Improvement in soil water availability in pastures by excavating and mixing buried soil horizons from multilayered Pumice Soils (Vitrands) at Galatea, central North Island, New Zealand

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Abstract

Pumice Soils (Typic Udivitrands) in the Galatea Basin in the eastern Bay of Plenty, central North Island, New Zealand, are formed on weakly weathered, coarse textured, glassy, pumice tephra deposits and associated buried soil horizons. The Galatea Basin tends to experience summer drought and decreased summer pasture production.

Observations that refilled holes had better summer pasture growth in the disturbed materials compared to growth in adjacent undisturbed soils led to trials where the underlying finer-textured, buried soil horizons were "flipped" (excavated and mixed into the pumiceous surface horizons) using a mechanised digger. The main objective of this study was to test the hypothesis that the mixing of the finer textured buried horizons into the pumiceous surface soils will give increased water holding capacity and thus improve water availability to plants during dry summer periods.

The top 2.5 m of a reference sequence of four tephra deposits and associated buried soil horizons in an exposed section through a terrace at the southern end of Galatea Basin was described. The tephras and their dates or ages of deposition are(from top) Kaharoa (AD 1314 ± 12), Taupo (AD 232 ± 10), Whakatane (5526 ± 145 calendar years BP), and Rotoma (9423 ± 120 calendar years BP). Undisturbed cores from each soil horizon and the pumiceous tephra layers were collected for water retention and bulk density determination. Four sites were identified that had previously been modified by flipping. Each site contained a flipped area comprising excavated and mixed soil materials and an adjacent "undisturbed" (control) area comprising undisturbed soil. At each of site, three pits were excavated in the flipped area and three in the undisturbed area. Detailed soil descriptions were made and undisturbed soil cores were taken from all horizons in each pit to a depth of 0.6 m. Water retention was determined using a hanging water column and a pressure plate extractor.

The water retention curves for the undisturbed horizons from the reference profile show that most of the water was held in the soil at lower tensions (<100 kPa). The 3bBw horizon (Whakatane Tephra) had the highest readily available water (25 % v,v) while the 2bAB horizon (Taupo Tephra) had the highest total available water capacity (37 % v,v). The mean profile readily-available water contents to 600 mm depth from the flipped soils were higher ($P<0.01$) than those of the undisturbed soils. Plant readily-available water content was calculated in the flipped soils to 600 mm depth and to 450 mm depth in the undisturbed soils (based on plant root observations in the field over summer). Plant readily-available water content was greater in the flipped soils compared to that in the undisturbed soils at sites 1, 2 and 3 ($P<0.05$) and at site 4 ($P\leq 0.1$).

Assuming an evaporation rate of 4 mm per day and that plant rooting depth is deeper in flipped soils than in undisturbed soils (~600 mm compared to ~450 mm), the flipped soils can hold more readily-available water (mean of 39 days) than the undisturbed soils (mean of 19 days) between rainfall/irrigation events (assuming soils were wet to field capacity at the start) before the soil water drops below the readily available limit.

The hypothesis that "flipping" of the multilayered Pumice Soils will give increased water holding capacity in modified surface horizons (mixed buried soil horizon materials), and thus improve moisture availability to plants during dry summer periods, was accepted.

Acknowledgements

Though only my name appears on the cover of this thesis, many people have contributed to its production. Firstly, I would like to sincerely thank my supervisors Dr Megan Balks and Professor David Lowe. I express my sincere gratitude to Megan who provided me with great support and unending guidance every step of the way. Her patience while "kindly" marking pages and pages of drafts in *blue* pen, and her sense of humour and willingness to be available whenever I needed help is much appreciated. I also thank David, who was happy to provide useful comments and suggestions for improvement while marking my work. He also attended a field trip to Galatea to identify the tephras in the reference section. I am grateful for his encouragement and enthusiasm throughout the learning process of writing a thesis.

I would like to thank Bill Adam for introducing the topic and for his help with getting the work started. I also thank the landowners for allowing me to collect samples from the large holes that were dug in their paddocks. The Smeith, Mills, and the Garner families provided me with help in the field, delicious home cooked meals, and a homely place to stay while completing my field work and I cannot thank them enough.

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I acknowledge and thank Dean Sandwell and Janine Ryburn for helping me in the laboratory in setting up the pressure plate apparatus, fixing parts, and ordering new parts when needed.

Special thanks are afforded to friends and my go-to "tech support" guy (who put up with the most drama in the end). These people helped me stay relatively sane in the last leg of the journey. Thanks are due to my family who have been there for me in the good times and the bad with constant love and care which helped me stay focussed on my graduate study.

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Chapter 1

Introduction

1.1 Pasture production on Pumice Soils

Pasture production on Pumice Soils can be limited by water availability especially during the summer months. The Galatea Basin is an area of Pumice Soils situated in the inland Bay of Plenty region (Figure 1.0) which often has low summer rainfall. In order to run a successful dairy farm in Galatea, various strategies have been used to improve the sustainability of farming including extensive use of lucerne for grazing and supplementary feeding, lowering stocking rates, and irrigation.

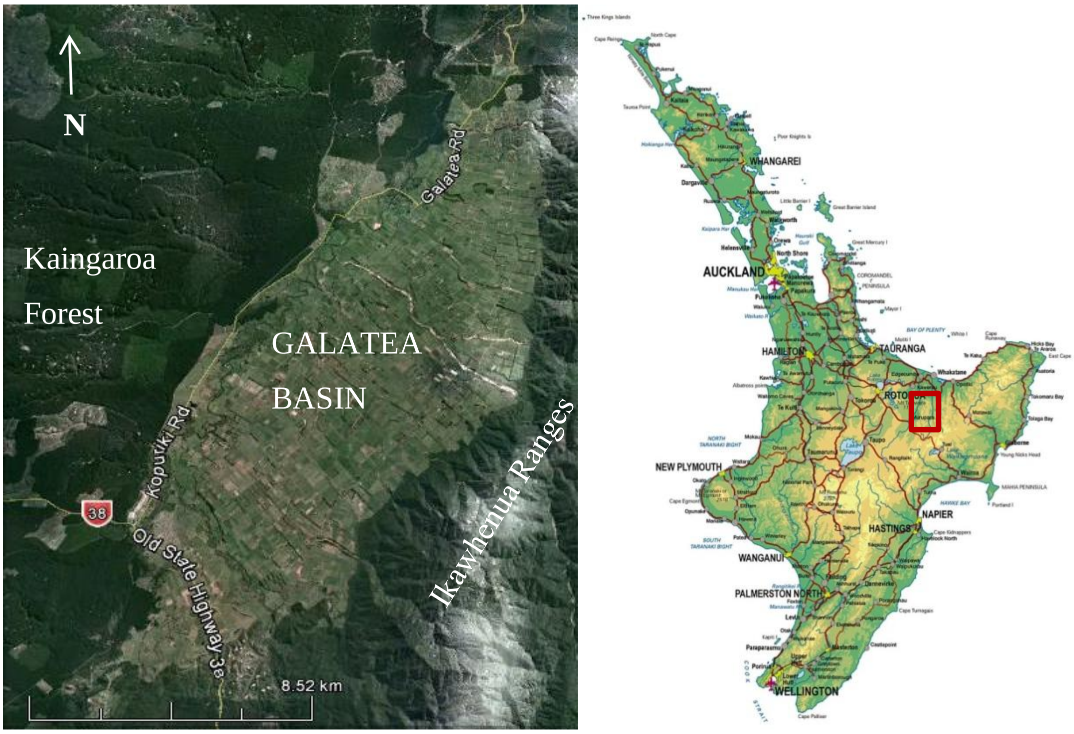


Figure 1.1: Location of Galatea Basin (south-eastern Bay of Plenty region, North Island, New Zealand).

Farmers in Galatea have noticed that refilling holes or trenches resulted in better pasture growth in the disturbed materials than on the undisturbed land. These observations led to experimental soil “flipping” trials being established on dairy farms in the area. Soil “flipping” is a mechanical process whereby a digger is used to invert and mix the top 1-2 m of soil-tephra sequences, hence breaking up the pumice horizons and excavating buried soil materials that have formed on older tephras (i.e. bringing them to the land surface). Pasture growth in the trial paddocks on the “flipped” soil is visibly better than that in the control areas (undisturbed soils), and the improvement has persisted (Figure 1.2).

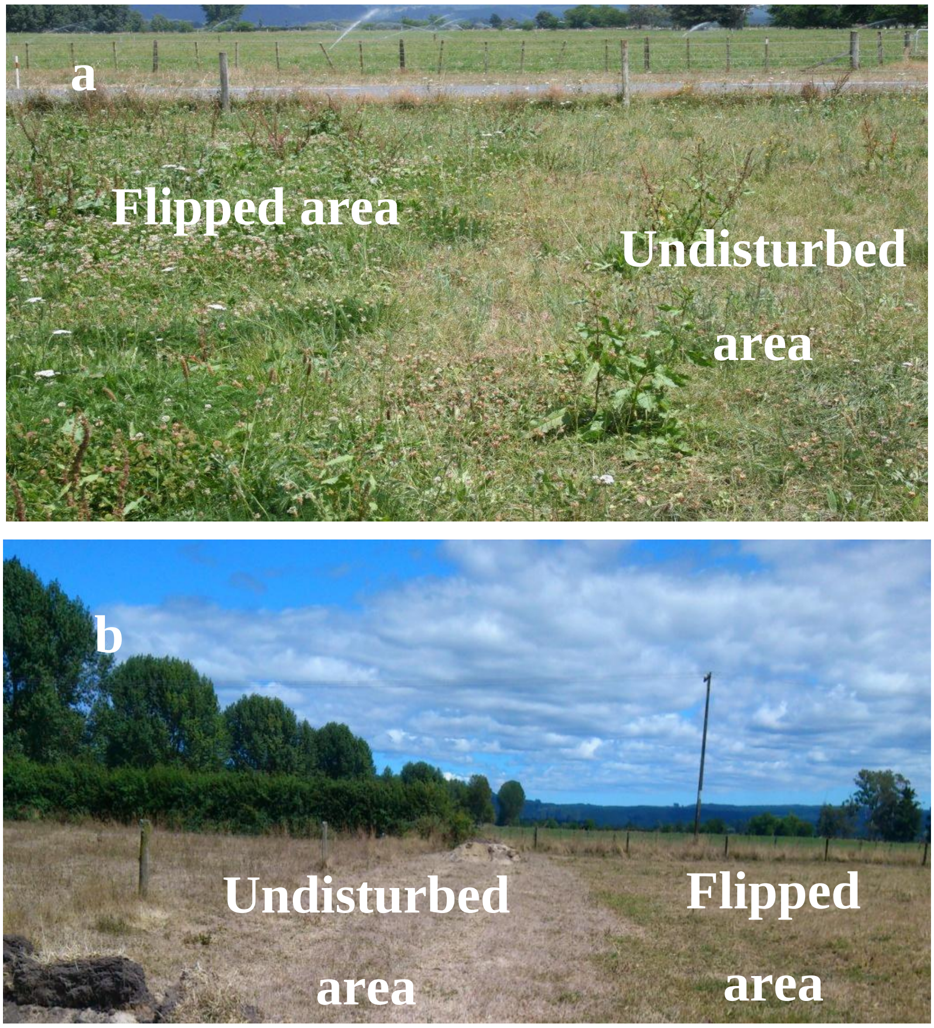


Figure 1.2: Pasture growth on the flipped soil compared to pasture growth on the “undisturbed” soil (control area). a: pasture growth in winter/early spring. b: pasture growth during 2013 summer drought.

1.2 Aim and objectives of the study

The overall aim of the study was to investigate how the multilayered Pumice Soils modified by “flipping” differ from “undisturbed” soils in adjacent (control) areas to better understand why grass growth increases.

1.2.1 Hypothesis and specific objectives

My hypothesis is that, the mixing of the excavated buried soil horizons with the pumiceous surface soil materials (on Kaharoa Tephra) will give increased water holding capacity in the modified surface horizons, and thus improve water availability to plants during dry summer periods.

Specific objectives were to:

- Characterise soil materials in the “undisturbed” buried soil-tephra sequence to a depth of 2.5 m including a soil profile description, percentage allophane in buried soil horizons and particle size analysis.
- Determine the water holding capacity of previously “flipped” soils and adjacent “undisturbed” soils (control area).
- Compare soil properties e.g. soil bulk density and permeability class estimates in the “flipped” soils and adjacent “undisturbed” soils
- Determine the differences in root density with depth in “flipped” and “undisturbed” soils.

1.3 Outline of remainder of thesis

The following chapter includes a literature review, chapter 3 provides details about the methods used in the field and laboratory, chapter 4 covers the results of the study and chapter 5 includes a summary of the study and the results, a discussion, recommendations for future study and conclusions drawn from this study.

Chapter 2

Literature review

2.1 Introduction

Tephras are the explosively erupted, loose, pyroclastic (fragmental) products of volcanic eruptions that include volcanic ash (fragments < 2 mm in diameter) and pumiceous lapilli (fragments 2−64 mm in diameter) (Lowe & Palmer, 2005; Lowe, 2010). Tephra deposits cover a large area of the central North Island of New Zealand and soils formed from these include Recent, Pumice, and Allophanic soils which tend to be sandy to silty and free draining (Hewitt, 2010). Pumice Soils are mainly distributed within central North Island in the regions peripheral to Taupo and Rotorua (Figure 2.1: Pumice Soils in the North Island (shaded light green).) and occupy ~7 % of land in New Zealand (Hewitt, 2010). Many features of soils with volcanic origin are linked to the glassy and fragmental parent material and distinguishable physical properties include low bulk densities and a clay fraction dominated by nanocrystalline (previously called short-range order) minerals namely allophane, ferrihydrite, and metal-humus complexes (McDaniel et al., 2012). Pumice and Allophanic soils are widely used for pasture, crop and forestry production (Gibbs & Pullar, 1966; Lowe & Palmer, 2005).

In this review I give a brief introduction to the Galatea Basin and the soils within the area. Soil physical and chemical properties affecting plant growth, the importance of soil structure and soil physical properties such as texture, bulk density, available water holding capacity of Pumice Soils, and the effects of modifying sandy soils using clay amendments are also discussed

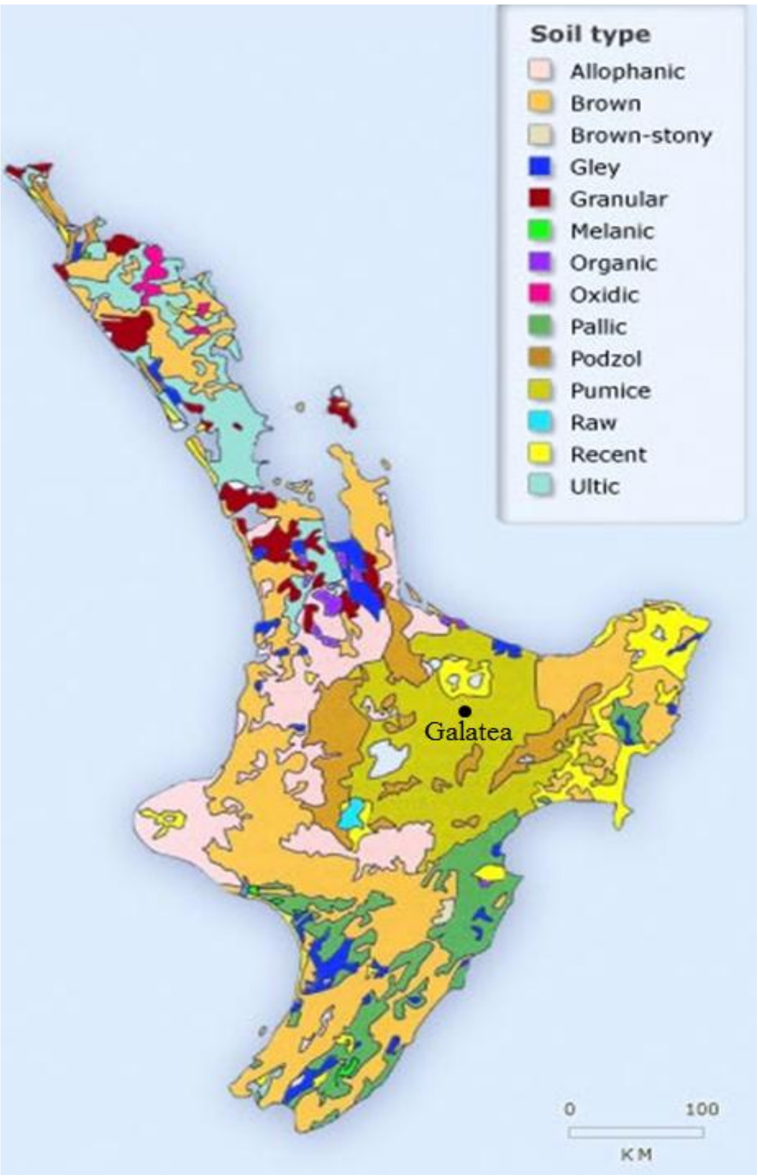


Figure 2.1: Pumice Soils in the North Island (shaded light green). Figure sourced from Molloy (1998)

2.2 Geologic and geographic features in the central Bay of Plenty

The Galatea Basin is an oval shaped fault-bound depression roughly 23 km long and 7–9 km wide, orientated in a northeast-southwest direction on the eastern margin of the Kaingaroa Plateau (Manville et al., 2005). The eastern side of the Basin is bounded by the Whaeo, Te Whaiti and Waiohau faults and the south-west side of the Basin is confined by the welded ignimbrite sheet of the Kaingaroa Plateau (Leonard et al., 2010). Other geographic features that surround the Galatea Basin include the low-lying Rangitaiki plains, the Te Urewera National

Park and the Kaingaroa Forest (Figure 2.2). In a geological time frame, the landscape of the Galatea Basin is relatively young and the underlying volcanic rocks are generally much less than 1 million years old (Molloy, 1998).

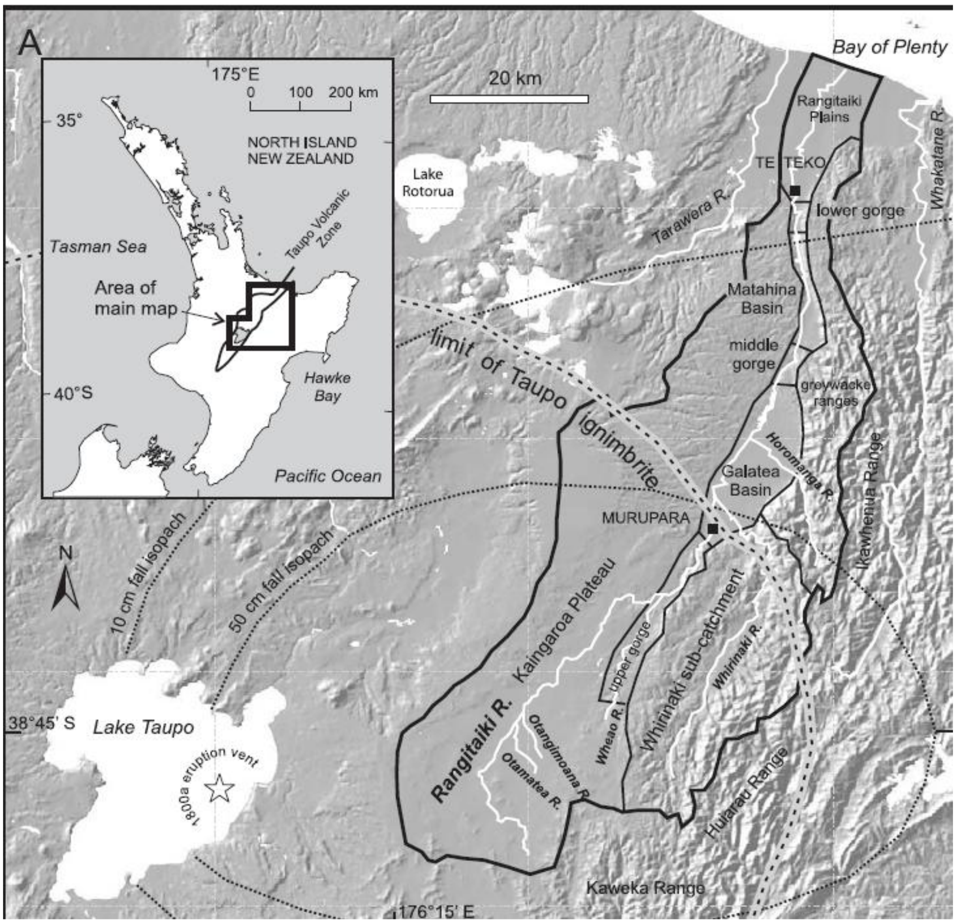


Figure 2.2: Map of the major geological features surrounding the Galatea Basin and isopachs of some of the eruptives of the Taupo event of c. AD 232. From Manville et al. (2005).

2.3 Soils of the Galatea Basin

2.3.1 Introduction

The upper (near-surface) parts of the soils of the Galatea Basin are formed on weakly weathered, relatively coarse, glassy and dense pumice deposits of the Kaharoa Tephra, which act as a barrier to plant roots and make the soil free draining. The soil forming factors of topography, climate, vegetation, biological processes, parent material, and time for weathering have given the soils of the Bay of Plenty distinctive characteristics and are discussed in the following sections.

2.3.2 Climate

The Galatea Basin is relatively sheltered from the prevailing winds. In summer the Galatea Basin can be several degrees warmer than coastal areas (Rijkse & Guinto, 2010). In winter the sheltered areas are prone to heavy frosts (Vucetich, 1960). The lowest mean annual rainfall occurs on the plains e.g. the Kaingaroa Plateau and the Galatea Basin and increases at higher elevations (Manville et al., 2005). Weather data collected from 1971 to 2000 at a station in Murapara (38.459 ° S, 176.695 ° E) show that the annual rainfall is ~1220 mm per year (Figure 2.3) and the mean air temperature is ~13.5 °C (NIWA, undated, Figure 2.4).

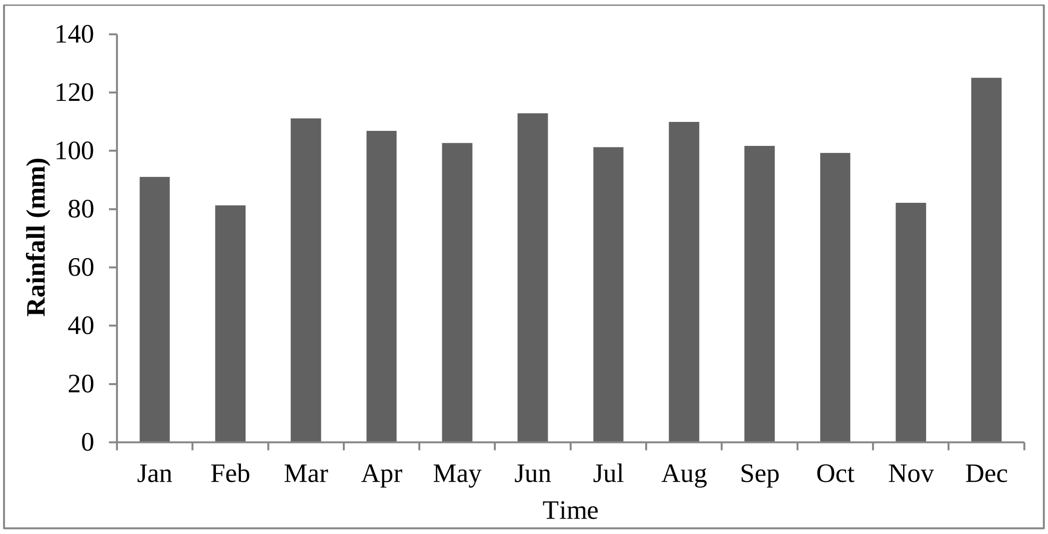


Figure 2.3: Mean annual rainfall for Murupara (1971-2000). Data from NIWA, (undated).

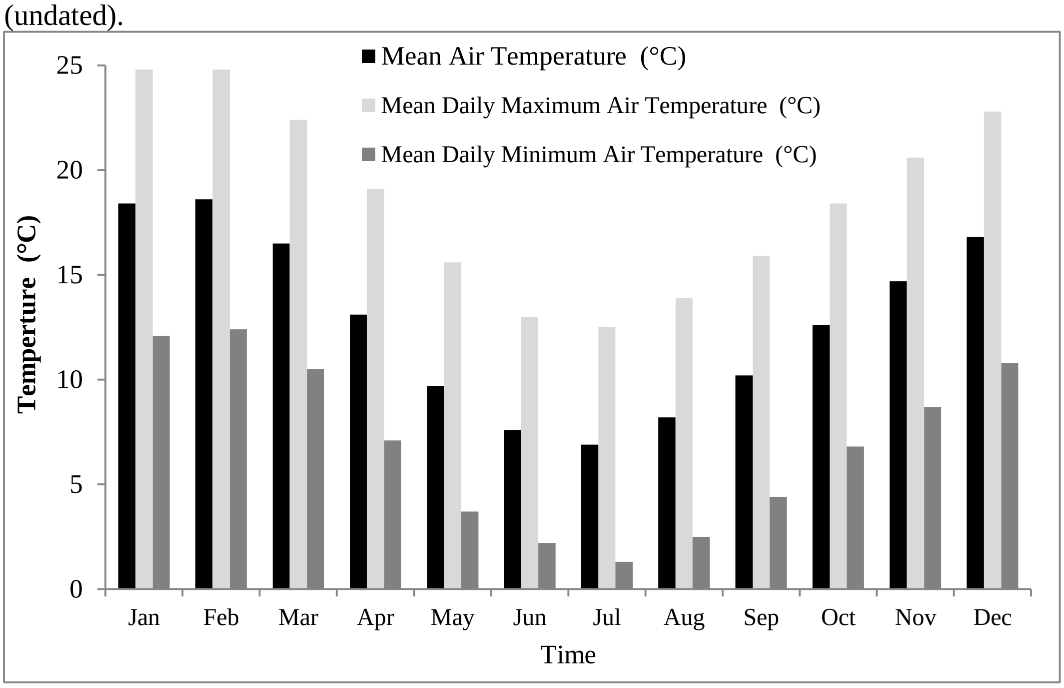


Figure 2.4:Mean air temperature for Murupara (1971-2000). Data from NIWA, (undated).

2.3.3 Biological processes

Vegetation plays an important role in soil development. Changes in vegetation since the beginning of farming and commercial forestry in the region have had considerable effects on properties such as soil aggregate stability (Rijkse & Guinto, 2010). Despite most of the land around Rotorua being suitable for forest growth, only a third of the land was forest-covered by mid-eighteenth century. The remaining patches of forest suggest that the dominant forest cover of the North Island had been burnt off most probably by the Polynesian settlers (Nicholls, 1963). Before European settlement, the practice of burning forest was the only way to clear land for food crops, but it was unable to be controlled. From an early date it is likely the Kaingaroa Plateau was periodically cleared by fire (Vucetich, 1960; McGlone, 1989;). According to Lowe (2008) archaeological evidence suggests that initial settlement was between c. 1250–1300 AD. Pollen, phytolith and associated studies indicate that deforestation by burning began in New Zealand shortly after Polynesian settlers arrived (Lowe & McDaniel, 2008).

Pollen analysis and examination of plant fragments found in the black A horizon on Pumice Soils has revealed that that the previous plant cover was dominated by bracken fern (Birrell et al., 1971). Bracken is an aggressive, highly productive plant that colonises disturbed sites (McGlone et al., 2005).

Humus is stored within the black A horizons of volcanic soils because humus becomes complexed with Al (Nanzyo, 2002). According to Notario (2010), both the structure of the soils and the accumulation of humus influence water dynamics in volcanic soils. Water repellence in soil is caused by organic compounds such as waxes on plants, coating the soil particles and tends to be more common in coarse textured soils. Soils which have a hydrophobic nature slow down water infiltration (Doerr, 2000). Water repellent soils will eventually wet up at some stage, but the uneven infiltration of water leaves variations in soil water which can affect plant growth (Cann, 2000).

Earthworms enhance soil development by the addition and breakdown of organic matter and the mixing of the topsoil. However, macrobiota populations are lower in Pumice Soils because organisms such as earthworms are limited by the water and texture of the soil (Lee, 1959). Extreme disturbance of soil leads to the breakdown of the soil organic matter and therefore reduces the food supplies available to earthworms. Direct mechanical damage such as tillage contributes to a decline in earthworm populations (Aslam et al., 1999).

2.3.4 Topography and parent material

Tephra has covered the Galatea Basin landscape and partially filled in the valleys with the exception of steeply sloping land. Kaharoa Tephra is usually found on fans and terraces in the Galatea Basin while river deposited sediments of mixed origin (greywacke, gravel, sand, silt and weakly weathered tephra from the Kaharoa and Taupo eruptions) form soils on flood plains and outwash fans (Vucetich, 1960)

Most of the central North Island has been covered by tephra derived mainly from rhyolitic eruptions. Soil patterns of the Bay of Plenty region are a result of variations in the age, thickness, and mineralogical composition of the tephra deposits within the area. Recurrent eruptions during the Quaternary led to the formation of multisequal soils comprising tephras and associated soil horizons (Figure 2.5) (Lowe & Palmer, 2005). Eruptions in the Okataina and Taupo Volcanic Centres generated the Whakatane, Taupo, and Kaharoa Tephras which are all rhyolitic in composition. In the northern part of the Basin a thin basaltic deposit of black scoria, the Tarawera Scoria Member of the Tarawera Tephra (Froggatt & Lowe, 1990), occurs in topsoils. The scoria was not observed in the topsoils of the southern basin. The ages and compositions of three tephras that underlie the soils in the southern part of the basin (my field area) are listed in Table 2.1.

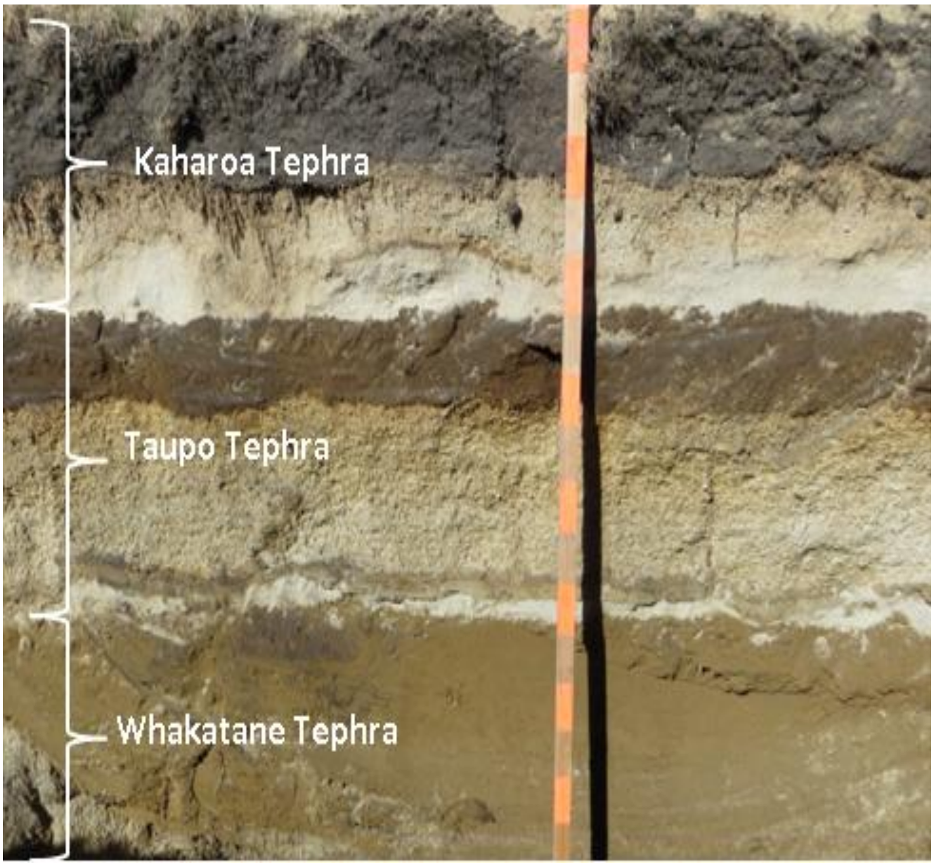


Figure 2.5:Soils have developed on tephra deposits. In this section, Whakatane, Taupo, and Kaharoa tephras are shown.

Table 2.1: Soil-forming tephras of the southern Galatea Basin and their ages*.

Name	**Origin**	**Composition**	**Texture**	**Chronology Date/cal. yr BP (95% probability ranges)**
Kaharoa Tephra	Mt Tarawera (OkatainaVC)	Rhyolitic pumice	Sand	1314 ±12 AD (636 ± 12 cal. yr BP)
Taupo Tephra	Taupo VC	Rhyolitic pumice	Loamy sand & sand	232 ±10 AD (1718 ± 10 cal. yr BP)
Whakatane Tephra	Haroharo (Okataina VC)	Rhyolitic pumice	Sandy loam Stones & gravel	5526 ± 145 cal. yr BP
Rotoma Tephra	Rotoma (Okataina VC)	Rhyolitic pumice	Sandy loam	9423 ± 120 cal. yr BP

* Table based on Vucetich (1960) and Rijkse & Guinto (2010). Chronology from Hogg et al. (2003, 2012) and Lowe et al. (2013)**. VC, Volcanic Centre; cal., calendar/calibrated; BP, before present (‘present’ = 1950 AD)**

2.3.5 Time

Tephra is erupted over short geological time frames, spreads widely and has the same age wherever it occurs. Therefore it provides a marker bed of a known age (Lowe, 1990). Once the age of the tephra is known, the time of weathering of the soil whilst at the land surface (before it is buried by a subsequent tephra deposit) can be calculated (Table 2.2). Finer textures, greater clay contents, and deepening subsoils (downward-moving front) generally develop as the tephra becomes more weathered (Rijkse & Guinto, 2010).

Table 2.2: Amount of weathering time for parent materials of soils in the Galatea Basin.

Tephra	Weathering time (years)
Tarawera	127
Kaharoa	527 (699)*
Taupo	1082
Whakatane	3808

*527 years for northern part of the basin where Tarawera tephra occurs, but 699 years in southern part of the basin (no Tarawera Tephra).

2.4 Soil classification

The soils of the southern part of the Galatea Basin are classified as Buried-Allophanic Orthic Pumice Soils in the New Zealand Soil Classification (NZSC) (Hewitt, 2010).

Anthropic Soils are constructed by or altered by people so that it no longer resembles the original composition or soil properties (Hewitt, 2010). They can be formed by severe mixing, deposition of landfill materials, or “scalping”. The soil sequences in the Galatea Basin that have been mechanically excavated so that deeper layers and associated buried soil horizons are inverted and mixed at the land surface (referred to as ‘flipping’)and can be classified as Mixed Anthropic Soils (Buried-allophanic Pumice Soils).

2.5 Soil characteristics and plant growth

2.5.1 Introduction

It is necessary that the soil provides a favourable physical environment for root development in order to extract water and nutrients for satisfactory plant growth

(Gardener, 1999). The composition and proportion of minerals, organic matter, water and air present in soil influences the soil’s physical properties such as texture, structure, porosity and the fraction of pore space in a soil. Physical properties contribute to water movement in the soil and therefore the soil’s suitability as a medium for plant growth (McCaughley, 2004).

2.5.2 Allophane

Although Pumice Soils have a low clay content (<10%), the clay fraction typically contains allophane and imogolite (Rijkse & Guinto, 2010). Allophane occurs as coatings around the sandy particles in soils formed on volcanic ash where there is sufficient water for leaching of silica to occur (Parfitt, 2009). Allophane has a similar atomic structure to imogolite but is different morphologically (Figure 2.6). Allophane consists of hollow irregular spherical shaped particles with outside diameters of 3 to 5 nm (Shoji et al., 1993; McDaniel et al., 2012). Such minerals are referred to as nanocrystalline because the structural units (spherules) are within the nanoscale range (<100 nm) (McDaniel et al., 2012). Based on variations of Al:Si atomic ratio allophane can be divided into threetypes. Al-rich allophane has a ratio of 2:1 ratio of Al and Si (termed proto-imogolite allophane) whereas Si-rich allophane has a 1:1 ratio of Al and Si (termed hallosite-like allophane) (Parfitt, 2009). A third type of allophane is called stream-deposit allophane. Al-rich allophane is the most abundant type of allophane..

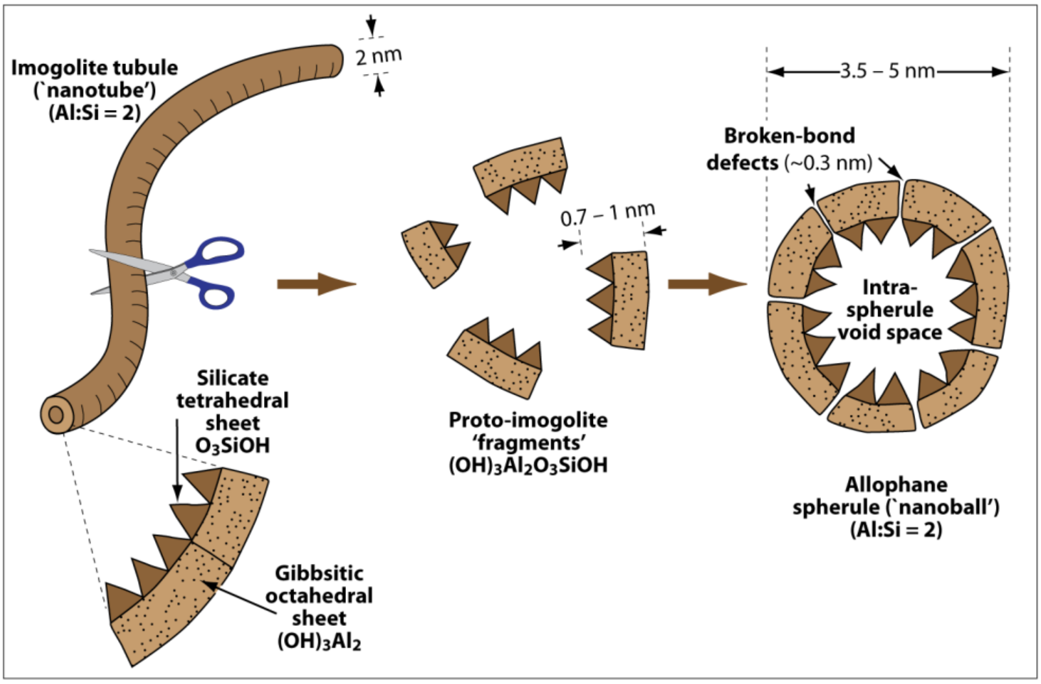


Figure 2.6: The morphologies and chemical compositions of allophane and imogolite. From McDaniel et al. (2012) after Lowe (1995).

2.1.1.1 Reactive-aluminium test

Soils with > 2% allophane can be identified by a characteristic greasy feel (Parfitt, 2009). The reactive-aluminium test (also known as the NaF test, allophane test, or the Fields and Perrott test) can also be used to differentiate allophanic soils by the reaction of NaF with hydroxy-aluminium in the nanominerals allophane and ferrihydrite (Milne et al., 1995). The reaction releases hydroxyl ions and raises the pH which causes the phenolphthalein colour development. In most other soils the pH remains low so the phenolphthalein indictor colour does not develop (Brydon & Day, 1970).

