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**Soil recovery on landslides in hill country  
at Whatawhata Research Station, western  
Waikato, New Zealand**

A thesis  
submitted in partial fulfilment  
of the requirements for the degree of

Master of Science (Research) in Earth Sciences  
at  
The University of Waikato

by

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**The University of Waikato  
Te Whare Wānanga o Waikato**

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# Abstract

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My thesis investigates soil recovery following landsliding in steep land and hill country on part of the Whatawhata Research Station, 25 km west of Hamilton, North Island, New Zealand. Underlain mainly by Mesozoic greywacke, six landslides were studied, ranging in activation time from pre-1953 to 2014. On the basis of geomorphological analysis the landslides were divided into five zones: shear zones (mean of 25 % of landslide area), intact accumulation zones (20 %), transition zones (40 %), and re-deposition zones (15 %), plus an adjacent control zone. Soil physical and chemical properties including: solum depth, A horizon depth, particle size, and soil dry bulk density, along with, soil C, N, P, and pH were determined for each zone of each landslide.

Soils were well-developed in the control and intact accumulation zones and least recovered in the shear and re-deposition zones. Mean A horizon depths ranged from 2 cm in the shear and re-deposition zones to 7 cm in the transition zones, 17 cm in the intact accumulation zones, and 20 cm in the control. Mean solum depths ranged from 24 cm in the shear zones, 91 cm in the intact accumulation zones, 72 cm in the transition zones, 90 cm in the re-deposition zones and >100 cm in the control zones.

The differences between zones within the landslides were greater than the differences between landslides. The controls had higher ( $P < 0.05$ ) C contents than any of the zones within the landslides, and the intact accumulation zones had higher ( $P < 0.05$ ) C contents than the shear, transition or re-deposition zones. Mean soil C contents ranged from 8.2 % in the controls through 5.4 % (intact accumulation zones), 4.2 % (transition zones), 3.2 % (re-deposition zones) to 2.6 % in the shear zones.

Similarly to C, the total N was higher in the controls than the other zones ( $P < 0.05$ ). Mean N content ranged from 0.2 % in the shear zones, 0.3 % in the transition and re-deposition zones, 0.5 % in the intact accumulation zones to 0.7 % in the control zones.

The C:N ratio was consistent across all zones in all six landslides and controls, ranging from 11 to 16. There were no significant differences in the C:N ratio between zones of the landslides or with landslide age.

Soil Olsen P was lower ( $P < 0.05$ ) in the shear and re-deposition zones than the control, intact accumulation, and transition zones. There were no significant differences in Olsen P between the intact accumulation, transition, and control zones. Soil pH was generally low (4.8 to 5.6) across all zones in all six landslides and soil dry bulk density was variable. Thus soil pH, dry bulk density, and Olsen P were not correlated with soil recovery and development.

Overall the shear zone occupied <25 % of the landslide area, was the slowest zone to recover, and was the least productive. The intact accumulation,

transition, and re-deposition zones generally consisted of about 75 % of the landslide area, and once stabilised were expected to be relatively productive.

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*“...a scientist must be absolutely like a child. If he sees a thing, he must say that he sees it, whether it was what he thought he was going to see or not. See first, think later, then test. But always see first. Otherwise, you will only see what you were expecting”*

*(Douglas Adams, 1952 – 2001)*



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# Chapter 1: Introduction

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## 1.1. Occurrence and impact of landsliding in New Zealand

More than 40 % of New Zealand is moderately to very steep, forming extensive hill country (~21 to 25 °) and steeplands (>~26 °) (Leathwick *et al.*, 2003). Steepland and hilly landforms are prone to slope failure resulting in landslides, particularly during periods of high rainfall which often triggers earth movement once soil water holding capacity has been reached (Crozier, 2005; De Rose, 2013). Landsliding (mass movement) results in soil materials and nutrients such as carbon (C), nitrogen (N), and phosphorus (P) being transported down-slope, leaving an exposed surface that then needs time for soil to regenerate to be productive once more (Sparling *et al.*, 2003; Heaphy *et al.*, 2014).

## 1.2. Recovery of soils following landsliding

The recovery of topsoil following erosion through landsliding is a process that takes considerable (decades to millennia) time before soil will reach equilibrium; for example, in terms of increases in organic matter (Sparling *et al.*, 2003). Field studies have been conducted on several sites in New Zealand that have measured the effects landslides have had on soil horizon development, total carbon, total nitrogen, Olsen p, soil pH, CEC, bulk density, particle density, and porosity over time (Sparling, *et al.*, 2003; Rosser & Ross, 2011; De Rose, 2013). Recovery of soil C stores will steadily increase over a 20 year period after landslide events before plateauing, returning to only ~80 % of total C and N of control levels taken from adjacent undisturbed sites representative of pre-landslide occurrence (Sparling *et al.*, 2003). The rate of soil recovery is dependent on the soil forming factors, particularly parent material. For instance, Sparling *et al.*,

(2003) and De Rose *et al.*, (1995) reported that the rate of pasture recovery following landslides on indurated sandstones was slower when compared to pasture recovery rates on softer mudstones and siltstones in the Wairarapa studied by Lambert, *et al.*, (1984).

