kPa	**1500 kPa	#RAW	##TAW
Tokoroa	PF	44.1	32.6	23.2	11.5	20.9
	C 2	50.0	38.4	24.5	11.6	25.5
	C 3	56.0	45.4	30.2	10.6	25.8
	C 5	48.7	38.7	25.1	10.0	23.6
	DF	51.9	43.6	25.0	8.3	26.9
	SB F	51.0	44.3	27.8	6.7	23.2
Taupo	PF	34.1	19.5	16.7	14.6	17.4
	C 3	45.6	29.4	17.8	16.2	27.7
	C 4	39.2	25.4	14.6	13.8	24.6
	C 5	43.2	29.6	21.6	13.7	21.6
	DF	50.2	30.5	22.9	19.7	27.3

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

*10 KpA = field capacity, 1500 kPa = permanent wilting point; RAW= readily available water capacity (10-100 kPa), TAW =total available water capacity (10-1500 kPa)

At both Tokoroa and Taupo the long term dairy farm sites and long term sheep and beef farm at Tokoroa had the highest amounts of available water (TAW) (Table 6.3). Assuming a 400 mm potential rooting depth and evapotranspiration of 4 mm/day gives 11.5 days of plant readily available moisture (RAW) supply in the pine forest soil or 6.7 days in the long term sheep and beef farm at Tokoroa (Table 6.3).

Table 6.3 Amounts of available water in millimetres held in Ap and Bw horizon for the Tokoroa and Taupo study areas

		*Ap horizon		#Ap +Bw horizon		+Days of supply Ap+ Bw TAW		++Days of supply RAW 4 mm ET roots deep in mm		
Study area	Land use	mm thickness	TAW mm	mm thickness	TAW mm	4 mm ET	6 mm ET	200	300	400
Tokoroa	PF	118	24.7	280	58.6	14.65	9.8	5.7	8.6	11.5
	C 2	111	28.3	180	45.9	11.49	7.6	5.8	8.7	11.6
	C 3	108	27.9	230	59.3	14.84	9.9	5.3	7.9	10.6
	C 5	101	23.9	200	47.3	11.82	7.9	5.0	7.5	10.0
	DF	123	33.0	240	64.6	16.14	10.8	4.1	6.2	8.3
	SB F	123	28.5	310	71.8	17.96	12.0	3.3	5.0	6.7
Taupo	PF	145	25.2	370	64.4	16.11	10.7	7.3	11.0	14.6
	C 3	135	37.4	310	86.0	21.50	14.3	8.1	12.2	16.2
	C 4	183	44.9	360	88.4	22.11	14.7	6.9	10.4	13.8
	C 5	152	32.8	360	77.8	19.46	13.0	6.8	10.3	13.7
	DF	161	44.0	360	98.4	24.60	16.4	9.9	14.8	19.7

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

[*] Ap horizon thickness data adopted from Lewis, (2011).

[#] Based on assumption that water holding capacity of Pumice Soil in A and B horizon is same (Jackson, 1974).

[+] Water supply (number of days) assuming that a crop can utilize water held in a soil between 10-1500 kPa water potential (total available water), assuming daily evapotranspiration rate is 4 or 6 mm.

[++] Water supply in a number of days assuming a crop can utilize water held in a soil between 10-100 kPa water potential (readily available water), roots reaching 200mm, 300mm or 400mm deep in soil horizon.

6.7 Field moisture content

Soil sampling was generally undertaken during dry periods and field moisture contents were mainly in the range of 20 – 40 % (gravimetric) (Table 6.4). At the Tokoroa study area where a buried B horizon was encountered within the soil profile it generally had higher (mean 77.42 % gravimetric moisture) moisture content than overlying soil horizons.

Table 6.4 Field moisture contents (% gravimetric) for the Tokoroa and Taupo study areas

Study area	Horizon	PF	C 2	C 3	C 5	DF	SB F	Mean
Tokora	*Ap*	29.53	19.36	55.16	51.18	40.36	52.13	41.29
	Bw	29.36	29.60	47.15	28.19	37.25	36.92	34.75
	Cu	20.18	21.55	37.22	29.25	29.85	26.45	27.42
	Bb	50.26	90.15	86.67	79.71	73.22	84.49	77.42
		PF	C 3	C 4	C 5	DF		
Taupo	*Ap*	29.53	32.41	33.88	43.13	51.59		38.11
	Bw	29.36	33.33	27.61	11.48	42.79		28.92
	Cu	20.18	32.54	14.93	21.81	45.75		27.04

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

Soil moisture samples were collected mainly in dry periods of the year 2010 (March- May), but Long term dairy pasture in Taupo was sampled in October 2010 (Figure 6.11). At the time of field sampling most of the soils had volumetric moisture content higher than water potential at 1500 kPa (Permanent wilting point), but lower than 100 kPa water potential (Readily available water) (Table 6.5).

Figure 6.11 2 years since conversion pasture at Tokoroa (left) and the long term dairy pasture at Taupo study area (right) at the time of sampling

Table 6.5 Ap horizon volumetric field moisture contents compared to water potential at 100 kPa and 1500 kPa for the Tokoroa and Taupo study areas

	Ap horizon	P F	C 2	C 3	C 5	D F	SB F
Tokoroa	Field moist (%v/v)	$^{+}$17.0	$^{+}$12.6	39.5	34.0	28.1	33.9
	100 kPa	32.6	38.4	45.4	38.7	43.6	44.3
	1500 kPa	23.2	24.5	30.2	25.1	25.0	27.8
		PF	C 3	C 4	C 5	D F	
Taupo	Field moist	19.6	23.9	21.6	25.2	*40.3	
	100 kPa	19.5	29.4	25.4	29.6	30.5	
	1500 kPa	16.7	17.8	14.6	21.6	22.9	

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

+ indicates field volumetric water content values below permanent wilting point (1500 kpa)

* indicates field volumetric water content values between 10-100 kPa water potential, (RAW=readily available water)

6.8 Soil pH

At both study areas pH values in the pine forest were from 4.5 to 5.8. Only two measurements exceeded pH 6, which were in 2 and 3 years old pastures converted from pine forest at the Tokoroa study area.

Table 6.6 Soil pH values for the Tokoroa and Taupo study areas

TOKOROA	PF	C 2	C 3	C 5	DF	SB F
Ap	4.54	6.08	6.03	5.4	5.51	5.28
Bw	5.44	5.87	5.90	5.76	5.73	5.63
Cu	5.78	5.81	5.85	5.66	5.81	6.00
Bb	5.78	5.89	5.71	5.78	5.76	5.85
TAUPO	PF	C 3	C 4	C 5	DF	
Ap	5.28	4.92	4.78	5.33	5.24	
Bw	5.35	5.41	4.98	4.99	5.32	
Cu	5.14	5.43	5.11	5.55	5.48	

Where: PF = pine plantation forest, C 2 = pasture converted from pine forest 2 years ago, C 3 = pasture converted from pine forest 3 years ago, C 4 = pasture converted from pine forest 4 years ago, C 5 = pasture converted from pine forest 5 years ago, DF = long term (50+ years) dairy farm, SB = long term (50+ years) sheep and beef farm.

6.9 Particle size distribution

The Pumice Soil at the Tokoroa and Taupo study areas had low (generally less than 5%) clay content (particles < 0.002 mm) in all soil horizons. Dominant particle size in A and B horizons were silt (particles 0.06-0.002 mm) up to 67%, and sand in C horizon (particles > 0.06 mm) up to 66%. In most cases A and B horizon soil has been classified as sandy loam and soil from the C horizon as loamy sand.

Detailed particle size distribution analyses are presented in Appendix 2.