2.1.1.2 Ammonium oxalate- extractable silicon, iron and aluminium

Acid ammonium oxalate (acid oxalate) extracts iron (Fe), silicon (Si) an aluminium (Al) from nanocrystalline minerals and metal-humus complexes (Rayment & Lyons, 2010). It is used in conjunction with pyrophosphate extraction which extracts Fe and Al from metal-humus complexes to identify sources of allophane and ferrihydrite in soils and to quantify them (USDA, 2010). Hodder et al. (1990) measured allophane contents for B horizons of undisturbed paleosols developed on rhyolitic tephras in the Rotorua region (using acid oxalate extraction). The calculated allophane contents of the B horizons on Whakatane Tephra samples (on whole-soil/fine-earth basis) were 3.5 and 4.5%, Kaharoa tephra 1%, Taupo Tephra 1.5%, and Rotoma Tephra 2.5 %. According to Parfitt (2010) allophane contents of up to 60% (w/w) have been measured for B horizons and the limit of detection is 0.5 % allophane with an Al:Si ratio of 2.

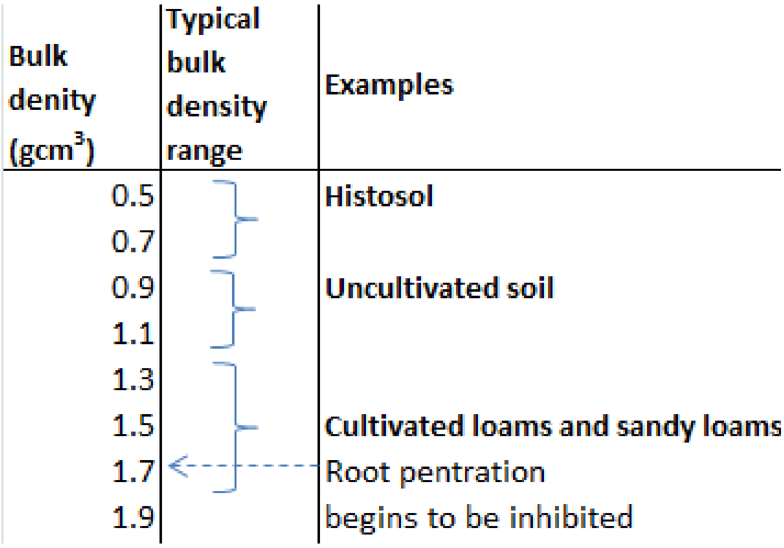
2.5.3 Soil structure (pedality)

The internal arrangement or organisation of the particles in the soil is referred to as the soil structure (Hillel, 2005). Both clay and organic matter bind soil particles together to form aggregates. The size and arrangement of aggregates forms the soil structure (Molloy, 1998). Soil structure determines the amount of water present at field capacity because of its influences on pore size distribution and therefore its ability to store water. It also affects plant nutrient uptake and root growth (Gardener, 1999). When roots are also restricted by a dense soil horizon it limits plant growth and supply of water is further decreased.

2.5.4 Soil dry bulk density

Soil dry bulk density provides a measure of the compactness of soil which is an important structural characteristic for soil activity. A high soil bulk density can indicate a compacted layer (Table 2.3). Root penetration begins to be restricted at ~1.7 g/cm^3 (Coyne & Thompson, 2006). The vesicular nature of pumice particles results in soils with low bulk density.

Table 2.3: Typical soil bulk density ranges. Adapted from Coyne & Thompson (2006).



Bulk denity (gcm^3)	**Typical bulk density range**	**Examples**
0.5		**Histosol**
0.7		
0.9		**Uncultivated soil**
1.1		
1.3		
1.5		**Cultivated loams and sandy loams**
1.7		Root pentration
1.9		begins to be inhibited

Numerous studies have demonstrated a connection between the compactness of the soil and water retention. A study by Dec et al. (2008) investigated the effects of bulk density on hydraulic properties in homogenised and structured soils. It was found that a decrease in saturated water content with increasing bulk density occurs. However, undisturbed samples start losing more water at higher tensions compared to those of disturbed samples. Packard (1957) also found that the least compacted soils (pasture) had the lowest available water expressed volumetrically.

2.5.5 Penetration resistance

Penetration resistance is related to soil strength and is the capacity of the soil in its natural confined state to resist penetration by rigid objects (usually expressed in bar or kPa) (Milne et al., 1995). Although easy to define it is harder to measure as it is a highly variable property (Hillel, 2004). Soil strength can be evaluated by the force required to push the tip of the penetrometer into the soil. Penetrometers can be used to measure resistance of soil to root penetration, tillage, tracking etc.

However, measurements are variable as shear strength is linked to water content (McLaren & Cameron, 1996).

Low soil dry bulk densities usually indicate friable soils which can be readily penetrated by roots. However, coarse textured pumice lapilli can “bridge” together and severely restrict root growth at many points (Will & Stone, 1967). Limited rooting depth in pumiceous horizons can also result in limited availability of water and nutrients to plants. Soils developed from Mt Mazama tephra (in Oregon, USA) show increased plant productivity where the pumice horizons have been mixed in varying degrees with finer material so that particle bridging is reduced (Geist & Cochran, 1990).

2.6 Soil water and plant roots

2.6.1 Capillary and non-capillary pore space

Soil water content affects the gas exchange of the soil which influences plant root respiration, the activity of microbes and the redox potential of the soil (Hillel 2004). The relative amounts of capillary and non-capillary pore space affect soil drainage and aeration. Capillary pore spaces are the smaller pores in the soil (30-60 µm) that hold water against the force of gravity. Non-capillary pore spaces are the larger pores that drain water with the force of gravity (Kramer, 1995)(Figure 2.7).

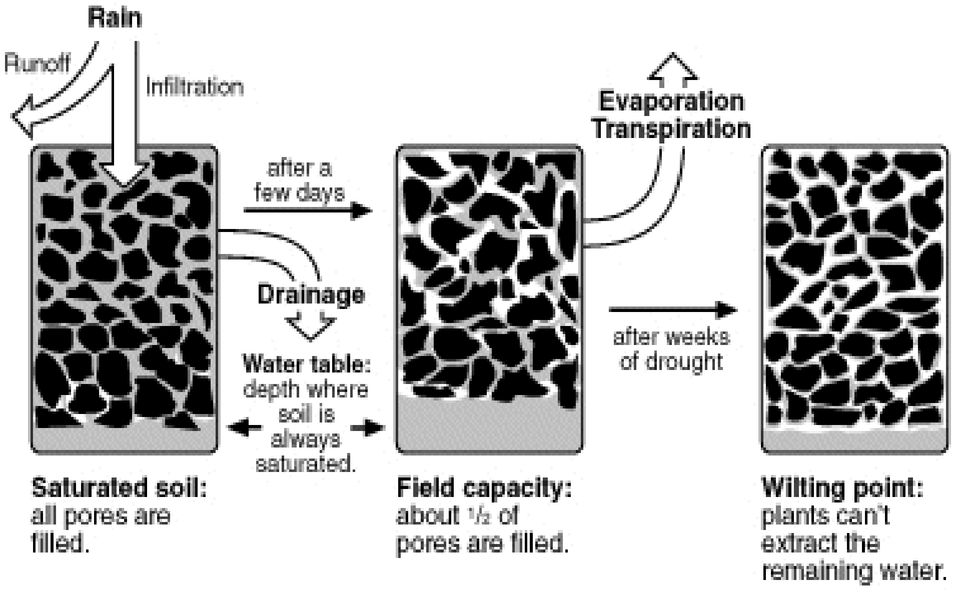


Figure 2.7: Soil water retention and drainage process which link the concepts of saturation, field capacity and wilting point. Image sourced from Rijkse & Guinto (2010).

2.6.2 Water potential

Soil water potential regulates water availability to plants and a difference in potential causes water movement from one part of the soil profile to another. The soil water potential depends on four components: the matric potential which is created by capillary action (Ψ_m), the gravitational forces operating on the soil (Ψ_g), osmotic potential created by dissolved salts in the soil (Ψ_s), and external pressure (Ψ_p). The water potential in soils (Ψ_{soil}) is described as the sum of the four components (Eq. 2.1) (Kramer, 1995; Kirkham, 2005).

Equation 2.1: $\Psi_{soil} = \Psi_m + \Psi_s + \Psi_g + \Psi_p$

Water moves from high potential to low potential energy, i.e., water will move into plant roots if the root water potential is less than that of the surrounding soil (Gardener, 1999). After the soil is saturated, water moves through the large pores under the force of gravity. Once equilibrium is reached and the soil retains some of the water against the force of gravity by capillary forces in smaller pores, the soil is at field capacity (Kramer, 1995). When water is tightly held within the soil matrix, the lower limit of soil water availability is approached (known as the permanent wilting point) (Sauer et al, 1984).

2.6.3 Soil water release characteristic

A soil water retention curve can be generated when a water potential measurement is combined with the water content measurement (Bittelli & Flury, 2009). Placing a saturated soil core on a porous plate attached to a hanging water column is lowered so that the suction is increased and water is removed from the core. The loss of water at each suction can be measured by reweighing the soil core (once equilibrium is reached, i.e., after the soil core has stopped draining for a particular suction) (White, 2009). This method is used to measure water held in the soil at lower matric potentials (0–10 kPa) while the use of a pressure plate apparatus is more suitable for higher tensions (100–1500 kPa). This is because pressure plates are susceptible to inaccuracies at lower matric potentials (Bittelli & Flury, 2009).

2.6.4 Available water capacity

The amount of water held in soil between field capacity and permanent wilting point is known as the available water capacity (Kirkham, 2005). Available water capacity is a measure of the ability of the soil to sustain good growth and high yields of crops and pastures. Available water capacity is also a measure of the capacity of the soil to store water after a rainfall event or irrigation (Rijkse & Guinto, 2010).

2.6.5 Readily available water

Water between field capacity and wilting point is not equally available to plants. Best plant growth occurs if water is maintained near field capacity (Packard, 1957). As tension increases to wilting point, plant growth declines. Readily Available Water (RAW) is the water that a plant can easily extract from the soil and can be calculated by deducting volumetric water content held at PWP from volumetric water content at 100 kPa (Figure 2.8) (Singleton, 1991).

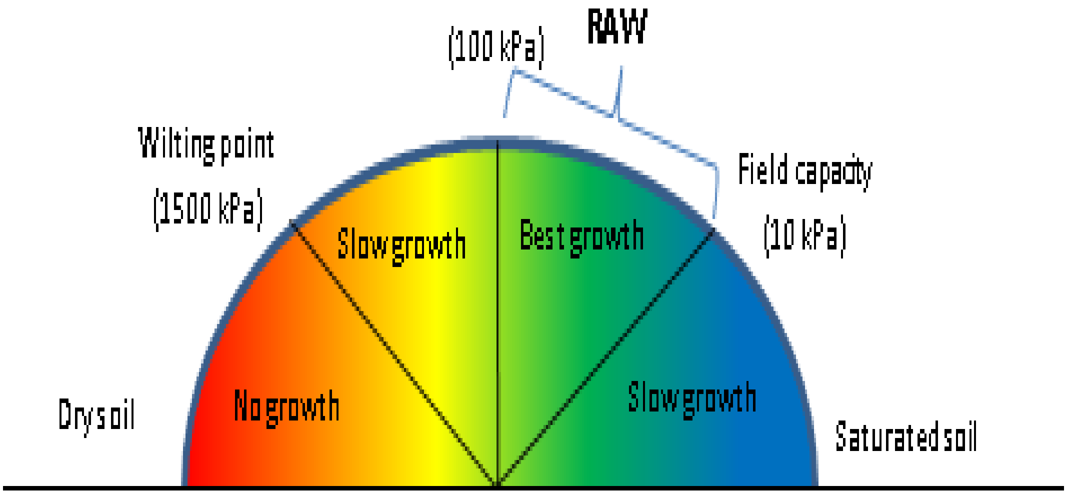


Figure 2.8: Available water capacity (between 10–1500 kPa) and readily available water (RAW) (between 10–100 kPa).

2.6.6 Texture

Soil texture (proportion of sand, silt and clay size particles within the soil) influences the soil's ability to retain water for plants and also drain excess water (Cornforth, 1998). There is a wide variation in soil water holding capacities within a given texture class and the literature itself is inconsistent. In general, sandy/coarse textured soils are well drained and have a limited water storage capacity in comparison to soils with a higher clay content (Kramer, 1995; Table 2.4).

Table 2.4: Available water capacity (mm/m) of various soil textures classes

Texture	Sources			
	(Gardner, 1990)	(Hargreaves & Merkley, 1998)	(Ingram et al., 2008)	(Burton, 2010)
Coarse sand	60-100	20-65	100	80
Fine sand		60-80		
Loamy sand		65-110	120	
Sandy loam	250	90-130	140	120
Fine sandy loam		100-170		
Clay loam				190
Silty clay			160	210

2.6.7 Plant rooting in Pumice Soils

Year-to-year variations in ryegrass yields are dynamic. In temperate grassland, root distribution and maximum rooting depth differ between seasons, species and also with soil texture and nutrient availability (Crush et al., 2012). Lower soil fertility and drought stress influence root mass and length under grazed grass-cover pastures (Dodd et al., 2011). In a study of growth patterns of perennial ryegrasses under well watered and drought conditions, drought conditions resulted in an increase in root counts down the soil profile compared to well-watered ryegrass controls, except in the immediate post-drought period (Wedderburn et al., 2010). Other studies have shown that changes in the rooting system can be a result of needing to capture a resource in a limited growing environment. For example, root proliferation (in the top 0.1 m) of two types of lettuce cultivars was triggered during drought conditions (Kerbiriou et al., 2013). Packard (1957) reported the phenomenon of roots proliferating through Pumice Soils to gain water in the wet zones which he attributed to the slow unsaturated movement of water through pumiceous horizons.

Rooting depth influences the available water content within the soil profile. The available water reservoir increases the deeper the roots grow and therefore the volume of water that can be applied during irrigation and the time interval between irrigation also increases. However, not all the water is extracted uniformly across the rooting depth; the majority of water is extracted within upper root zone. As the water content of the soil decreases, the deeper roots start becoming important for extracting water (Burton, 2010).

The available water contents (expressed on a volume basis) of Pumice Soils from the central region of the Kaingaroa forest were "high" (Will & Stone, 1961). Plant available water for *Pinus radiata* was calculated to be 914 mm over a plant rooting depth of 2.7 m. Although the water contents were taken to a depth of 2.7 m, the upper layers of the soil (containing Kaharoa pumice deposits) hold the majority of the fine root system and may be reduced to near wilting point long before the remainder of the profile (horizons with higher water holding capacities). The coarser materials add to the water holding capacity of the profile but have slow unsaturated water movement due to the disruption of pore continuity between and within pumice particles (Geist & Cochran, 1990).

2.6.8 Water storage in Pumice Soils

Because of the vesicular nature of pumice particles, water storage occurs within particles rather than within capillary pores and external water films around particles (Will & Stone, 1967). Pumice has been used as a soil conditioner as it lowers soil bulk density and improves drainage. In a study comparing various media and mixed media for container grown plants, pumice was able to hold on to more water at all tensions when compared to sand but both materials lost most of the water at tensions less than 50 cm (0.5 kPa) (Haynes & Goh, 1978). When comparing pumice particle size and hydraulic conductivity on growth rates of greenhouse crops, Gizas & Savvas (2007) found that the coarsest pumice grade (4–8 mm) were characterised by a steep drop in the water content between 0-1 kPa. As the suction increased to 100 kPa, soil water decreased to ~20% water content (w/w).

Contrary to the perception of low water holding capacities of pumice, there are numerous reports of Pumice Soils having surprisingly high water storage capacities. New laboratory data in the National Soils Database indicate that calculations of plant available water in Pumice Soils near Lake Taupo have underestimated water storage characteristics in these soils as previous estimates of lapilli were regarded as stones (no water-holding capacity). At present, experimental data of soil water retentions measured under field conditions (which would allow further calibrations of plant available water estimates for Pumice Soils in the central North Island) are not available (Landcare Research, 2013). Earlier work done by Packard (1957) revealed that Pumice Soils (collected from the Rotorua region) had 2 to 3 times the available water when compared with a non-pumiceous silt loam at corresponding tensions under laboratory conditions. The surprisingly high water storage of pumice soils was speculated to be because of the vesicular nature of the individual particles.

2.6.9 Water retention of allophanic material

The percentage and fraction of the clay minerals present in a soil influences the soil water retention curve (Mile & Mitkov, 2012) (Figure 2.9). Soils containing allophane usually have low bulk densities and high water retention which are attributed to the abundance of inter and intra-particle pores of allophane (Fontes et al., 2004).

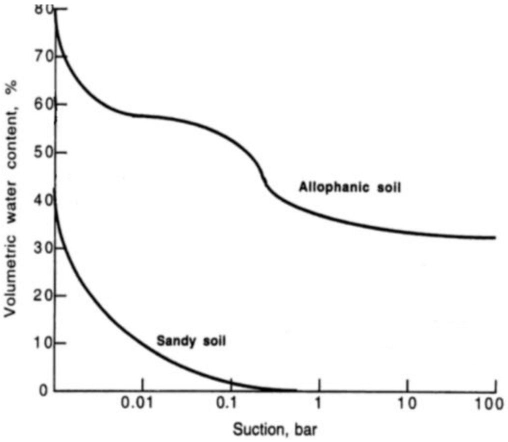


Figure 2.9: A typical water release curve for allophanic and sandy soils soil. Figure adapted from Juo & Franzluebbers (2003).

Irreversible changes to the physical properties of Allophanic Soils occur upon drying (Maeda et al., 1971). Physical properties affected include water retention and clay dispersibility. The water retention of allophanic soils decreases on air drying due to microscopic aggregation of allophane (Karube & Abe, 1998).

2.7 Soil flipping

2.7.1 West coast of New Zealand (South Island)

Soil flipping is a land development practice used to break up the iron pans and improve drainage in the Perch-gley Podzol Soils ('pakihi soils') on the West

Coast of the South Island (Thomas et al., 2007). Soil flipping has facilitated the expansion of productive land on the Perch-gley Podzols for dairying over the last 15 years (Horrocks et al., 2010).

2.7.2 Sandy soil modification in Australia

There are millions of hectares of sandy soils or sandy soils overlying clay rich subsoils (known informally as duplex soils) in Western and South Australia which are used for agricultural purposes (Figure 2.10a). The sandy soils have limitations including poor water holding capacity, low fertility, and hydrophobic properties. Soil modification such as "delving" (Figure 2.10b) or "claying' have been shown to increase the productivity of Australian duplex soils (Leonard, 2011). Delving is used to mix subsoil clay into sandy top soils, and claying refers to the application of clay-rich material (which may be from an external source) to sandy topsoils (Churchman et al., in review).

Figure 2.10: Soil mixing to improve physical properties in Australia. (a): example of a duplex soil. From http://grains.agric.wa.gov.au/node/deep-sandy-duplex. **(b): Clay delving .** From http://www.precisionag.com.au/page16.php.

2.7.3 Clay additions and C sequestration

Techniques that involve the addition of clay to sandy surface soil may also lead to increased C sequestration because organic matter can then be protected from decomposition (Shi & Marschner, in press). Hall et al. (2010) measured an increase of 0.2 % in organic carbon (~250 kg C ha^{-1} yr^{-1}) during 8 years for the treatment with the highest claying rate (300 t subsoil clay/ha added to the top 10 cm of soil). Shi & Marschner (in press) also reported that the addition of clay-rich subsoil materials to sandy soils can increase carbon sequestration by reducing

CO_2 emissions and extractable C concentrations probably because organic matter particles are less accessible to microbes in the soil once binding to clay occurs.

2.7.4 Additions of clay to manage hydrophobicity

Following the addition of clay-rich subsoil materials to water-repellent sandy soils, the clay spreads over and coats hydrophobic particles when the clay disperses. This is the only technique that provides a long-term solution for managing water-repellent soil (Hall et al., 2010). However, Ward & Oades (1993) concluded that clay additions only had an influence on water repellent soils once the modified soil mixture has been through a wetting and drying cycle.

2.7.5 Soil amendments to improve water availability

Sandy soils have a low nutrient and water retention capacity due to the lack of small pores and low cation exchange capacity of sand particles (Saleth et al., 2009; Shi & Marschner, in press). In areas dominated by sandy soils such as northeast Thailand, the use of clay-based soil amendments such as bentonites and termite mound-derived material can be considered as options to sustainably intensify and increase productivity by improving soil physical properties (Saleth et al., 2009; Mekuria et al., 2013). Suzuki et al. (2007) reported that amendements such as bentonites, termite mound material, and compost changed the water holding capacity and soil structural stability two years after initial application. Available water contents under the termite mound and bentonite material treatments were higher than the controls (>31% increase).

The water use efficiency of cucumber and maize grown in sandy soil treated with clay improved with additions of clay. Additions of clay to surface soils improved the soil water distribution throughout the soil profile, and plant yield from the clay overlay treatment was 2.5 times greater than that of the control (Ismail & Ozawa, 2007).

The A horizons of duplex soils in Australia have a low clay content and water storage capacity while the B horizons often comprise kaolinite clay. The clayey B horizons in duplex soils have low permeability, fertility, and saturated hydraulic conductivity leading to water logging (Tennant et al., 1992) The A and B horizons of duplex soils often obstruct root growth as soil dry bulk density frequently exceeds 1.8 Mg/m^3 (Dracup et al., 1992). Mechanically modifying duplex soils enhances water availability for plant up-take. Betti (2013) evaluated the effects of delving sandy duplex soils in South Australia (Figure 2.11). Relatively little clay was needed to increase the plant available water in the top soil as the greatest incremental increase was found with an increase in clay contents from 2-6%.

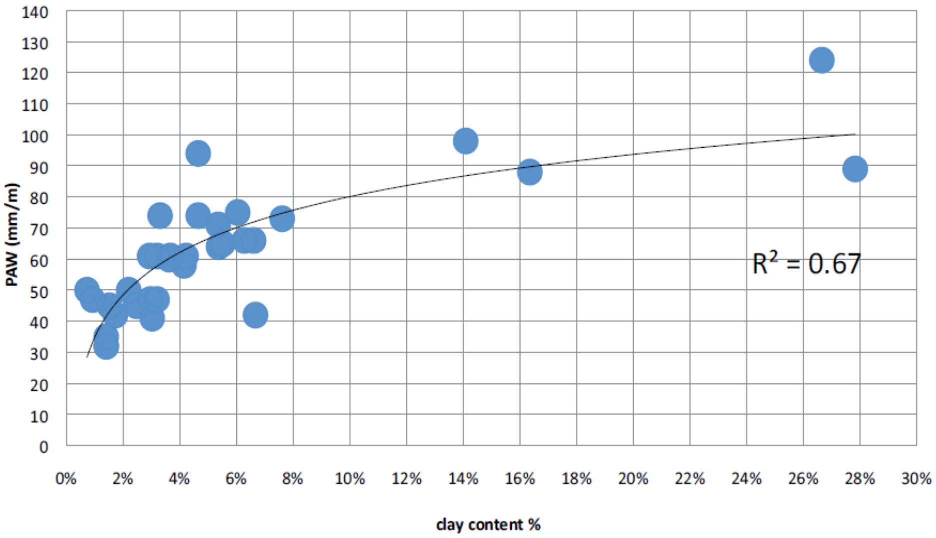


Figure 2.11: Effects of increasing clay contents on plant available water. From Betti (2013).

2.8 **Summary**

Pumice Soils cover a large proportion of central North Island. Soils formed on pumice and layered tephra deposits have distinctive characteristics which impact on water storage and plant growth. Water retention is influenced by physical properties such the texture and structure of the soil. In general, coarse textured soils are well drained and have a limited water storage capacity than finer textured soils. Pumice particles hold water within vesicles and external water films rather than within capillary pores. Pumice and sands lose most of the water at low suctions (tensions less than 0.5 kPa), whereas soils containing allophane have higher water retentions due to abundance of inter and intra-particle pores of tiny allophane spherules and microaggregates of allophane.

Numerous studies demonstrate the beneficial effects of clay additions to sandy soil with the goal of improving productivity. An improved understanding of how flipping enhances the soil characteristics in the Galatea Basin may provide farmers with an innovative way to improve efficiency of water use for pasture production especially in dry periods

Chapter 3

Methods

3.1 Introduction

This chapter describes the field and laboratory methods used. The majority of the soil sampling field work was carried out in February and March 2013 during a particularly dry summer.

3.2 Characterisation of undisturbed soil using a reference profile

In an initial investigation of the soil in the southern end of Galatea Basin, tephra deposits and associated buried soil horizons within the top 2.5 m of a tephra-soil sequence in an exposed cutting of a quarry wall, were identified and a detailed profile description was made using the *New Zealand Soil Description Handbook* (Milne et al., 1995). Horizon properties described included colour, texture, pedality, root abundance, consistence, horizon boundary, and parent material. Horizon notation was recorded following Clayden & Hewitt (1994).

The vertical profile in an exposed quarry wall was cleared and then sampled (Figure 3.1a). Samples for allophane analysis were taken from horizons 2bAB, 3bBw, 3bBC1, 3bBC2 and 4bBw. Samples for bulk density and particle size analysis were taken from every horizon (Figure 3.1b).

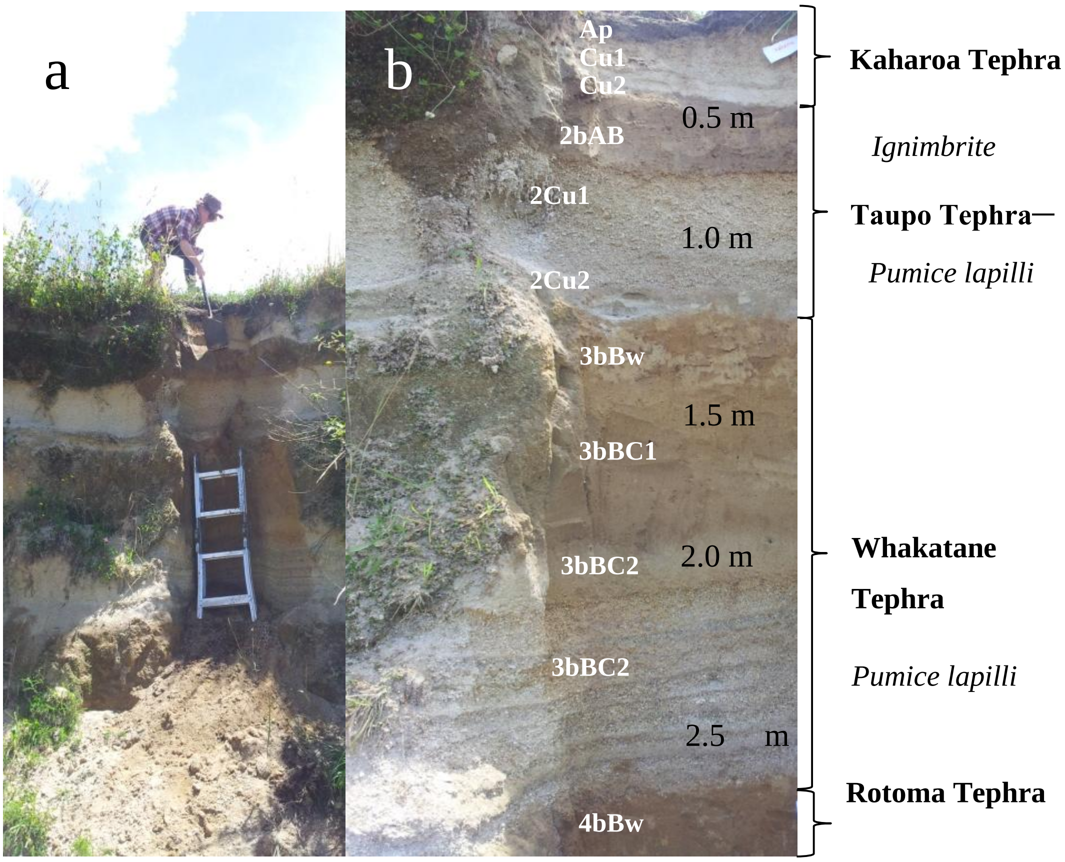


Figure 3.1: Reference tephra-buried soil section: (a) clearing the exposure, (b) depths and character of tephras and associated buried horizons of the undisturbed deposits in the exposed quarry wall. Named tephra formations (see Table 2.1).

3.3 Bulk density sampling and measurement

Soil dry bulk density (ρb) is the oven-dry mass of soil (dried at 105ºC) in an undisturbed state per given volume (Equation 3.1). The dry bulk density is expressed in g cm^{-3} or t m^{-3} (McLaren & Cameron, 1993).

$$\text{Equation 3.1: Bulk density } (\rho b) = \frac{\text{mass of oven dry soil (g)}}{\text{volume of soil } (\text{cm}^3)}$$

Soil dry bulk density cores were collected by inserting stainless steel rings (with known volume) into the soil. Once the core was removed with a putty knife, the excess soil from around the core was neatly trimmed, cleaned and the whole core was emptied into a bag. The soil was maintained within the extra cores to preserve structure. The cores were double-wrapped in cling film to prevent soil from falling out of the core, and transported back to the laboratory. Soils were kept in a fridge at 4^0C prior to analysis.

Three bulk density cores collected from each sampled horizon were emptied into separate bags. The same procedure was done for the soils in the flipped areas. Undisturbed cores (3 for bulk density and 2 for water retention analysis) were collected from the predominant material/horizons within the flipped pits.

Soil samples collected from bulk density rings (stored in sealed bags) were transferred into pre-weighed tins and placed in an oven to dry out at 105 ^{0}C (Figure 3.2). The samples were kept in the oven for at least 30 hours and then taken out and placed in a desiccator to cool before weighing. The mass was recorded and bulk density was calculated for each sample (Equation 3.1).

Figure 3.2:Soil samples ready for oven drying in pre-weighed tins.

3.4 Soil water content

3.4.1 Gravimetric moisture content (Θ_m)

In order to determine gravimetric moisture content, the samples collected from bulk density rings were weighed in pre weighed tins before being placed in the oven. This step was taken in order to calculate the gravimetric (Θ_m) and volumetric (Θ_v) moisture contents. Gravimetric water content is expressed as a percentage and is calculated as the ratio of the mass of water to the mass of soil (McLaren & Cameron, 1993) (Equation 3.2).

Equation 3.2: $\Theta m = \frac{\text{mass of field moist soil (g)} - \text{mass of oven dry soil (g)}}{\text{mass of oven dry soil (g)}}$

3.4.2 Volumetric water content (Θ_v)

The volumetric water content was calculated as the ratio of volume of water to the total volume of the soil using the following equation from McLaren & Cameron (1993) (Equation 3.3).

Equation 3.3: $\Theta v = \Theta m \text{ (field moist soil) } x \frac{\rho b \text{ (gcm}^{-3})}{\text{density of water } (1.0 \text{ gcm}^{-3})}$

3.5 *Soil water release characteristic*

3.5.1 Water retention curve

A soil water retention curve can be generated when a water potential measurement is combined with the water content measurement (Bittelli & Flury, 2009). A hanging water column (or Haines apparatus) was used to measure water held in the soil at lower matric potentials (0-10 kPa) whereas a pressure plate apparatus was used for higher tensions (100 -1500 kPa). The pressure plates are susceptible to inaccuracies at lower matric potentials (Bittelli & Flury, 2009).

3.5.2 Sub-sampling cores for water retention measurements

Soil cores were extracted from each horizon (close to where the bulk density cores were collected: within ~15 cm proximity) to use for water retention measurements. The cores were sub-sampled in order to fit into the Haines apparatus using pre-weighed PVC cores (19 mm high and 42 mm in diameter). The PVC core was pushed into the "undisturbed soil" core (sub-sampled from the larger soil core). A pre-weighed filter paper (Whatman 42 ashless filter paper) was attached at the bottom with a pre-weighed rubber band and labelled (Figure 3.3)

Figure 3.3: Sub-sampling bulk density cores. The smaller core (2) was sub-sampled from the larger "undisturbed" soil core (1) so that the white PVC pipe could be

inserted into the "undisturbed" soil more easily. (3) Sub-sampled core ready to go into the Buchner funnel

3.5.3 Haines apparatus

The water column of the Haines apparatus was lowered to tensions of 4, 25, and 75 cm. The soil water content at each tension was determined by re-weighing the core once it had stopped draining (water level equilibrated). Before a new tension was applied, the soil core was placed in a tray of water and left to become saturated (to ensure the top of the core was not dry before the measurements were taken) then put in the Haines apparatus on the porous plate in the *Büchner* funnel (Figure 3.4). The cores were left for a day to equilibrate in the Haines apparatus. While the cores were equilibrating, a plastic cover was placed over the *Büchner* funnel to minimise moisture loss by evaporation.

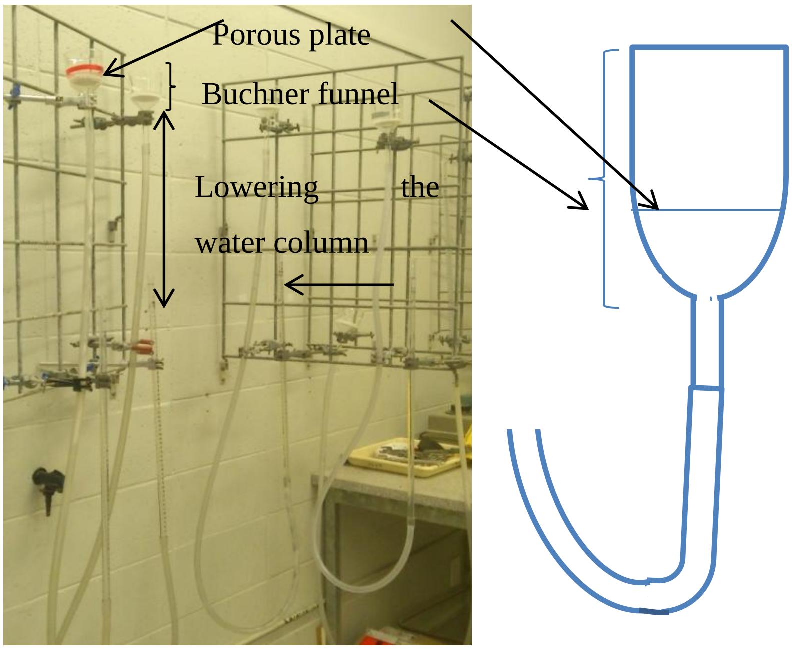


Figure 3.4: Haines apparatus and schematic diagram of the *Büchner* funnel .

3.5.4 Pressure plate apparatus

Prior to use, the ceramic plates were soaked overnight in a mild solution of water and bleach to prevent build-up of micro-organisms and to ensure they were saturated. The prepared samples were also left overnight to soak in a tray of water to become saturated. An open container of water was placed at the bottom of the extraction vessel to prevent the soil cores from drying out while in the pressure vessel (Figure 3.5). The saturated ceramic plates were put into the pressure vessel and then the samples were placed onto the saturated ceramic plates. The outflow tube connection between the ceramic plate and the outflow pipe on the extraction vessel was attached before the lid was placed over top and tightened by bolts. A measuring cylinder was placed at the end of the outflow pipes to collect water flowing out of soil samples. Compressed air was released into the chamber at the required pressure until equilibrium was reached (outflow of water stops). Measurements were made at 1, 3, and 5 kPa.

- Total available water capacity (TAWC) was calculated by subtracting the amount of water held at field capacity (assumed 10 kPa:) from the water held 1500 kPa). Samples from each horizon at the reference profile (from exposed quarry wall) were sent to Landcare Research to evaluate water retention at 1500 kPa.
- Readily available water content (RAWC) was calculated by subtracting the amount of water held at field capacity (10 kPa) (read off the soil water release curve) from the amount of water held at 100 kPa.

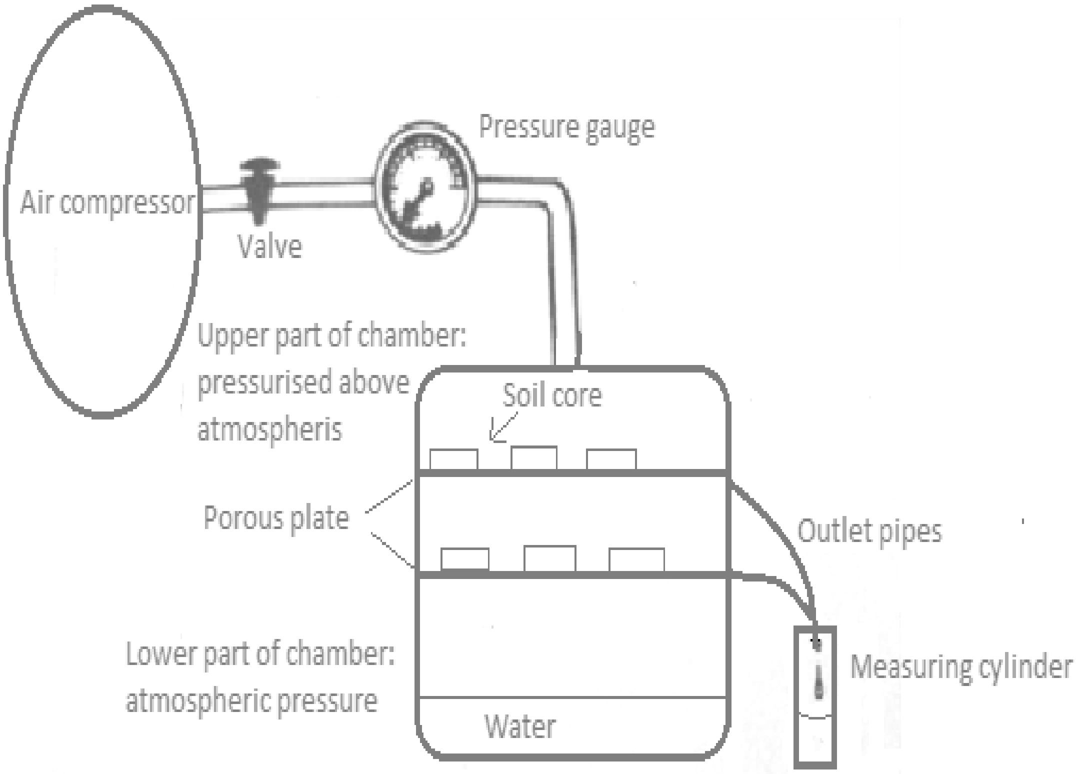


Figure 3.5: Pressure plate extractor for determination of soil water content at potentials from 1-500 kPa. Figured adapted from McLaren & Cameron (1996).