### 1.3. Whatawhata Hill Country Research Station

The Whatawhata sheep and beef research station is located in the Waikato Region of New Zealand, west of Hamilton city in the North Island (Figure 1.1). The field area on the station comprises mainly moderately steep to steep hill country with Ultic Soils (of the New Zealand Soil Classification: Hewitt, 2010) on steep slopes over deeply weathered argillaceous greywacke rocks of Mesozoic age and Allophanic Soils (Hewitt, 2010) on Quaternary tephra deposits on the moderately sloping areas (Bruce, 1978).

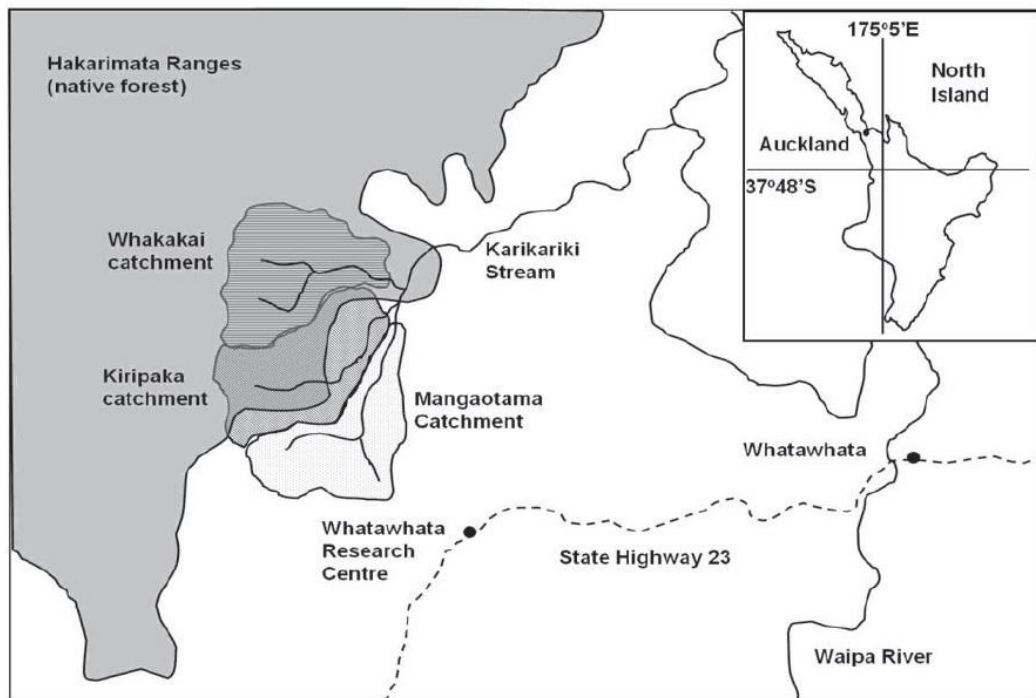


Figure 1.1: Location map of study site (Source: Dodd *et al.*, 2008a).

The Whatawhata Research Station was established in 1949 to study agricultural issues including soil survey and pasture production, fertiliser application rates, animal production, and stream ecology (Dodd, *et al.* 2008a).

The hills throughout the Whatawhata Research Station were deforested to establish pastoral agriculture. Forest clearance has likely contributed to an increase in landslide events. One landslide event that occurred in 1995 at the Whatawhata Research Station in the Mangaotama Catchment was documented in 1996 and in this study I revisit that landslide and investigate others in the area to determine the rates of soil recovery at each landslide site.

## **1.4. Research objectives**

The overall aim of my thesis was to improve the understanding of soil recovery following landslides. My hypothesis was that topsoil will have increased in depth and organic matter with time since disturbance, and that soils on more gently sloping landslide areas will show greater recovery than those on steeper slopes.

The specific objectives of my research were to:

- Map and identify landslides on the Whatawhata Research Station farm and then choose landslides to research in-depth based on geomorphology, age, and soil characteristics.
- Develop geomorphic maps of selected landslides.
- Determine topsoil depth, colour, horizon development, and C, P, and N content in each geomorphic zone within each of the chosen landslides and a control for each.
- Develop a chronosequence of the C and P content using landslides of varying ages to determine how well soil is recovering following

landslide events and relate the findings to previous studies from New Zealand.