Chapter 7

Discussion and conclusions

7.1 Introduction

The Central North Island of New Zealand is currently undergoing a change in land use from forest to dairy pasture. Sustainable management of the land and water resources requires understanding of the functioning of the soil, and its resilience, so that soil health and fertility can be sustained and even enhanced in the quest for development of pastoral production systems.

The overall objective of this study was to investigate changes in soil physical properties in Pumice Soils following land use change from forest to pasture. Specific objectives were investigation of individual soil physical properties including: penetration resistance, degree of packing, soil dry bulk density, soil hydrophobicity, unsaturated (K_{-40}) and saturated (K) hydraulic conductivity, soil moisture retention, aggregate stability, and soil pH.

At each study area a series of sites including: plantation pine forest, pasture converted from pine forest 2,3,4 and 5 years ago, long term (>50 years) dairy and long term sheep and beef farm were identified, all on Taupo Pumice Soil, in similar landscape positions.
This chapter discusses methods and findings described in the previous two chapters; it presents conclusions, and offers recommendations for further research.

7.2 Discussion of attributes measured

The most of analysis resulted in highly variable data which may be attributed to natural soil variability as well as differences in the presence of pine remnants and pumice clasts.

7.2.1 Soil profile description

At the Tokoroa study area 6 study sites were identified and at the Taupo study area 5 study sites were identified. A total of 33 soil profile pits were dug, 3 on each study site. Pits were used for soil sampling, soil consistency measurement (penetration resistance and degree of packing) and one pit per study site was used for soil profile description.

The main obstacles during the field investigation process were weather-related (wind or rain). Each profile was photographed under natural light, which was challenging especially in pine forest sites. Soil profile description is time consuming process but necessary because it provided descriptive and quantitative information on Pumice Soil features and on the differences between soils under different stages of pasture development.

7.2.2 Penetration resistance and degree of packing

Penetration resistance and degree of packing measurements are indicative when taken from soils at or near field capacity (soil water held at -10 to -30 kPa) (Milne *et al.,* 1995; Griffiths, *et al.,* 1999; Sojka *et al.,* 2001). The readings for this research were undertaken in dry periods of the year 2010 and soil moisture of Ap horizons was generally held in range -100 and -1500 kPa of water potential (Chapter 6, Table 6.5). Penetration resistance and degree of packing measurement at varying moisture content in our research was useful to compare individual horizons in the same profile. However data have to be interpreted with care with regard to comparison between sites. The penetration resistance and degree of packing were generally lower in the A horizon than deeper horizons at both study areas across all land uses.

The degree of packing was lower ($P < 0.01$) in the A horizon of the pine forest in Tokoroa than any other site. At Taupo the degree of packing of the pine forest soil was generally lower than the rest of the sites (except highly variable sites, 4 and 5 years ago converted).

7.2.3 Bulk density

The undisturbed soil cores used for measuring water infiltration rate were also used to measure soil dry bulk density in five replicates. After the water infiltration rate analyses were completed, the undisturbed cores were subsampled using smaller stainless steel cores (144 cm^3volume) driven into the bigger core using a block of wood and a mallet. The soil dry bulk density data means were varied less than ±5 % and were comparable to measurements undertaken by Lewis, (2011), in a parallel project sampling at the same sites. Murty *et al.,* (2002) reported that soil dry bulk density generally increases upon conversion from forest to agricultural land. Our results from both study areas (Tokoroa and Taupo) suggest that conversion from pine plantation forest to pasture was associated with increased soil dry bulk density in the A horizon.

7.2.4 Hydraulic conductivity

Unsaturated and saturated hydraulic conductivity were determined in the laboratory on undisturbed soil cores (Figure 7.1). Methods and equipment were trialled by running a number of trials on spare soil cores which were taken for training purpose during the sampling process.

Figure 7.1 Undisturbed soil cores used for hydraulic conductivity and soil dry bulk density measurement.
Dashed line showing pumice material and pine cone present in cross section of the core.

The results for saturated and unsaturated hydraulic conductivity were highly variable. The data variability was generally highest in measurements of hydraulic conductivity performed on cores from conversion sites. However, the highest standard deviation at the Tokoroa study area saturated hydraulic conductivity was for the pine forest and the long term dairy pasture.

Unsaturated hydraulic conductivity was measured in the laboratory using a disc-permeameter, which required that soil cores were equilibrated to a -0.4 kPa water potential and steady state of water movement established before measurement was undertaken. This prevented the effect of soil water repellency (evident particularly at conversion sites) on unsaturated hydraulic conductivity rate.

At the Tokoroa study area there was no significant difference in unsaturated hydraulic conductivity (K_{-40}) between the pine forest, and pastures converted from pine forest or long term pastures. At the Taupo study area, only the pasture converted from pine forest 3 years ago (the most recent conversion) had significantly lower ($P < 0.05$) unsaturated hydraulic conductivity compared to the pine forest samples.

The mean saturated hydraulic conductivity (K_{sat}) at the Tokoroa study area in the pine forest samples were the highest. However only pastures converted from pine forest 5 years ago (C 5) and the long term sheep and beef farm had significantly lower ($P < 0.05$) saturated infiltration rate than the pine forest. At the Taupo study area the saturated hydraulic conductivity values measured on the dairy farm samples (mean 91.32 mm/hour) were the highest and the pine forest second highest (mean 72.28 mm/hour). However none of the land uses had significantly different infiltration rate compared to the pine forest.

Taylor *et al*. (2009) investigated infiltration characteristics of Pumice Soil by in situ measurements using a double ring infiltrometer at five paired sites, under agriculture and forestry, for 5 soils typical of the upper Waikato catchment (Central North Island). The results from their measurements showed infiltration under grazed pasture (between 3 and 99 mm h/hour) was an order of magnitude less than that under pine forest (121-1207 mm/hour) for all 5 sites.

K_{sat} measurement is sensitive to occasional occurrence of large macro-pores and the lower bulk density of the pine forest soils implies greater porosity. It may be that the larger samples captured by the double rings (Taylor *et al*. (2009)) increased the probability of capturing occasional large macro-pores, thus giving the higher K_{sat} reported by Taylor *et al*. (2009) than we found. Also removing soils in smaller cores may lead to some compaction and blocking of macro-pores. Another possible explanation for the difference between my results and those of Taylor *et al*. (2009) is that in the laboratory my samples were soaked overnight to ensure saturation before measurement. In the field it is often difficult to achieve truly saturated soil conditions, often resulting in higher K_{sat} being recorded.

7.2.5 Soil aggregate stability

Soil aggregate stability measurement was laborious and time consuming, the results generally suggested lower stability of 2-4 mm soil aggregates from samples taken from conversion sites of the Ap horizon compared to Ap horizon soil samples from pine forest or long term pastures. Data for B, C, and bB horizons did not suggesting any change in aggregate stability as a result of the conversion process.

7.2.6 Soil water repellency

Simple soil water repellency measurement gave variable, but meaningful, and sufficiently conclusive data, for this kind of research. In most studies to date, soils have exhibited WDPT (Water drop penetration time) of less than 600 seconds (values exceeding 1 or even 5 hours have been reported) (Doerr, 2000). Our measurements of water repellency for the Ap horizon at conversion sites (both study areas) and the long-term dairy farm at the Tokoroa study area were in the range 5 – 600 seconds (only one reading was >900 seconds). All three Ap horizon soil samples from dairy pastures converted from pine forest at the Taupo study area, and soil from 2 years since converted pasture and the dairy farm at the Tokoroa study area, were categorised as strongly water repellent soils ($60 < \text{WDPT} \geq 900$).