3.6 Ammonium oxalate-extractable silicon, iron and aluminium

Acid ammonium oxalate (acid oxalate salt) extracts iron (Fe), silicon (Si) and aluminium (Al) from nanocrystalline minerals and organic matter (Rayment & Lyons, 2010). It is used in conjunction with pyrophosphate, extraction which extracts Fe and Al from organic matter, to identify sources and to quantify allophane and ferrihydrite contents in the soil (USDA, 2010). Acid oxalate-extractable Fe, Al, and Si determination is an extraction using a 0.2 M solution of ammonium oxalate with 0.2 M solution of oxalic acid (Blakemore et al., 1987). The extraction method involves shaking the solution on an end-over-end shaker in the dark as oxalate is light sensitive (UV light causes a catalytic effect which speeds up the attack of crystalline oxides (Gleyzes et al., 2002)). After dissolution in acid oxalate reagent, the concentrations of Si and Al in solution were measured by inductively coupled plasma (ICP), which is a common method used for quantitative analysis of allophane (Parfitt, 2009).

The calculation of allophane content is based on the dissolution data from the Si content of a number of allophane samples of various Al/Si atomic ratios obtained by Parfitt & Wilson (1989). Parfitt & Wilson (1989) established a linear relationship between the Al/Si atomic ratio and the percentage of Si in allophane samples (Figure 3.6)

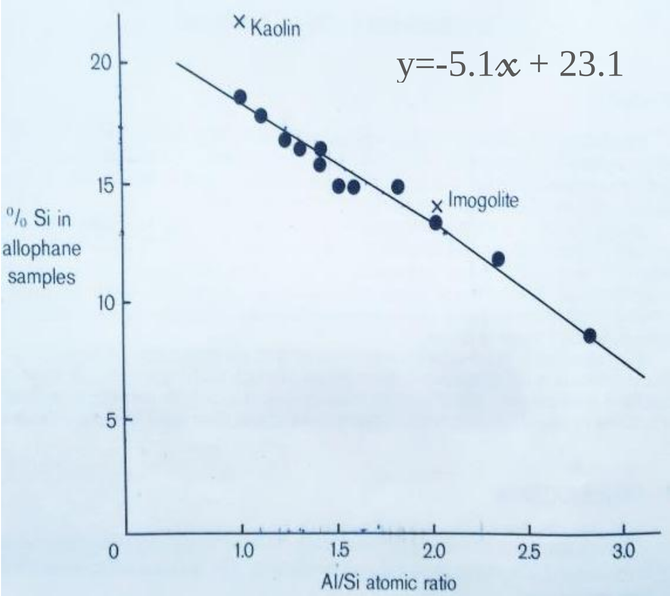


Figure 3.6: Si contents of allophanes with different Al:Si ratios. From Parfitt and Wilson (1989).

The measured concentrations of Al and Si extracted by acid oxalate (depicted as Al_o and Si_o) are used in conjunction with the concentrations of Al extracted by pyrophosphate (Al_p) to calculate the Al/Si atomic ratio (Parfitt, 2009) (Equation 3.4). In order to use the computerised calculation of allophane contents, Mizota & Reeuwijk (1989) produced an equation which describes the linear relationship between the Al/Si ratio and Si content of allophane (Equation 3.4, Figure 3.6).

Eq. 3.4: $\text{Al/Si atomic ratio} = \frac{\text{Alo (mg g}-1) - \text{Alp}\left(\text{mg g}^{-1}\right)}{\text{Sio (mg g}^{-1})}$

Eq. 3.5: $\text{Allophane \%} = \frac{100}{(-5.1(\text{ Alo} - \text{ Alp})/\text{ (Sio)} + 23.1)} \text{ x \%Si}_{o}$

3.7 *Particle-size analysis*

Particle-size distribution refers to the proportions of both the coarse fraction (>2 mm) and fine-earth fraction (clay, silt, and sand size particles <2 mm) (Table 3.1).

Table 3.1: Particle size fractions. From Milne et al. (1995).

Coarse fraction	**size (mm)**
boulders	>200
very coarse gravel	200-600
coarse gravel	60-20
medium gravel	20-6
fine gravel	6-2
Fine-earth fraction	
coarse sand	2.0-0.6
medium sand	0.6-0.2
fine sand	0.2-0.06
silt	0.06-0.002
clay	<0.002

The percentage of the coarse and fine-earth fractions of the individual horizons was determined by taking a cupful of the air-dried soil from each horizon collected from the exposed pit (Fig. 3.1b), and sieving them with a 2 mm, 0.6 mm, 0.2 mm, and a 0.06 mm sieve. In between sieving, the sieves were thoroughly brushedclean.. After sieving, the soil was placed in oven dry tins (pre-weighed) then put in an oven overnight at 105 °C. The fractions of oven-dry weight were used to calculate the percentage of course sand, medium sand, fine sand and particles smaller than 0.06 mm.

3.7.1 Malvern laser-sizer

The Malvern laser-sizer was used for particle-size analysis of the < 2 mm fractions. Approximately ½ a teaspoon of field moist soil (<2 mm sieved) was placed in a 50 ml beaker. The beakers were left in the fume cupboard with sufficient hydrogen peroxide (10% solution) to cover the sample. Additional 5 ml of hydrogen peroxide were intermittently added until the samples stopped fizzing (~ 1 week duration). After the fizzing subsided the beakers were placed on a hot plate and gently heated. The samples were reduced to approximately 5 ml of slurry and left to cool, 5 ml of 10% calgon was added, and then left overnight. The samples were mixed before 0.2–0.5g of material was sucked up with a dropper and put in the Malvern laser-sizer for analysis.

3.8 Investigation of "flipped" sites

Four sites were identified in the Galatea Basin that had previously been modified by flipping. Each contained a flipped area and an adjacent undisturbed area within the same paddock. At each site within the same paddock, 3 pits ~0.8-1.0 m deep, were excavated, using a tractor with a bucket loader (Figure 3.7) in the "flipped" area and 3 pits in the "undisturbed" area (Figure 3.8). The depth of flipping, time since flipping, and whether or not topsoil was preserved and placed back on top of the mixed soil materials varied between sites (Table 3.2). In each pit, a detailed pedological description was made following the methods described in section 3.2).

Table 3.2: Description of sites sampled

Site	Years since flipping	Depth (m)	*Topsoil retained	Latitude & longitude		treatment
1	3	~1.8	Yes	38°27'25.84"S	176°44'39.41"E	"deep sort"
2	10	~1.8	Yes	38°27'37.80"S	176°45'7.72"E	"deep sort"
3	3	~0.6	No	38°24'49.71"S	176°47'51.76"E	"shallow mix"
4	3	~0.6	Yes	38°25'37.48"S	176°45'22.57"E	"shallow sort"

***** Topsoil was taken off before flipping and put back after the rest of the soil was flipped.

Figure 3.7: A tractor with a bucket loader excavating pits.

At **site 1** during the flipping process, the topsoil (Ap horizon) was stripped and stock piled then the horizons Cu1, Cu2, 2bAB, and 2Cu were put aside and the second buried horizon (3bBw) was placed to one side while horizons Cu1, Cu2, 2bAB, and 2Cu were placed back and buried by the 3bBw horizon. The topsoil was then placed back at the top of the sorted soil material (referred to as "deep sort" treatment, Table 3.2).

At **site 2** during the flipping process, the topsoil (Ap horizon) was stripped and stock piled, then the sandy horizons Cu1 and Cu2 were put aside. Horizon 2bAB (a buried soil horizon formed on Taupo Tephra) was put aside with the underlying buried soil horizon 3bBw. The horizons Cu1, Cu2, and 2Cu were buried with the 2bAB and 3bBw horizon materials. The topsoil was then placed back at the top of the sorted soil material ("deep sort" treatment, Table 3.2).

At **site 3**, horizons Ap, Cu1, Cu2 and buried soil horizon 2bAB were excavated in small sections and tipped back into the hole to mix these materials ("Shallow mix" treatment, Table 3.2).

At **site 4**, the topsoil (Ap horizon) was stripped and stock-piled. The sandy horizons Cu1, Cu2, and buried soil horizon 2bAB on Taupo Tephra were excavated in small sections and tipped back into the hole to mix the sub-soil material ("shallow" sort treatment, Table 3.2).

Figure 3.8: Paddocks in Galatea Basin that contain flipped soils (sites 1-4).

3.9 Penetration resistance

A hand-held penetrometer was used to measure the penetration resistance of each of the horizons in the undisturbed soil pits and the predominant materials/horizons within the flipped soils. The penetrometer was pushed into the soil until the engraved line (6 mm from the tip) was level with the soil surface. Once the penetrometer was removed from the soil the scale was read. The penetration resistance is given in bar and was calculated by multiplying the divisions by the spring factor of 0.67. The readings were converted to kPa and placed into penetration resistance classes (Table 3.3). Approximately 10 replicate measurements were made for each soil horizon and the mean value was calculated.

Table 3.3: Penetration resistance classes (from Milne et al. (1995)).

Class	Penetration resistance (kPa)
Extremely low	0-500
Very low	500-1000
Low	1000-1500
Moderate	1500-2200
High	2200-3000
Very high	3000-4000
Extremely high	>4000

3.9.1 Degree of packing

The degree of packing was measured in each horizon using a Singleton blade and hand-held penetrometer (Figure 3.9) using the method described by Milne et al. (1995). The force required to push the Singleton blade sideways (using the penetrometer) was used as a measure for the degree of packing (Griffiths et al., 1985). The readings were converted to kPa and placed into classes (Table 3.4)

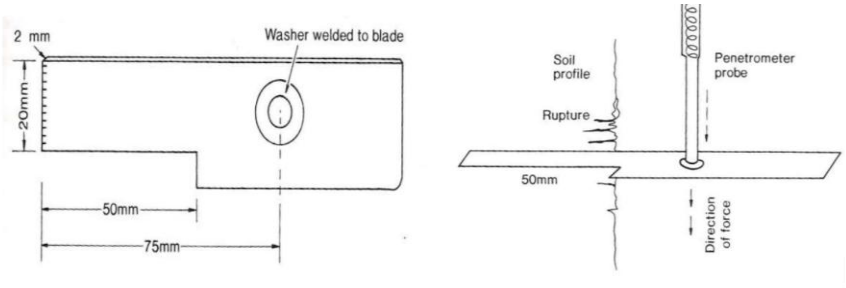


Figure 3.9: Singleton blade (LHS) being pushed by penetrometer (RHS). From Milne et al. (1995).

Table 3.4 Degree of packing by Singleton Blade and penetrometer tip. *From Griffiths (1985). ** From Milne et al., (1995).

Degree of packing	Bar*	kPa**
Very low	0-4	0-500
Low	5-9	500-1000
Moderate	10-22	1000-2200
High	23-30	2200-3000
Very high	31-40	3000-4000
Extremely high	>40	>4000

3.10 Permeability assessment

3.10.1 Introduction

Soil permeability is a property that is difficult to measure but can be assessed by examining the physical characteristics of the soil (Griffith, 1985).The procedure for the field assessment of permeability class was undertaken using the methods of Griffiths (1985). Permeability class was assessed at the individual undisturbed pits at site 1 from the biological porosity and degree of packing to give an overall estimation of permeability class for each soil horizon.

3.10.2 Permeability related to vertical continuity

Dye tracking, using methylene blue dye (0.1% solution), was used to assess permeability and biological porosity following Griffiths (1985). To estimate the permeability and biological porosity, a large metal ring was inserted into the soil and ~80 ml of dye were added (Figure 3.10 a). When the dye disappeared, the soil was cut back with a spade to see how far the dye had travelled and also to see if the dye travelled through any macropores (Figure 3.10 b). Permeability is directly related to porosity, infiltration rate and vertical continuity and hence the permeability classes are based on the number and diameter of dyed patches in each cut-open block of soil (Table 3.5).

3.10.3 Permeability related texture and degree of packing

Permeability classes were also assessed. A penetrometer and Singleton Blade were used to assess the penetration resistance and degree of the degree of packing in order to estimate permeability. The permeability class of non-coherent apedal single grain horizons, such as those of the modern soil formed on Kaharoa tephra (the Cu1 and Cu2 horizons), was assessed using Table 3.5 while the permeability class of the non-coherent apedal massive horizons, such as those of the buried horizon formed on Taupo tephra (2bAB), was assessed using Table 3.6.

Figure 3.10: Assessment of pore continuity: (a) addition of methylene blue dye in metal rings, (b) cutting the soil back to see how far the dye had travelled through it.

Table 3.5: The relationship between permeability, biological posity, and infiltration rates. Adapted from Griffiths (1985).

Diameter of holes	# of holes	Porosity	Permeability class	Infiltration rates at 1.27 cm head (mm/hr)
<2 mm	any	Very low	1	<1
2-5 mm* (worm holes)	1	Low	2	1-4
	2 -3	Moderately low	3	5-19
	4-7	Medium	4	20-64
	8-11	Moderately high	5	65-129
	12-16	High	6	130-250
	>16	Very high	7	>25

*larger holes should be reduced to worm hole equivalents

Table 3.6: Permeability class of dry apedal soil (non-coherent horizons/ single grain). From Griffiths (1985).

Single grain horizons	Degree of packing	Permeability class
Fragmental	Very low	7
	Low	7
	Moderate	7
	High	6
Sandy skeletal	Very low	6
	Low	6
	Moderate	6-5

Table 3.7: Permeability class of moist apedal material (massive & weakly developed structure). From Griffiths (1985).

		Particle size	
Degree of packing	coatings	Sandy	Coarse & fine loamy
Low	absent	5	4
	present	N/A	4
Medium	absent	5-4	4-3
	present	N/A	3
High	absent	4	3-2
	present	N/A	2
Very high	absent	3	2-1
	present	N/A	2
Extremely high	absent	2	2-1
	present	N/A	2

3.11 Plant root density experiment

In order to determine the differences in root density at various depths in “flipped” and “undisturbed” soils, soil cores were extracted from profiles in a flipped area and an undisturbed area of an experimental trial site that had been flipped (~1.8 m deep) 1 year prior to sampling (location : 38°27'43.87"S 176°45'17.91"E). A corer was inserted into the ground at 10 cm increments down to a depth of 60 cm. Eight cores taken on the flipped side. Each core was inserted 60 cm deep into the ground and taken in 10 cm increments (0-10, 10-20, 20-30, 30-40, 40-50, 50-60 cm). There were 4 cores taken on the undisturbed side. The cores were also taken in 10 cm increments to a depth of 60 cm. The incremental cores were bagged individually and taken back to the lab to wash the roots. Roots were separated by washing the sample with a 2 mm sieve (Figure 3.11). The excess water was kept in a container and poured into a 1.8 mm sieve again. Water was added to the container a few times and the roots that were left behind were picked out with tweezers. Once the roots had been collected from the individual cores they were placed in brown paper envelopes and dried in an oven at 65 ºC for 30 hours, and cooled in a desiccator then weighed. The root weight collected from the individual cores was converted to gm^{-2} (Equation 3.6).

Equation 3.6: Root density ($g\ m^{-2}$) for each soil depth increment = $\frac{\text{root weight(g)}}{\text{area of core (m}^2\text{)}}$

Figure 3.11: Extracting roots from soil cores by sieving

Chapter 4

Results

4.1 Introduction

In this chapter I describe the results and observations obtained from the field and laboratory. Full profile descriptions and water retention data are included in Appendix 1.

4.2 Referenc*e soil profile*

An exposed cutting on a terrace margin located in the southern end of Galatea Basin (Figure 4.1) was used as a reference tephra-soil sequence to characterise the individual buried soil horizons and associated parent tephras to a depth of 2.5 m. The modern soil is formed on pumice deposits of the Kaharoa Tephra which overlie fine textured buried soils and graded pumice lapilli deposits formed successively on Taupo, Whakatane, and Rotoma tephras (Figure 4.2, Table 4.1).

Figure 4.1: Site of reference tephra-buried soil profile on an exposed quarry wall located close to the Whirinaki River.

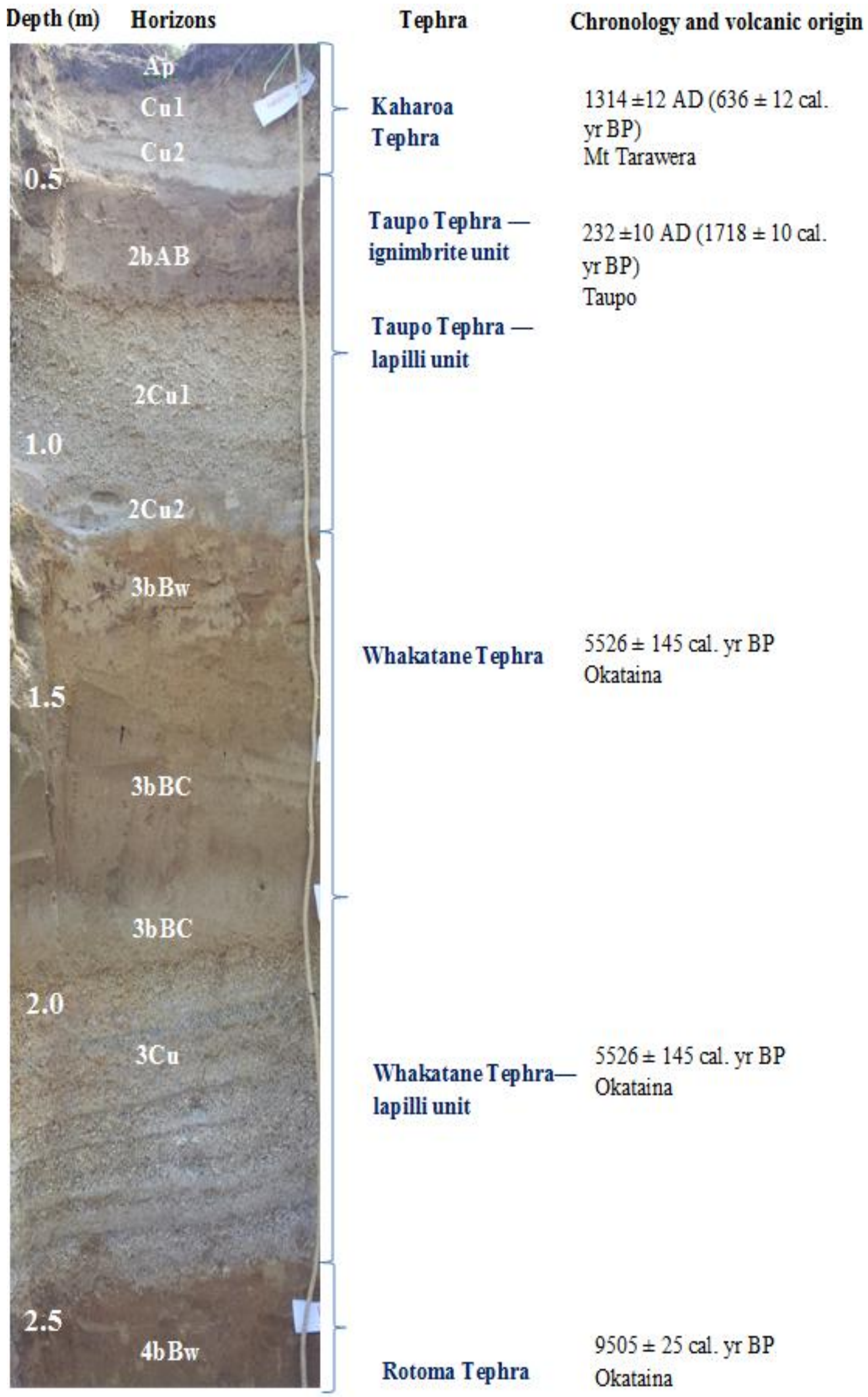


Figure 4.2: Reference tephra-buried soil sequence.

Table 4.1: Reference soil profile description: Galatea loamy sand.

Reference Data	
Soil classification	**Soil Taxonomy:** Typic Udivitrands **NZSC:** Buried-allophanic Pumice Soil
Soil type	Galatea loamy sand
Location	Exposed cutting on the property of 260 Whirinaki Rd ~ 200 m north of Whirinaki River (38°27'47.73"S 176°43'59.46"E)
Annual rainfall	1700 mm **Elevation** 200 m
Geomorphic position	Terrace above Whirinaki River flood plain
Parent material	Rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)

Horizon Depth (cm)	**Description of Galatea loamy sand**
Ap 0-10	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; very weak to weak soil strength; very friable; apedal earthy; abundant extremely fine roots: abrupt smooth boundary. [Kaharoa Tephra.]
Cu1 10-40	Light grey (2.5Y 8/1) slightly gravelly coarse and medium sand; non sticky; non plastic; apedal single grain; abundant extremely fine roots; abrupt smooth boundary. [Kaharoa Tephra.]
Cu2 40-50	Light yellowish brown (2.5Y 6/3) medium and fine sand; non sticky; non plastic; apedal single grain; few extremely fine roots; abrupt smooth boundary. [Kaharoa Tephra.]
2bAB 50-75	Dull yellow brown (10YR 5/4) loamy sand with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; slightly firm soil strength; apedal massive breaking to apedal earthy; abrupt wavy boundary. [Taupo Tephra – ignimbrite unit.]
2Cu175-115	Light grey (10YR 8/1) very gravelly sand with medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abrupt smooth boundary [Taupo Tephra – lapilli unit.]
2Cu2 115-125	Light grey (10YR 7/1) evenly sorted loose fine sand (marker bed); abrupt smooth boundary [Taupo Tephra – Hatepe unit.]
3bBw 125-140	Bright brown (7.5YR 5/6) sandy loam; common medium greyish yellow (2.5Y 7/2) mottles; non sticky; non plastic; weak soil strength; apedal massive breaking to earthy; abundant fine polyhedral peds; abrupt smooth boundary. [Whakatane Tephra.]
3bBC1 140-160	Olive brown (2.5Y 4/6) sandy loam with few fine charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; apedal earthy; abrupt smooth boundary. [Whakatane Tephra.]
3bBC2 160-185	Dull yellow (2.5Y 6/3) fine sand; non sticky; non plastic; weak soil strength; friable; apedal single grain; abrupt smooth boundary. [Whakatane Tephra.]
3Cu 185-250	Pale yellow (2.5Y 7/3) very gravelly sand with medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abrupt smooth boundary [Whakatane Tephra – lapilli unit.]
4bBw 250	Dull reddish brown (5YR 4/4) sandy loam with few medium greyish yellow (2.5Y 7/2) mottles; slightly sticky; slightly plastic; slightly firm soil strength; apedal massive [Rotoma Tephra.]

4.3 Comparisons between flipped and adjacent undisturbed sites

4.3.1 Profile descriptions

Multiple profile descriptions were made at each of the four sites. The four research sites had a different flipping treatment (Section 3.8). At each site three pits were excavated in the "flipped" area and three pits in the "undisturbed" area, giving a total of six excavated pits per site and twenty four pits all together. In this section a summary of the observations of several pits at each site is included. Full descriptions are included in Appendix 1.

4.3.1.1 Site 1

The "undisturbed" (control) area at **site 1** was similar to the reference profile site. However, there was a 2-cm thick layer of white loamy sand between the Cu1 and Cu2 horizons. The white loamy sand layer (an ash-fall bed of different texture deposited at this site during the complex Kaharoa eruption event) marked a noticeable change in plant roots. The microfine roots seemed to decrease in abundance at the white loamy sand layer (Figure 4.3a). The undisturbed Ap horizon had a strongly developed platy surface layer about 2-5 cm thick (Figure 4.4).

Although the topsoil in the "flipped" area had a platy layer, it was less well developed than the undisturbed pits. The topsoil on the flipped area felt sandier than the topsoils in the undisturbed side. Particle size analysis shows that the flipped topsoils had more coarse material in the topsoil compared to the undisturbed topsoil (Appendix 3, Figure 8.1 & 8.6). Within the flipped subsoil matrix, there were clumps of top soil (Ap-horizon material) (Figure 4.3b). In other flipped pits there were lenses of pumice indicating that the excavated subsoil materials were not fully homogenised during the flipping process. Predominant pasture species at site 1 were cocksfoot and yarrow. Roots mainly occurred in the Ap and Cu1 horizon and were "abundant" to a depth of 350-400 mm in the undisturbed side. In contrast, the roots appeared to be more evenly spread throughout the profile on the flipped side to a depth of 600 mm and the root growth was prolific in pumice lenses at depths below 600 mm in the flipped areas.

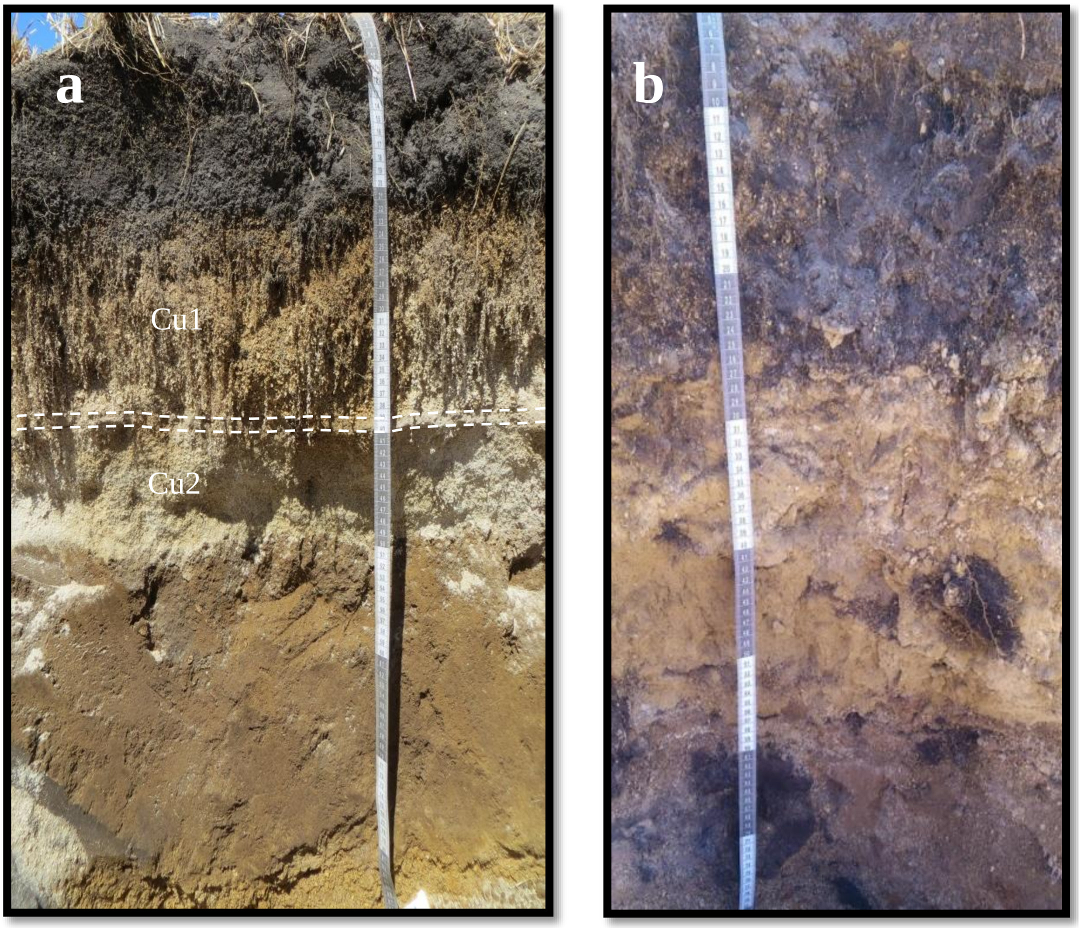


Figure 4.3:Examples of soil profiles at site 1, (a) undisturbed area, (b) flipped soil.

Figure 4.4: Strongly developed platy layer in the “undisturbed” Ap horizon.

4.3.1.2 Site 2

The undisturbed area at **site 2** was essentially similar to the reference profile (Figure 4.5 a). The top soil on the undisturbed area had a strongly developed platy surface layer 2-5 cm thick. The topsoil on the flipped area had a well-developed platy surface similar the topsoil on the undisturbed side. Although the site had been flipped 10 years ago, the large clumps of topsoil within the subsoil were still recognisable (Figure 4.5b). Predominant pasture species at site 2 were cocksfoot and yarrow and the “abundant’ roots extended to a depth of 400-450 mm in the undisturbed side.

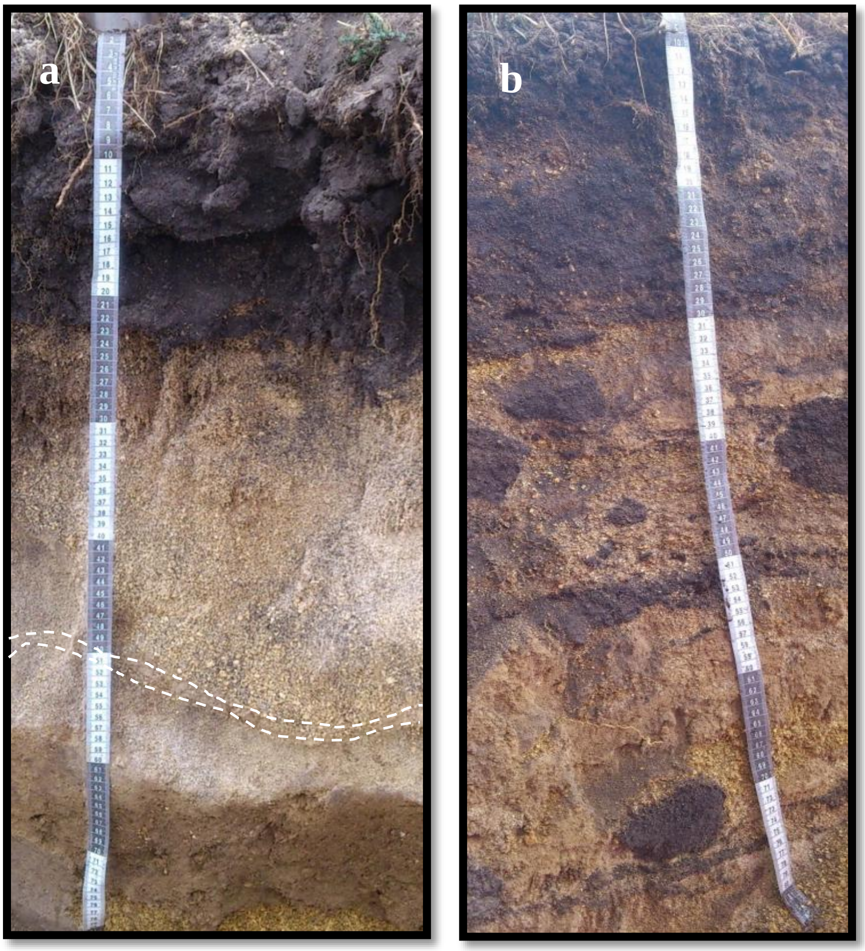


Figure 4.5: Typical Soil profiles at site 2, (a) undisturbed area (b) flipped area.

4.3.1.3 Site 3

The undisturbed profile at site 3 was slightly different from the reference profile in that there were lenses of white loamy sand between the Ap and Cu1 horizon (Figure 4.6a). The loamy sand lenses were found in 2 out of the 3 pits on the undisturbed area at site 3. The topsoil on the undisturbed side had a strongly developed platy surface layer. Throughout the profile, small spots of bright orange brown staining (mottles) on the pumice lapilli and white loamy sand patches were evident at site 3 as well as site 4. The bright-orange red staining on the pumice lapilli at site 3 and 4 indicates periodic water logging. Galatea mottled sands are most waterlogged during spring and dry out during summer (Vucetich, 1960).

Although the topsoil had been mixed into the soil during the flipping process, a new topsoil had started to form on the flipped area at site 3 (Figure 4.6b). At site 3 the soil was more uniformly mixed in the flipped pits than the flipped pits at site 1 and 2, but clumps of the original soil material in the flipped area were still recognisable. The predominant pasture species at site 3 was chicory and the “abundant” roots extended to 450-500 mm in the undisturbed area, and 700 mm depth in the disturbed area.

Figure 4.6: Typical soil profiles at site 3, (a) undisturbed area, an example of the lenses of white loamy sand between the (b) flipped areas.

4.3.1.4 Site 4

At site 4 the topsoil on the undisturbed area (Ap horizon) was thicker than that at any other site (~45 cm compared to ~ 20-25 cm). The Ap horizon was separated into two sections by a 5 cm whitish yellow loamy sand layer (Figure 4.7a). The lenses of various soil materials in the subsoil were still recognisable in the flipped area. The topsoil depths ranged from 25 cm to 40 cm on the flipped area at site 4 (Figure 4.7b). The predominant pasture species at site 4 was perennial ryegrass and clover. "Abundant" roots were observed to a depth of 400-450 mm in the undisturbed area, and to a depth >600 mm in the flipped area.

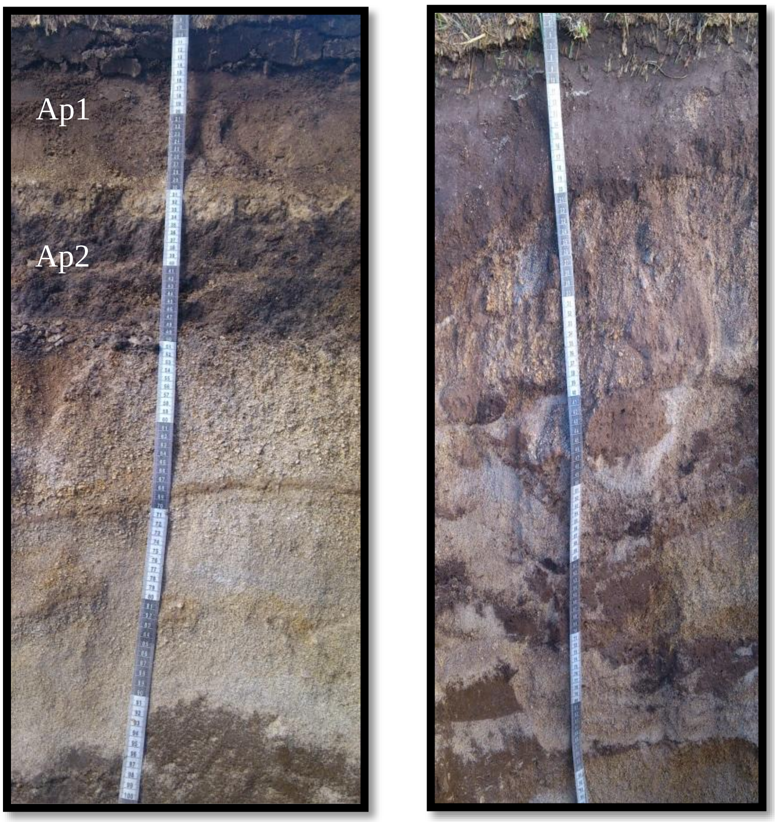


Figure 4.7: Typical soil profiles at site 4, (a) undisturbed area, (b) flipped area.

4.4 *Water retention curves*

The water retention curves for the undisturbed horizons from the reference profile show that most of the water held in the soil is lost at lower tensions (<100 kPa) (Figure 4.8-4.13). The water retention curves for the sandy, gravelly sand and pumice horizons (Cu1, Cu2, 3Cu) have volumetric water contents <10 % under tensions >100 kPa (Figures 4.9 & 4.12). The Taupo pumice horizon (2Cu1) holds more water (10-20 %) than the Cu1, Cu2, and 3Cu horizons (Figure 4.10). The buried soil horizon (2bAB) formed on Taupo Tephra holds more water than the Taupo pumice horizon (2Cu1) at every tension up to 500 kPa (Figure 4.10). Horizons 3bBw and 3bBC1 (in Whakatane Tephra) have similar water retention curves at every tension up to 500 kPa compared to those of horizon 3bBC2 which holds less water than 3bBw and 3bBC1 at every tension up to 500 kPa (figure 4.11).

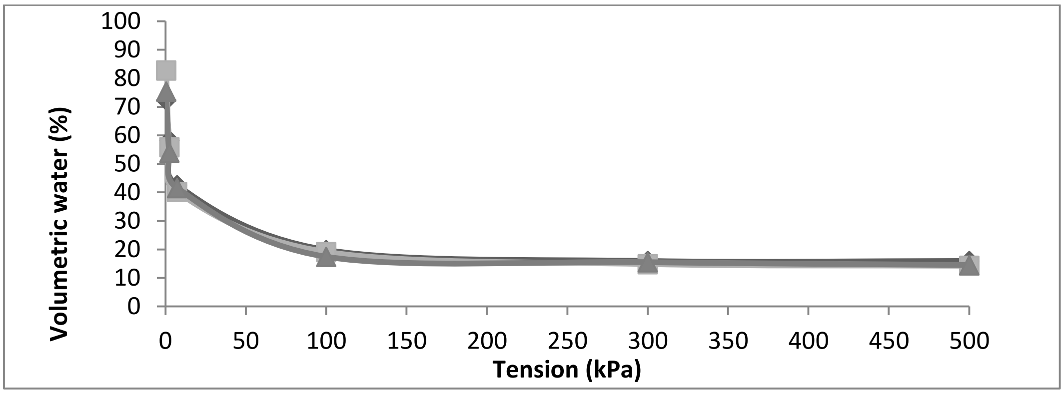


Figure 4.8: Water retention of undisturbed Ap horizon (3 replicates) from reference site

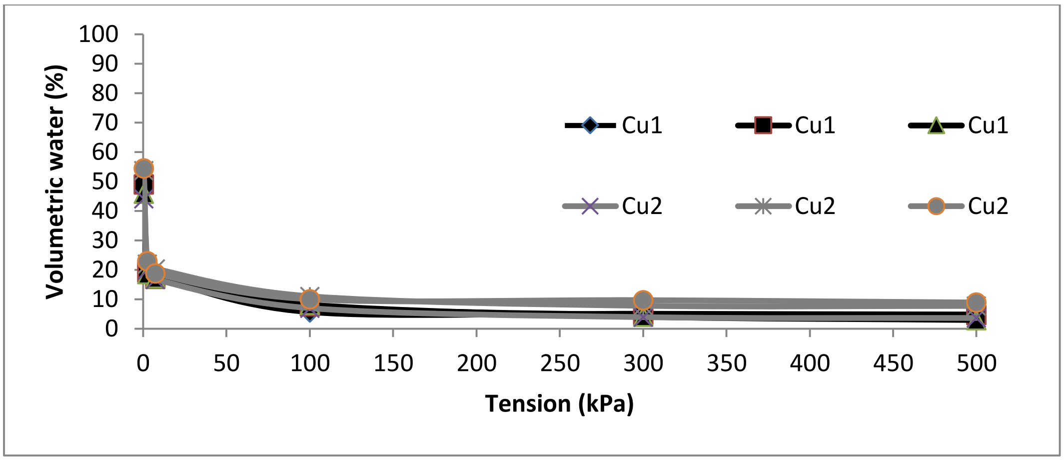


Figure 4.9:Water retention of undisturbed Cu 1 (black) and Cu2 (grey) horizon (3 replicates) from reference profile.

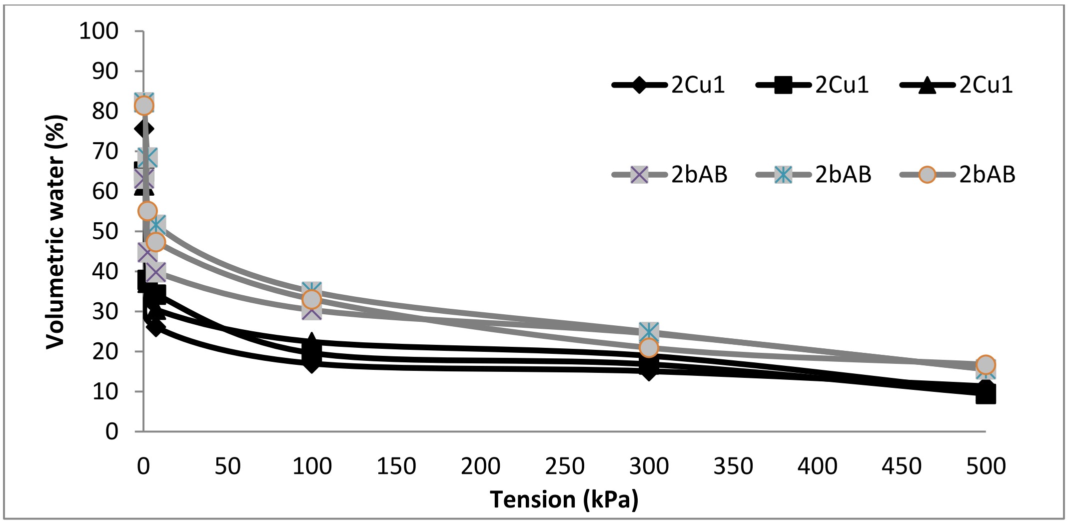


Figure 4.10: Water retention of undisturbed 2bAb (black) and 2Cu horizon (grey) (3 replicates) from reference profile.

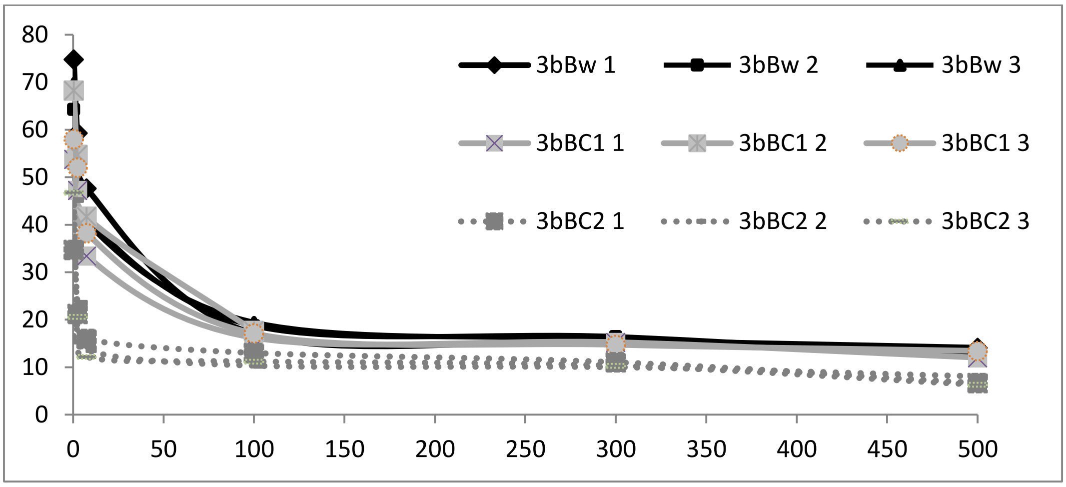


Figure 4.11: Water retention of undisturbed 3bBw, 3bBC1 and 3bBC2 horizons from reference profile

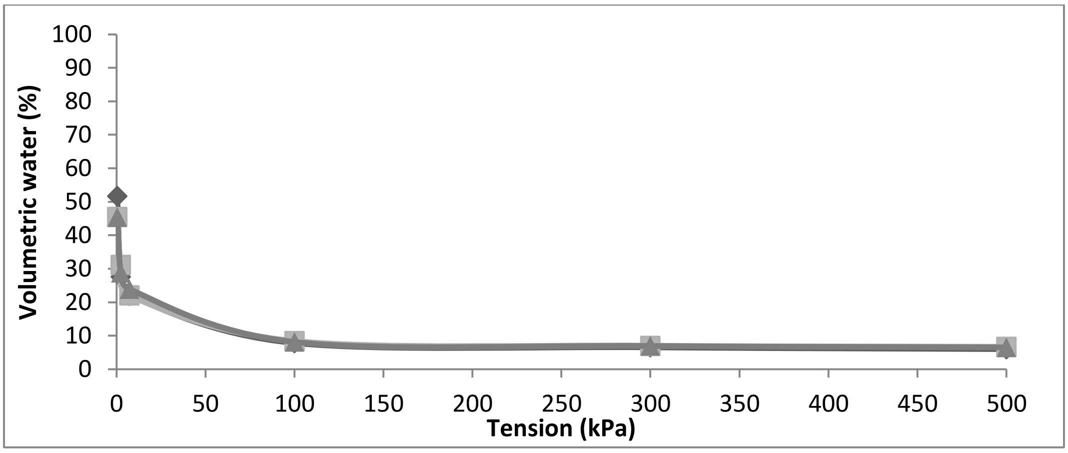


Figure 4.12: Water retention of undisturbed 3Cu horizon from reference profile.

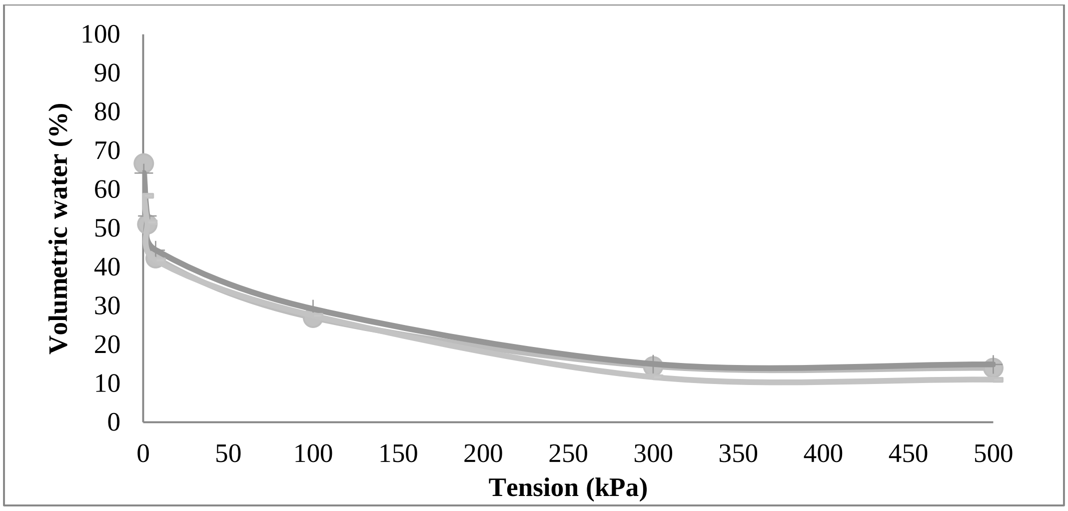


Figure 4.13: Water retention of undisturbed 4bBw horizon from reference profile.

The water retention curves for the flipped topsoil at site 1 are roughly similar to the water retention curves for the undisturbed topsoil (Ap horizon) at site 1 (Figure 4.14). One of the topsoil samples collected from flipped pit 3 at site 1 had a higher volumetric water content at all tensions to 500 kPa (Figure 4.14). The volumetric water content for the flipped topsoils at site 2 was higher than the volumetric water contents of the undisturbed topsoils (Ap horizon) at every tension to 500 kPa (Figure 4.15). The volumetric water contents of the flipped topsoil samples from site 3 were lower than the volumetric water contents of the undisturbed topsoil samples (Ap horizon) from site 3, at tensions between 100 kPa and 500 kPa (Figure 4.16). Soil samples from Ap2 horizon at site 4 had greater volumetric water contents at all tensions to 500 kPa compared to those of samples from the Ap1 horizon at site 4 (Fig 4.17).

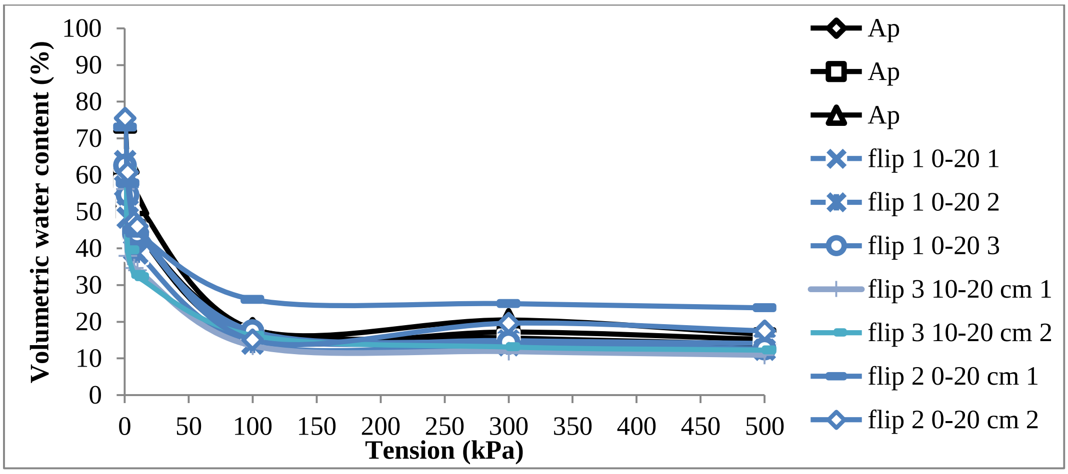


Figure 4.14: Water retention of undisturbed topsoil (Ap) and flipped topsoil from pits 1-3 on flipped area at site 1 (Three replicates from flipped pit 1 and two replicates from flipped pit 2 and 3).

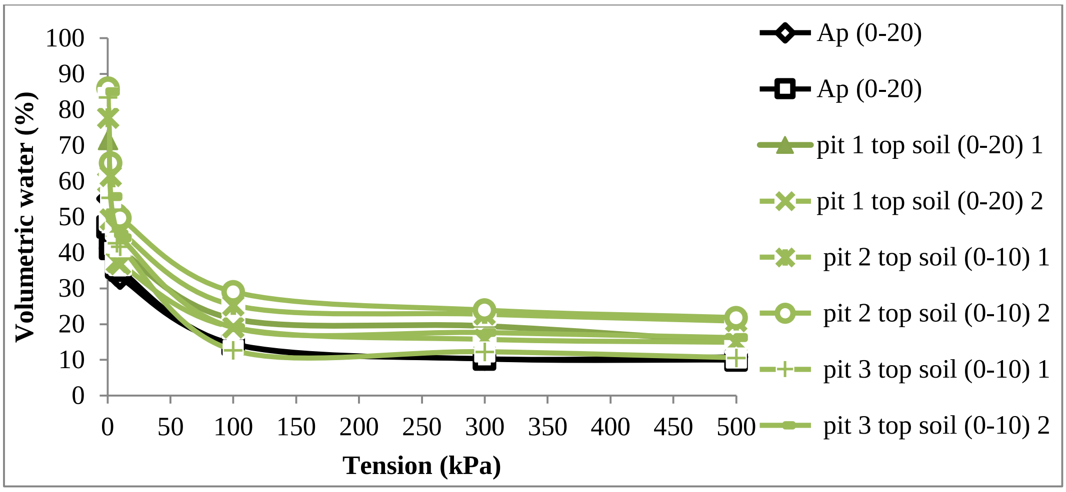


Figure 4.15:Water retention of undisturbed topsoil (Ap) and flipped topsoil from pits 1-3 on flipped area at site 2 (Two replicates from flipped pit 1 -3).

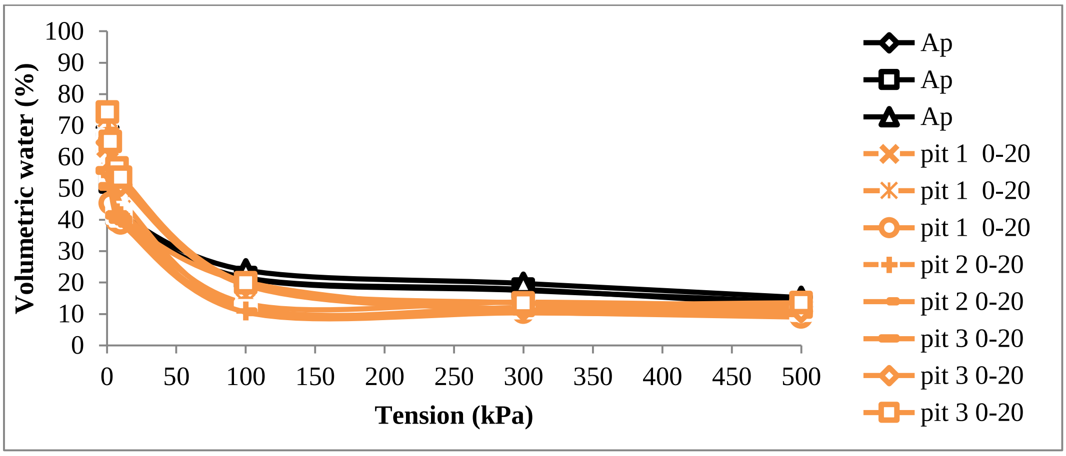


Figure 4.16:Water retention of undisturbed topsoil (Ap) and flipped topsoil from pits 1-3 on flipped area at site 3 (Three replicates for pit 1,two replicates from flipped pit 2).

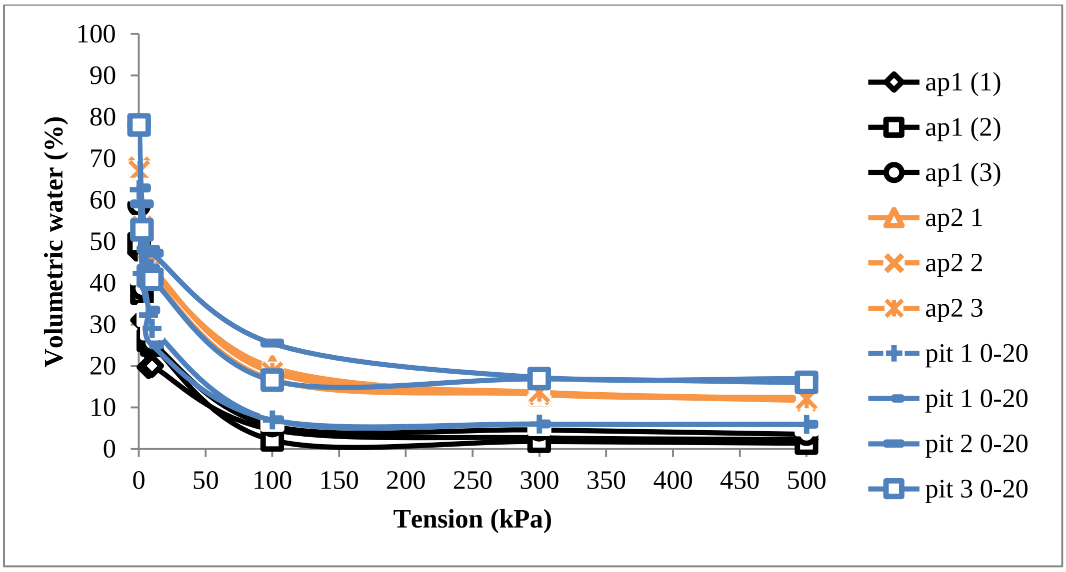


Figure 4.17: Water retention of undisturbed topsoil (Ap1 and Ap2) and flipped topsoil from pits 1-3 on flipped area at site 4.

4.5 Available water capacity

4.5.1 Total and readily available water (reference profile).

The total available water capacity (volumetric water content between 10 and 1500 kPa) was calculated for the individual horizons from the reference profile (Table 4.2). The buried soil horizon formed on Rotoma Tephra (4bBw horizon from reference profile) had the highest water content at 1500 kPa (18 % v,v). The pumice horizons (Cu1, Cu2, 3Cu horizon from reference profile) had the lowest water content at 1500 kPa (2-3 % v,v). The 2bAB horizon (on Taupo Tephra from reference profile) had the highest total available water capacity (37 % v,v), but the 3bBw horizon (on Whakatane Tephra from reference profile) had the highest readily available water (25 % v,v). When soil horizon depth is taken into account the 4bBw horizon (on Rotoma Tephra) has the greatest total and readily available water capacity (mm). However, the soil thickness for the 4bBw is not certain because the base of the horizon could not be seen. The three buried soil horizons/subhorizons formed on Whakatane tephra (3bBw, 3bBC1, 3bBC2 horizon) together have the greatest total and readily available water capacity (mm).

Table 4.2: Total and readily available water capacity for undisturbed soil horizons from reference profile

ID	Water content at 10 kPa (% v/v)	Water content at 100 kPa (% v/v)	Water content at 1500 kPa (% v/v)	TAWC 10 kPa-1500 kPa (% v/v)	RAW 10 kPa-100 kPa (% v/v)	Soil depth (mm)	TAWC (mm)	RAW (mm)	Water storage at FC (mm)
Ap	40	19	7	33	21	200	66	42	38
Cu1	17	7	**3**	14	10	150	21	15	11
Cu2	19	9	**2**	17	10	100	17	10	9
2bAB	46	33	9	**37**	13	150	56	20	50
2Cu1	29	20	9	20	9	300	60	27	60
3bBw	43	18	12	31	**25**	150	47	38	27
3bBC1	38	17	11	27	21	200	54	42	34
3bBC2	14	11	5	9	3	150	14	5	17
3Cu	22	8	2	20	14	400	80	56	32
4bBw	43	28	**18**	25	15	400	100	60	112

*TAWC=total available water capacity. RAW=readily available water capacity. The mean water contents held under 10 and 100 kPa were calculated from 3 replicates. NB: 2Cu2 was unable to be sampled. FC=field capacity (volumetric water content at 10 kPa).

4.5.2 Profile readily-available water

The mean profile readily-available water contents to 600 mm depth (profile RAW) from all the undisturbed soil materials was 100 mm (standard deviation: 15 mm), whereas the flipped soil materials had a mean RAW content of 154 mm (standard deviation: 25 mm) (Appendix 1, Table 6.41). Profile RAW contents were greater (P <0.01) in the flipped soil materials compared with those of the undisturbed soil materials when all data were considered together using a paired t test (Table 4.3).

Profile RAW contents were greater in the soil materials in the flipped area than the soil horizons in the undisturbed areas at 1-3 sites ($P<0.05$) and at site 4 ($P\leq0.1$) (Table 4.3, Figure. 4.18).

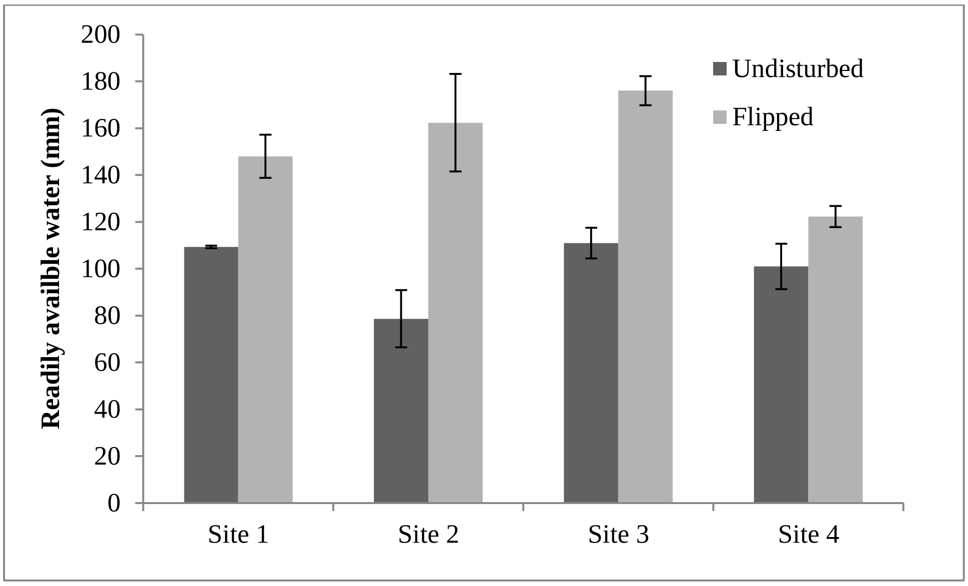


Figure 4.18: Mean profile readily available water (mm) to 600 mm soil depth. Error bars are one standard deviation of the mean of 3 samples.

4.5.3 Plant readily available water

It was observed that plant roots were most abundant in the “undisturbed” areas at depths between 0 and 450 mm during summer (roots were less abundant below the Cu1 and Cu2 horizon). While it was harder to find a set depth range for the abundant rooting depth in the flipped areas, at many of the flipped soil pits the abundant rooting exceeded 450 mm. Root growth was still abundant at 600 mm in many of the flipped pits. If rooting depth is considered to be deeper in the flipped areas compared to the depths in undisturbed areas, the RAW difference becomes greater (Figure 4.19).

Plant RAW contents were greater (P <0.01) in the flipped soil materials compared with those of the undisturbed soil materials (mean of 75 mm vs 152 mm) when all data were considered together using a paired t test (Table 4.3, Appendix 1 Table 6.41).

To calculate plant readily available water, a rooting depth of 450 mm was used for the undisturbed areas and 600 mm for flipped areas. Plant RAW contents were greater in soil materials in the flipped area compared to those of the undisturbed areas at sites 1-3 (P<0.05) and at site 4 (P≤0.1)(Table 4.3).

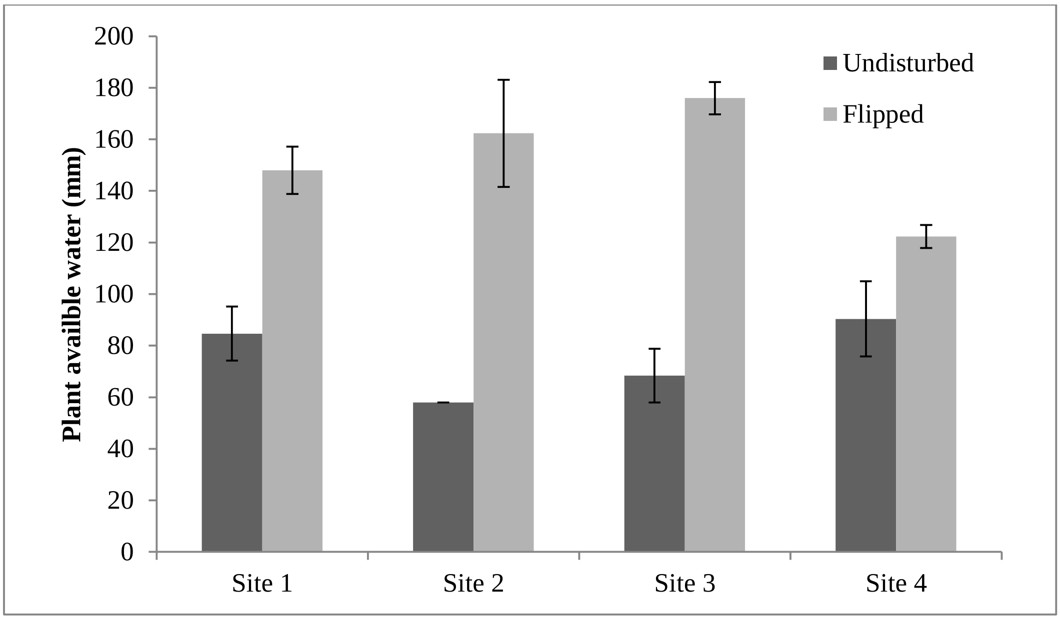


Figure 4.19: Mean plant readily available water at sites 1-4, Plant RAW was calculated in the flipped areas to 600 mm depth and in the undisturbed areas to 450 mm depth

Table 4.3: Two tailed paired t-test (paired two samples for means) comparisons between paired flipped and adjacent undisturbed areas for sites 1-4.

t-test	profile RAW P(T<=t) two-tail	plant RAW P(T<=t) two-tail
All flipped vs all undisturbed at all sites	5.20E-04	4.40E-05
flipped vs undisturbed (site 1)	0.02	0.03
flipped vs undisturbed (site 2)	0.04	0.01
flipped vs undisturbed (site 3)	0.01	0.01
flipped vs undisturbed (site 4)	0.1	0.1

**Profile RAW to 600 mm depth in flipped and undisturbed areas, plant RAW to 450 mm depth in undisturbed area and 600 mm depth in flipped area.*

4.5.4 Days between rainfall

Assuming an evaporation rate of 4 mm per day and that plant rooting depth is deeper in flipped areas compared to undisturbed areas (i.e., ~600 mm compared to ~450 mm), the flipped soils can hold more readily-available water than the undisturbed soils. The soils in the undisturbed area at site 1 can last about 21 days between rainfall/ irrigation events (assuming soils were wet to field capacity at the start) before the soil water drops below the readily available limit, while the soils in the flipped area can last about 37 days (Table 4.4). At sites 2 and 3, the flipped soils can last 27-28 days longer (42 to 44 days compared to 15 to 17 days) than the undisturbed soils between rainfall/irrigation events before they dry to below the readily available water content. At site 4 the flipped soils can last 9 days longer (31 days compared to 23 days) than the undisturbed soils before plants start becoming stressed (Table 4.4).

Table 4.4: Periods of time following rainfall/irrigation (to field capacity) before plants start becoming stressed (exceeds 100 kPa water tension).

Days plants are not stressed*		
Site	**Undisturbed**	**Flipped**
1	21	37
2	15	42
3	17	44
4	23	31

**Assuming readily available water is between 10-100 kPa and Evapotranspiration rate of 4 mm per day, and a rooting depth of x mm in undisturbed and y mm in flipped areas.*

4.6 Soil dry bulk density

The mean soil dry bulk densities for the topsoil and buried soils formed on Whakatane Tephra (3BC1 & 3BC2) and Rotoma (4bBw) were ≥1 g/cm^3 (Figure 4.20) The Taupo lapilli horizon (2Cu) had the lowest soil dry bulk density and was noticeably lower than that of the Whakatane lapilli horizon (3Cu) (Figure 4.20). The full soil dry bulk density data set is included in Appendix 2.

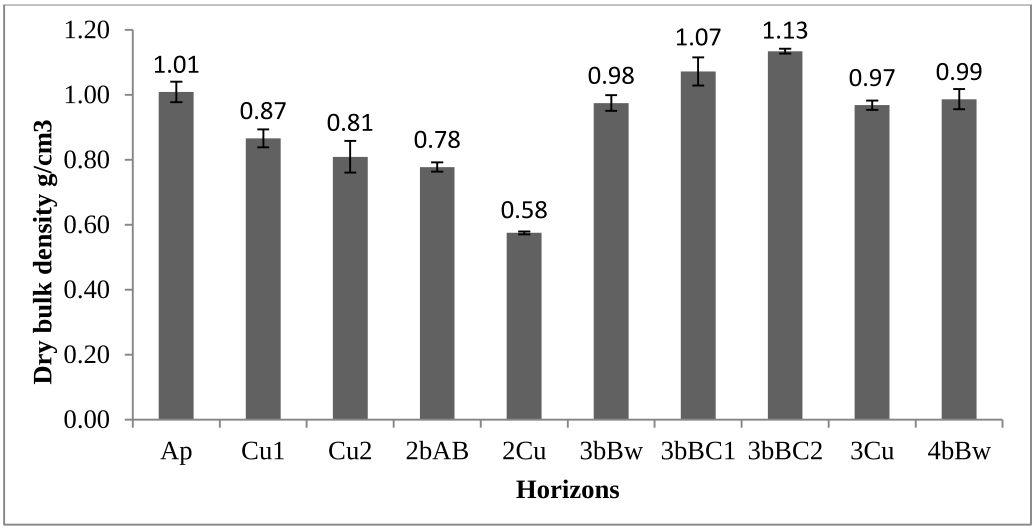


Figure 4.20: Soil dry bulk density of samples collected from the reference profile. Mean bulk density measured from 3 samples. Ap, Cu1, Cu2: (Kaharoa Tephra), 2bAB, 2Cu: (Taupo Tephra), 3bBw, 3bBC1, 3bBC2, 3Cu: (Whakatane tephra), 4bBw: (Rotoma Tephra).

The mean soil dry bulk density for the undisturbed horizons at sites 1-4 were similar to the mean soil dry bulk densities of the undisturbed horizons at the reference profile site. There was little variation between the mean soil dry bulk density of the undisturbed Ap, Cu1, Cu2, 2bBw and 2Cu horizons at sites 1-4 (Figure 4.21).

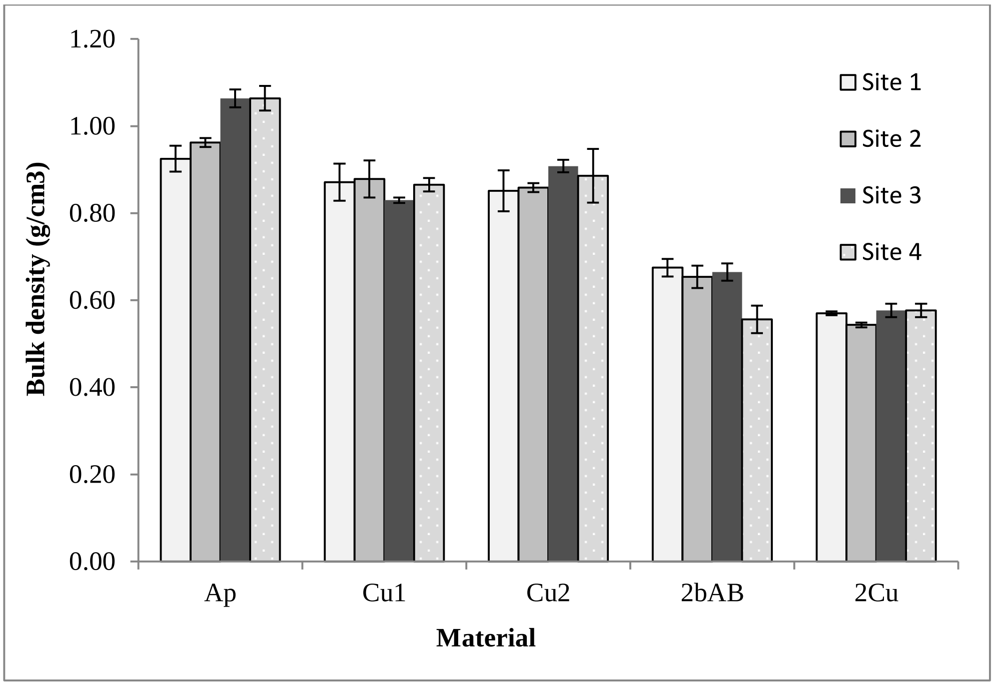


Figure 4.21: Soil dry bulk density of undisturbed horizons at site 1-4. Error bars are one standard deviation of the mean of at least x samples.

There was no significant difference found between the soil dry bulk density for the undisturbed and flipped topsoils (0-20 cm) at sites 1, 3 and 4. At site 2, the undisturbed topsoil had a higher soil dry bulk density (P<0.05) than the flipped topsoil (Fig 4.22).

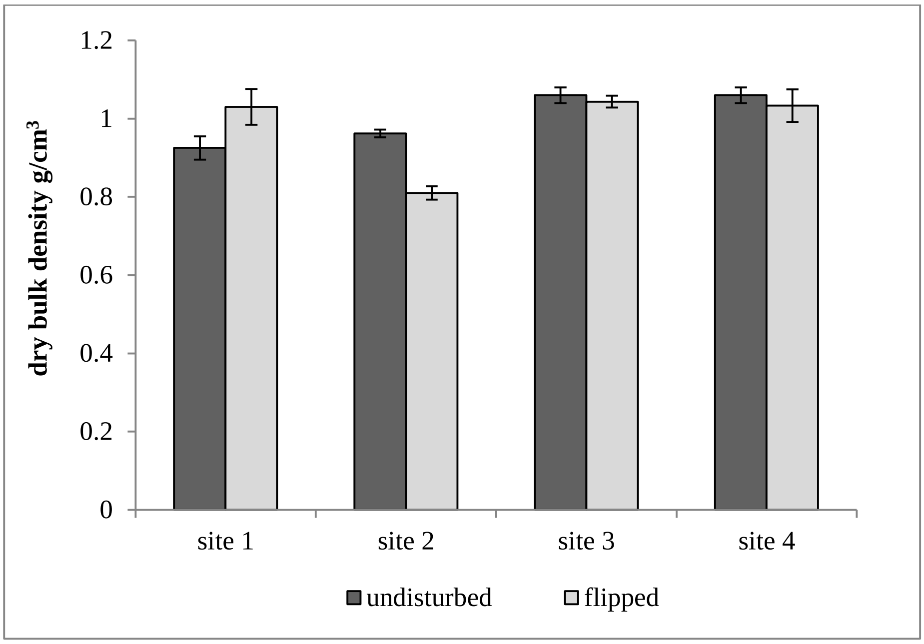


Figure 4.22: Soil dry bulk density of topsoil (0-20cm depth) from flipped and undisturbed areas at site 1-4. Error bars are one standard deviation, data are means of at least 3 samples.

4.7 Soil clay content and texture

4.7.1 Clay content and allophane analysis

The soil clay contents (<2 µm fractions) of the buried soil horizons formed on Taupo, Whakatane, and Rotoma tephras were ~1-2 % (Appendix 3 Figure 8.4 & 8.5). The soil horizons on the Kaharoa Tephra (Cu1 and Cu2) had a clay content ~0.1-0.2% (Appendix 3 Figure 8.2 & 8.3). The allophane content of the soil formed on Taupo Tephra was 2 % (fine-earth basis). The soil formed on Whakatane Tephra had an allophane content of 3 %, and the soil formed on Rotoma Tephra had an allophane content of 5 % (Appendix 3 Table 8.1).

4.7.2 Soil texture

The topsoil (Ap horizon) had a large portion of coarse sand and also some gravel-size fragments > 2 mm (Figure 4.23). The Cu1 horizon was predominantly coarse sand while the Cu2 horizon had near equal proportions of coarse and medium sand. The soil formed on Taupo Tephra (2bAB) had near equal amounts of fine and coarse sand. Medium sand made up a large proportion of the soil horizons formed on Whakatane and Rotoma tephras in the lower half of the profile (3bBw, 3bBC1, 3bBC2, 4bBw). The 2Cu horizon (Taupo lapilli) and the 3Cu horizon (Whakatane lapilli) were similar in composition and were mostly comprised of material > 2 mm and coarse sand (Figure 4.23).

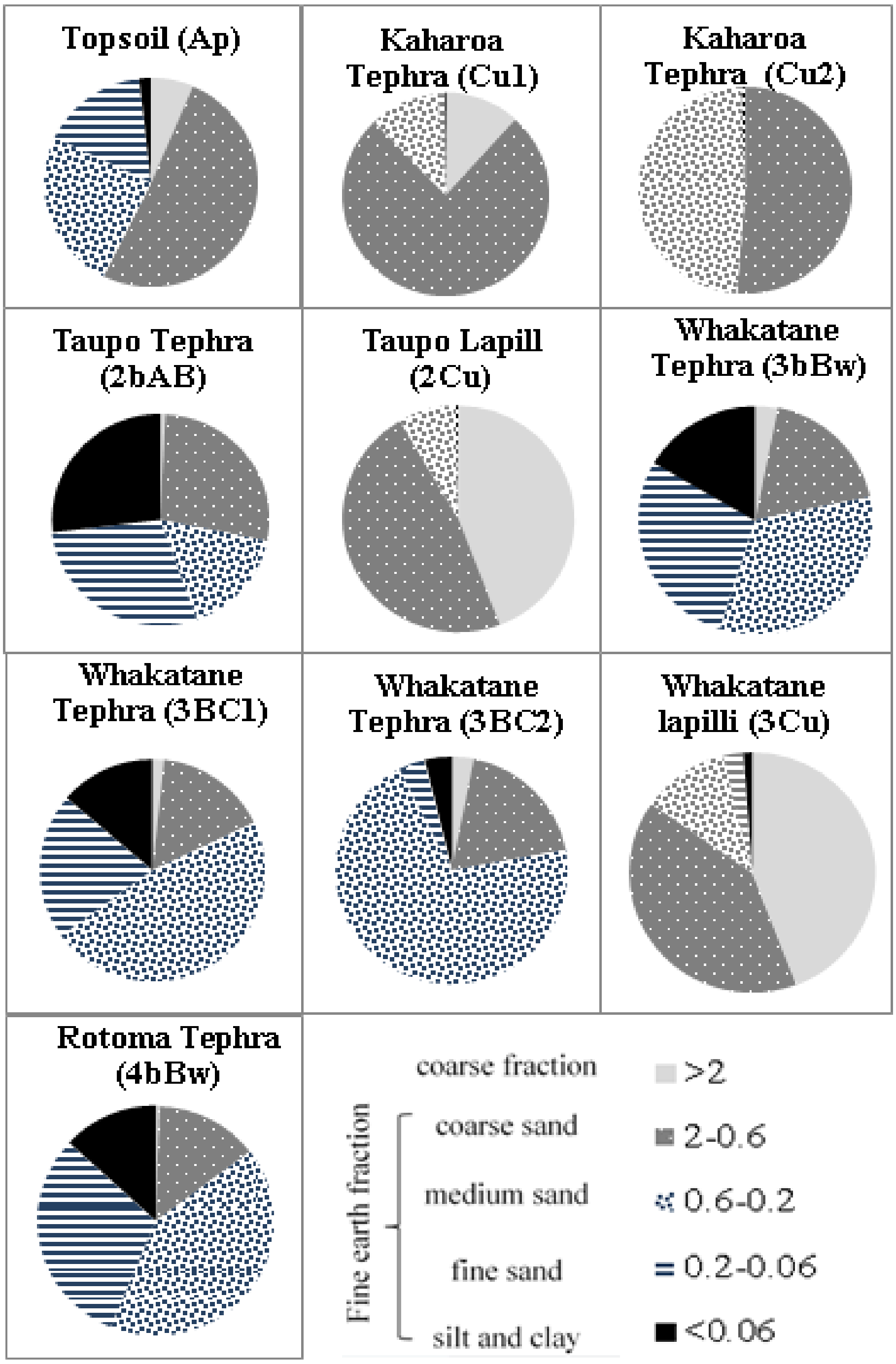


Figure 4.23:Coarse & fine earth fractions of paleosols from the reference profile

4.7.3 Particle size

Particle size analysis (<2 mm) show that all of the horizons including the buried soil horizons had a low clay content (<5 %, 2-5% in the topsoils and buried paleosols and ~0.5 % in the gravelly sand and pumice horizons) and that the soil materials were predominately comprised of sand (70-80% in the topsoils and buried paleosols, ~90 in the gravelly sand and pumice horizons). The topsoils and buried paleosols had a ~15-25% silt content while the gravelly sand and pumice horizons had a ~ 5 -10 % silt content. Particle size analysis of undisturbed horizons and flipped topsoils at reference profile and sites-4 are included in Appendix 3.