7.2.7 Particle size distribution and soil pH

Particle size distribution and soil pH are laboratory methods performed under controlled conditions. There was low clay content (< 5%) in all horizons with no marked differences between sites or study areas. Dominant particle size in A and B horizon were silt (particle size 0.06 – 0.002 mm) up to 67% and sand (particles > 0.06 mm) in C horizon up to 66%.

Higher soil pH values at the Tokoroa study area conversion sites compared to the pine forest can be contributed to high rate (3.5 T/ha) lime application during conversion process.

7.2.8 Moisture release characteristic

The pressure plate method was used to determine the soil moisture curve. Undisturbed soil cores were used for water potentials between 1 to 500 kPa and disturbed homogenised soil samples for 1500 kPa water potential. Some difficulty was experienced when fine adjustment for low pressure potentials (1-10 kPa) was required (the controlling knobs and gauge scale are designed for higher pressure adjustment). However the pressure plate and measurement provided data which are meaningful and useful to recognize important soil characteristics change in process of conversion from pine forest to dairy pasture. The range of data for Ap horizon field capacity from our measurements (34 - 56% vol.) was similar to published data for New Zealand's sandy loam soils (29 - 51.5% vol.) (McLaren and Cameron, 1996). The range for PWP (permanent wilting point) for the Ap horizon for both, the Tokoroa and Taupo study areas, was 14.6 - 30% vol. compared to 7 - 28% vol. for published sandy loam soil data range (McLaren and Cameron, 1996). Our range for TAW (total available water) was 17-27% vol., lower than published data for Taupo Pumice Soil, which was 30% vol. (New Zealand Soil Bureau, 1968).

7.3 Conclusions

In general, soil properties change after conversion from pine plantation to pasture, reflects in 3 main aspects:

- There was increased soil compaction as evidenced by increased soil dry bulk density, increased penetration resistance, and degree of packing, of the A horizon on recently converted sites compared to pine forest sites.
- The water repellency of recently converted pastures was higher ($P < 0.05$) than pine forest at both study areas. Two of the three long-term pasture sites investigated had very low water repellency.
- The long term pasture sites had markedly higher total available water holding capacity than either the recent converted or the pine forest sites.

Recently converted sites had distinct and coherent A horizons with no clear pattern of changes in colour pedality or boundary distinctiveness and shape between different land use histories. This illustrates soil's resilience given the major disturbances that are undergone in tree removal and pasture establishment.

Depths of A horizon at both study areas were deepest (15-20 cm) under long term dairy followed by forest and shallowest (8-13 cm) on sites converted from pine plantation forest.

Pine forest sites had a less developed soil structure (apedal earthy) then some of the other sites (moderately developed: blocky or polyhedral).

The degree of packing was lower ($P< 0.01$) in the A horizon of the pine forest in Tokoroa than any other site. At the Taupo area the degree of packing of the pine forest was generally lower then rest of sites (except the highly variable sites, converted 4 and 5 years ago).

The soil dry bulk density at both study areas (Tokoroa and Taupo) was generally low, ranging from 0.58 to 0.78 g/cm^3. At the Tokoroa study area the pine forest soil had a significantly lower dry bulk density ($P < 0.05$) than any of the pasture sites (Figure 6.1). At the Taupo study area only long term dairy (mean 0.78 g/cm^3) and the youngest pasture site (3 years since converted from pine forest) (mean 0.74 g/cm^3) had higher ($P < 0.05$) bulk density compared to the plantation pine forest soil .

Soil water repellency was evident in the A horizon in both study areas. The soil samples from most recently converted pastures had the higher water repellency than other sites

There were no significant differences in hydraulic conductivity between sites in each study area except the Taupo 3 years since conversion, was lower ($P < 0.05$) than the Taupo pine forest site.

At the Taupo study area none of the land uses had significantly different saturated infiltration rate compared to the pine forest, at the Tokoroa study area the pine forest saturated hydraulic conductivity rate was significantly higher than the 5 years old conversion and the long term sheep and beef farm.

Aggregate stability of the A horizon was noticeably lower in recently converted pastures than in the pine forest or long term pasture sites. Bw and Cu horizons across all land uses in both areas had generally low aggregate stability which was not affected by land use.

The pine forest soil water potential at 10 kPa (Field capacity) and 100 kpa (Readily available water) was generally lowest amongst all land uses. At both Tokoroa and Taupo the long term dairy farm sites and long term sheep and beef farm at Tokoroa had the highest amounts of available water (TAW) held in the Ap horizon.

7.4 Recommendations for future research

Further research is required to investigate change in soil physical properties in pastures converted from pine forest. The following recommendations are suggested.

- Sampling and investigation of soil physical properties after pine forest clearance before and during pasture establishment and also before stocking. This might show what soil properties change is caused by stock trampling and grazing, what change is contributed to forest clearance and pasture establishment.
- To investigate the effect of soil water repellency on unsaturated water infiltration rates.
- To determine the effects of different soil moisture on contents penetration resistance and degree of packing.
- Time series with repeated investigations of the same sites.
- To compare grass/clover pasture water efficiency to deep rooted crops (maize or lucerne) on Pumice Soil.

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Personal communications

Ricky Tuck, Farm manager, Maxwell Farms, Tokoroa, New Zealand.
In discussion, April 2010.

Alan Bullick, Farm manager, Wairakei Estate, Taupo, New Zealand,
In discussion, April 2010.

Appendix 1: Soil profile descriptions

P F Tokoroa – Plantation pine forest

Location:	Approximately 4 km west north-west of the intersection between Jack Henry Road and the entrance to Maxwell Farms
WGS 84 reference:	S: 38˚ 12’ 56.3” E: 175˚ 44’ 34.9”
Altitude:	300 m
Topography:	Profile on flat area in plantation forest, some small undulation in the area around the pit
Drainage:	Well drained
Vegetation:	Pine (*Pinus radiata*), blackberry, fern
Land use:	Plantation pine forest
NZ Soil classification	Pumice Soil
Paleosol	Ignimbrite

Horizon depth	**Description**
Ap 0-13 cm	Black (10YR 1.7/1) loamy sand, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, abundant very fine to coarse roots, moderate NaF reaction, distinct smooth boundary.
Bw 13-28 cm	Dark brown (10YR 3/3) loamy sand, non- sticky, non-plastic, weak soil strength, friable, apedal earthy, many very fine to fine roots, light grey (10YR 8/2) common very fine to fine pumice lapilli, moderate NaF reaction, indistinct smooth boundary.
Cu 28-68 cm	Dull yellow orange (10YR 6/4) loamy sand, non-sticky, non-plastic, weak soil strength, friable, weak pedality, common fine polyhedral peds breaking to apedal earthy, light grey (10YR 8/1) few very fine pumice lapilli, moderate NaF reaction.
bB 68- >84 cm	Brown (7.5YR 4/6) silt loam, moderately sticky, moderately plastic, weak soil strength, apedal massive, moderate NaF reaction.