4.8 Plant root density experiment

The root density at 20-30 cm in the flipped area was higher ($P<0.05$) than that of the undisturbed area (Figure 4.24), this depth corresponding to that of the Cu1 horizon of the Kaharoa Tephra in the undisturbed soil. There were no significant differences between root mass at depths 0-10, 10-20, and 30-60 between soils in the flipped and undisturbed areas

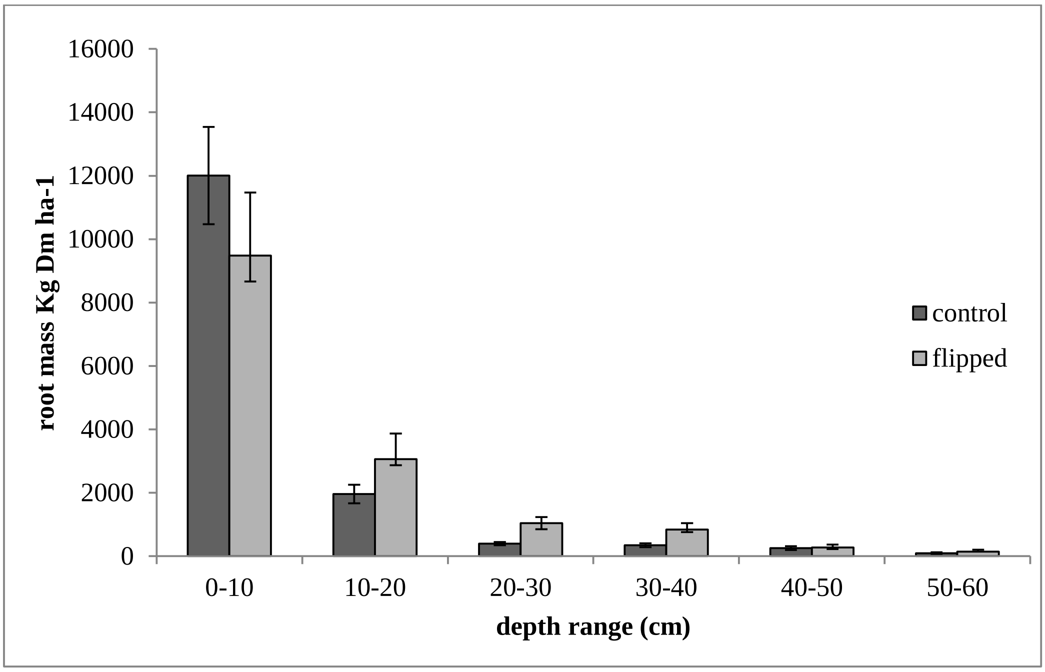


Figure 4.24: Mean root density with depth in the flipped and undisturbed area. Data are a mean of 4 reps in undisturbed soil and 8 in the flipped soils. Samples were taken from a site that had been flipped 1 year prior to sampling with topsoil replaced at the surface.

4.8.1 Permeability assessment of “undisturbed” horizons at site 1

The permeability of each horizon (“undisturbed”) was assessed following the methods of Griffiths (1985) at site 1. Dye tracking using methylene blue was used to assess continuous pores and degree of packing and other properties were also assessed. There was little evidence of earthworms at site 1. Three earthworms were found in the 6 profiles described at site 1, and all were rolled up tightly in a ball in the dry topsoil. When the dye was poured onto the topsoil (Ap horizon) it took over 15 seconds for the dye to disappear into the soil (Figure 4.625.

Figure 4.25: Assessing permeability of undisturbed Ap horizon at site 1.

The permeability classes of the undisturbed horizons were variable with depth (Table 4.5). The Ap had a “moderately slow” permeability while the sandy Cu1 and Cu2 horizons below the Ap horizon had a “rapid” permeability. The 2bAB horizon had a “moderate” to “moderate slow” permeability while the 2Cu horizon had a “rapid” permeability.

Table 4.5: Permeability class of horizons on undisturbed area at site 1

Estimated method	Ap (0-20 cm)	Cu1(20-14 cm)	Cu2 (40-55 cm)	2bAB (55-68 cm)	2Cu (>68 cm)
bio pores	“slow”	“rapid”	“rapid”	“Moderately slow”	“rapid”
Dry pedal soil and degree of packing	“Moderate”				
Dry apedal soil and degree of packing		“Rapid”	“Rapid”		“Rapid”
Moist appedal soil and degree of packing				“Moderate”	
Overall permeability class	**“moderately slow”**	**“Rapid”**	**“Rapid”**	**“Moderate” to “moderately slow”**	**“Rapid”**

4.8.2 Permeability assessment of “flipped” soil at site 1

The flipped soils were less variable in permeability and porosity with depth than the “undisturbed” area (Tables 4.6). The estimations of permeability class depended on the mixture of the material. Generally at the “flipped” sites, there was more coarse sand spread throughout the profile (excavated and mixed in during flipping) and when the dye was poured into the ring the dye passed through n the patches of coarse sand more quickly than through the surrounding black topsoil (Ap) or encapsulating soil-horizon material. The flipped topsoil was estimated to have a “moderate” to “moderately slow” permeability with the subsoil matrix estimated to have an overall “moderate” permeability.

Table 4.6: Permeability class of a flipped area at site 1 (flipped pit 2).

Estimated Method	Topsoil (Ap) (0-20)	Matrix (40-60)	Matrix (20-40 cm)
bio pores	“Moderately slow”	“Moderate”	“Moderate to rapid”
Dry apedal soil and degree of packing	“Moderate”		“Moderate” in topsoil and paleosol patches “Rapid” in sandy patches
Moist apedal soil and degree of packing		“Moderate” paleosol patches	
Overall permeability class estimate	**“Moderate” to “moderately slow”**	**“Moderate”**	**“Moderate” to “rapid”**

Chapter 5

Discussion & conclusion

5.1 Introduction

The main objective of this study was to investigate the differences between soils modified by excavating buried soil horizons (on Taupo and Whakatane Tephras) and mixing them with surface soil materials (the “flipped” soils), and adjacent undisturbed soils to understand why there are differences in pasture growth. The hypothesis was that the mixing of the excavated buried soil materials with the pumiceous surface soil materials (on Kaharoa Tephra) will give increased water holding capacity in the modified surface horizons, and thus improve water availability to plants during dry summer periods. In this chapter I discuss the results and present the main conclusions from the study.

Specific objectives were to:

- Characterise soil materials in the “undisturbed” buried soil-tephra sequence to a depth of 2.5 m including a soil profile description, percentage allophane in buried soil horizons, and particle size analysis.
- Determine the water holding capacity of previously “flipped” soils and adjacent “undisturbed” soils (control area).
- Compare soil properties, e.g. soil bulk density and permeability class estimates, in the “flipped” soils and adjacent “undisturbed” soils
- Determine the differences in root density with depth in “flipped” and “undisturbed” soils.

5.2 Summary of the work undertaken

Buried soil horizons and parent tephras within the top 2.5 m of a tephra-soil sequence in an exposed quarry wall cutting (referred to as the reference profile), were identified, the profile was described, and undisturbed cores from each horizon were collected for water retention and bulk density analyses.

Four sites were identified in the southern end of the Galatea Basin that had previously been modified by flipping. Each site contained a flipped area comprising mixed soil materials and an adjacent “undisturbed” (control) area comprising undisturbed soil, within the same paddock. At sites 1 and 2, the topsoil was stripped and the pumice horizons and buried soil horizons were excavated to a depth of ~1.8 m and separated into piles. The pumice horizons were then buried first and paleosols were placed back next; lastly the original topsoil was placed back on top. At site 3, all the horizons and tephra deposits to a depth of 0.6 m (including topsoil) were excavated in small sections and tipped back into the hole to roughly mix the materials mixed. At site 4, the topsoil was stripped and the horizons below the topsoil (to a depth of 0.6 m) were excavated in small sections and tipped back into the hole to mix the sub-soil materials. The topsoil was placed back on top of the mixed soil materials.

At each site, three pits were excavated in the flipped area and three in the undisturbed area. Detailed soil descriptions were made and undisturbed soil cores were taken from all horizons in each pit to a depth of 0.6 m. Water retention was determined using a hanging column and a pressure plate extractor.

5.3 Summary of key results

- Profile readily available water contents were greater ($P < 0.01$) in the flipped soil materials (mean of 152 mm) compared with those of the undisturbed soil materials (mean of 75 mm) when all data are considered together using a paired t test.
- Profile readily-available water contents were greater in the soils of the flipped area than soils of the undisturbed areas at sites 1, 2 and 3 ($P<0.05$) and at site 4 ($P \leq 0.1$).

- Plant readily-available water content was calculated in the flipped areas to 600 mm depth and to 450 mm depth in the undisturbed areas (based on plant root observations in the field over summer). Plant readily-available water content was greater in the flipped compared to that of the undisturbed areas at site 1, 2 and 3 ($P<0.05$) and at site 4 ($P\leq 0.1$).
- Assuming an evaporation rate of 4 mm per day and that plant rooting depth is deeper in flipped soil compared to undisturbed soils (~600 mm compared to ~450 mm, respectively), the flipped soils can hold more readily-available water (mean of 39 days) than the undisturbed soils (mean of 19 days) between rainfall/ irrigation events (assuming soils in both areas were initially wet to field capacity).
- The buried soil horizon formed on Rotoma Tephra (4bBw horizon from reference profile) had the highest water content at 1500 kPa (18 % v,v). The pumice horizons (Cu1, Cu2, 3Cu horizons from reference profile) had the lowest water content at 1500 kPa (2-3 % v,v). The 2bAB horizon (on Taupo Tephra from reference profile) had the highest total available water capacity (37 % v,v), but the 3bBw horizon (on Whakatane Tephra from reference profile) had the highest readily available water (25 % v,v).
- Particle size analyses (<2 mm size-fractions) show that all of the horizons including the buried soil horizons had a low clay content (<5 %, 2-5% in the topsoils and buried soil horizons and ~0.5 % in the gravelly sand and pumice horizons) and that the soil materials were predominately comprised of sand (70-80% in the topsoils and buried soil horizons, ~90 in the gravelly sand and pumice horizons). The topsoils and buried soil horizons had a ~15-25% silt content while the gravelly sand and pumice horizons had a ~ 5 -10 % silt content.
- The allophane content (fine-earth fraction) of the (now) buried soil horizon formed on Taupo Tephra was 2 %. The soil horizon formed on Whakatane Tephra had an allophane content of 3 %, and the soil horizon formed on Rotoma Tephra had an allophane content of 5 %.
- The undisturbed Ap horizon had a “moderately slow” permeability class while the sandy Cu1 and Cu2 horizons below the Ap horizon had a “rapid” permeability class. The 2bAB horizon had a “moderate” to “moderately

slow" permeability class while the 2Cu horizon had a "rapid" permeability class (results obtained at site 1).

- The permeability class of flipped soils was more uniform with depth than that of the "undisturbed" soils. The estimations of permeability class depended on the mixture of the material. The flipped topsoil was estimated to have a "moderate" to "moderately slow" permeability class and the "flipped" sub-soil matrix was estimated to have an overall "moderate" permeability class.

5.4 Discussion

5.4.1 Readily available water

The profile and plant readily available water was greater in the soil materials in the flipped soils than in the soil horizons in the undisturbed area at site 2 ($P<0.05$). This finding indicates that the effects of "flipping" are long lasting because site 2 was flipped 10 years prior to sampling.

The topsoil at site 4 was somewhat different to that of the reference profile (located in the southern end of the Galatea Basin). At site 4, the Ap horizon was separated into two sections by a 5 cm whitish yellow loamy sand layer. This may have been Horomanga sediments–which overlie the Kaharoa Tephra (Vucetich, 1960). Horomanga soils are most widespread as outwash deposits extending from the Mangamate Stream. The Horomanga sediments were deposited over a period of extensive flooding and occur on both the fans and lower flats. According to Vucetich, (1960), Horomanga soil has an improved water holding status due to the total thickness of loamy sand over the underlying droughty pumice lapilli (Cu1 and Cu2) horizons. This local layer, rather than the type of flipping treatment, may explain the why difference between the plant and profile readily available water of the undisturbed flipped soils was not as great as the difference found for soils at sites 1, 2 and 3. At site 4 the topsoil on the undisturbed area (Ap horizon) was thicker than that at any other site (~45 cm compared to ~ 20-25 cm).

5.4.2 Seasonal variations in root mass

The roots were observed to be proliferating at the pumice horizon (Cu1 and partly through Cu2 horizon) in the top 200 mm. Packard (1957) reported the phenomenon of roots proliferating through Pumice Soils to gain water in the wet zones which he attributed to the slow unsaturated movement of water through pumice horizons or layers. However, it is more likely that the roots were desperately trying to spread out to access water. Greater mass and length of roots in pasture species is associated with drought stress and lower fertility (Dodd et al., 2011).

In a study of growth patterns of perennial ryegrasses under well watered and drought conditions, drought conditions resulted in an increase in root counts down the soil profile compared to counts in well-watered ryegrass controls one month after the stimulated drought conditions began. Root death in the top 15 cm followed in the post-drought period while lower root death rates were observed further down the soil profile after the drought (Wedderburn et al., 2010).

5.4.3 Plant readily available water

The rooting depth used to calculate plant readily available water for the undisturbed area was 450 mm. When the root density was measured in August, the root data were different from those pertaining to the observations made in summer. This difference was probably because of dynamic seasonal changes in root density and structure. In summer (during a drought), the roots appeared to be growing deeper (>400 mm depth) in the profile under the flipped and undisturbed soils at sites 1-4 than in the undisturbed soils. However, the measured root density with depth (measured in a paddock that had been flipped one year prior to sampling) found little root growth deeper than 400 mm in the flipped soils and little growth below 300 mm in the undisturbed soils in August when the sampling was undertaken. According to Caradus & Evans (1977), new plant roots (ryegrass and cocksfoot) are formed during autumn and winter and grow nearer the surface from May until August. Wedderburn et al. (2010) warned that seasonal patterns in root development vary with slope, aspect and region and cannot be extrapolated generally throughout New Zealand. A continual measurement in the root structure and density throughout the whole year would provide valuable data in order to help estimate plant readily available water throughout the year

A significant difference in root density at the depth range 20-30 cm, corresponding to that of the Cu1 horizon, was found (root mass was higher

(P<0.05) in the flipped soils compared to those of the undisturbed area). This result suggests that the Cu1 horizon restricts root growth in the undisturbed soil in August and that the physical process of "flipping" also loosens the Kaharoa pumice layers, allowing easier root penetration.

5.4.4 Texture

Texture influences the soil's ability to retain water for plants and also drain excess water. Because of textural differences, the gravelly sand and pumice layers had different water retention curves to those of the buried soil horizons. The buried soill horizons formed on Taupo and Whakatane Tephras had higher volumetric water contents at all tensions to 500 kPa compared to Taupo and Whakatane pumice (2Cu and 3Cu) and sand horizons (3bBC1) (Figure 4.10, 4.11 and 4.12). In a study comparing various media and mixed media for container grown plants, pumice was able to hold on to more water at all tensions when compared to (non-pumiceous) sand, but both materials lost most of the water at tensions less than 50 cm (0.5 kPa) (Haynes & Goh, 1978). When comparing the fine sand horizon (3bBC2) and the very gravelly sand horizon (3Cu), the 3Cu horizon held on to more water than the 3bBC2 horizon at all tensions to 500 kPa (Figure 4.11 and 4.12). The retention curves for the undisturbed horizons from the Ap horizon to the 3Cu horizon were steep between 0.4 and ~ 10 kPa, and less steep between 10 and 100 kPa. The curves were almost horizontal at tensions >100 kPa and were almost horizontal at tensions >300 kPa for the buried horizon formed on Rotoma Tephra (4bBw horizon). All samples were predominantly sandy and hold most of the water at lower tensions (<100 kPa), confirming the general findings in the literature review that sandy/coarse textured soils are well drained and have a limited water storage capacity in comparison to soils with a higher clay content (Kramer, 1995; Table 2.4). Packhard (1957) reported the "high" water storage of pumice soils was speculated to be because of the vesicular nature of the individual particles. When comparing the sandy and gravelly sand horizons formed on Kaharoa Tephra (Cu) with those of Taupo pumice (2Cu) and Whakatane Tephra (3Cu), the more vesicular pumice horizons have a higher total available water capacity (20 % v,v) compared to the sandy Cu1 and Cu2 horizons (14 and 17% v,v) (Table 4.2).

The water storage of the undisturbed soil is limited because of the underlying coarse textured horizons (Cu1 and Cu2). The topsoil only has the capacity to store 38 mm of water at field capacity (Table 4.2). Vucetich (1960) also reported that the topsoil has the capacity to store moisture estimated to be the equivalent of 1 inch (25 mm) of water at field capacity. The implication is that frequent rainfall is needed to offset the soil moisture dropping below the readily available limit due to plant uptake of water and evaporation. "Flipping" improves the modified soil's ability to hold more readily-available water than the undisturbed soils. On average, the plants remain within the readily available range between rainfall events (assuming soils were wet to field capacity at the start) for about twice the time in flipped soils compared to undisturbed soils (mean of 19 days compared to a mean of 39 days).

5.4.5 Bulk density of undisturbed soil horizons and tephra layers at the exposed quarry wall

The mean dry soil bulk densities for the topsoil and buried horizons formed on Whakatane Tephra (3bBw, 3bBC1 & 3bBC2) and Rotoma Tephra (4bBw) were $\geq$1 g/cm^3. Rijkse & Guinto (2010) reported that the topsoil of a Galatea sandy loam had a bulk density of 1 g/cm^3 and the subsoil bulk density of 1.18 g/cm^3. Will & stone (1967) reported a dry soil bulk density value for the buried horizon formed on Taupo Tephra (2bAB) to be 0.76 g/cm^3 and the bulk density of the underlying pumice lapilli horizons to be 0.57-0.97 g/cm^3 which is a close match to my bulk density values for the buried soil horizon formed on Taupo Tephra (0.78 g/cm^3) and for Taupo lapilli (0.58 g/cm^3) and Whakatane lapilli (0.97 g/cm^3) layers. The bulk density of the Whakatane lapilli layer (3Cu) was greater than that of the Taupo lapilli (2Cu) because it contained tiny rock fragments (lithics) in amongst the pumice lapilli. Although the bulk density of the Kaharoa pumice deposit (Cu1 and Cu2 horizon) is low (<1 g/cm^3), the gravelly sand acts as a barrier because of mechanical impedance (pumice particle bridging), low moisture storage, and rapid permeability (Griffiths, 1985). Bulk density alone is not a reliable indicator of potential problems with root penetration and water movement though the soil (Henderson, et al. 1988).

There was no significant difference found between the dry soil bulk density for the undisturbed and flipped topsoils (0-20 cm) at sites 1, 3 and 4. At site 2 the undisturbed topsoil had a higher soil dry bulk density ($P<0.05$) than that of the flipped topsoil. This finding would suggest “flipping” the soil has not caused compaction of the topsoil at all sites.

5.4.6 Permeability assessment “Undisturbed” and “flipped” soils

The permeability assessment revealed that water does not travel evenly through the soil profile (non-homogenous with depth). Permeability is slow in the topsoil, rapid in the horizons below (Cu1 and Cu2), and moderately slow in the 2bAB horizon. When the soil profile is non-homogenous with depth, the vertical movement of water is restricted between the boundaries of contrasting textures (Griffiths, 1985). In the flipped soil the sharp contrasting texture boundaries were removed and the permeability with depth did not vary as much as it did at the undisturbed side.

5.5 Review of hypothesis

My hypothesis that “flipping” of the layered Pumice Soils (i.e., excavating buried soil horizons and associated pumiceous tephra layers and mixing them with surface soil materials) will give increased water holding capacity in the modified surface horizons (flipped soils), and thus improve moisture availability to plants during dry summer periods, can be accepted. There were clear significant differences found between the readily available water and plant available water in ‘flipped’ soils at sites 1, 2 and 3, and a significant difference at the 90 % level at site 4. On average, the plants remain within the readily available range between rainfall events (assuming soils were wet to field capacity at the start) for about twice the time in flipped soils compared to undisturbed soils.

5.6 Limitations of study

Root growth measurements were made in winter and differed from the observed summer situation. It would have been better to get the root density cores at the same time the profile descriptions were made. The root density with depth was made as a visual observation in summer. Rooting depth influences the available water content within the soil profile and therefore more accurate estimations of RAW could have been made from root data that were measured in summer instead of observed. If all of the pits were sampled to a depth of 1 m, the profile RAW contents would have been more easily compared with data from online sources such as *Smap online*.

5.7 Suggestions for further work

Future work could include the collection of soil samples (for moisture retention) from the northern part of the Galatea Basin to determine if Tarawera scoria (from the 10 June 1886 Tarawera eruption) makes a difference to the readily available water capacity. Tarawera scoria was not found in soils in my field area in southern Galatea Basin.

Buried soil horizons have the potential to store carbon if brought upwards. Future work could include monitoring carbon contents of the soil over time to determine if paddocks of flipped soils have accumulated more carbon over the years.

It was noted in the literature review that direct mechanical damage such as tillage contributes to a decline in earthworm populations. Since earthworms enhance soil development by the addition and breakdown of organic matter and the mixing of the topsoil, it could be useful to look into the effect of flipping on the earthworm populations and how long the population of earthworms take to recover after a section of soil is “flipped”.

5.8 Conclusions

Better grass growth as a consequence of flipping is probably a combination of things:

- Bringing the finer-textured buried soil horizon materials to the land surface means that the “flipped” soils are able to hold more readily-available water than the undisturbed soils. This is because the excavated finer textured buried soil horizons have higher clay and allophane contents than the undisturbed pumiceous surface horizons (in Kaharoa Tephra). The moisture availability to plants during dry summer periods is improved and the physical process of mixing also breaks up the Kaharoa pumice materials, allowing easier root penetration.
- At the flipped sites, soil permeability was more homogenous with depth compared to permeability in soils in the undisturbed areas as there were

fewer contrasting texture boundaries, thus water could more readily pass down through the soil.

- There were clear significant differences found between the readily available water and plant available water in ‘flipped’ soils at sites 1, 2 and 3, and a significant difference ($p \leq 0.1$) at site 4. On average, the plants remain within the readily available range between rainfall events (assuming soils were wet to field capacity at the start) for about twice the time in flipped soils compared to undisturbed soils. Based on the results of this study, the hypothesis that “flipping” of the multi-layered Pumice Soils (i.e., excavating buried soil horizons and associated pumiceous tephra layers and mixing them with surface soil materials) will give increased water holding capacity in the modified surface horizons (flipped soils), and thus improve moisture availability to plants during dry summer periods, was accepted.

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Appendix 1

6.1 *Profile descriptions at site 1*

Soil profile description of undisturbed soil pit 1

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, elevation: 206 m
  Paddock adjacent to Whirinaki road, approximately 1.5 km north west of the intersection at Whirinaki and Troutbeck Rd. Pit in far south corner (closest to road) 10 m from the fence facing the road and 2 m from the fence of neighbouring paddock (opposite from the race).
- Geomorphic position: flat to gently undulating land on alluvial terrace
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and depth (cm)	**Profile description of undisturbed soil pit 1**
Ap (0-20)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds slightly firm and brittle; very low penetration resistance (900 kPa); low degree of packing (700 kPa); strongly developed platy surface layer 2-5cm thick breaking weakly pedal with very coarse to medium blocky peds breaking to weakly pedal with very fine to fine polyhedral peds breaking to apedal single grain; many microfine roots and few extremely fine roots; sharp smooth boundary [Kaharoa Tephra].
BC (20-30)	Dull yellow orange (10YR 7/4) slightly gravelly coarse and medium sand with many fine sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; indistinct wavy boundary [Kaharoa Tephra].
Cu1 (30-39)	Light yellow orange (10YR 8/3) slightly gravelly coarse and medium sand with many fine sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu2 (39-40)	Light grey (2.5Y 8/2) loamy sand; non sticky; non plastic; apedal single grain; common microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu3 (40-53)	Light grey (10YR 8/1) medium and fine sand with common fine sub-angular pumice; non sticky; non plastic; apedal single grain; common extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].

2bAB (53-65)	Brown (7.5 YR 4/3) sandy loam with few fine sub-angular pumice and charcoal fragments; non sticky; non plastic; peds slightly firm and brittle; very low penetration resistance (900 kPa); very low degree of packing (500 kPa) massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots; abrupt wavy boundary [Taupo Tephra – ignimbrite].
2Cu (>65)	Light grey (10YR 8/1) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa); apedal single grain; common microfine roots; abrupt smooth boundary [Taupo Tephra – lapilli]

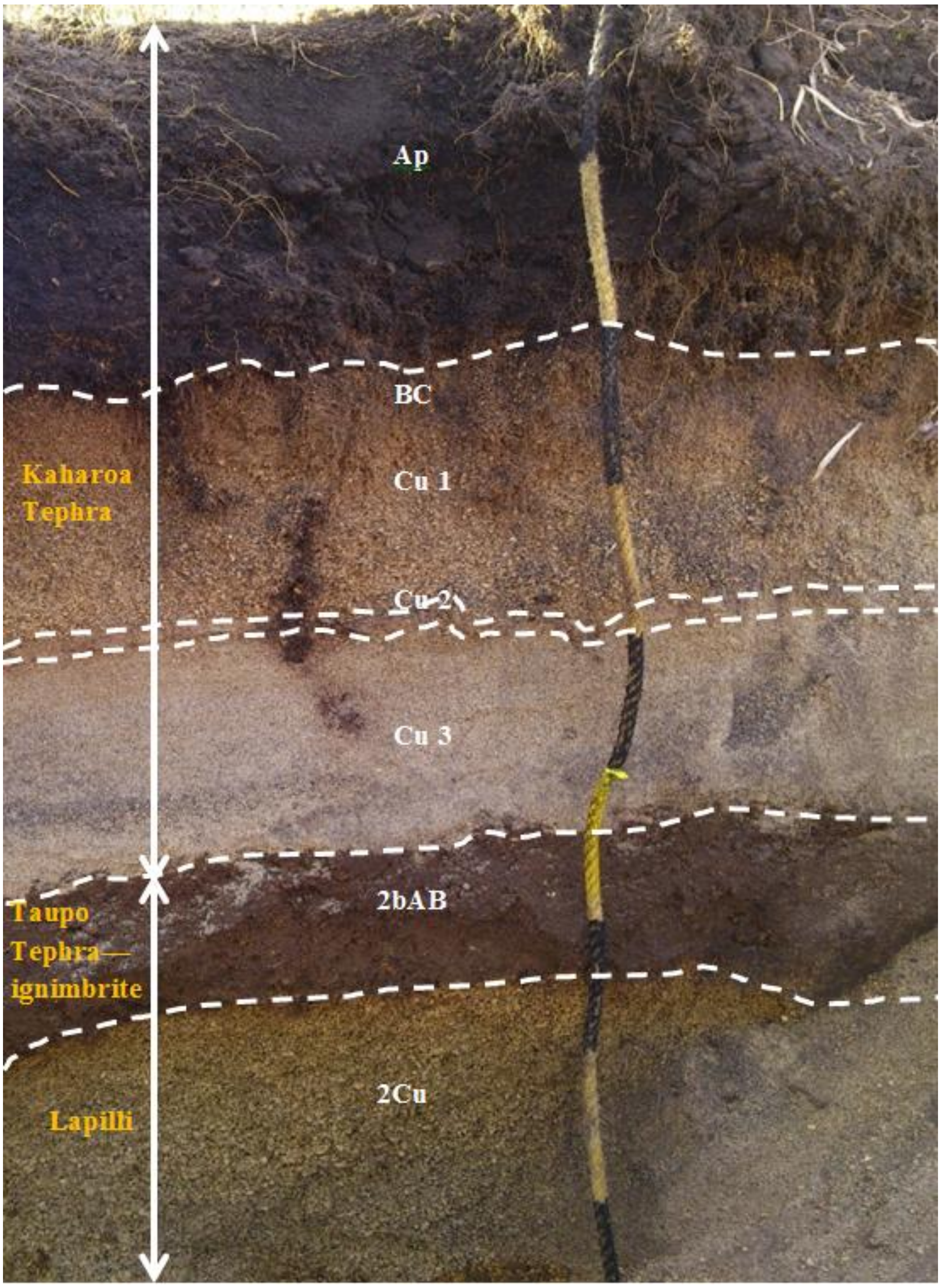

Figure 6.1: Undisturbed pit 1 at site 1.

Soil profile description of flipped soil pit 1

- Soil classification (NZSC): Mixed Anthropic Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, elevation: 206 m
- Paddock adjacent to Whirinaki road, approximately 1.5 km north west of the intersection at Whirinaki and Troutbeck Rd. Pit is approximately in the middle of the paddock 50 m from the fence facing the road and 80 m away from the race.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and depth (cm)	**Profile description of flipped soil pit 1**
Ap (0-20)	Brownish black (2.5YR 3/1) loamy sand [Ap horizon] with few medium olive brown (2.5 YR 4/4) sandy loam fragments [Whakatane B horizon]; non sticky; non plastic; peds firm and brittle; low penetration resistance (1000 kPa); medium degree of packing (1200 kPa); platy surface layer 2-5cm thick breaking to moderately pedal with medium polyhedral peds breaking to apedal single grain; abundant microfine roots; indistinct smooth boundary.
B/Cu1 (20-80)	Yellowish brown (2.5YR 5/4) sandy loam [Whakatane B horizon] with brownish black (10YR 2/2) loamy sand lenses [Ap horizon], light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon]; non sticky; slightly plastic; fragments slightly firm and brittle; moderate penetration resistance (1600 kPa); medium degree of packing (1200 kPa); apedal massive breaking to apedal earthy; abundant microfine roots in brownish black [Ap horizon] lenses and sand lenses [Kaharoa C horizon], many microfine roots in matrix 20-60 cm; common microfine roots in matrix at 60-80 cm depth; indistinct wavy boundary.
B/Cu2 (80-100)	Greyish yellow (2.5YR 7/2) moderately gravelly coarse and medium sand [Kaharoa C horizon] with brownish black (10YR 2/2) loamy sand material [Ap horizon] and yellowish brown (2.5 YR 5/4) sandy loam material [Whakatane B horizon]; non sticky; non plastic; extremely low penetration resistance (300 kPa); very low degree of packing (300 kPa); apedal single grain; few microfine roots.

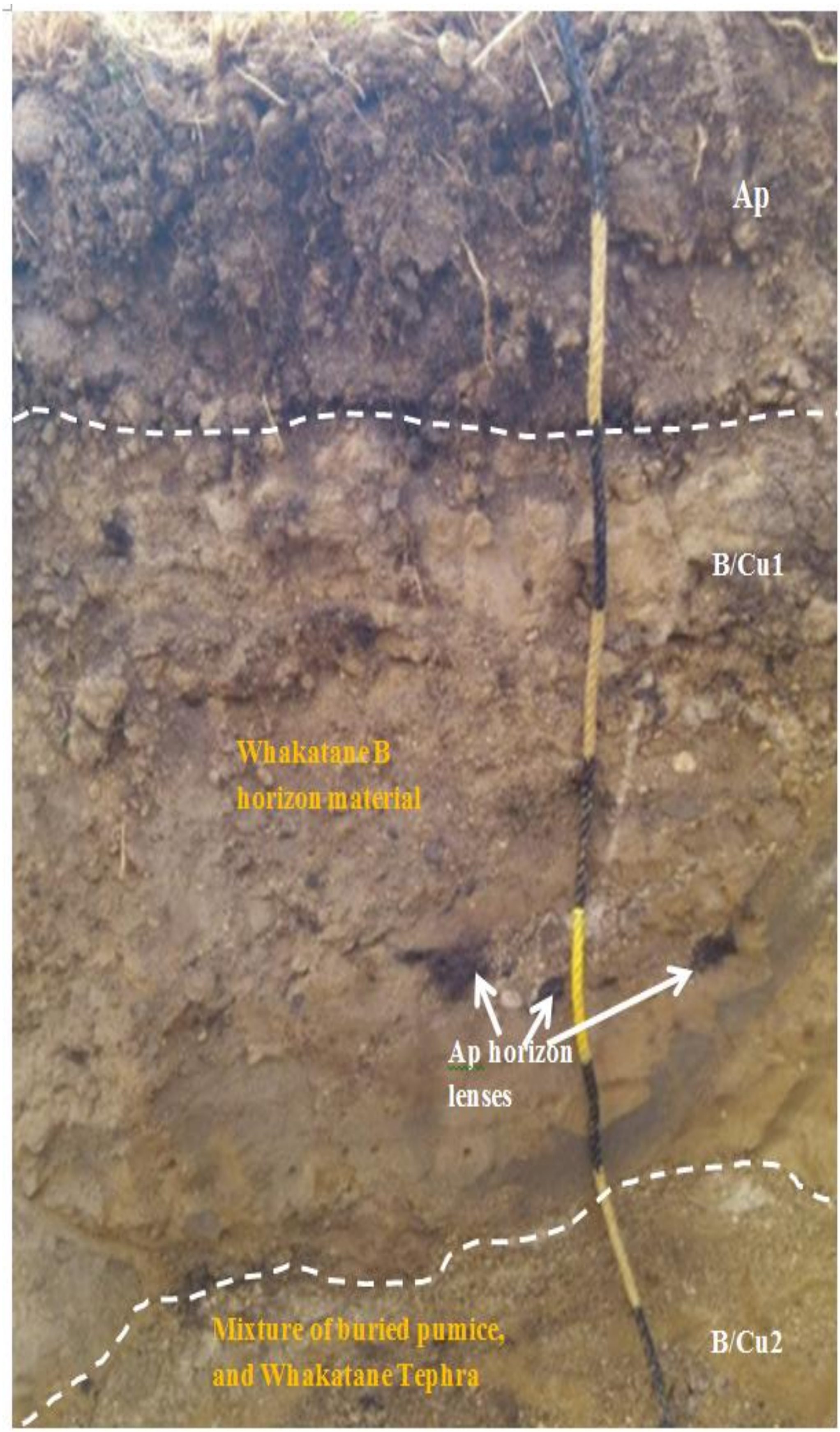

Figure 6.2: Flipped soil pit 1 at site 1.

Soil profile description of undisturbed pit 2

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38^0 27’26.08” S 176^{0}44’40.48 ” E, elevation: 206 m
  Paddock adjacent to Whirinaki road, approximately 1.5 km north west of the intersection at Whirinaki and Troutbeck Rd. Pit is 100 m from the fence facing the road and 5 m from the fence of neighbouring paddock (away from race).
- Geomorphic position: Flat to gently undulating land on alluvial terrace.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and Depth (cm)	Profile description of undisturbed soil pit 2
Ap (0-20)	Brownish black (10YR 3/1) loamy sand; non sticky; non plastic; peds slightly firm and brittle; very low penetration resistance (900 kPa); low degree of packing (800 kPa); strongly developed platy surface layer 2-5cm thick, apedal massive breaking to apedal earthy; abundant microfine roots; sharp smooth boundary [Kaharoa Tephra].
BC (20-30)	Dull yellow orange (10YR 7/4) slightly gravelly coarse and medium sand with abundant fine sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu1 (30-45)	Light yellow orange (10YR 8/3) slightly gravelly coarse and medium sand with abundant fine sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu2 (45-46)	Light grey (2.5Y 8/2) loamy sand; non sticky; non plastic; apedal single grain; common microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu3 (46-50)	Light grey (10YR 8/1) very gravelly medium and fine sand with many sub-angular pumice lapilli; non sticky; non plastic; common microfine roots; abrupt smooth boundary [Kaharoa Tephra].
2bAB (50-60)	Brown (7.5YR 4/3) sandy loam with few fine sub-angular pumice lapilli and charcoal fragments; non sticky; non plastic; peds slightly firm and brittle; low penetration resistance (1300 kPa); low degree of packing (900 kPa) massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots ; abrupt wavy boundary [Taupo Tephra – ignimbrite]

2Cu (>60)	Dull yellow orange(7/4) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (300 kPa); apedal single grain; common microfine roots; abrupt smooth boundary [Taupo Tephra – lapilli]

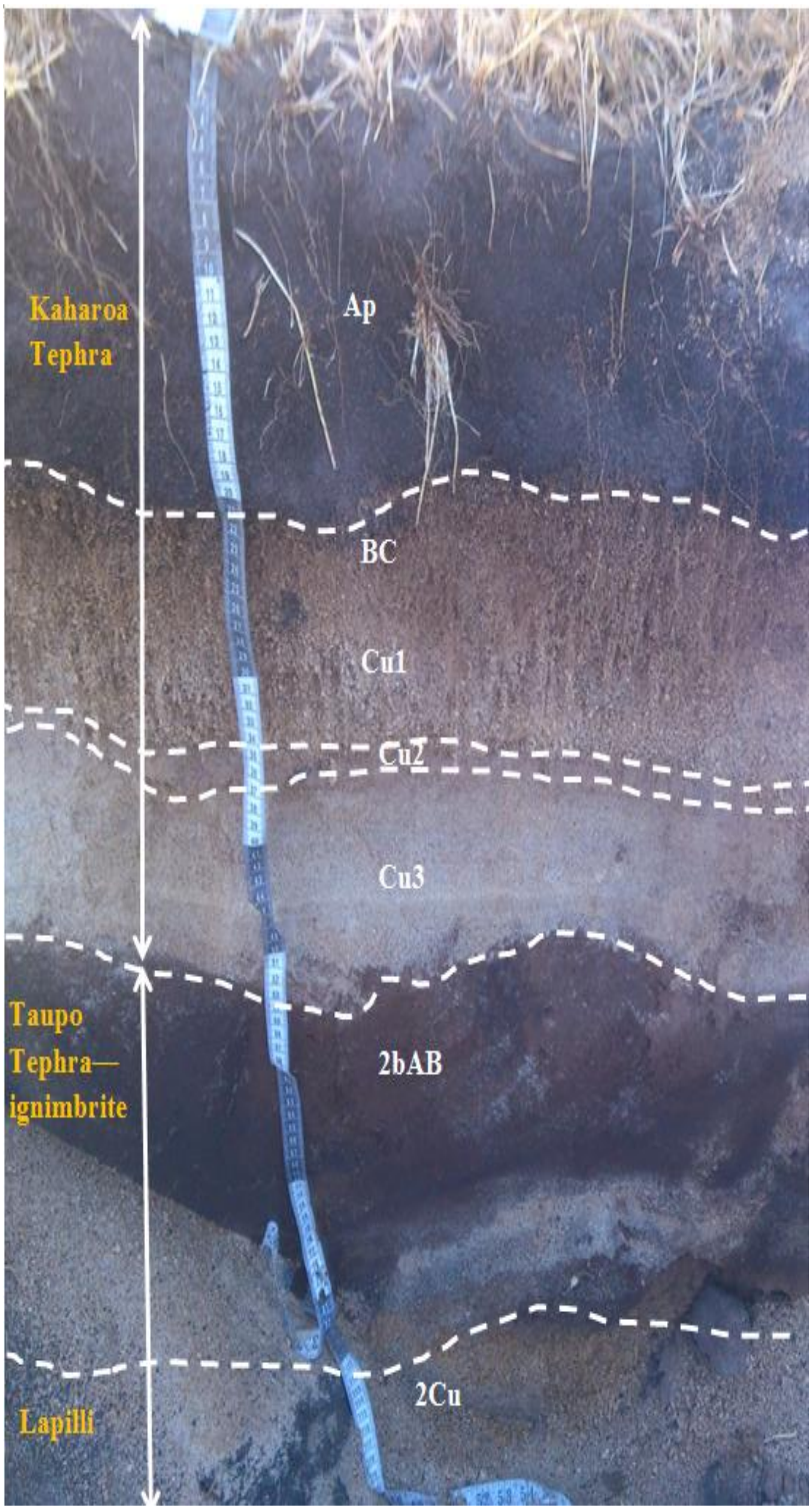

Figure 6.3: Undisturbed soil pit 2 at site 1

Soil profile description of flipped soil pit 2

- Soil classification (NZSC): Mixed Anthropic Soils
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, elevation: 206 m
  Paddock adjacent to Whirinaki road, approximately 1.5 km north west of the intersection at Whirinaki and Troutbeck Rd. Pit is approximately in the middle of the paddock 100 m from the fence facing the road and 80 m away from the race.
- Geomorphic position: Flat to gently undulating land on alluvial terrace.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and depth (cm)	**Profile description of flipped soil pit 2**
Ap (0-25)	Brownish black (2.5YR 3/1) loamy sand [Ap horizon]; non sticky; non plastic; peds firm and brittle; low penetration resistance (1000 kPa); low degree of packing (500 kPa); platy surface layer 2-5cm thick; weak pedality with few medium blocky peds breaking to apedal earthy; abundant microfine roots; indistinct smooth boundary.
B (25-55)	Olive brown (2.5Y 4/6) sandy loam [Whakatane B horizon] with brownish black (10YR 2/2) loamy sand lenses [Ap horizon], light grey (2.5Y 8/1); non sticky; slightly plastic; fragments slightly firm and brittle; moderate penetration resistance (1000 kPa); medium degree of packing (1000 kPa); apedal massive breaking to apedal earthy; abundant microfine roots in brownish black lenses and sand lenses, many microfine roots in matrix 25-55 cm; indistinct smooth boundary.
B/Cu (55-80)	Brown (10YR 4/4) sandy loam [Taupo Tephra] with 20% light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon] and 20% brownish black (10YR 2/2) loamy sand lenses [Ap horizon]; non sticky; slightly plastic; fragments slightly firm and brittle; moderate penetration resistance (1000 kPa); medium degree of packing (1000 kPa); apedal massive breaking to apedal earthy; abundant microfine roots in brownish black lenses and sand lenses, many microfine roots in Taupo Tephra matrix; indistinct wavy boundary.
Cu (>80)	Dull yellow orange (10YR 7/4) very gravelly coarse sand with abundant medium sub-angular pumice lapilli [Kaharoa C horizon]; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa); apedal single grain.

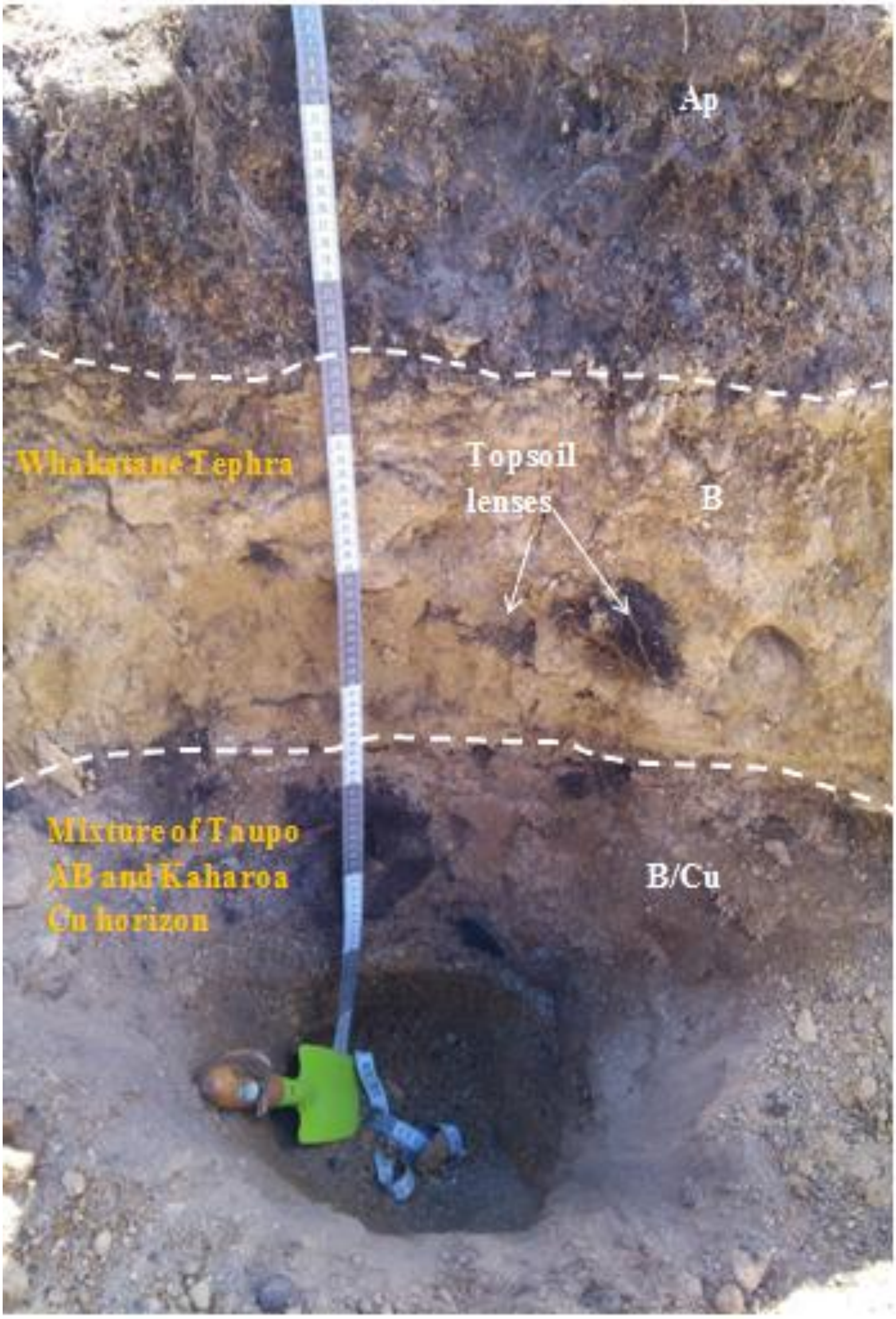

Figure 6.4: Flipped pit 2 at site 1.

Soil profile description of undisturbed soil pit 3

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, elevation: 206 m
  Paddock adjacent to Whirinaki road, approximately 1.5 km north west of the intersection at Whirinaki and Troutbeck Rd. Pit is 180 m from the fence facing the road and 5 m the fence of neighbouring paddock (away from race).
- Geomorphic position: Flat to gently undulating land on alluvial terrace.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and depth (cm)	**Profile description of undisturbed pit 3**
Ap (0-25)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds slightly firm and brittle; low penetration resistance (900 kPa); low degree of packing (700 kPa); strongly developed platy surface layer 5cm thick breaking to very coarse to medium blocky peds breaking to weakly pedal very fine to fine polyhedral peds breaking to apedal single grain; abundant microfine roots; sharp smooth boundary [Kaharoa Tephra].
BC (25-35)	Dull yellow orange (10YR 7/4) slightly gravelly coarse and medium sand with abundant fine sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu1 (35-55)	Light yellow orange (10YR 8/3) slightly gravelly coarse and medium sand with abundant fine sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu2 (55-56)	Light grey (2.5Y 8/2) loamy sand; non sticky; non plastic; apedal single grain; common microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu3 (56- 70)	Light grey (10YR 8/1) gravelly medium and fine sand with many sub-angular pumice lapilli; non sticky; non plastic; common extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
2bAB (70-80)	Brown (7.5 YR 4/3) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; apedal massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots; abrupt wavy boundary [Taupo Tephra – ignimbrite].

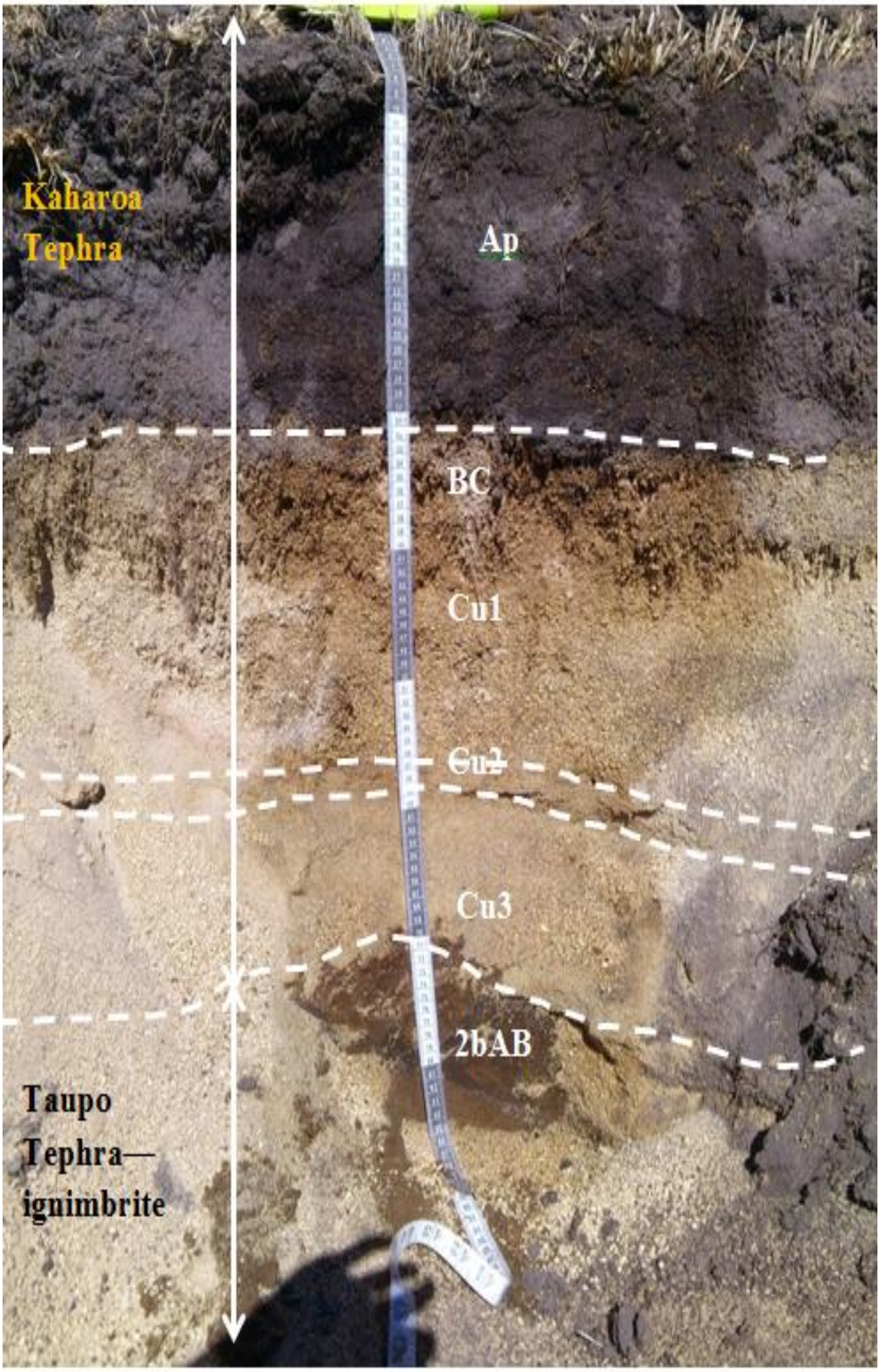

Figure 6.5: Undisturbed pit 3 at site 1

Soil profile description of flipped soil pit 3

- Soil classification (NZSC): Mixed Anthropic Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock adjacent to Whirinaki road, approximately 1.5 km north west of the intersection at Whirinaki and Troutbeck Rd. Pit is approximately 250 m from the fence facing the road and 80 m away from the race
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow
-

Horizon and depth (cm)	**Profile description of flipped soil pit 3**
Ap1 (0-20)	Olive brown (2.5 Y 4/4) sandy loam [Ap horizon and Whakatane B horizon]; slightly sticky; non plastic; peds firm and brittle; low penetration resistance (1200 kPa); low degree of packing (900 kPa); apedal massive breaking to apedal earthy; abundant microfine roots; indistinct occluded boundary.
Ap2 (20-35)	Brownish black (2.5YR 3/1) loamy sand [Ap horizon]; non sticky; non plastic; peds slightly firm and brittle; low penetration resistance (1400 kPa); low degree of packing (800 kPa); apedal massive breaking to apedal earthy; many microfine roots and few extremely fine roots ; sharp smooth boundary.
B/Cu1 (35-70)	Light yellow (2.5Y 7/3) slightly gravelly coarse and medium sand [Kaharoa C horizon] with dull yellowish brown (10 YR 5/4) sandy loam [Taupo AB ,Whakatane B horizon]; non sticky; non plastic; peds weak and brittle; low penetration resistance (1400 kPa); low degree of packing (1000 kPa); apedal single grain; abundant microfine roots; indistinct smooth boundary.

Figure 6.6:Flipped pit 3 at site 1.

6.2 Soil profile descriptions at site 2

Soil Profile Description of undisturbed pit 1

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38°27'36.98"S 176°45'8.35"E, Elevation: 206 m
  Paddock adjacent to Whirinaki road (~200m from the road) , approximately 700 m north west of the intersection at Whirinaki and Troutbeck Rd. Pit in .located ~50 m from cow shed (in line with the edge of the cow shed) and ~ 10 m away from the bee boxes in the paddock.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and Depth (cm)	**Profile description of undisturbed pit 1**
Ap (0-25)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds slightly firm to firm and brittle; very low penetration resistance (900 kPa); low degree of packing (1000 kPa); strongly developed platy surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to weakly pedal with very fine to fine polyhedral peds breaking to apedal single grain; abundant microfine roots; abrupt smooth boundary.
Cu1 (25-45)	Light grey (2.5Y 8/1) coarse and medium sand with medium sub-angular slightly weathered pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt smooth boundary.
Cu2 (45-48)	Light grey (2.5Y 8/1) loamy sand; non sticky; non plastic; apedal single grain; common microfine roots; abrupt wavy boundary.
Cu3 (48-60	Light yellowish brown (2.5Y 6/3) medium and fine sand; non sticky; apedal single grain; common microfine fine roots; abrupt smooth boundary.
2bBw (60-75)	Brown (7.5 YR 4/3) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; peds firm and brittle; low penetration resistance (1500 kPa); medium degree of packing (1100 kPa) massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots ; abrupt wavy boundary.
2Cu (>75)	Light grey (10YR 8/1) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; common microfine roots; abrupt smooth boundary.

Figure 6.7: Undisturbed pit 1 at site 2.

Soil Profile Description of flipped pit 1

- Soil classification (NZSC): Mixed Anthropic Soils
- Location: 38°27'36.98"S 176°45'8.35"E, Elevation: 206 m
  Paddock adjacent to Whirinaki road (~200m from the road) , approximately 700 m north west of the intersection at Whirinaki and Troutbeck Rd. Pit in .located ~50 m from the gate (in line with gate) and ~ 15 m away from the neighbouring paddock fence (away from cow shed)..
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Maximum root depth observed: 85 cm

Horizon and Depth (cm)	**profile description of flipped pit 1**
Ap (0-25)	Dark brown (7.5 YR 3/4) loamy sand; non sticky; non plastic; peds slightly firm and brittle; very low penetration resistance (600 kPa); low degree of packing (500 kPa); surface platy layer 2-5 cm thick, weakly pedal with very fine to fine polyhedral peds breaking to apedal single grain; abundant microfine roots and few extremely fine roots ; abrupt smooth boundary.
Bu (25-80)	Brown (7.5 YR 4/3) loamy sand mixture with gravel and brownish black (10YR 2/2) top soil lenses; non sticky; non plastic; peds slightly firm and brittle; low penetration resistance (1200 kPa); low degree of packing (500 kPa) in matrix, low penetration resistance (1000 kPa) and low degree of packing (700 kPa) in topsoil lenses ; apedal massive breaking to apedal single grain; in matrix :many microfine roots, in the pumice lense at 65 cm: many microfine roots, in topsoil lenses below 65 cm: few microfine roots ; distinct smooth boundary.

Figure 6.8: Flipped pit 1 at site 2.

Soil Profile Description of undisturbed pit 2

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38°27'36.98"S 176°45'8.35"E, Elevation: 206 m
  Paddock adjacent to Whirinaki road (~200m from the road) , approximately 700 m north west of the intersection at Whirinaki and Troutbeck Rd. Pit in .located ~30 m from cow shed (in line with the edge of the cow shed) and approxamly 10 m away from the bee boxes in the paddock.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and Depth (cm)	**profile description of undisturbed pit 2**
Ap (0-25)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds slightly firm to firm and brittle; low pentration resistance (1000 kPa); medium degree of packing (1200 kPa); strongly developed platey surface layer 2-5cm thick breaking to very coarse to medium blocky peds breaking to weakly pedal very fine to fine polyhedral peds breaking to apedal single grain; abundant microfine roots; abrupt smooth boundary.
Cu1 (25—45)	Light grey (2.5Y 8/1) coarse and medium sand with medium sub-angular slightly weathered pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt smooth boundary.
Cu2 (45-48)	Light grey (2.5Y 8/1) loamy sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa); apedal single grain; common microfine roots; abrupt wavy boundary.
Cu3 (48-55)	Light yellowish brown (2.5Y 6/3) medium and fine sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; common extremely fine roots; abrupt smooth boundary.
bBw (55-70)	Brown (7.5 YR 4/3) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; medium penetration resistance (1500 kPa); medium degree of packing (1200 kPa) apedal massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots ; abrupt wavy boundary.
2Cu (>70)	Light grey (10YR 8/1) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; common microfine roots; abrupt smooth boundary.

Figure 6.9: Undisturbed pit 2at site 2.

Soil Profile Description of flipped pit 2

- Soil classification (NZSC): Mixed Anthropic Soils
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m Paddock adjacent to Whirinaki road (~200m from the road) , approximately 700 m north west of the intersection at Whirinaki and Troutbeck Rd. Pit in .located ~60 m from the fence with the gate (approximately the middle of the paddock) and ~ 30 m away from the neighbouring paddock fence (away from cow shed)..
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: coxfoot and yarrow

Horizon and Depth (cm)	**profile description of flipped pit 2**
Ap (0-20)	Brownish black (10YR 3/1) loamy sand ; non sticky; non plastic; peds slightly firm to firm and brittle; low penetration resistance (1000 kPa); low degree of packing (700 kPa); strongly developed platy surface layer 2-5cm thick breaking to apedal single earthy; abundant microfine roots in top 10cm and many microfine roots 10-20 cm; abrupt smooth boundary.
Bu (20-80)	Brown (10 YR 4/4) sandy loam with dark reddish brown (5YR 3/2) topsoil lenses; non sticky; slightly plastic; peds firm soil and brittle; medium penetration resistance (1700 kPa) and medium degree of packing (1200 kPa) in matrix, medium penetration resistance (1200 kPa) and low degree of packing (1100 kPa) in topsoil lenses ; apedal massive breaking to apedal earthy ; In matrix :common microfine roots, below 70 cm few microfine roots, in topsoil lenses around 50 cm: common microfine roots ; abrupt wavy boundary.

Figure 6.10: Flipped pi 2 at site 2.

Soil Profile Description of undisturbed pit 3

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38°27'36.98"S 176°45'8.35"E, Elevation: 206 m
  Paddock adjacent to Whirinaki road (~200m from the road) , approximately 700 m north west of the intersection at Whirinaki and Troutbeck Rd. Pit in .located ~20 m from cow shed (in line with the edge of the cow shed) and approxamly 10 m away from the bee boxes in the paddock.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow
-

Horizon and Depth (cm)	**profile description of undisturbed pit 3**
Ap (0-25)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds firm and brittle; low penetration resistance (1000 kPa); medium degree of packing (1200 kPa); strongly developed platy surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to weakly pedal very fine to fine polyhedral peds breaking to apedal single grain; abundant microfine roots; abrupt smooth boundary.
Cu1 (25—45)	Light grey (2.5Y 8/1) coarse sand with medium sub-angular slightly weathered pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt smooth boundary.
Cu2 (45-48)	Light grey (2.5Y 8/1) loamy sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa); apedal single grain; common microfine roots; abrupt wavy boundary.
Cu3 (48-55)	Light yellowish brown (2.5Y 6/3) medium and fine sand; non sticky; non plastic; extremely low pentration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; common extremely fine roots; abrupt smooth boundary.
bBw (55-70)	Brown (7.5 YR 4/3) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; medium pentration resistance (1500 kPa); medium degree of packing (1200 kPa)massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots; abrupt wavy boundary.
2Cu (>70)	Light grey (10YR 8/1) coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; common microfine roots; abrupt smooth boundary.

Figure 6.11: Undisturbed pit 3 at site 2.

Soil Profile Description of flipped pit 3

- Soil classification (NZSC): Buried-allophanic Pumice Soil
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock adjacent to Whirinaki road (~200m from the road) , approximately 700 m north west of the intersection at Whirinaki and Troutbeck Rd. Pit in .located ~20 m from the telephone pole close to the cow shed (in line with the pole) and ~ 20 m away from the bee boxes in the paddock.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: cocksfoot and yarrow

Horizon and Depth(cm)	**profile description of flipped pit 3**
Ap (0-10)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds firm and brittle; low penetration resistance (1000 kPa); low degree of packing (900 kPa); strongly developed platy surface layer 2-5cm thick breaking apedal single grain; abundant microfine roots ; abrupt smooth boundary.
Bw (10-40)	Brown (10 YR 4/4) sandy loam with 25% brownish black (10YR 3/1) topsoil lenses; peds firm and brittle; low penetration resistance (1100 kPa) low/medium degree of packing (1000 kPa); apedal massive breaking to apedal single earthy; common microfine roots in matrix; abundant microfine roots in topsoil lenses; abrupt smooth boundary.
BC (40-60)	Light grey (10 YR 8/1) gravelly coarse and medium sand with 30% brownish black (10YR 3/1) topsoil lenses; non sticky; non plastic; ; extremely low penetration resistance (~150 kPa); very low degree of packing (200 kPa); apedal single grain; abundant microfine roots in sand and many roots in topsoil lenses; .

Figure 6.12:Flipped pit 3at site 2.

6.3 *Soil profile descriptions at site 3*

Soil profile description of undisturbed pit 1

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: chicory

Horizon and Depth(cm)	**Profile description of undisturbed pit 1**
Ap (0-30)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (2100 kPa); medium degree of packing (1500 kPa); strongly developed platey surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to apedal single grain; abundant microfine roots and few extremely fine roots; sharp smooth boundary [Kaharoa Tephra].
Cu1 (30-35)	Light yellow orange (10YR 8/3) gravelly coarse and medium sand with abundant fine sub-rounded pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu2 (35-50)	Light yellowish brown (2.5Y 6/3) gravelly medium and fine sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; many extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
2bAB (50-70)	Dark brown (10 YR 3/3) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; low penetration resistance (900 kPa); medium degree of packing (1100 kPa); massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; common microfine roots; abrupt wavy boundary [Taupo Tephra—ignimbrite].
2Cu1 (70-100)	Light grey (10YR 8/1) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; few microfine roots; abrupt smooth boundary [Taupo Tephra—lapilli].
2Cu2 (100-104)	Light grey (10YR 8/1) fine sand; non sticky; non plastic; apedal single grain; abrupt wavy boundary.
2bBw (>104)	Olive brown (2.5Y 4/6) sandy loam with common medium yellowish grey distinct (2.5 Y 6/1) mottles with sharp; non sticky; slightly plastic; peds slightly firm and brittle when dry and semi deformable when moist; apedal massive breaking to apedal earthy.

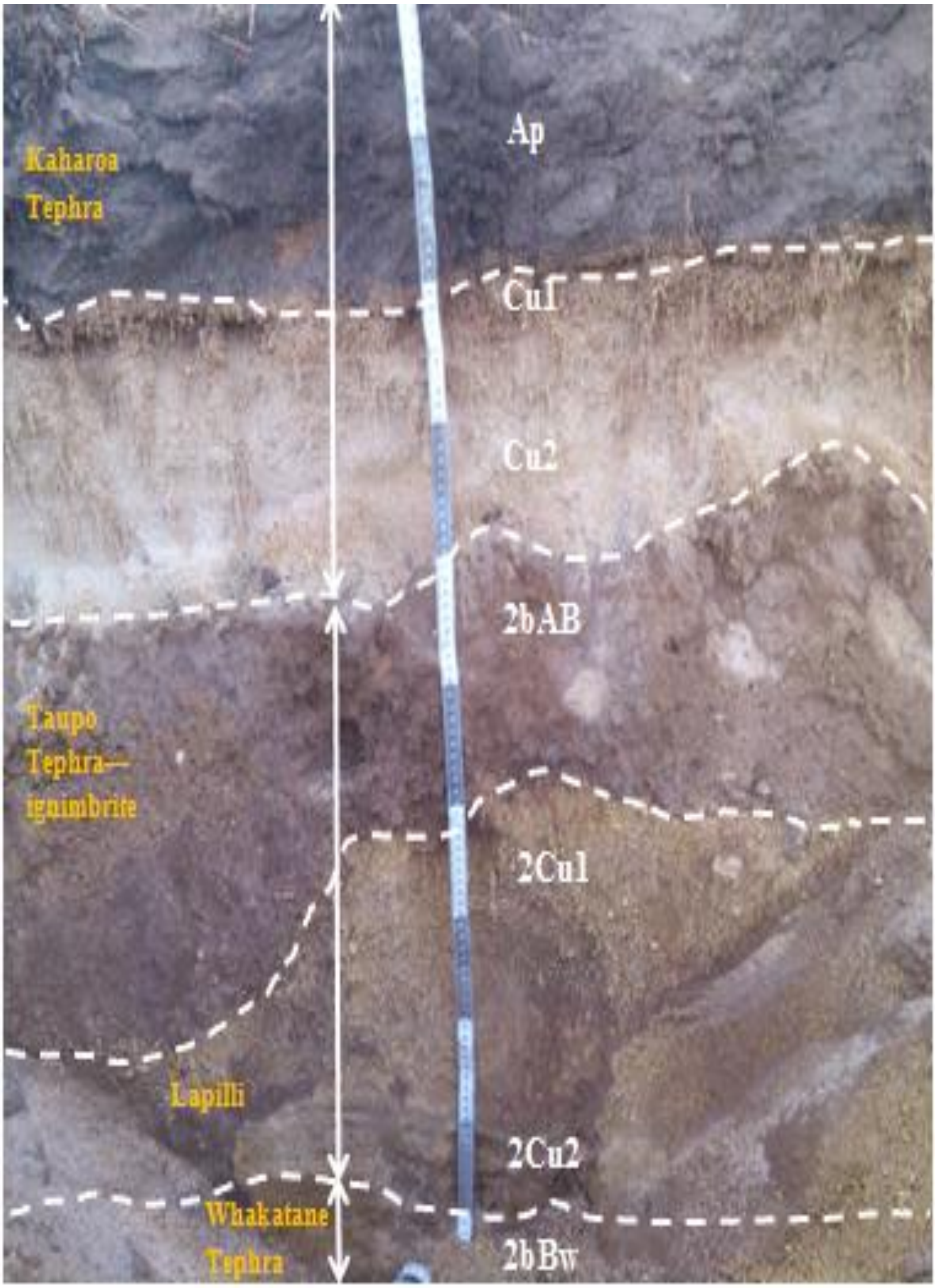

Figure 6.13: Undisturbed pit 1 at site 3.

Soil profile description of flipped pit 1

- Soil classification (NZSC): Anthropic Mixed soil (Mottled Orthic Pumice Soils)
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: chicory

Maximum root depth observed: 95 cm

Horizon and Depth(cm)	**Profile description of flipped pit 1**
Ap (0-15)	Brownish black (2.5YR 3/2) loamy sand [Ap horizon]; non sticky; non plastic; peds firm and brittle; low penetration resistance (1100 kPa); low degree of packing (800 kPa); platy surface layer 2-5cm thick breaking to moderately pedal with medium polyhedral peds breaking to apedal single grain; abundant microfine roots; indistinct smooth boundary.
B/C (15-80)	Brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon] with 15 % light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon] with very few and very fine reddish brown (2.5 YR 4/8) redox segregations; 5% light grey (10 YR 8/1) loamy sand lenses [Kaharoa C horizon]and 40% brown (10 YR 4/4) loamy sand lenses [Taupo tephra—ignimbrite]; non sticky; slightly plastic; fragments slightly firm and brittle; very low penetration resistance (600 kPa); low degree of packing (800 kPa) in Taupo Tephra lense; low penetration resistance (1400 kPa); medium degree of packing (1200 kPa) in Ap horizon lenses; apedal massive breaking to apedal earthy; common microfine roots in Kaharoa C horizon lenses and many microfine roots in brownish black [Ap horizon] and white loamy sand lenses [Kaharoa C horizon], few microfine roots in soil matrix below 70 cm depth.

Figure 6.14: Flipped pit 1 at site 3.

Soil profile description of undisturbed pit 2

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: chicory

Maximum root depth observed: 95 cm

Horizon and Depth(cm)	**Profile description of undisturbed pit 2**
Ap (0-25)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (2100 kPa); medium degree of packing (1500 kPa); strongly developed platy surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to apedal single grain; abundant microfine roots and few extremely fine roots; occluded abrupt boundary [Kaharoa Tephra].
Cu1 (25-32)	light grey (10 YR 8/1) loamy sand; non sticky; non plastic; peds firm and brittle; low penetration resistance (1200 kPa); medium degree of packing (1000 kPa); apedal single grain; common microfine roots; wavy abrupt boundary [Kaharoa Tephra].
Cu2 (32-45)	Light yellow orange (10YR 8/3) gravelly coarse and medium sand with abundant fine sub-rounded pumice lapilli ; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu3 (45-60)	Light yellowish brown (2.5Y 6/3) gravelly medium and fine sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; many extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
bAB (60 onwards)	Brown (10 YR 4/4) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots; abrupt wavy boundary [Taupo Tephra—ignimbrite].

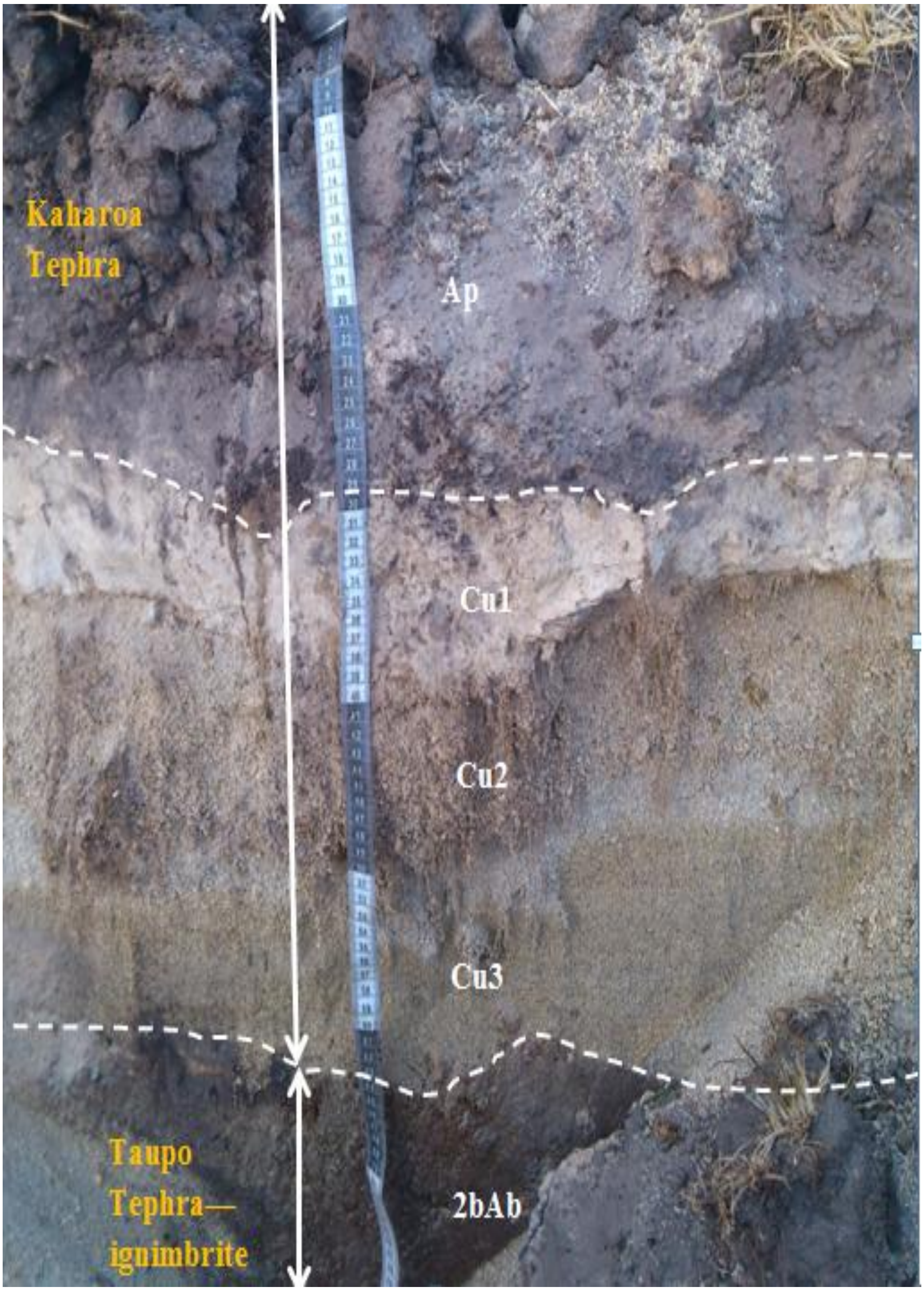

Figure 6.15: Undisturbed pit 2 at site 3.

oil profile description of flipped pit 2

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: chicory

Maximum root depth observed: 95 cm

Horizon and Depth(cm)	**Profile description of flipped pit 2**
Ap (0-15)	Brownish black (2.5YR 3/2) loamy sand [Ap horizon]; non sticky; non plastic; peds firm and brittle; moderate penetration resistance (1600 kPa); moderate degree of packing (1600 kPa); platy surface layer 2-5cm thick breaking toapedal single grain; abundant microfine roots; indistinct smooth boundary.
B/C (15-80)	Brown (10 YR 4/4) loamy sand lenses [Taupo tephra—ignibright] with few fine reddish brown (2.5 YR 4/8) redox segregations; 45% brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon] with 10 % light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon]; 10% light grey (10 YR 8/1) loamy sand lenses [Kaharoa C horizon]; non sticky; slightly plastic; Taupo tephra mixture of fragments slightly firm and brittle; moderate penetration resistance (1800 kPa); moderate degree of packing (1500 kPa) ; apedal massive breaking to apedal earthy; common microfine roots in Kaharoa C horizon lenses and many microfine roots in brownish black [Ap horizon] and white loamy sand lenses [Kaharoa C horizon], common microfine roots in matrix below 75 cm depth.
Cu (80-90)	Light grey (10YR 8/1) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; few microfine roots; abrupt smooth boundary [Taupo Tephra—lapilli].

Figure 6.16: Flipped pit 2 at site 3.

Soil profile description of undisturbed pit 3

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: chickery

Maximum root depth observed: 95 cm

Horizon and Depth (cm)	**Profile description of flipped pit 3**
Ap (0-20)	Brownish black (10YR 2/2) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (1900kPa); medium degree of packing (1500 kPa); strongly developed platey surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to apedal single grain; abundant microfine roots and few very fine roots; abrupt abrupt boundary [Kaharoa Tephra].
Cu2 (20-35)	Light yellow orange (10YR 8/3) gravelly coarse and medium sand with abundant fine sub-rounded pumice lapilli ; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Cu3 (35-45)	Light yellowish brown (2.5Y 6/3) gravelly medium and fine sand; non sticky; non plastic; extremely low pentration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; many extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
bAB (45-60)	Brown (10 YR 4/4) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; few microfine roots; abrupt wavy boundary [Taupo Tephra—ignibrite].
2Cu1 (60-80)	Dull yellow orange(10 YR 7/4) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; common microfine roots; abrupt smooth boundary [Taupo Lapilli]

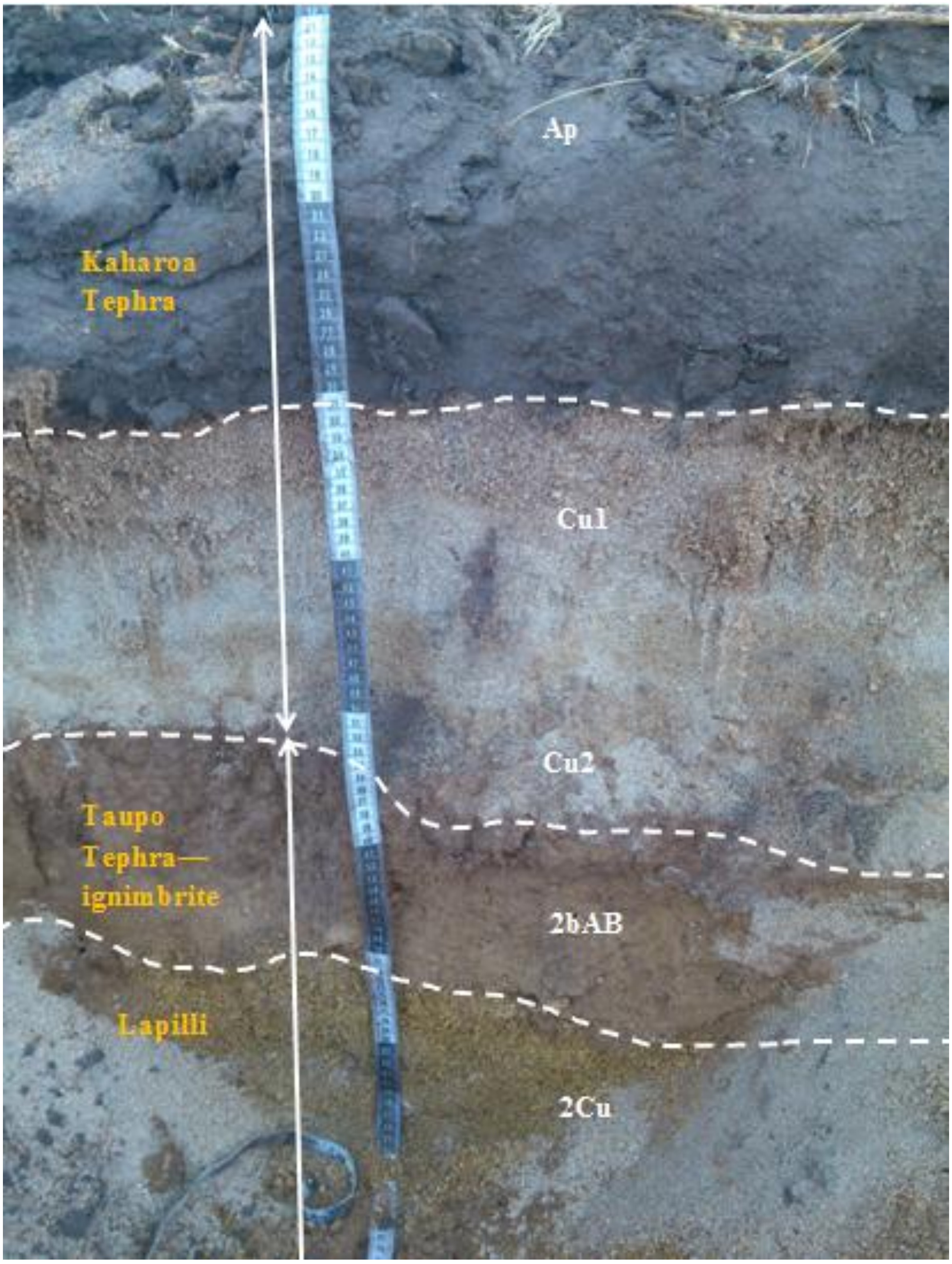

Figure 6.17: Undisturbed pit 3 at site 3

Soil profile description of flipped pit 3

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: chickery

Maximum root depth observed: 95 cm

Horizon and Depth(cm)	**Profile description of flipped pit 3**
Ap (0-20)	Brownish black (10YR 3/2) loamy sand with few fine reddish brown redox segregations; non sticky; non plastic; peds firm and brittle; very low penetration resistance (600 kPa); medium degree of packing (1100 kPa); apedal single grain; abundant microfine roots and few fine roots; indistinct smooth boundary.
B/C (15-90)	Brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon] with 10 % light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon]; sub- rounded pumice lapilli; light grey (10 YR 8/1) loamy sand lenses [Kaharoa C horizon] and Brown (10 YR 4/4) loamy sand lenses [Taupo tephra—ignimbrite]; non sticky; slightly plastic; slightly firm and brittle; low penetration resistance (1200 kPa); moderate degree of packing (1100 kPa) in brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon] low penetration resistance (1200 kPa); moderate degree of packing (1100 kPa) in Taupo Tephra—ignimbrite lenses; apedal massive breaking to apedal earthy; abundant microfine roots in Kaharoa C horizon lenses (30-75 cm) and many microfine roots in brownish black lenses (30-60) [Ap horizon]; and white loamy sand lenses [Kaharoa C horizon], few microfine roots in matrix below 70 cm depth.