C 2 Tokoroa – 2 years since conversion (converted 2008)

Location:	Maxwell Farms Tokoroa, Unit 6 paddock 23, approximately 7 km west north west of the intersection between Jack Henry Road and the entrance to Maxwell Farms
WGS 84 reference:	S: 38˚ 12’ 36.6” E: 176˚ 42’ 38.5”
Altitude:	324 m
Topography:	Shoulder of low hill approximately 100 m south of sheep farm boundary, 50 m south east of gully edge
Drainage:	Well drained
Vegetation:	Grass and clover mixture, broadleaf weeds: foxglove, willow weed, blackberry, Yorkshire fog, ink weed, fox glove, scotch thistle, nodding thistle
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands
Paleosol	Ignimbrite

Horizon depth	Description
Ap 0-12 cm	Brownish black (7.5YR 2/2) sandy silt; spot mottles, pumice gravel bright brown (7.5YR 5/6), inclusions of charcoal 3% (2-30 mm in size), wood and B horizon material; slightly plastic, slightly sticky, sandy in lower part, very friable, moderate coarse, platy pedality breaking to apedal earthy, peds soft fine crumb and granular structure, weak to moderate positive reaction on NaF test, slightly firm, many fine fibrous roots few woody brown dead roots up to 50 mm in diameter, abrupt convolute boundary.
Bw 12-18 cm	Brown (10YR 4/4), sandy loam, yellow-brown to dark grey mottles, non-plastic slightly sticky, sandy, weak pedality degree, fine to coarse blocky, light grey (10YR 8/2) common fine pumice lapilli, occasional pumice gravel 2% (2-5 mm), common fine roots, boundary distinct wavy
Cu 18-52 cm	Yellow brown (10YR 5/6) silty sand to coarse sand, weakly compact, structureless, pumice gravel present 10%, no roots present, boundary wavy distinct.
bB 52- >70 cm	Pale brown (7.5YR 4/6), silty loam, weathered ignimbrite, moderately sticky, moderately plastic, pumice lapilli present in upper part of horizon.

C 3 Tokoroa – 3 years since conversion (converted 2008)

Location:	Maxwell Farms, Tokoroa, Unit 6, paddock 15, highest point of the paddock, 80-90 m west from the fence
WGS 84 reference:	S: 38º 13' 02.7" E: 176º 43' 15.5"
Altitude:	327m
Topography:	Relatively small area of flat, rest of the paddock steep
Drainage:	Well drained
Vegetation:	Grass and clover mixture, broadleaf weeds: foxglove, scotch thistle, willow weed, blackberry, Yorkshire fog,
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands
Paleosol	Ignimbrite

Horizon depth	Description
Ap 0-10 cm	Black (10YR 1.7/1) sandy silt; spot mottles, pumice gravel light brownish grey (7.5YR 7/1), inclusions of pumice 1% (1-60 mm) and charcoal 5% (2-30 mm in size), wood and B horizon material; slightly plastic, slightly sticky, very friable, moderate coarse, blocky pedality breaking to apedal earthy fine crumbs, peds soft fine crumb and granular structure, weak to moderate positive reaction on NaF test, slightly firm, many fine fibrous roots few woody brown dead roots up to 50 mm in diameter, weak NaF reaction, distinct smoth boundary.
Bw 10-23 cm	Brown (7.5YR 4/4), sandy loam, yellow-brown to dark grey mottles, non-plastic slightly sticky, sandy, weak pedality degree, fine to coarse blocky, occasional pumice gravel 5% (2-15 mm), common fine roots, weak NaF reaction, boundary distinct smooth.
Cu 23-61 cm	Yellowish brown (10YR 5/6) silty sand to coarse sand, weakly compact, structureless, pumice gravel present 10%, no roots present, weak NaF reaction, boundary distinct smooth.
bB 61- >85 cm	Pale brown (7.5YR 4/6), silty loam, weathered ignimbrite, moderately sticky, moderately plastic, pumice lapilli present in upper part of horizon weak NaF reaction.

C 5 Tokoroa – 5 years since conversion

Location:	Maxwell Farms, Tokoroa, Unit 6, paddock 49, approximately 4.5 km west north west of the intersection between Jack Henry Road and the entrance to Maxwell Farms
WGS 84 reference:	S: 38˚ 12' 37.4" E: 176˚ 44' 06.4"
Altitude:	312 m
Topography:	Undulating to rolling slopes surroundings, profile on terrace, shoulders of low hill
Drainage:	Well drained
Vegetation:	Grass and clover mixture, broadleaf weeds: foxglove, scotch thistle, willow weed, blackberry, ragwort
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands
Paleosol	Ignimbrite

Horizon depth	**Description**
Ap 0-10 cm	Black (10YR 1.7/1) loamy sand; few fine prominent brown (7.5YR 5/6) mottles; non sticky, non-plastic, slightly firm soil strength, brittle, moderate pedality, many fine to coarse blocky peds breaking to apedal earthy, many very fine to fine roots, light grey (10YR 8/2) very few very fine pumice lapilli, weak NaF reaction, distinct occluded boundary.
Bw 10-20 cm	Brown (10YR 4/4) loamy sand, non-sticky, non-plastic, slightly firm soil strength, brittle failure, weak pedality, common fine to course blocky peds breaking to apedal earthy, common very fine roots, light grey (10YR 8/2) few fine to medium pumice lapilli, weak NaF reaction, indistinct smooth boundary.
Cu 20-44 cm	Light yellow (10YR 5/6) loamy sand, non-sticky, non-plastic, weak soil strength, brittle failure, weak pedality, common fine to course blocky peds breaking to apedal earthy, few very fine roots, light grey (10YR 8/1) few very fine to fine pumice lapilli, weak NaF reaction, distinct smooth boundary.
bB 44- >80 cm	Brown (7.5YR 4/6) silt loam, moderately sticky, moderately plastic, weak soil strength, apedal massive breaking to apedal earthy, moderate NaF reaction.

D F Tokoroa – Long term (> 50 years) dairy farm pasture

Location:	Hunt farm approximately 7.5 km west north west of the intersection between Jack Henry Road and the entrance to Maxwell Farms
WGS 84 reference:	S: 38˚ 12' 32.6" E: 175˚ 42' 17.9"
Altitude:	333 m
Topography:	Flat paddock with some small undulations, gully directly south of paddock
Drainage:	Well drained
Vegetation:	Grass and clover mixture, broadleaf weeds: foxglove, scotch thistle, willow weed, ragwort, plantain, yarrow,
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Paleosol	Ignimbrite

Horizon depth	**Description**
Ap 0-15 cm	Very dark brown (7.5YR 2/3) sandy loam, slightly sticky, slightly plastic, weak soil strength, brittle failure, moderate pedality, abundant very fine to fine polyhedral peds breaking to apedal earthy, abundant very fine to fine roots, light grey (10YR 8/1) few very fine pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Bw 15-24 cm	Yellowish brown (10YR 5/6) loamy sand, slightly sticky, non-plastic, weak soil strength, brittle failure, weak pedality, common very fine to fine polyhedral peds breaking to apedal earthy, few fine roots, light grey (10YR 8/1) few very fine pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Cu 24-43 cm	Yellowish Brown (10YR 5/8) loamy sand, non-sticky, non-plastic, weak soil strength, brittle failure, weak pedality, common fine to medium polyhedral peds breaking to apedal earthy, common fine roots, light grey (10YR 8/1) fine very fine to medium pumice lapilli, moderate NaF reaction.
bB 43- >70 cm	Brown (7.5YR 4/6) silt loam, moderately sticky, moderately plastic, weak soil strength, apedal massive, strong NaF reaction.

SB F Tokoroa – Long term (> 50 years) sheep and beef farm pasture

Location:	Ranger sheep and beef farm approximately 6 km west north west of the intersection between Jack Henry Road and the entrance to Maxwell Farms
WGS 84 reference:	S: 38˚ 12' 31.2" E: 175˚ 43' 19.4"
Altitude:	314 m
Topography:	Flat paddock with some small undulations
Drainage:	Well drained
Vegetation:	Grass and clover mixture, broadleaf weeds: brown top, scotch thistle, ragwort, plantain, yarrow.
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Paleosol	Ignimbrite

Horizon depth	**Description**
Ap 0-12 cm	Black (7.5YR 2/1) sandy loam, slightly sticky, slightly plastic, weak soil strength, brittle failure, moderate pedality, abundant very fine to fine polyhedral peds breaking to apedal earthy, abundant microfine to fine roots, light grey (10YR 8/1) very few very fine to medium pumice lapilli, moderate NaF reaction, distinct occluded boundary.
Bw 12-31 cm	Brown (10YR 4/6) loamy sand, slightly sticky, slightly plastic, weak soil strength, friable, weak pedality, common very fine to coarse polyhedral peds breaking to apedal earthy, many microfine roots, light grey (10YR 8/1) common extremely fine to fine pumice lapilli, moderate NaF reaction, indistinct smooth boundary.
Cu 31-63 cm	Yellowish Brown (10YR 5/8) loamy sand, non-sticky, non-plastic, weak soil strength, brittle failure, weak pedality, common fine to medium polyhedral peds breaking to apedal earthy, common fine roots, light grey (10YR 8/1) fine very fine to medium pumice lapilli, moderate NaF reaction.
bB 63- >76 cm	Brown (7.5YR 4/6) silt loam, moderately sticky, moderately plastic, weak soil strength, apedal massive, strong NaF reaction.