Figure 6.18: Flipped pit 3 at site 3.

6.4 Soil profile descriptions at site 4

Soil profile description of undisturbed pit 1

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S $176^0$44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: bealy and clover

Horizon and Depth(cm)	**Profile description of undisturbed pit 1 (**
Ap (0-25)	Brownish black (7.5 YR 3/4) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (2100 kPa); medium degree of packing (1500 kPa); strongly developed platy surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to apedal single grain; abundant microfine roots and few extremely fine roots; sharp smooth boundary [Kaharoa Tephra].
Cu (25-30)	Yellow orange (10YR 6/4)sandy loam; slight sticky; non plastic; peds firm and brittle; apedal massive breaking to apedal single grain; common microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Ap2 (30-45)	Black (7.5 YR) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (2100 kPa); medium degree of packing (1500 kPa); apedal single grain; abundant microfine roots; sharp smooth boundary [Kaharoa Tephra].
2Cu1 (45-65)	Light grey (10YR 8/2) coarse and medium sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; many microfine fine roots; abrupt smooth boundary [Kaharoa Tephra].
2Cu2 (65-66)	Greyish yellow (2.5Y 6/3 gravelly coarse and medium sand with abundant fine sub-rounded pumice lapilli; non sticky; non plastic; apedal single grain; many microfine roots; abrupt wavy boundary [Kaharoa Tephra].
2Cu3 (66-90)	Greyish yellow (2.5Y 6/3) gravelly medium and fine sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; common extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
bAB (50-70)	Dark brown (10 YR 3/4) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; low penetration resistance (900 kPa); medium degree of packing (1100 kPa); massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; common microfine roots; abrupt wavy boundary [Taupo Tephra—ignibrite].
3Cu (60-80)	Dull yellow orange(10 YR 7/4) very gravelly coarse sand with abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; common microfine roots; abrupt smooth boundary [Taupo Lapilli]

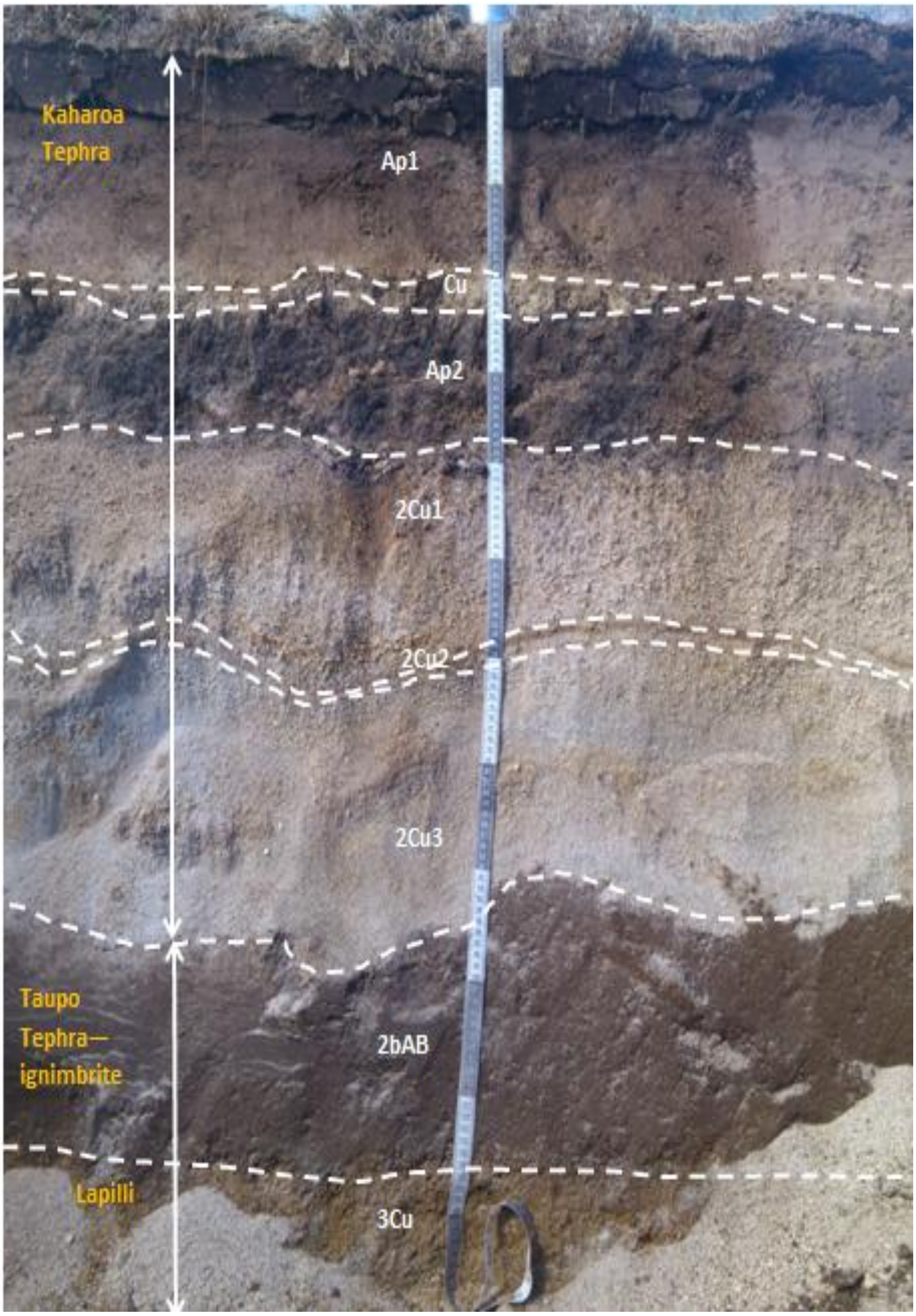

Figure 6.19: Undisturbed pi t 1 at site 4.

Soil profile description of undisturbed pit 1

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: bealy and clover

Maximum root depth observed: 95 cm

Horizon and Depth(cm)	**Profile description of flipped pit 1**
Ap (0-35)	Brownish black (10YR 3/4) loamy sand [Ap horizon] with redox segregations ; non sticky; non plastic; peds slightly firm and brittle; low penetration resistance (1200 kPa); low degree of packing (1000 kPa); apedal massive breaking to apedal single grain; abundant microfine roots; abrupt wavy boundary.
B/C (35-90)	Brown (10 YR 4/4) loamy sand lenses [Taupo tephra—ignibright] with brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon] with light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon]; light grey (10 YR 8/1) fine to medium sand lenses [Kaharoa C horizon]; non sticky; non plastic; Taupo tephra mixture of fragments slightly firm and brittle; moderate penetration resistance (1700 kPa); low degree of packing (700 kPa) in Taupo lenses; apedal massive breaking to apedal earthy breaking to apedal single grain; abundant microfine roots in sand lenses [Kaharoa C horizon] 30-50cm and few microfine roots in sand lenses [Kaharoa C horizon] below 80 cm; many microfine roots in brownish black [Ap horizon] 30-50 cm, common microfine roots in Taupo Tephra matrix below 65 cm depth; abrupt wavy boundary.
BC (90-94)	pale yellow (2.5YR 8/4) coarse and medium sand with bright orange (7.5 YR 5/8) abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; few microfine roots; abrupt smooth boundary [Taupo Tephra—lapilli].

Figure 6.20: Flipped pit 1 at site 4.

Soil profile description of undisturbed pit 2

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: bealy and clover

Maximum root depth observed: 95 cm

Horizon and Depth(cm)	**Profile description of undisturbed pit 2**
Ap (0-23)	Brownish black (7.5 YR 3/4) loamy sand; non sticky; non plastic; peds firm and brittle; strongly developed platey surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to apedal single grain; abundant microfine roots and few extremely fine roots; sharp smooth boundary [Kaharoa Tephra].
Cu1 (23-27)	Yellow orange (10YR 6/4)sandy loam; slight sticky; non plastic; peds firm and brittle; apedal massive breaking to apedal single grain; common microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Ap2 (27-37)	Black (7.5 YR) loamy sand; non sticky; non plastic; peds firm and brittle; apedal single grain; abundant microfine roots; sharp smooth boundary [Kaharoa Tephra].
2Cu1 (37-51)	Light grey (10YR 8/2) coarse and medium sand; non sticky; non plastic; apedal single grain; many extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
2Cu2 (51-52)	Greyish yellow (2.5Y 6/3 gravelly coarse and medium sand with abundant fine sub-rounded pumice lapilli ; non sticky; non plastic; apedal single grain; many microfine roots; abrupt wavy boundary [Kaharoa Tephra].
2Cu3 (52-75)	Greyish yellow (2.5Y 6/3) gravelly medium and fine sand; non sticky; non plastic ; apedal single grain; common extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
bAB (75-85+)	Dark brown (10 YR 3/4) sandy loam with few fine sub-rounded pumice lapilli and charcoal fragments; non sticky; non plastic; weak to slightly firm soil strength; brittle; massive breaking to weakly pedal with abundant fine polyhedral peds breaking to apedal earthy; common microfine roots; abrupt wavy boundary [Taupo Tephra—ignibrite].

Figure 6.21: Undisturbed pit 2 at site 4.

soil profile description of flipped pit 2

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^0 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: bealy and clover
  Maximum root depth observed: 95 cm

Horizon and Depth (cm)	**Profile description of flipped pit 2**
Ap (0-40)	Brownish black (10YR 3/4) loamy sand [Ap horizon]; non sticky; non plastic; peds slightly firm and brittle; moderate penetration resistance (1500 kPa); medium degree of packing (1200 kPa); apedal massive breaking to apedal single grain; abundant microfine roots; abrupt wavy boundary.
B/C (40-100)	Brown (10 YR 4/4) loamy sand lenses [Taupo tephra—ignimbrite] with 5 % brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon] with 15 % light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon]; 15% light grey (10 YR 8/1) fine to medium sand lenses [Kaharoa C horizon]; non sticky; non plastic; Taupo tephra mixture of fragments slightly firm and brittle; low penetration resistance (1000 kPa); medium degree of packing (1100 kPa) in Taupo lenses; apedal massive breaking to apedal earthy breaking to apedal single grain; many microfine roots in sand lenses [Kaharoa C horizon] 30-60cm and few microfine roots in sand lenses [Kaharoa C horizon] below 85 cm; many microfine roots in Taupo Tephra matrix 30-60 cm depth few micro fine roots in Taupo Tephra matrix below 70 cm.
BC (90-94)	pale yellow (2.5YR 8/4) coarse and medium sand with bright orange (7.5 YR 5/8) abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; few microfine roots; abrupt smooth boundary [Taupo Tephra—lapilli].

Figure 6.22: Flipped pit 2 at site 4.

Soil profile description of undisturbed pit 3

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: bealy and clover

Horizon and Depth(cm)	**Profile description of undisturbed pit 3**
Ap (0-15)	Brownish black (7.5 YR 3/4) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (2100 kPa); medium degree of packing (1500 kPa); strongly developed platy surface layer 2-5cm thick breaking to weakly pedal with very coarse to medium blocky peds breaking to apedal single grain; abundant microfine roots and few extremely fine roots; sharp smooth boundary [Kaharoa Tephra].
Cu1 (15-19)	Yellow orange (10YR 6/4)sandy loam; slight sticky; non plastic; peds firm and brittle; apedal massive breaking to apedal single grain; common microfine roots; abrupt wavy boundary [Kaharoa Tephra].
Ap2 (19-32)	Black (7.5 YR) loamy sand; non sticky; non plastic; peds firm and brittle; medium penetration resistance (2100 kPa); medium degree of packing (1500 kPa); apedal single grain; abundant microfine roots; sharp smooth boundary [Kaharoa Tephra].
2Cu1 (32-50)	Light grey (10YR 8/2) coarse and medium sand non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; many extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].
2Cu2 (50-51)	Greyish yellow (2.5Y 6/3 gravelly coarse and medium sand with abundant fine sub-rounded pumice lapilli; non sticky; non plastic; apedal single grain; abundant microfine roots; abrupt wavy boundary [Kaharoa Tephra].
2Cu3 (51-69)	Greyish yellow (2.5Y 6/3) gravelly medium and fine sand; non sticky; non plastic; extremely low penetration resistance (100 kPa); very low degree of packing (100 kPa) apedal single grain; common extremely fine roots; abrupt smooth boundary [Kaharoa Tephra].

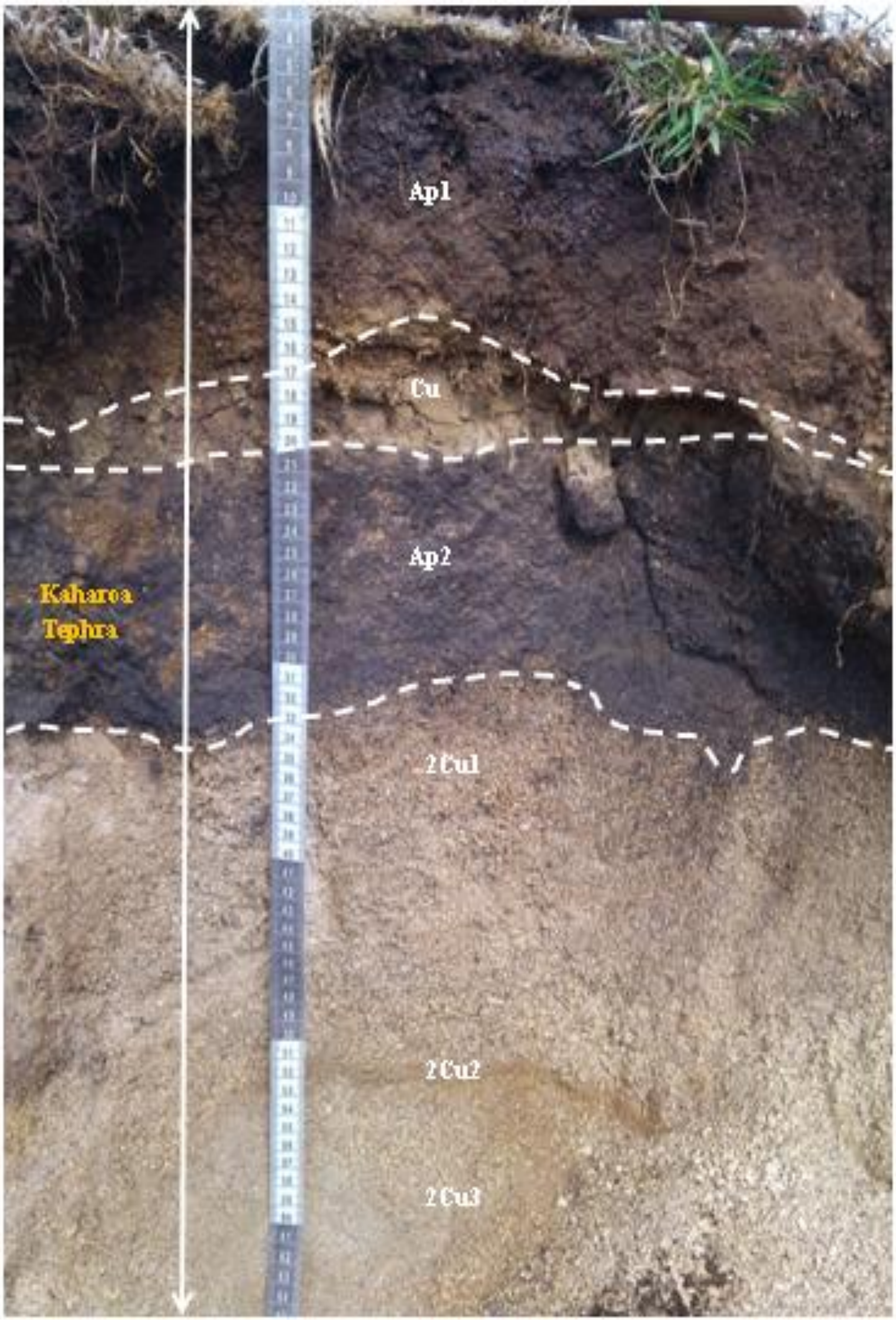

Figure 6.23: Undisturbed pit 3 at site 4.

Soil profile description of flipped pit 3

- Soil classification (NZSC): Mottled Orthic Pumice Soils
- Location: 38^{0} 27’26.08” S 176^{0}44’40.48 ” E, Elevation: 206 m
  Paddock on the property of 1225 Troutbeck Rd, Galatea, approximately 250m south west from Troutbeck Rd.
- Geomorphic position: Flat to gently undulating land.
- Parent material: rhyolitic tephras (Kaharoa, Taupo, Whakatane, and Rotoma tephras)
- Predominant pasture species: bealy and clover

Maximum root depth observed: 95 cm

Horizon and Depth	**Profile description of flipped pit 3**
Ap (0-25)	Brownish black (10YR 3/4) loamy sand [Ap horizon]; non sticky; non plastic; peds slightly firm and brittle; moderate penetration resistance (1800 kPa); medium degree of packing (1100 kPa); apedal massive breaking to apedal single grain; abundant microfine roots; abrupt wavy boundary.
B/C (25-90)	Brown (10 YR 4/4) loamy sand lenses [Taupo tephra—ignibright] with brownish black (2.5YR 2/2) loamy sand lenses [Ap horizon]; light grey (2.5Y 8/1) gravelly coarse and medium sand lenses [Kaharoa C horizon]; light grey (10 YR 8/1) fine to medium sand lenses [Kaharoa C horizon]; non sticky; non plastic; Taupo tephra mixture of fragments slightly firm and brittle; low penetration resistance (1000 kPa); medium degree of packing (1100 kPa) in Taupo lenses; apedal massive breaking to apedal earthy breaking to apedal single grain; abundant microfine roots in sand lenses [Kaharoa C horizon] 30-50cm and few microfine roots in sand lenses [Kaharoa C horizon] below 70 cm; many microfine roots in Taupo Tephra matrix 30-60 cm depth few micro fine roots in Taupo Tephra matrix below 70 cm.
Cu (90+)	Pale yellow (2.5YR 8/4) coarse and medium sand with bright orange (7.5 YR 5/8) abundant medium sub-angular pumice lapilli; non sticky; non plastic; apedal single grain; few microfine roots; abrupt smooth boundary [Taupo Tephra—lapilli].

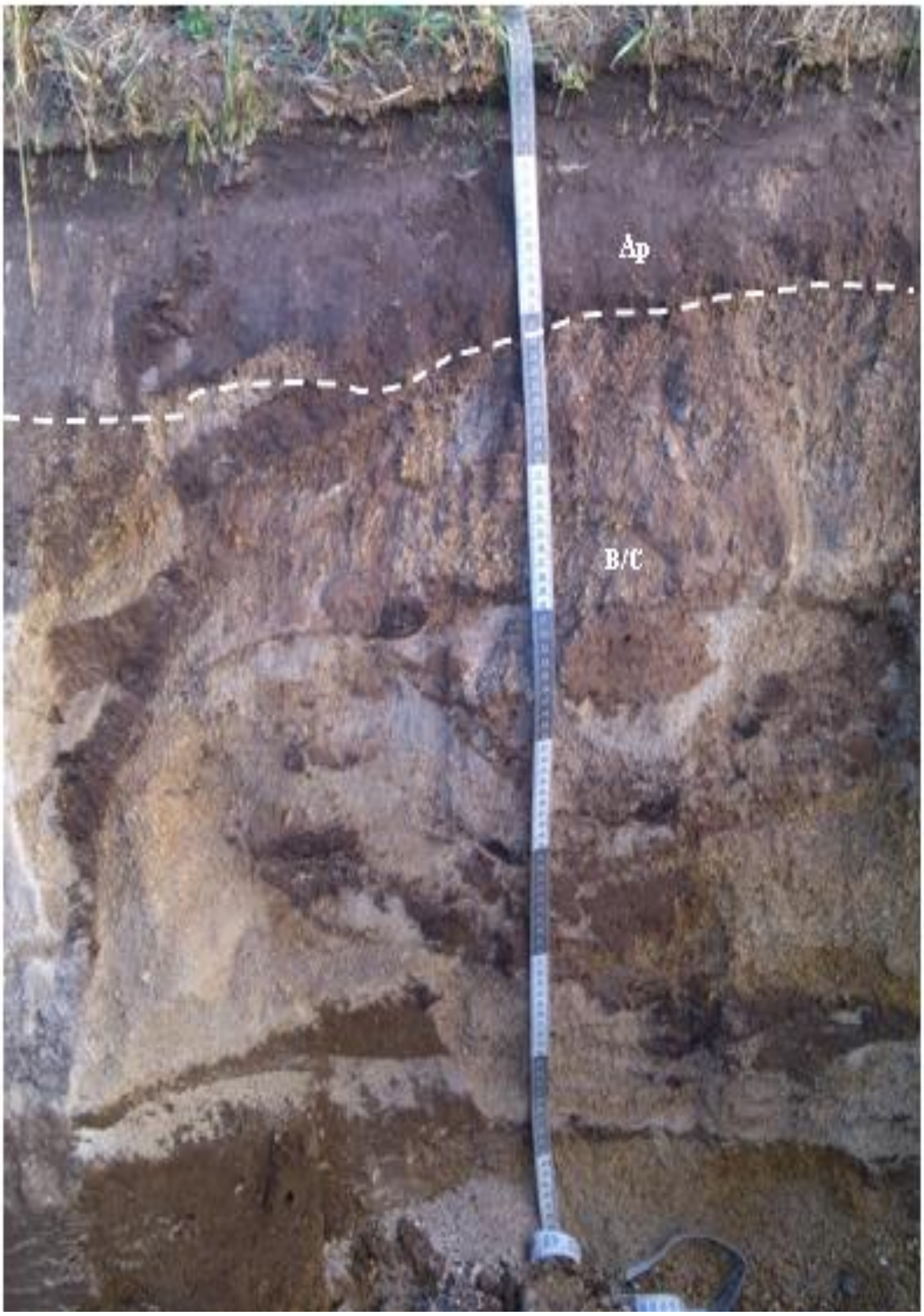

Figure 6.24: Flipped pit 3 at site 4.

6.5 Readily available water

6.5.1 Site 1

Table 6.1:Water retention at 0.4,2.5,7.4,10, 100,300 and 500 kPa for the undisturbed and flipped materials at site 1.

horizons sampled undisturbed	predominant material	0.4 Kpa	2.5 kPa	7.4 kPa	10 kPa	100 kPa	300 kPa	500 kPa	RAW (% v,v)	Mean RAW (%)
Ap		57.2	51.2	45.3	44.4	17.9	15.6	13.9	26.5	
Ap		59.2	50.8	44.8	43.9	15.5	17.2	15.2	28.4	
Ap		94.5	63.3	53.3	52.0	18.0	20.5	16.6	34.0	30
Cu2		52.2	23.6	20.4	20.0	10.6	10.5	10.6	9.4	
Cu2		56.9	25.5	21.9	21.5	12.0	11.9	11.9	9.5	
Cu2		48.1	24.0	20.0	19.6	10.5	6.7	10.3	9.1	9
Cu1		59.8	32.1	19.3	17.8	5.8	5.5	6.0	12.0	
Cu1		44.5	21.3	17.2	16.9	6.9	7.6	7.5	10.0	10
2Cu1		49.6	31.5	28.4	26.8	5.6	14.0	5.6	21.2	
2Cu2		41.6	29.3	26.5	25.9	2.7	12.3	2.7	23.2	
2Cu3		59.3	35.9	32.1	31.2	4.6	14.9	4.6	26.6	24
2bAB		89.5	69.2	57.3	56.3	27.6	21.7	18.5	28.7	
2bAB		96.3	73.0	59.7	58.4	25.0	23.7	22.0	33.4	
2bAB		96.2	69.4	56.9	55.6	24.3	27.9	23.4	31.3	31
3bBw		75.1	52.6	40.9	39.8	10.5	10.9	7.6	29.3	
3bBw		71.1	52.3	39.6	38.5	9.2	10.1	8.7	29.3	
3bBw		65.1	52.3	41.3	40.1	8.5	10.4	9.0	31.6	
3bBw		74.9	58.3	44.6	44.3	8.9	10.9	9.3	35.4	
3bBw		71.5	54.9	42.3	42.1	10.2	10.8	9.4	31.9	32
flip 1 0-10 1	Ap horizon	63.8	54.6	43.9	43.8	16.3	14.8	14.1	27.5	
flip 1 0-10 2	Ap horizon	56.9	48.4	39.6	38.6	14.0	13.6	12.3	24.6	
flip 1 0-10 3	Ap horizon	62.5	54.6	44.0	43.9	17.4	14.3	12.6	26.5	26
flip 1 0-20 1	Ap horizon	77.4	69.8	58.2	51.8	32.7	25.5	23.9	19.1	
flip 1 0-20 2	Ap horizon	99.5	40.8	33.5	32.7	10.7	10.3	8.6	22.0	
flip 1 0-20 3	Ap horizon	34.1	49.0	39.8	39.0	16.4	10.7	8.5	22.6	23
Flip 1 30cm	3bBw horizon	83.0	66.7	54.4	53.2	29.0	13.2	10.0	24.2	
Flip 1 30cm	3bBw horizon	70.1	59.2	48.3	46.3	26.6	15.6	14.1	19.7	
Flip 1 30cm	3bBw horizon	56.9	44.7	35.9	35.0	16.0	22.5	18.2	19.0	19
Flip 1 50 cm 1	3bBw horizon & fine/medium sand	70.8	56.9	50.4	48.9	23.0	24.4	23.6	25.9	
Flip 1 50 cm 2	" "	73.1	59.9	52.1	50.9	20.0	23.0	21.9	30.9	

Flip 1 50 cm 3	" "	72.6	58.9	51.7	50.8	27.0	13.5		23.8	27
flip 2 0-20 cm 1	Ap horizon	73.0	57.8	45.0	44.1	26.1	24.9	23.8	18.0	
flip 2 0-20 cm 2	Ap horizon	75.5	60.7	47.2	46.0	15.0	19.6	17.5	31.0	
flip 2 0-20 cm 3	Ap horizon	71.0	54.3	42.9	42.1	22.6	25.5	23.7	19.5	23
flip 2 30 cm	Ap lense	65.8	52.4	42.7	41.1	10.3			30.8	
flip 2 30 cm	Ap lense	62.1	42.9	34.8	44.1	9.9			34.2	
flip 2 30 cm	Ap lense	48.1	31.6	26.1	25.5	6.3			19.2	28
flip 2 40-60 cm 1	4bBw	63.0	52.1	42.8	41.9	17.1	13.8	11.6	24.8	
flip 2 40-60 cm 2	4bBw	60.4	54.4	45.6	44.5	14.7	11.6	9.5	29.8	
flip 2 40-60 cm 3	4bBw	62.9	54.7	47.2	46.2	12.9	13.2	11.4	33.3	29
flip 2 60-70 cm 1	2bBw & fine/meduim sand	61.1	42.7	33.8	33.0	11.9	10.3	12.7	21.1	
flip 2 60-70 cm 2	" "	58.6	42.0	33.8	33.0	12.6	9.9	11.3	20.4	
flip 2 60-70 cm 3	" "	66.9	41.8	34.3	33.5	12.7	11.4	10.5	20.8	25
flip 3 0-20 cm 1	Ap and 3bBw	54.6	31.2	30.6	30.0	3.4	14.7	14.0	26.6	
flip 3 0-20 cm 2	“ “	61.8	40.6	32.2	31.0	3.7	14.7	14.0	27.3	
flip 3 0-20 cm 3	“ “	66.9	38.7	37.2	36.2	6.3	13.5	11.6	29.9	28
flip 3 20-30 cm 1	Ap lense	56.2	37.9	34.6	34.0	13.5	11.9	10.9	20.5	
flip 3 20-30 cm 2	Ap lense	61.0	39.5	32.8	32.2	16.3	13.1	12.3	15.9	
flip 3 20-30 cm 3	Ap lense	64.1	43.9	34.9	34.0	12.8	11.3	9.1	21.2	19
flip 3 30-60 cm 1	2bBw & sand	50.4	42.6	37.3	36.5	14.5	4.2	4.1	22.0	
flip 3 30-60 cm 2	" "	56.2	46.8	40.2	39.3	16.4	3.5	3.4	22.9	
flip 3 30-60 cm 3	" "	83.0	66.7	54.4	53.2	29.0	8.0	7.2	24.2	
flip 3 30-60 cm 4	" "	70.1	59.2	48.3	42.3	26.6	11.9	2.5	15.7	
flip 3 30-60 cm 5	" "	56.9	44.7	35.9	35.0	16.0	10.6	2.3	19.0	
flip 3 30-60 cm 6	" "	64.0	43.8	34.8	34.0	12.8	10.0	6.1	21.2	21

Site 1

1.1..1 Undisturbed pit 1

Table 6.2: Profile RAW calculation for undisturbed pit 1 at site 1(600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	150	0.3	45
Cu1	200	0.1	20
cu2	150	0.09	14
2bAB	100	0.31	31
total	600		110

Table 6.3:plant RAW calculation for undisturbed pit 1 at site 1 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	150	0.3	45
Cu1	200	0.1	20
cu2	100	0.09	9
	450		74

Undisturbed pit 2

Table 6.4: profile RAW calculation for undisturbed pit 2 at site 1(600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.3	60
Cu1	200	0.1	20
Cu2	150	0.09	13.5
2bAB	50	0.31	15.5
total	600		109

Table 6.5: profile RAW calculation for undisturbed pit 2 at site 1 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.3	60
Cu1	200	0.1	20
Cu2	50	0.09	4.5

total	450		85

Undisturbed pit 3

Table 6.6: profile RAW calculation for undisturbed pit 3 at site 1 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	250	0.3	75
Cu1	200	0.1	20
cu2	150	0.09	13.5
total	600		109

Table 6.7: plant RAW calculation for undisturbed pit 3 at site 1 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	250	0.3	75
Cu1	200	0.1	20
total	450		95

Flipped pit 1

Table 6.8: RAW calculation for flipped pit 1 at site 1(600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap 0-10	1	200	200	0.24	48
Flip 1 10-30 cm	1	100	100	0.21	21
Flip 1 30-60 cm	1	300	300	0.27	81
total		600			150

Flipped pit 2

Table 6.9:RAW calculation for flipped pit 2 at site 1 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap (0-20)	1	200	200	0.23	46
matrix 20-60	1	300	300	0.29	87
60-70	0.9	100	90	0.25	23

kaha F	0.1	100	10	0.09	1
		600			156

Flipped it 3

Table 6.10:RAW calculation for flipped pit 3 at site 1 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap (0-10)	1	200	200	0.28	56
Ap lense (20-30)	1	10	10	0.19	1.9
Cu1 lense	1	15	15	0.1	1.5
matrix 30-60	1	375	375	0.21	79
		600			138

6.5.2 Site 2

Table 6.11: Water retention at 0.4,2.5,7.4,10, 100,300 and 500 kPa for the undisturbed and flipped materials at site 2.

horizons sampled	predominant material	0.4 Kpa	2.5 kPa	7.4 kPa	10 kPa	100 kPa	300 kPa	500 kPa	RAW (% v,v)	Mean RAW
undisturbed										
Ap (0-20)		55.1	41.3	33.7	33.0	14.5	10.3	10.8	18.5	
Ap (0-20)		47.2	41.2	35.9	35.1	14.4	10.3	10.0	20.7	
Ap (0-20)		57.4	47.1	35.7	34.9	14.6	10.4	10.9	20.3	20
2bAB		63.2	44.8	37.8	37.5	32.4	24.5	24.0	5.1	
2bAB		82.3	68.5	61.7	60.5	29.0	24.9	24.0	31.5	
2bAB		81.4	55.1	47.4	47.0	33.1	20.0	19.8	13.9	23
2Cu1		75.7	38.7	26.2	25.6	17.0	15.1	15.6	8.6	
2Cu2		65.0	38.0	34.3	33.8	19.7	16.8	15.6	14.1	
2Cu3		61.5	37.2	30.5	30.0	22.5	19.0	18.8	7.5	10
Cu1		48.9	20.1	17.6	17.0	10.7	10.8	12.4	6.3	
Cu1		51.9	20.3	17.0	17.0	11.6	10.1	8.5	5.4	
Cu1		53.4	25.3	21.0	20.5	11.1	11.0	11.1	9.4	7
Cu2		55.9	27.3	19.4	19.0	11.7	9.8	9.5	7.3	
Cu2		52.4	23.4	15.8	15.5	8.2	6.4	7.3	7.3	
Cu2		54.5	23.7	16.7	16.0	8.4	6.7	6.7	7.6	7
Flipped										
pit 1 top soil (0-20) 1	Ap horizon	71.6	55.6	41.5	40.8	21.5	19.5	15.1	19.3	
pit 1 top soil (0-20) 2	Ap horizon	59.8	49.4	37.5	36.8	19.1	15.7	14.9	17.7	
pit 1 top soil (0-20) 3	Ap horizon	79.4	55.7	40.5	39.7	19.1	18.3	17.3	20.6	19
pit 1 sandy matrix >50 cm	lapilli, Ap, 3bBw, 2bAB mix	53.7	38.0	30.0	30.0	9.3	8.5	7.2	20.7	

pit 1 sandy matrix >50 cm	lapilli, Ap, 3bBw, 2bAB mix	63.5	53.2	40.5	40.0	11.9	7.8	6.3	28.1	
pit 1 sandy matrix >50 cm	lapilli, Ap, 3bBw, 2bAB mix	*43.4*	*31.7*	*20.7*	20.0	*9.5*	10.4	9.9	10.5	20
pit 1 20-50	3bBw, 2bAB mix	77.8	64.7	54.4	53.1	7.4	11.9	9.8	45.7	
pit 1 20-50	3bBw, 2bAB mix	77.9	64.4	52.5	51.1	13.7	16.8	14.5	37.4	
pit 1 20-50	3bBw, 2bAB mix	68.7	52.0	44.4	43.2	11.3	9.4	8.4	31.9	38
pit 2 top soil (0-10) 1	Ap horizon	77.8	61.5	46.8	45.9	25.3	22.8	20.9	20.6	
pit 2 top soil (0-10) 2	Ap horizon	86.1	65.1	50.6	49.7	29.1	23.9	21.8	20.6	
pit 2 top soil (0-10) 3	Ap horizon	91.7	65.7	52.0	51.0	28.9	24.4	20.0	22.1	21
pit 2 10-60	3bBw, 2bAB & fine/med sand	68.5	53.8	43.5	41.7	10.0	9.4	7.5	31.7	
pit 2 10-60	3bBw, 2bAB & fine/med sand	60.0	42.0	32.1	44.2	15.1	11.4	9.8	29.1	
pit 2 10-60	3bBw, 2bAB & fine/med sand	75.8	55.1	43.9	43.8	17.4	13.1	11.1	26.4	29
topsoil lense	Ap horizon & fine/med sand	53.2	39.1	30.1	29.2	8.4	7.8	7.3	20.8	
topsoil lense	Ap horizon & fine/med sand	55.4	38.9	30.4	29.6	11.3	10.3	9.8	18.3	
topsoil lense	Ap horizon & fine/med sand	58.0	42.5	32.2	31.5	12.6	11.2	10.1	18.9	19
pit 3 top soil (0-10) 1	Ap horizon	83.5	55.4	42.7	41.7	12.7	12.3	10.6	29.0	
pit 3 top soil (0-10) 2	Ap horizon	85.1	55.7	45.3	44.2	19.0	17.7	16.2	25.2	
pit 3 top soil (0-10) 3	Ap horizon	88.8	58.4	44.7	43.8	20.1	15.9	13.9	23.7	26
pit 3 10-40	(2bAB 3bBw)	82.9	65.9	55.8	54.0	12	11.5	11.1	46.5	
pit 3 10-40	(2bAB 3bBw)	79.6	65.5	53.3	52.0	12	11.7	9.8	44.1	
pit 3 10-40	(2bAB 3bBw)	88.4	73.6	63.6	62.0	13.2	13.1	9.2	48.8	43
flip 3 40-60	3bBw, 2bAB & fine/med sand	58.3	39.9	27.3	26.5	6.4	7.9	7.3	20.1	
flip 3 40-60	3bBw, 2bAB & fine/med sand	91.9	65.3	50.4	44.0	11.1	9.7	8.9	32.9	
flip 3 40-60	3bBw, 2bAB & fine/med sand	87.7	49.3	37.9	36.0	6.2	5.1	3.8	29.8	28

Undisturbed pit 1

Table 6.12: Profile RAW calculation for undisturbed pit 1 at site 2(600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.2	40
Cu1	200	0.07	14
cu2	200	0.07	14
	600		**68**

Table 6.13: Plant RAW calculation for undisturbed pit 1 at site 2 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.2	40
Cu1	200	0.07	14
cu2	50	0.07	3.5
	450		**58**

Undisturbed pit 2

Table 6.14: Profile RAW calculation for undisturbed pit 2 at site 2(600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.2	40
Cu1	150	0.07	10.5
cu2	100	0.07	7
Taupo	150	0.23	34.5
	600		**92**

Table 6.15: Plant RAW calculation for undisturbed pit 2 at site 2(450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.2	40
Cu1	150	0.07	10.5
cu2	100	0.07	7
	450		58

Undisturbed pit 3

Table 6.16: Profile RAW calculation for undisturbed pit 3 at site 2 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.2	40
Cu1	200	0.07	14
cu2	150	0.07	10.5
Taupo	50	0.23	11.5
	600		76

Table 6.17: RAW calculation for undisturbed pit 3 at site 2 (450 mm depth)

	Thickness	RAW	Total RAW

Horizon	(mm)		(mm)
Ap	200	0.2	40
Cu1	200	0.07	14
cu2	50	0.07	3.5
	450		58

Flipped pit 1

Table 6.18:RAW calculation for flipped pit 1 at site 2 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	150	0.19	28.5
20-50 cm	300	0.38	114
sandy mix >50	150	0.2	30
	600		173

Flipped pit 2

Table 6.19:RAW calculation for flipped pit 2 at site 2 (600 mm depth).