P F Taupo – Plantation pine forest

Location:	Approximately 300 m north west of State Highway 5, 25 km north north-east of Taupo Town
WGS 84 reference:	S: 38˚ 32’ 06.3” E: 176˚ 15’ 44.0”
Altitude:	386 m
Topography:	Profile on flat area in plantation forest, many small ridges (1m), some small undulation in the area around the pit
Drainage:	Well drained
Vegetation:	Pine (*Pinus radiata*), blackberry, fern
Land use:	Plantation pine forest
NZ Soil classification	Pumice Soil

Horizon depth	**Description**
Ap 0-19 cm	Black (7.5YR 2/1) loamy sand, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, abundant very fine to fine roots, light grey (10YR 8/2) common very fine to coarse pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Bw 19-37 cm	Orange (7.5YR 6/6) loamy sand, non-sticky, non-plastic, weak soil strength, brittle, cloddy, many very fine to medium roots, light grey (10YR 8/2) many very fine to coarse pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Cu 37->95 cm	Light brownish grey (7.5YR 7/1) loamy sand, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, many fine to medium roots, light grey (10YR 8/1) abundant very fine to coarse pumice lapilli, moderate NaF reaction.

C 3 Taupo – 3 years since conversion (converted 2007)

Location:	Approximately 150m south east of State Highway 5 in paddock 521, Pinta farm, Wairakei Pastoral LTD
WGS 84 reference:	S: 38˚ 31’ 59.6” E: 176˚ 16’ 03.3”
Altitude:	364 m
Topography:	flat part of paddock on a small terrace
Drainage:	Well drained
Vegetation:	Grass and clover mixture, chicory, broadleaf weeds: Californian thistle, blackberry
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands
Paleosol	Ignimbrite

Horizon depth	**Description**
Ap 0-13 cm	Dark reddish brown (5YR 3/2) sandy loam, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, abundant very fine to fine roots, light grey (10YR 8/2) common fine pumice lapilli, weak NaF reaction, distinct smooth boundary.
Bw 13-31 cm	Brown (7.5YR 4/6) loamy sand, non-sticky, non-plastic, moderate soil strength, brittle failure, moderate pedality, abundant fine to course blocky peds breaking to apedal earthy, abundant fine roots, light grey (10YR 8/2) many fine to coarse pumice lapilli, moderate NaF reaction, indistinct smooth boundary.
Cu 31->76 cm	Orange (7.5YR 7/6) loamy sand, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, light grey (7.5YR 8/2) many very fine to medium pumice lapilli, weak NaF reaction.

C 4 Taupo – 4 years since conversion (converted 2006)

Location:	Approximately 300 m north west of State Highway 5 on Renown farm, Wairakei Pastoral LTD
WGS 84 reference:	S: 38˚ 30’ 49.7” E: 176˚ 17’ 00.9”
Altitude:	354 m
Topography:	Flat part of paddock on a small terrace, small undulations in rest of the paddock
Drainage:	Well drained
Vegetation:	Grass and clover mixture, chicory, broadleaf weeds: Californian thistle, blackberry
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands

Horizon depth	**Description**
Ap 0-16 cm	Brownish black (7.5YR 2/2) loamy sand, slightly sticky, non plastic, weak soil strength, friable, apedal earthy, abundant very fine to fine roots, light grey (10YR 8/2) common very fine pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Bw 16-36 cm	Brown (7.5YR 4/4) loamy sand, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, common fine roots, light grey (10YR 8/1) abundant fine pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Cu 36->90 cm	Light brownish grey (7.5YR 7/2) loamy sand, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, light grey (10YR 8/1) abundant very fine to very coarse pumice lapilli, moderate NaF reaction.

C 5 Taupo – 5 years since conversion (converted 2005)

Location:	Approximately 100 m west of State Highway 5 paddock 308 Renown farm Wairakei Pastoral LTD.
WGS 84 reference:	S: 38˚ 29’ 53.0” E: 176˚ 17’ 20.1”
Altitude:	356 m
Topography:	Flat part of paddock on a small terrace, small undulations in rest of the paddock, western paddock boundary is a steep cliff
Drainage:	Well drained
Vegetation:	Grass and clover mixture, chicory, broadleaf weeds: blackberry
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands

Horizon depth	**Description**
Ap 0-8 cm	Brownish black (7.5YR 2/2) sandy loam, non-sticky, non-plastic, weak soil strength, brittle, moderate pedality, abundant fine to medium polyhedral peds, abundant very fine to fine roots, light grey (7.5YR 8/1) few very fine pumice lapilli, moderate NaF reaction, indistinct smooth boundary.
Bw 8-36 cm	Bright black (7.5YR 5/8) sandy loam, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, common fine roots, light grey (7.5YR 8/1) abundant fine to medium pumice lapilli, moderate NaF reaction, indistinct smooth boundary.
Cu 36->70 cm	Orange (7.5YR 6/6) sandy loam, non-sticky, non-plastic, weak soil strength, friable, apedal earthy, light grey (10YR 8/1) abundant fine to medium pumice lapilli, moderate NaF reaction.

D F Taupo – Long term (> 50 years) dairy farm pasture

Location:	Approximately 600 m north of Tutukau Road, Nui Friesian Farm,paddock 31, 27 km north north-east of Taupo Town
WGS 84 reference:	S: 38˚ 29’ 13.7” E: 176˚ 15’ 01.4”
Altitude:	376 m
Topography:	very flat paddock with small undulations
Drainage:	Well drained
Vegetation:	Grass and clover mixture, chicory, broadleaf weeds: yarrow, coxfoot, scotch thistle, nodding thistle
Land use:	Dairy pasture
NZ Soil classification	Pumice Soil
Soil Taxonomy	Vitrands

Horizon depth	**Description**
Ap 0-20 cm	Black (7.5YR 2/1) loamy sand, slightly sticky, non-plastic, weak soil strength, very friable, apedal earth, abundant very fine to fine roots, light grey (7.5YR 8/2) common fine pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Bw 20-36 cm	Black (7.5YR 2/1) loamy sand, slightly sticky, non-plastic, weak soil strength, very friable, apedal earth, abundant very fine to fine roots, light grey (7.5YR 8/2) common fine pumice lapilli, moderate NaF reaction, distinct smooth boundary.
Cu 36->81 cm	Bright yellowish brown (10YR 6/6) loamy sand, non-sticky, non-plastic, weak soil strength, very friable, apedal earthy, common fine roots, light grey (10YR 8/1) abundant fine to coarse pumice lapilli, moderate NaF reaction.

Appendix 2: Raw Data

Table A2.1: Penetration resistance and degree of packing (Tokoroa)

	TOKOROA											
Horizon	Penetration resistance Mpa						Degree of packing Mpa					
Ap	P F	C 2	C 3	C 5	D F	SB F	P F	C 2	C 3	C 5	D F	SB F
	0.27	2.68	1.34	2.55	0.67	1.01	0.47	2.68	1.61	1.14	1.68	1.74
	0.54	2.68	2.08	2.68	1.68	1.68	0.74	2.68	1.61	2.35	1.21	1.34
	1.41	2.68	1.47	2.68	1.21	2.01	0.54	2.68	1.74	2.68	2.55	1.88
	0.47	2.68	1.68	2.68	2.01	1.47	0.80	2.21	1.47	1.81	2.68	2.55
	0.54	2.68	2.68	1.34	0.80	1.34	0.40	2.01	1.21	2.35	2.35	2.01
	1.01	2.68	2.68	2.35	1.68	1.01	0.54	2.68	2.14	2.55	2.68	1.21
	1.41	2.68	2.55	2.68	1.21	2.55	0.54	2.68	1.54	1.88	2.35	1.68
	1.07	2.68	2.68	2.68	1.74	2.01	0.27	2.68	1.34	2.68	2.21	2.55
	0.54	2.68	2.35	2.68	2.01	1.34	0.40	2.68	1.81	2.68	1.81	1.54
	0.47	1.34	2.48	1.34	1.94	1.41	0.94	2.68	1.61	1.94	1.81	2.28
Bw	P F	C 2	C 3	C 5	D F	SB F	P F	C 2	C 3	C 5	D F	SB F
	2.55	2.68	2.68	1.34	2.14	2.68	2.55	2.68	2.68	2.68	1.74	2.35
	2.68	2.68	2.68	2.68	2.68	2.14	2.35	2.68	2.14	2.68	2.68	2.68
	2.41	2.68	2.35	2.68	2.68	2.55	2.01	2.68	2.68	2.68	2.48	2.68
	2.01	2.68	2.68	2.68	2.55	1.74	2.08	2.68	2.68	2.68	2.48	2.68
	1.47	2.68	2.68	2.68	2.14	2.28	2.68	2.68	2.68	2.68	1.61	2.68
	2.68	2.68	2.68	2.01	2.68	2.01	2.41	2.68	2.68	2.68	2.01	2.35
	2.68	2.68	2.68	2.68	2.68	1.61	2.01	2.68	2.68	2.68	2.01	2.68
	2.41	2.68	2.55	2.68	2.35	1.68	2.14	2.68	2.68	2.68	1.94	2.68
	2.68	2.68	2.68	2.68	2.28	2.01	2.68	2.68	2.68	2.68	1.74	2.68
	2.68	2.68	2.68	2.68	2.68	2.08	2.68	2.68	2.68	2.55	2.14	2.48
Cu	P F	C 2	C 3	C 5	D F	SB F	P F	C 2	C 3	C 5	D F	SB F
	2.68	2.68	2.55	2.28	1.68	2.14	1.74	2.68	2.68	2.68	2.68	2.68
	2.55	2.68	2.68	2.41	2.01	2.55	2.68	1.88	2.68	2.68	1.94	2.68
	2.68	2.68	2.68	2.01	1.68	2.35	2.68	1.88	2.68	2.68	2.68	2.68
	2.68	2.68	2.35	2.48	1.88	2.55	1.61	2.68	2.68	2.68	2.68	1.68
	2.68	2.68	2.68	2.68	2.68	2.68	2.68	1.61	2.68	2.68	2.68	2.68
	2.68	2.68	2.68	2.68	2.35	2.55	2.68	2.68	2.68	2.68	2.68	2.35
	2.55	2.01	2.68	2.68	2.35	2.14	1.61	2.68	2.68	2.68	2.68	2.41
	2.68	2.28	2.55	2.68	2.21	2.35	2.68	2.68	2.68	2.68	2.68	2.55
	2.35	2.01	2.68	2.68	2.55	2.01	2.68	2.68	2.68	2.68	2.68	2.68
	2.61	2.01	2.68	2.41	2.35	2.28	2.55	2.68	2.68	2.68	2.68	2.21

Table A2.2: Penetration resistance and degree of packing (Taupo)

	TAUPO										
Horizon	Penetration resistance Mpa					Degree of packing Mpa					
Ap	P F	C 3	C 4	C 5	D F		P F	C 3	C 4	C 5	D F
	0.34	1.54	1.61	1.14	1.01		1.01	1.88	1.47	1.61	2.01
	0.47	1.68	1.68	1.01	1.74		0.54	2.35	1.74	0.67	2.35
	0.27	1.47	0.67	2.01	1.01		0.67	1.68	1.34	0.80	2.55
	0.54	1.81	1.61	1.01	2.01		0.74	2.41	2.68	0.94	2.14
	0.34	2.01	1.14	1.54	1.01		0.54	1.81	1.34	0.74	2.28
	0.27	1.47	2.14	0.40	0.94		0.87	1.68	1.61	1.47	2.55
	0.40	1.34	0.80	1.47	0.87		0.80	2.01	2.01	1.88	2.61
	0.47	1.61	0.94	1.41	1.21		0.54	2.08	1.47	1.61	2.01
	0.47	1.14	1.14	1.27	2.01		0.94	1.68	1.54	1.74	2.68
	0.67	1.41		1.14	1.88		0.74	1.81	1.74	1.94	2.35
Bw	P F	C 3	C 4	C 5	D F		P F	C 3	C 4	C 5	D F
	0.67	2.68	2.01	1.68	2.55		1.47	2.68	1.68	2.55	2.68
	1.21	2.68	2.55	2.68	2.01		1.27	2.68	2.01	2.61	2.55
	0.80	2.68	2.68	2.55	2.55		1.41	2.68	2.68	2.01	2.61
	0.94	2.68	2.68	2.48	1.68		1.54	2.68	2.68	2.48	2.68
	0.67	2.55	2.14	1.74	1.68		1.68	2.68	2.68	1.34	2.01
	1.14	2.61	2.01	2.61	1.81		1.94	2.68	2.68	2.68	1.88
	1.21	2.68	2.68	2.14	2.01		1.94	2.68	2.68	2.55	2.35
	1.07	2.68	2.68	2.41	2.08		1.81	2.68	2.68	2.41	2.48
	0.94	2.68	2.35	2.28	2.61		1.47	2.68	2.68	2.68	2.68
	1.27	2.68	2.55	1.94	1.81		2.68	2.68	2.68	2.35	2.68
Cu	P F	C 3	C 4	C 5	D F		P F	C 3	C 4	C 5	D F
	2.55	2.68	2.68	2.35	2.28		1.47	2.68	2.68	0.80	2.68
	2.61	2.68	2.68	0.67	2.55		2.35	2.68	2.68	1.21	2.68
	2.68	2.68	2.68	0.80	2.61		2.28	2.68	2.68	1.34	2.68
	2.01	2.68	2.68	2.61	2.35		1.88	2.68	2.68	1.41	2.68
	2.41	2.68	2.68	2.55	2.68		2.14	2.68	2.68	1.94	2.55
	2.68	2.68	2.68	2.68	2.55		2.08	2.68	2.68	2.68	2.68
	2.68	2.68	2.01	2.55	2.41		2.68	2.68	2.68	1.81	2.48
	2.14	2.68	2.68	2.68	2.35		2.55	2.68	2.68	1.81	2.68
	2.55	2.68	2.68	2.68	2.28		2.61	2.68	2.68	1.94	2.68
	2.48	2.68	2.55	2.48	2.68		2.68	2.68	2.68	2.48	2.68

Table A2.3: Soil dry bulk density (Tokoroa and Taupo)