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap	1	100	100	0.21	21
topsoil lense	1	100	100	0.19	19
30-60 cm palesol mix	0.8	400	320	0.29	92.8
topsoil lense	0.2	400	80	0.19	15.2
		600			148

Flipped pit 3

Table 6.20:RAW calculation for flipped pit 3 at site 2 (600 mm depth).

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	150	0.26	39
10-40 cm	300	0.43	138
Cu1 & Cu2 lense	150	0.07	10.5
	600		179

6.5.3 Site 3

Table 6.21:Water retention at 0.4,2.5,7.4,10, 100,300 and 500 kPa for the undisturbed and flipped materials at site 3.

horizons sampled undisturbed	prodominant material	0.4 Kpa	2.5 kPa	7.4 kPa	10 kPa	100 kPa	300 kPa	500 kPa	RAW (% v,v)	Mean RAW
Ap (0-20)		69.4	55.3	42.2	40.6	21.4	17.5	13.8	19.2	
Ap		64.4	52.0	41.9	40.5	21.5	17.8	12.7	19.0	
Ap		67.7	54.4	43.9	41.5	24.0	19.7	15.2	17.5	19
white loamy sand		55.3	52.0	46.0	45.0	11.5	6.2	5.6	33.5	
white loamy sand		56.7	51.5	46.2	45.0	10.6	6.6	6.3	34.4	
white loamy sand		56.3	52.1	46.8	45.8	10.2	6.7	6.6	35.6	34
Cu1		41.0	23.5	15.1	14.5	4.2	3.5	2.4	10.3	
Cu1		45.2	21.2	14.7	14.2	3.6	3.0	2.3	10.6	
Cu1		47.7	20.6	14.9	14.5	4.1	3.5	3.1	10.4	10
Cu2		51.2	25.1	18.4	18.0	10.4	10.1	10.0	7.6	
Cu2		51.7	25.5	18.3	19.0	10.5	9.9	9.4	8.5	
Cu2		53.5	28.8	19.3	19.0	13.3	10.3	10.0	5.7	7
2bAB		77.0	61.1	53.9	51.5	17.5	11.8	11.3	34.0	
2bAB		58.3	40.7	33.8		27.6	19.8	19.3		
2bAB		71.0	50.0	41.8	40.5	15.4	14.3	7.6	25.1	30
flipped										
pit 1 0-20	Ap horizon	63.2	54.5	44.2	45.9	11.9	12.0	11.5	34.0	
pit 1 0-20	Ap horizon	72.5	55.0	46.8	43.1	13.4	13.8	12.6	29.7	
pit 1 0-20	Ap horizon	65.8	45.2	39.6	38.9	11.9	10.5	9.0	27.0	30
pit 1 white loamy sand patches	Ap horizon & white loamy sand	53.5	47.3	40.5	44.5	9.5	9.4	9.1	35.0	
pit 1 white loamy sand patches	Ap horizon & white loamy sand	56.1	50.1	45.6	42.1	8.4	7.9	7.7	33.7	
pit 1 white loamy sand patches	Ap horizon & white loamy sand	55.5	49.7	43.4	39.5	8.2	8.6	7.6	31.3	33
pit 1 Topsoil lense	Ap horizon	59.3	51.1	44.5	43.1	12.5	12.5	10.8	30.6	
pit 1 Topsoil lense	Ap horizon	57.3	49.4	42.6	44.5	10.6	10.6	8.6	33.9	
pit 1 Topsoil lense	Ap horizon	59.0	51.4	45.4	44.4	12.1	12.1	11.0	32.3	32
pit 1 2bAB patches	2bAB & fine sand	78.0	62.0	53.9	52.0	17.5	11.8	11.3	34.5	
pit 1 2bAB patches	2bAB & fine sand	57.3	40.7	33.8	33.8	20.6	19.8	18.3	13.2	
pit 1 2bAB patches	2bAB & fine sand	76.0	48.0	41.8	40.5	15.4	14.3	7.6	25.1	24
pit 2 0-20	Ap horizon	65.4	54.1	42.2	41.3	10.9	12.0	11.2	30.4	
pit 2 0-20	Ap horizon	68.1	50.5	39.6	38.8	10.6	10.3	9.8	28.2	29
pit 2 paleosol patches	Ap and 2bBw	69.0	56.6	47.7	46.8	22.9	13.4	14.0	23.9	
pit 2 paleosol patches	Ap and 2bBw	69.0	57.8	48.3	47.5	21.2	12.4	12.2	26.3	
pit 2 paleosol patches	Ap and 2bBw	72.2	55.2	45.8	44.9	21.6	15.5	15.1	23.3	25
pit 3 0-20	Ap horizon	55.6	50.5	41.4	40.0	20.2	10.9	10.7	19.8	
pit 3 0-20	Ap horizon	64.5	55.3	52.7	51.0	19.2	11.4	10.8	31.8	
pit 3 0-20	Ap horizon	74.2	64.8	56.4	53.5	19.9	13.5	13.5	33.6	28
pit 3 topsoil lense	Ap horizon	58.2	48.9	42.6	42.3	13.6	11.6	11.7	28.7	

pit 3 topsoil lense	Ap horizon	62.8	55.8	51.5	51.0	16.2	16.0	15.4	34.8	32
pit 3 paleosol patches	flip 3 taupo topsoil mix	55.6	50.5	41.4	40.0	20.5	17.2	16.5	19.5	
pit 3 paleosol patches	flip 3 taupo topsoil mix	64.5	52.7	55.3	54.3	19.2	15.2	14.2	35.1	
pit 3 paleosol patches	flip 3 taupo topsoil mix	74.2	56.4	64.8	64.5	19.9	14.5	13.5	44.6	33

Undisturbed pit 1

Table 6.22: Profile RAW calculation for undisturbed pit 1 at site 3 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	250	0.19	47.5
Cu1	100	0.1	10
cu2	100	0.07	7
Taupo	150	0.3	45
Total	600		110

Table 6.23: Plant RAW calculation for undisturbed pit 1 at site 3 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	250	0.19	47.5
Cu1	100	0.1	10
cu2	100	0.07	7
Total	450		**65**

Undisturbed pit 2

Table 6.24: Profile RAW calculation for undisturbed pit 2 at site 3 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.19	38
white loamy sand	80	0.34	27
Cu1	100	0.1	10
Cu2	100	0.07	7
Taupo	120	0.3	36
	600		118

Table 6.25: Plant RAW calculation for undisturbed pit 2 at site 3 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)

Ap	200	0.19	38
white loamy sand	80	0.34	27
Cu1	100	0.1	10
Cu2	70	0.07	4.9
	450		80

Undisturbed pit 3

Table 6.26: Profile RAW calculation for undisturbed pit 3 at site 3 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.19	38
Cu1	150	0.1	15
Cu2	100	0.07	7
Taupo	150	0.3	45
	600		105

Table 6.27: Plant RAW calculation for undisturbed pit 3 at site 3 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap	200	0.19	38
Cu1	150	0.1	15
Cu2	100	0.07	7
	450		60

Flipped pit 1

Table 6.28:RAW calculation for flipped pit 1 at site 3 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap	1	150	150	0.3	45
topsoil l	0.3	450	135	0.24	32.4
paleosol patch	0.5	450	225	0.33	74.25
Cu1 lense	0.1	450	45	0.1	4.5
white loamy sand patches	0.1	450	45	0.33	14.85
	1				171

Flipped pit 2

Table 6.29:RAW calculation for flipped pit 2 at site 3 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap	1	150	150	0.29	43.5
topsoil lense	0.35	450	157.5	0.32	50.4
white laomy sand patches	0.1	450	45	0.34	15.3
sandy paleosol patches	0.4	450	180	0.25	45
2bAB patches	0.15	450	67.5	0.3	20.25
	1	600			174

Flipped pit 3

Table 6.30:RAW calculation for flipped pit 3 at site 3 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap	1	150	150	0.28	42
topsoil lense	0.8	450	360	0.32	115.2
sandy paleosol patches	0.15	450	67.5	0.35	23.625
Cu1 lense	0.05	450	22.5	0.1	2.25
	1	600			**183**

6.5.4 Site 4

Table 6.31: Water retention at 0.4,2.5,7.4,10, 100,300 and 500 kPa for the undisturbed and flipped materials at site 4.

		0.4 Kpa	**2.5 kPa**	**7.4 kPa**	**10 kPa**	**100 kPa**	**300 kPa**	**500 kPa**		
horizons sampled	**predominant**	0.4	2.5	7.4	10	100	300	500	**RAW (% v,v)**	**Mean RAW**

undisturbed	**material**									
undisturbed										
Cu 12-20 cm		64.3	57.5	49.8	49.5	9.3	9.3	8.2	40.2	
Cu 12-20 cm		61.4	56.4	49.4	47.0	13.0	13.0	12.2	34.0	
Cu 12-20 cm		65.5	56.4	48.3	47.0	8.5	8.5	10.0	38.5	38
ap1 (1)		47.3	31.0	19.7	20.0	4.7	2.7	2.3	15.3	
ap1 (2)		49.4	37.5	26.1	25.0	2.1	1.8	1.4	22.9	
ap1 (3)		58.7	38.6	26.6	25.6	5.6	4.6	3.5	20.0	19
ap2 1		65.7	53.2	43.5	42.6	19.7	13.2	12.4	22.9	
ap2 2		67.8	53.5	42.0	41.0	16.7	13.3	11.7	24.3	
ap2 3		67.0	52.9	44.4	43.5	18.4	13.7	12.1	25.1	24
2bAB		51.2	42.6	34.7	34.0	14.8	14.8	14.1	19.2	
2bAB		57.5	42.8	36.6	35.8	12.8	12.8	11.9	23.0	
2bAB		60.4	46.7	38.3	37.5	14.5	14.7	13.8	23.0	22
Cu1		47.1	24.7	21.4	22.7	13.1	10.4	8.4	9.6	
Cu1		52.4	26.2	23.1	21.2	14.0	11.0	10.4	7.2	
Cu1		48.0	24.9	21.4	21.2	13.2	10.3	7.0	8.0	8
Cu2		58.0	26.3	20.6	20.2	11.3	10.1	8.8	8.9	
Cu2		54.3	23.7	18.8	18.5	9.7	7.3	5.8	8.8	
Cu2		57.8	26.7	21.1	20.8	11.9	11.9	9.4	8.9	9
Flipped										
pit 1 0-20	Ap1, Cu & Ap2	62.4	42.3	32.2	31.3	7.0	8.8	8.1	24.3	
pit 1 0-20	Ap1, Cu & Ap2	62.8	44.7	33.4	32.4	7.0	7.9	7.0	25.4	27
pit 1 0-20	Ap1, Cu & Ap2	71.1	52.7	66.2	65.0	33.9	11.9	11.3	31.1	
pi1 sandy paleosol patches	2bAB & medium sand	58.4	36.6	30.6	30.0	15.5	12.0	11.7	14.5	
pi1 sandy paleosol patches	2bAB & medium sand	55.0	35.2	30.1	29.8	15.1	10.9	9.4	14.7	
pi1 sandy paleosol patches	2bAB & medium sand	58.6	36.5	30.0	29.8	15.9	12.5	12.0	13.9	14
pit 2 0-20	Ap1, Cu & Ap2	77.9	59.0	48.0	47.1	25.4	17.2	17.0	21.7	
pit 2 0-20	Ap1, Cu & Ap2	79.0	55.2	46.0	45.2	26.3	19.4	18.9	18.9	
pit 2 0-20	Ap1, Cu & Ap2	72.2	53.5	43.0	42.2	24.0	17.0	16.0	18.2	20

pit 2 paleosol patches	2bAB	77.3	64.4	53.6	51.3	25.9	18.5	18.3	25.4	
pit 2 paleosol patches	2bAB	72.0	66.2	56.2	52.8	31.2	22.5	22.2	21.6	
pit 2 paleosol patches	2bAB	69.4	54.4	44.7	42.0	23.3	17.0	16.5	18.7	22
pit 3 0-20	Ap1, Cu & Ap2	78.0	52.7	41.7	40.8	16.5	16.9	16.0	24.3	
pit 3 0-21	Ap1, Cu & Ap2	70.1	49.4	40.1	39.2	16.4	18.0	17.9	22.8	
pit 3 0-22	Ap1, Cu & Ap2	77.5	49.6	38.8	37.9	16.4	16.3	15.3	21.5	23
pit 3 paleosol mix	Ap 1, Cu Ap2 & 2bAB	61.6	51.1	40.4	39.5	13.6	10.1	9.8	25.9	
pit 3 paleosol mix	Ap 1, Cu Ap2 & 2bAB	62.8	50.2	38.1	37.0	12.5	10.5	10.1	24.5	
Pit 3 paleosol mix	Ap 1, Cu Ap2 & 2bAB	59.7	51.6	41.6	40.5	14.9	10.5	10.1	25.6	25

Undisturbed pit

Table 6.32: Profile RAW calculation for undisturbed pit 1 at site 4 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap 1	250	0.19	47.5
Cu	40	0.38	15.2
Ap2	150	0.24	36
Cu1	160	0.08	12.8
	600		112

Table 6.33: Plant RAW calculation for undisturbed pit 1 at site 4 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap 1	250	0.22	55
Cu	40	0.38	15.2
Ap2	150	0.24	36
Cu1	10	0.08	0.8
	450		107

Undisturbed pit 2

Table 6.34: Profile RAW calculation for undisturbed pit 2 at site 4 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)

layer	thickness (mm)	RAW	total RAW
Ap 1	150	0.19	28.5
Cu	50	0.38	19
Ap2	100	0.24	24
Cu1	150	0.08	12
cu2	150	0.09	13.5
	600		97

Table 6.35: Plant RAW calculation for undisturbed pit 2 at site 4 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
Ap 1	150	0.19	28.5
Cu	50	0.38	19
Ap2	100	0.24	24
Cu1	150	0.08	12
	450		84

Undisturbed pit 3

Table 6.36: Profile RAW calculation for undisturbed pit 3 at site 4 (600 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
layer	thickness (mm)	RAW	total RAW
Ap 1	120	0.19	23
Cu	50	0.38	19
Ap2	100	0.24	24
Cu1	200	0.08	16
cu2	130	0.09	12
	600		94

Table 6.37: Plant RAW calculation for undisturbed pit 3 at site 4 (450 mm depth)

Horizon	Thickness (mm)	RAW	Total RAW (mm)
layer	thickness (mm)	RAW	total RAW
Ap 1	120	0.19	23
Cu	50	0.38	19
Ap2	100	0.24	24
Cu1	180	0.08	14

	450	80

Flipped Pit 1

Table 6.38:RAW calculation for flipped pit 1 at site 4 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap	1	300	300	0.27	72
sandy paleosol mix	0.5	300	150	0.14	21
2bAB lenses	0.3	300	90	0.22	19.8
Cu1 lense	0.2	300	60	0.08	4.8
	1	600			118

Flipped 2

Table 6.39:RAW calculation for flipped pit 2 at site 4 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
Ap	1	350	350	0.2	70
paleosol patches	0.7	250	175	0.22	38.5
2bAB lenses	0.2	250	50	0.22	11
Cu1 lense	0.1	250	25	0.08	2
	1	600			122

Flipped 3

Table 6.40:RAW calculation for flipped pit 3 at site 4 (600 mm depth)

Horizon	Estimated space	Thickness (mm)	Estimated thickness (mm)	RAW	Total RAW (mm)
layer	1	150	150	0.23	35
paleosol mix	0.4	450	180	0.25	45
2bAB	0.4	450	180	0.22	40
kaha	0.2	450	90	0.09	8
		600			127

Table 6.41: Summary of the profile readily available water (mm) at 600 mm depth for flipped and undisturbed side at site 1-4 (RHS). Plant readily available water (mm) at 450 mm depth for the undisturbed side and 600 mm depth for flipped side at site 1-4 (LHS).

Site		flipped	Site	Undisturbed	flipped
1	110	150	1	74	150
	109	156		85	156
	109	138		95	138
2	68	173	2	58	173
	92	148		58	148
	76	179		58	179
3	110	171	3	65	171
	118	174		80	174
	105	183		60	183
4	112	118	4	107	118
	97	122		84	122
	94	127		80	127
average	100	152	average	75	152

Appendix 2

7.1 Reference profile

The bulk density of the undisturbed horizons at the reference profile site are included below and were used to calculate gravimetric and volumetric water contents at 0.4-500 kPa.

Table 7.1: Soil dry bulk density of soil materials from the undisturbed at flipped area at the reference profile

Horizons sampled	Bulk density g/cm^3	gravimetric water content (%)	Volumetric water content (%)
Ap	0.97	16.01	15.58
Ap	1.03	12.32	12.63
Ap	1.03	10.94	11.25
Cu2	0.90	3.95	3.55
Cu2	0.85	5.79	4.91
Cu2	0.85	6.31	5.39
Cu1	0.86	6.46	5.53
Cu1	0.76	10.35	7.85
Cu1	0.81	9.65	7.84
2bAB	0.77	52.85	40.78
2bAB	0.79	54.19	43.04
2bAB	0.77	51.90	39.83
2Cu1	0.57	39.84	22.73
2Cu1	0.58	38.30	22.19
2Cu1	0.58	38.91	22.43
3bBw	0.96	30.52	29.36
3bBw	0.96	29.23	28.07
3bBw	1.00	25.36	25.44
3bBC1	1.08	20.93	22.51
3bBC1	1.03	27.17	27.93
3bBC1	1.11	22.10	24.62
3bBC2	1.14	11.54	13.17
3bBC2	1.13	11.86	13.37
3bBC2	1.14	15.10	17.14
3Cu	0.98	18.08	17.77
3Cu	0.95	18.73	17.88
3Cu	0.97	18.52	17.93
4bBw	1.00	29.50	29.56

4bBw	1.01	30.45	30.67
4bBw	0.95	31.00	29.49

7.2 Site 1

Table 7.2: Soil dry bulk density of soil materials from the undisturbed at flipped area at the site 1

Horizons sampled	**Bulk density g/cm3**	**gravimetric water content (%)**	**Volumetric water content (%)**
undisturbed			
Ap	0.95	2.86	2.71
Ap	0.94	3.55	3.33
Ap	0.89	3.16	2.82
Cu2	0.92	1.30	1.20
Cu2	0.84	0.82	0.70
Cu2	0.85	0.68	0.58
Cu1	0.81	8.08	6.50
Cu1	0.85	10.00	8.50
Cu1	0.90	6.64	5.97
2Cu1	0.57	39.81	22.72
2Cu2	0.58	38.30	22.19
2Cu3	0.58	38.91	22.43
2bAB	0.66	45.19	29.69
2bAB	0.67	45.71	30.63
2bAB	0.70	41.06	28.63
Flipped			
flip 1 0-10 1	1.08	4.46	4.83
flip 1 0-10 2	1.05	5.12	5.39
flip 1 0-10 3	1.10	4.52	4.95
Flip 1 30cm	1.25	9.29	11.64
Flip 1 30cm	0.88	8.20	7.21
Flip 1 30cm	0.93	8.73	8.13
Flip 1 50 cm 1	1.39	13.21	18.31
Flip 1 50 cm 2	1.10	16.98	18.73
Flip 1 50 cm 3	1.29	18.00	23.29
flip 2 0-20 cm 1	0.88	4.74	4.20
flip 2 0-20 cm 2	1.13	4.26	4.81
flip 2 0-20 cm 3	0.97	4.07	3.94
flip 2 30 cm	0.89	13.25	11.78
flip 2 30 cm	0.81	13.27	10.72
flip 2 30 cm	0.83	13.43	11.08
flip 2 40-60 cm 1	0.76	18.38	13.95

flip 2 40-60 cm 2	0.85	17.49	14.90
flip 2 40-60 cm 3	1.09	13.20	14.39
flip 2 60-70 cm 1	0.95	12.94	12.35
flip 2 60-70 cm 2	0.83	14.80	12.27
flip 2 60-70 cm 3	0.77	16.44	12.69
flip 3 0-10 cm 1	1.01	3.69	3.74
flip 3 0-10 cm 2	1.06	3.13	3.32
flip 3 0-10 cm 3	1.00	3.95	3.93
flip 3 10-20 cm 1	0.84	7.31	6.12
flip 3 10-20 cm 2	0.85	3.93	3.34
flip 3 10-20 cm 3	0.91	4.64	4.21
flip 3 50 cm 1	0.74	18.63	13.76
flip 3 50 cm 2	0.95	3.92	3.70
flip 3 50 cm 3	0.86	12.71	10.88
flip 3 70 cm 1	0.77	24.55	18.82
flip 3 70 cm 2	0.81	23.90	19.30
flip 3 70 cm 3	0.77	23.49	18.11

7.3 Site 2

Table 7.3:Soil dry bulk density of soil materials from the undisturbed at flipped area at the site 2

Horizons sampled	Bulk density g/cm3	Gravimetric water content (%)	Volumetric water content (%)
Undisturbed			
Ap (0-20)	0.96	6.11	5.89
Ap (0-20)	0.95	3.09	2.94
Ap (0-20)	0.97	3.52	3.42
2bAB	0.65	47.24	30.69
2bAB	0.67	45.86	30.71
2bAB	0.63	41.51	26.31
2Cu1	0.55	20.97	11.44
2Cu2	0.55	23.34	12.78
2Cu3	0.54	24.89	13.38
Cu1	0.86	1.25	1.07
Cu1	0.85	1.09	0.93
Cu1	0.93	1.40	1.29
Cu2	0.86	4.51	3.90
Cu2	0.87	7.75	6.71
Cu2	0.85	5.71	4.83
Flipped			
pit 1 top soil (0-20) 1	0.84	3.45	2.91
pit 1 top soil (0-20) 2	0.78	7.06	5.50
pit 1 top soil (0-20) 3	0.80	4.41	3.55
pit 1 sandy matrix >50 cm	0.77	5.84	4.49
pit 1 sandy matrix >50 cm	0.81	4.69	3.81
pit 1 sandy matrix >50 cm	0.82	6.09	5.01
pit 1 20-50	0.67	14.94	10.02
pit 1 20-50	0.73	10.12	7.36
pit 1 20-50	0.73	18.98	13.92
pit 2 top soil (0-10) 1	0.77	5.80	4.45
pit 2 top soil (0-10) 2	0.76	16.46	12.49
pit 2 top soil (0-10) 3	0.80	6.55	5.27
pit 2 10-60	0.69	8.42	5.80
pit 2 10-61	0.75	10.64	8.01
pit 2 10-62	0.68	10.80	7.30
pit 2 10-60	0.70	11.12	7.79
pit 2 10-60	0.68	9.62	6.58
topsoil mix (30 cm) 1	1.01	4.78	4.81
topsoil mix (30 cm) 2	0.81	5.92	4.81
topsoil mix (30 cm) 3	0.76	10.84	8.27

pit 3 top soil (0-10) 1	0.83	4.15	3.45
pit 3 top soil (0-10) 2	0.89	3.95	3.51
pit 3 top soil (0-10) 3	0.81	3.80	3.09
pit 3 10-30	0.92	2.89	2.67
pit 3 10-30	0.89	2.99	2.66
pit 3 10-30	0.95	2.55	2.41

7.4 Site 3

Table 7.4:Soil dry bulk density of soil materials from the undisturbed at flipped area at the site 3

Horizons sampled undisturbed	Bulk density g/cm3	Gravimetric water content (%)	Volumetric water content (%)
Ap	1.04	3.64	3.79
Ap	1.08	3.78	4.09
Ap	1.07	3.90	4.16
white loamy sand	1.14	1.81	2.07
white loamy sand	1.14	1.79	2.04
white loamy sand	1.19	1.76	2.10
Cu1	0.82	1.60	1.31
Cu1	0.84	1.54	1.28
Cu1	0.83	1.70	1.41
Cu2	0.92	6.81	6.28
Cu2	0.89	7.26	6.48
Cu2	0.91	7.25	6.59
2bAB	0.64	48.46	31.20
2bAB	0.67	46.11	30.72
2bAB	0.68	50.36	34.42
Flipped			
pit 1 0-20	0.99	3.98	3.93
pit 1 0-20	1.10	4.15	4.56
pit 1 0-20	1.10	2.49	2.74
pit 1 white loamy sand patches	1.01	5.93	6.00
pit 1 white loamy sand patches	0.89	6.77	6.05
pit 1 white loamy sand patches	1.02	3.48	3.53
pit 1 Topsoil lense	0.98	0.64	0.63
pit 1 Topsoil lense	0.95	7.66	7.26
pit 1 Topsoil lense	0.90	6.50	5.86
pit 1 2bAB patches	0.68	10.83	7.42
pit 1 2bAB patches	0.79	7.13	5.66
pit 1 2bAB patches	0.63	12.70	8.05
pit 2 0-20	1.05	3.31	3.49

pit 2 0-21	1.05	4.50	4.74
pit 2 0-20	1.03	4.19	4.30
pit 2 paleosol patches	0.97	8.98	8.73
pit 2 paleosol patches	0.89	13.51	12.09
pit 2 paleosol patches	0.84	15.37	12.95
pit 2 paleosol patches	0.70	23.52	16.56
pit 3 0-20	1.02	2.68	2.74
pit 3 0-20	0.99	2.22	2.18
pit 3 0-20	1.07	2.76	2.96
pit 3 topsoil lense	0.92	9.98	9.13
pit 3 topsoil lense	0.98	6.31	6.21
pit 3 topsoil lense	0.99	5.74	5.68
pit 3 paleosol patches	0.63	19.33	12.22
pit 3 paleosol patches	0.68	17.82	12.14
pit 3 paleosol patches	0.64	19.16	12.35

Appendix 3

8.1 Clay content for individual horizons

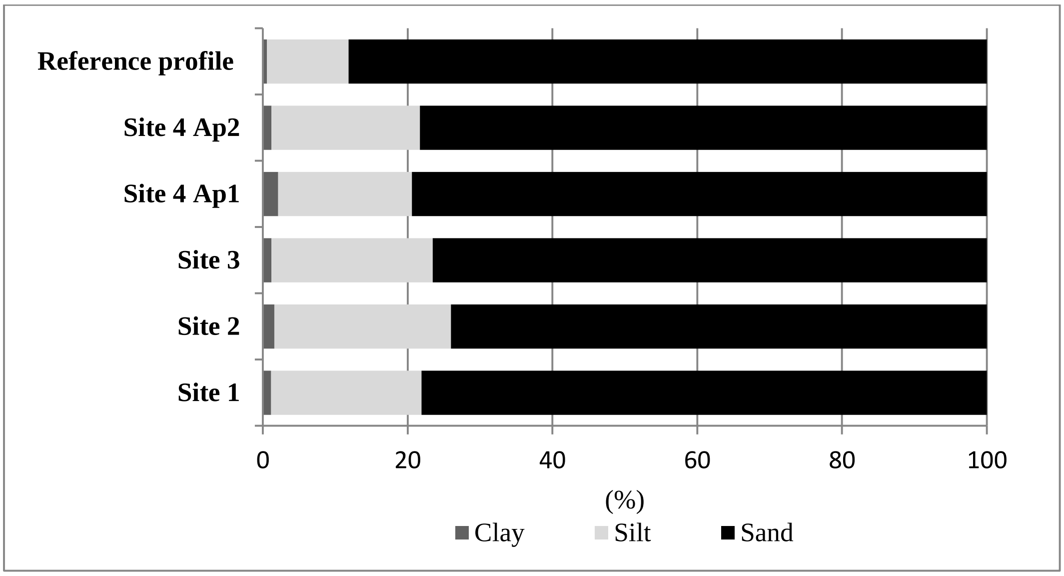

Figure 8.1 Particle size analysis (<2 mm) for topsoil (Ap horizon) at site 1 -4 and the reference profile site

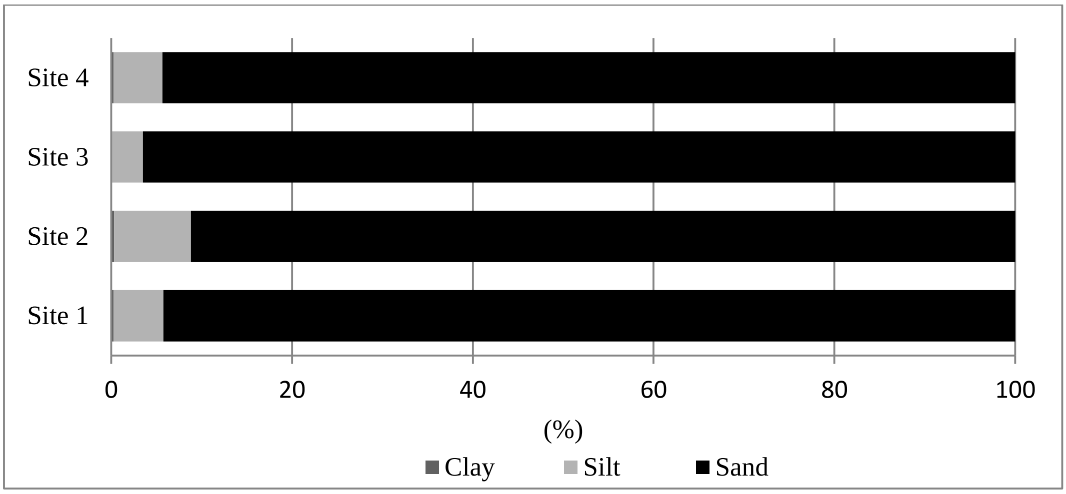

Figure 8.2: Particle size analysis (<2 mm) for undisturbed Cu1 horizon at site 1-4

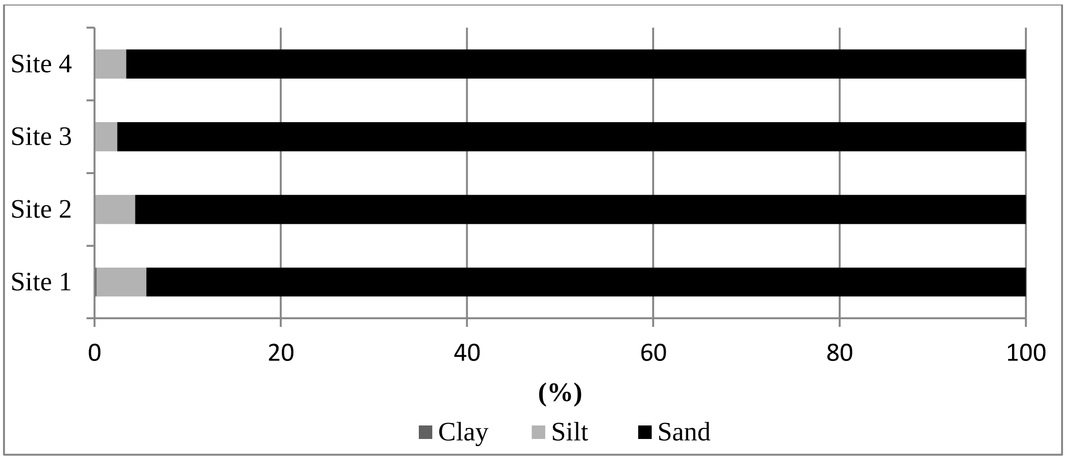

Figure 8.3: Particle size analysis (<2 mm) for undisturbed Cu2 horizon at site 1-4.

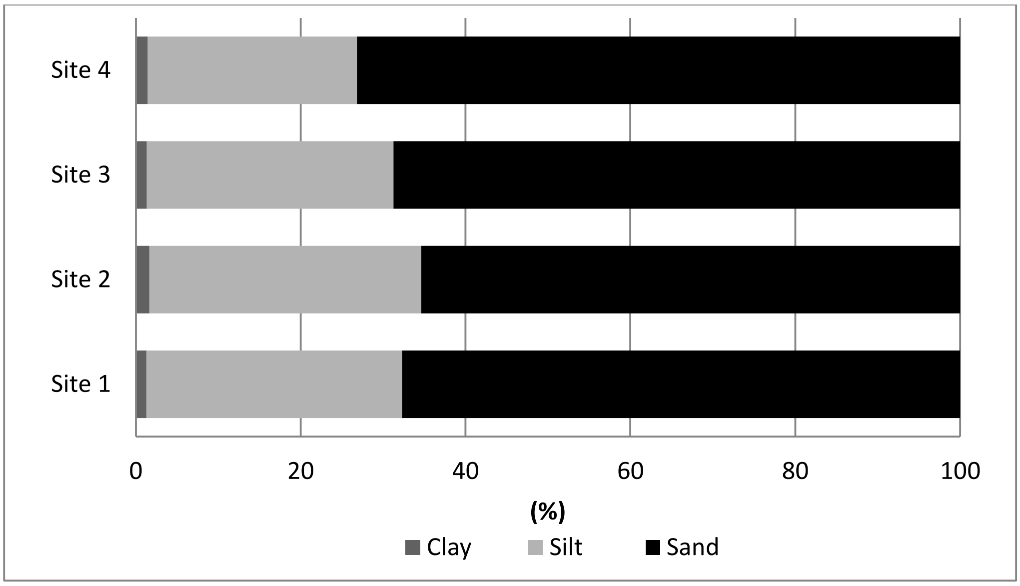

Figure 8.4: Particle size analysis (<2 mm) for undisturbed 2bBw horizon (paleosol formed on Taupo Tephra) at site 1-4.

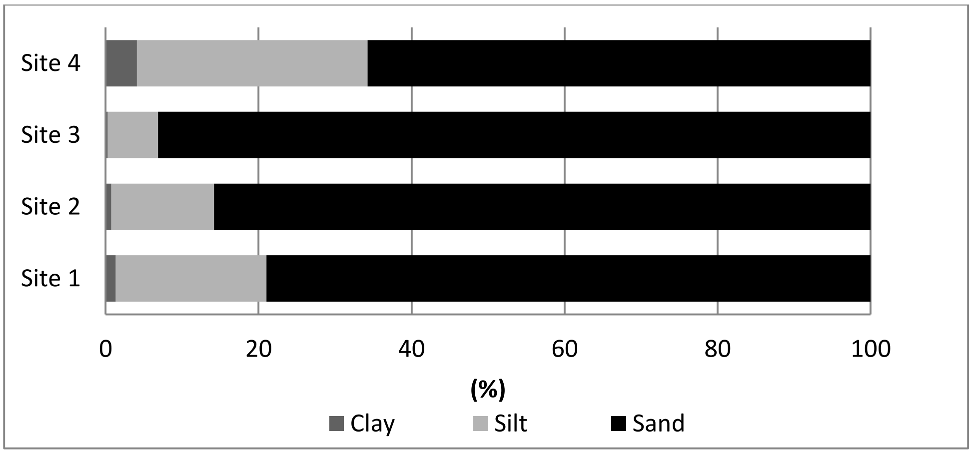

Figure 8.5: Particle size analysis (<2 mm) for paleosol formed on Whakatane Tephra (1):3bBw at reference profile for site 1-4.

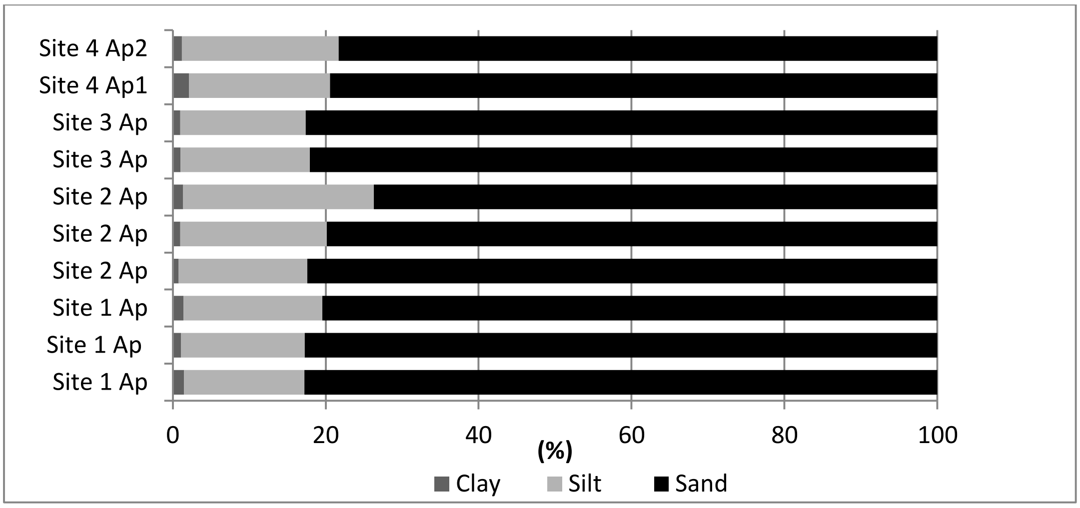

Figure 8.6: Particle size analysis (<2 mm) for flipped topsoils (0-20) at site 1-4.

1.2 Allophane analysis

Table 8.1:Allophane % calculation

Horizon	Alo %	Sio %	Alp %	Sip %	Al/Si ratio	Si %	Allophane %	Average* %
Taupo Tephra (2bAB)	0.68 0.69	0.28 0.24	0.12 0.12	0.05 0.05	1.97 2.36	13.73 11.91	2.1 2.1	2.1
Whakatane Tephra (3bBw)	0.60 0.60	0.65 0.53	0.05 0.04	0.07 0.06	0.84 1.05	19.07 18.09	3.4 2.9	3.2
Whakatane Tephra (3bBC1)	0.58 0.56	0.44 0.56	0.04 0.06	0.05 0.06	1.24 0.90	17.22 18.78	2.5 3.0	2.8
Whakatane Tephra (3bBC1)	0.30 0.31	0.32 0.36	0.04 0.04	0.03 0.03	0.82 0.76	19.17 19.46	1.6 1.9	1.8
Rotoma Tephra (4bBw)	1.09 1.03	0.87 0.78	0.03 0.05	0.06 0.04	1.23 1.26	17.25 17.10	5.0 4.6	4.8

*average of two samples