	Soil dry bulk density g/cm³						
Tokoroa						MEAN	ST. DEV.
PF	0.65	0.57	0.60	0.55	0.51	0.58	0.053
C 2	0.69	0.64	0.58	0.68	0.65	0.65	0.042
C 3	0.73	0.70	0.72	0.70	0.74	0.72	0.017
C 5	0.57	0.72	0.65	0.66	0.72	0.66	0.063
D F	0.66	0.70	0.74	0.68	0.71	0.70	0.031
SB F	0.61	0.62	0.66	0.68	0.68	0.65	0.036
Taupo							
PF	0.65	0.77	0.66	0.62	0.61	0.66	0.064
C 3	0.77	0.77	0.68	0.76	0.71	0.74	0.041
C 4	0.52	0.79	0.60	0.67	0.62	0.64	0.100
C 5	0.50	0.54	0.53	0.67	0.68	0.58	0.083
D F	0.74	0.80	0.79	0.81	0.76	0.78	0.031

Table A2.4: Soil water repellency (Tokoroa and Taupo)

Tokoroa	Ap Horizon water drop penetration time (WDPT) in seconds										MEAN	ST.DEV.
P F	12	3	6	24	5	7	4	6	22	21	11.00	8.21
C 2	5	5	61	115	900	659	5	5	270	203	222.80	312.52
C 3	95	5	31	94	70	131	5	57	9	5	50.20	46.05
C 5	50	5	27	111	14	86	5	131	45	62	53.60	44.09
D F	11	165	18	30	45	62	330	215	267	182	132.50	114.70
SB F	12	28	10	12	20	4	3	24	5	6	12.40	8.80
Taupo	Ap Horizon water drop penetration time (WDPT) in seconds										MEAN	ST.DEV.
P F	4	10	3	2	2	5	7	4	8	5	5.00	2.49
C 3	64	610	110	154	310	203	217	37	317	381	240.30	171.91
C 4	15	50	52	59	246	23	25	11	270	540	129.10	172.73
C 5	175	95	68	54	184	21	9	5	4	195	81.00	77.48
D F	2	2	2	2	3	4	3	1	1	4	2.40	1.07

Table A2.5: Unsaturated hydraulic conductivity K $_{-40}$ (Tokoroa and Taupo)

TOKOROA	Unsaturated hydraulic conductivity mm/hour					MEAN	ST. DEV.
PF	4.75	5.71	4.38	5.24	3.95	4.80	0.69
C 2	5.85	5.52	4.46	4.49	10.98	6.26	2.70
C 3	5.71	5.24	4.77	5.42	5.73	5.37	0.35
C 5	13.89	2.20	4.28	5.69	6.04	6.42	1.72
DF	6.82	7.08	5.96	4.93	4.01	5.76	1.15
SB F	8.83	9.29	7.67	7.92	9.97	8.74	0.95
TAUPO	Unsaturated hydraulic conductivity mm/hour					MEAN	ST. DEV.
PF	7.26	5.30	7.07	10.05	8.47	7.63	1.75
C 3	2.25	2.74	1.79	4.01	2.69	2.70	0.79
C 4	1.77	5.49	2.51	2.05	9.58	4.28	3.02
C 5	5.84	6.55	7.24	5.79	3.72	5.83	1.32
DF	8.00	4.28	4.84	5.30	4.84	5.45	0.46

Table A2.6: Saturated hydraulic conductivity K $_{sat}$ (Tokoroa and Taupo)

TOKOROA	Saturated hydraulic conductivity K sat mm/hour					MEAN	ST. DEV.
PF	102.24	95.10	20.82	42.86	100.40	72.28	37.83
C 2	55.71	45.10	46.73	48.98	43.67	48.04	4.72
C 3	43.06	22.86	44.49	21.22	55.71	37.47	14.92
C 5	28.16	57.55	20.41	13.06	20.00	27.84	17.45
DF	8.98	17.75	20.00	35.92	24.49	21.43	9.87
SB F	18.77	18.57	20.00	19.59	22.04	19.80	1.38
TAUPO	Saturated hydraulic conductivity K sat mm/hour					MEAN	ST. DEV.
PF	38.80	22.10	17.17	47.03	136.38	52.29	48.54
C 3	35.74	44.21	42.80	32.68	71.95	45.48	15.56
C 4	38.60	38.30	52.20	19.00	59.50	41.52	15.52
C 5	28.45	15.05	35.04	13.17	20.22	22.39	9.22
DF	171.65	44.68	78.07	129.56	32.68	91.33	58.53

Table A2.7: Aggregate stability, % of 2 mm aggregates in Ap horizon (Tokoroa and Taupo)

Area		initial weight g		dry soil weight g after wet sieving			sand + organic mat (pine)			Sand + org	dry soil - sand organic mat			**aggregate**
Site	Horizon	Air dry soil	soil - moist	2 mm sieve	1 mm sieve	0.5 mm	2 mm sieve	1 mm sieve	0.5 mm	g TOTAL	2 mm sieve	1 mm sieve	0.5 mm	**>2mm %**
TOKOROA														
P F	Ap	57.52	55.53	36.65	3.79	0.65	4.04	0.64	0.23	4.91	32.61	3.15	0.42	**64.4**
	Bw	23.44	22.91	8.71	1.45	0.34	6.56	1.11	0.3	7.97	2.15	0.34	0.04	**14.4**
	Cu	52.77	52.35	10.55	6.4	2.35	6.52	5.2	0.3	12.02	4.03	1.2	2.05	**10.0**
	Bb	58.34	55.39	36.35	3.59	0.6	12.56	2.29	0.32	15.17	23.79	1.3	0.28	**59.2**
C 2	Ap	32.49	30.92	12.86	5.53	0.78	4.25	2.12	0.52	6.89	8.61	3.41	0.26	**35.8**
	Bw	38.9	37.42	13.98	8.24	1.51	6.54	3.24	0.75	10.53	7.44	5	0.76	**27.7**
	Cu	18.52	18.15	2.2	2.04	0.67	2.1	1.89	0.22	4.21	0.1	0.15	0.45	**0.7**
	Bb	36.72	33.31	20.4	1.8	0.23	7.55	0.68	0.21	8.44	12.85	1.12	0.02	**51.7**
C 3	Ap	52.04	50.12	19.67	7.22	1.45	9.87	4.65	1.33	15.85	9.8	2.57	0.12	**28.6**
	Bw	30.75	29.93	7.63	3.34	0.63	3.78	2.11	0.41	6.3	3.85	1.23	0.22	**16.3**
	Cu	34.82	34.29	8.81	3.24	0.5	4.45	2.01	0.23	6.69	4.36	1.23	0.27	**15.8**
	Bb	41.5	38.27	23.87	1.14	0.1	6.69	0.7	0	7.39	17.18	0.44	0.1	**55.6**
C 5	Ap	70.18	66.38	39.57	5.47	0.81	8.45	3.21	0.64	12.3	31.12	2.26	0.17	**57.5**
	Bw	72.32	69.86	35.17	10.74	1.46	12.36	4.44	0.45	17.25	22.81	6.3	1.01	**43.4**
	Cu	40.14	39.22	8.24	4.29	2.18	3.56	2.11	1.12	6.79	4.68	2.18	1.06	**14.4**
	Bb	58.3	53.25	39.9	1.66	0.22	5.65	0.80	0.16	6.61	34.25	0.86	0.06	**73.4**
D F	Ap	84.44	80.99	57.75	4.08	0.42	6.04	1.45	0.12	7.61	51.71	2.63	0.3	**70.5**
	Bw	42.64	41.45	11.67	6.61	1.15	2.25	0.23	0.12	2.60	9.42	6.38	1.03	**24.2**
	Cu	35.77	35.05	7.68	3.28	0.57	2.29	1.18	0.20	3.67	5.39	2.10	0.37	**17.2**
	Bb	64.73	60.24	42.26	3.01	0.12	5.6	1.87	0.00	7.47	36.66	1.14	0.12	**69.5**
SB F	Ap	126.11	119.06	82.06	13.74	2.58	3.57	3.22	1.2	7.99	78.49	10.52	1.38	**70.7**
	Bw	47.12	45.91	17.9	5.52	1.29	2.8	1.20	0.21	4.21	15.1	4.32	1.08	**36.2**
	Cu	37.3	36.86	4.9	3.26	1.4	2.25	2.11	0.90	5.26	2.65	1.15	0.50	**8.4**
	Bb	57.31	51.14	33	4.32	0.93	4.59	2.60	0.56	7.75	28.41	1.72	0.37	**65.5**
TAUPO														
P F	Ap	30	28.69	21.99	3.94	0.36	3.93	0.57	0.11	4.61	18.06	3.37	0.25	**75.0**
	Bw	30	29.06	7.21	3.16	0.60	2.22	1.21	0.55	3.98	4.99	1.95	0.05	**19.9**
	Cu	30	29.29	7.41	2.73	0.42	4.89	1.91	0.20	7.00	2.52	0.82	0.22	**11.3**
C 3	Ap	30	28.86	12.97	1.31	0.31	3.63	0.33	0.2	4.16	9.34	0.98	0.11	**37.8**
	Bw	30	29.30	11.15	1.86	0.44	4.45	0.21	0.11	4.77	6.70	1.65	0.33	**27.3**
	Cu	30	29.72	6.00	3.64	1.34	4.78	2.14	0.82	7.74	1.22	1.50	0.52	**5.5**
C 4	Ap	30	28.82	17.84	3.47	1.33	11.16	1.43	0.56	13.15	6.68	2.04	0.77	**42.6**
	Bw	30	29.14	7.98	4.52	0.79	3.98	1.15	0.45	5.58	4.00	3.37	0.34	**17.0**
	Cu	30	29.45	6.32	2.70	0.47	3.17	1.51	1.13	5.81	3.15	1.19	0.00	**13.3**
C 5	Ap	30	28.49	19.06	3.88	0.75	10.33	1.21	0.25	11.79	8.73	2.67	0.5	**52.3**
	Bw	21.48	20.61	14.4	1.62	0	10.7	1.07	0	11.77	3.7	0.55	0	**41.9**
	Cu	17.62	17.23	12.18	1.87	0.29	11.54	1.61	0.28	13.43	0.64	0.26	0.01	**16.8**
D F	Ap	30	28.30	21.49	2.95	0.48	1.99	0	0.21	2.20	19.5	2.95	0.27	**74.7**
	Bw	30	29.19	9.64	2.97	0.69	8.21	2.11	0.23	10.55	1.43	0.86	0.46	**7.7**
	Cu	30	29.62	4.89	3.26	1.40	3.14	2.20	1.35	6.69	1.75	1.06	0.05	**7.6**

Table A2.8: A horizon moisture contents (% gravimetric and volumetric) held at 1-1500 KPa

	Moisture contents % gravimetric								
Tokoroa									
	1 KPa	5 Kpa	10 Kpa	20 Kpa	40 Kpa	100 Kpa	300 Kpa	500 Kpa	1500 Kpa
P F	83.37	79.56	76.67	70.82	65.53	56.72	45.60	43.12	40.28
C 2	88.17	81.55	77.08	70.69	64.31	59.16	57.89	55.66	37.76
C 3	86.97	81.78	78.22	74.56	66.92	63.47	60.78	55.27	42.18
C 5	81.10	76.54	73.31	69.62	63.47	58.26	56.55	53.68	37.75
D F	83.49	77.10	74.39	71.16	65.13	62.50	60.54	55.67	35.82
SB F	84.41	80.38	78.47	76.63	69.47	68.17	64.95	61.48	42.80
Taupo									
P F	67.24	55.08	51.46	46.07	39.56	29.44	21.80	19.56	25.22
C 3	74.66	65.25	61.71	53.46	51.66	39.76	27.92	26.21	24.16
C 4	74.06	65.43	61.37	54.88	47.14	39.71	26.93	24.71	22.91
C 5	86.60	78.13	74.13	68.41	63.26	50.69	40.26	36.33	37.05
D F	73.88	68.88	64.38	59.25	53.60	39.10	36.06	32.69	29.36
	Moisture contents % v/v								
Tokoroa									
	1 KPa	5 Kpa	10 Kpa	20 Kpa	40 Kpa	100 Kpa	300 Kpa	500 Kpa	1500 Kpa
P F	47.96	45.77	44.10	40.74	37.70	32.63	26.24	24.81	23.17
C 2	57.23	52.93	50.04	45.89	41.75	38.40	37.57	36.13	24.51
C 3	62.26	58.55	56.00	53.38	47.91	45.44	43.51	39.57	30.20
C 5	53.90	50.87	48.72	46.27	42.19	38.72	37.59	35.68	25.09
D F	58.23	53.77	51.88	49.63	45.43	43.59	42.23	38.83	24.98
SB F	54.84	52.22	50.99	49.79	45.14	44.29	42.20	39.94	27.81
Taupo									
P F	44.62	36.55	34.15	30.57	26.25	19.54	14.46	12.98	16.74
C 3	55.16	48.21	45.59	39.50	38.17	29.38	20.63	19.36	17.85
C 4	47.30	41.79	39.19	35.05	30.11	25.36	17.20	15.78	14.63
C 5	50.50	45.56	43.23	39.89	36.89	29.56	23.47	21.18	21.60
D F	57.65	53.74	50.24	46.23	41.82	30.51	28.14	25.50	22.91

Table A2.9: Soil particle size distribution for Tokoroa and Taupo Study area

Volume in %		Clay	Silt	Sand
		<0.002	0.002-0.063	>0.063
Tokoroa		mm	mm	mm
P F	Ap	0.87	55.58	43.56
	Bw	1.10	60.73	38.18
	Cu	0.80	47.61	51.59
	Bb	2.18	58.19	39.63
C 2	Ap	1.19	59.81	39.00
	Bw	1.19	59.75	39.06
	Cu	0.62	45.89	53.49
	Bb	2.26	61.71	36.03
C 3	Ap	1.12	56.07	42.81
	Bw	0.99	49.15	49.86
	Cu	0.86	49.72	49.42
	Bb	2.22	66.96	30.82
C 5	Ap	1.18	59.41	39.41
	Bw	1.13	56.96	41.91
	Cu	0.94	53.55	45.50
	Bb	1.22	45.45	53.33
D F	Ap	1.13	59.70	39.16
	Bw	0.95	53.54	45.51
	Cu	0.83	48.91	50.27
	Bb	2.54	62.37	35.08
SB F	Ap	0.98	57.64	41.38
	Bw	0.96	54.46	44.58
	Cu	0.80	49.50	49.70
	Bb	1.99	57.81	40.20

Volume in %		Clay	Silt	Sand
		<0.002	0.002-0.063	>0.063
Taupo		mm	mm	mm
P F	Ap	1.09	55.75	43.16
	Bw	0.67	45.59	53.74
	Cu	0.50	40.01	59.50
C 3	Ap	1.11	55.05	43.84
	Bw	0.61	39.34	60.05
	Cu	0.93	54.70	44.37
C 4	Ap	0.62	46.60	52.78
	Bw	0.86	47.10	52.03
	Cu	0.50	40.82	58.67
C 5	Ap	0.46	40.61	58.94
	Bw	0.34	34.81	64.85
	Cu	0.36	33.45	66.19
D F	Ap	1.37	63.09	35.55
	Bw	0.45	37.33	62.22
	Cu	0.49	37.62	61.89