## **1.5. Thesis structure**

Chapter 2 reviews literature that has discussed hillslope mass movement and its occurrence, soil and pasture recovery following landslides in New Zealand, the chemical properties of soil, and the impacts have on the environment.

Chapter 3 discusses the full methods used to conduct the field and laboratory work for my thesis.

Chapter 4 presents the field results of the study; including site descriptions, the history and land use of the Whatawhata Research Station, the main soils found at the Whatawhata Research Station, landslide geomorphology, and the individual landslides themselves.

Chapter 5 presents the laboratory results obtained from analysis of the soil samples collected from each landslide zone.

Chapter 6 discusses the results from the field and laboratory analyses, addressing the hypothesis, and the potential for further research. Finally, summaries and conclusions are presented.

Appendix A contains a paper accepted for publication in the proceedings of the 2016 Beef + Lamb Hill Country Symposium, by A. M. Noyes, M.R. Balks, V.G. Moon, and D.J. Lowe.

Appendix B contains raw data regarding auger holes, field descriptions, sampling transects, and soil dry bulk density measurements for each landslide.

Appendix C contains raw data from C, N, P, pH, particle size, landslide zone proportions, mean dry bulk density data and statistical analyses.

## Chapter 2: Literature review

---

### 2.1. Introduction

Much of New Zealand was formed through tectonic uplift of sedimentary rocks and volcanism which, along with generally fast rates of erosion and deposition, have created considerable areas of steepland and hill country (Basher, 2013). Many hill slopes prior to human settlement were covered in native forest, some of which was cleared by early Polynesians (Maori) and then by European settlers for agricultural purposes (Farrelly, 1986). The clearing of forest vegetation on steep hill country left hill slopes more vulnerable to erosion and landsliding. Landslides may be triggered by periods of heavy rainfall and earthquakes (Crozier, 2005; Basher, 2013). During hill slope mass movement, large quantities of topsoils and subsoils may be lost, rendering the landslide scar unproductive for an extended period of time. Soil nutrients are important factors in soil development and productivity (McLaren & Cameron, 1996; McBratney, *et al.*, 2014). Past research carried out in New Zealand on landslides, as part of a national programme to investigate pasture productivity following erosion events in New Zealand hill country, has shown that pasture will take between about 20 and 40 years to reach uneroded levels (DeRose, *et al.*, 1995; Rosser & Ross, 2011). Although soil samples taken from within landslide scars initially had lower nutrients and carbon (C) levels compared to those of undisturbed control sites, the physical and chemical soil properties took between 18 to 80 years to recover to about 80 % of levels recorded in undisturbed soil, with total C taking on average 45 years and microbial C taking 27 years to reach uneroded levels (Sparling, *et al.*, 2003).

Most New Zealand soils are nutrient poor; therefore, there is a requirement to add the missing essential elements to the soil in the form of fertiliser to maintain high productivity. P based fertilisers are used extensively on New Zealand farms to maximise pasture and crop yields, with P based fertilisers being applied predominantly to dairy and dry stock farm pasture systems (Gillingham & Thorrold, 2000). P is vital for plant growth and development (Parfitt *et al.*, 2005), whereas C is required for mineralization of nitrogen, sulphur and phosphorus as well as maintaining soil structure and stability (McBratney *et al.*, 2014). With a growing demand for food, as global population expands, the use of N and P based fertilisers has increased (Dodd *et al.*, 2012). As excess nutrients are applied to soil, there is an increased risk of negative environmental effects such as nutrient leaching into local water bodies resulting in eutrophication (Loganathan *et al.*, 2001; Schipper *et al.*, 2011).

The chapter reviews soil development in erosion scars following landsliding, covering soil chemical and physical properties. The effect landslides have on soils and hillslopes, the role soil C, N and P play in soil development, and how plants respond to them, and the relevant analytical methods are discussed. Environmental impacts caused by landslides such as nutrient runoff, and subsequent eutrophication of waterways are also discussed.

## **2.2. Hillslope mass movement and soil development**

### **2.2.1. Hillslope mass wasting**

Landslides occur when the stability and structure of a hillslope have been compromised which leads to increased shear stress resulting in mass wasting (Selby, 1993). Slope failure is caused by the weakening of

cohesive bonds holding the soil and rock materials in place often as a result of heavy rainfall or seismic activity. The loosened materials are then transported downslope through gravitational force to be deposited as colluvium (Selby, 1993; Crozier, 2005; Schaetzl & Anderson, 2005). In New Zealand hill country, slope failure events have often occurred in steep areas that have been deforested and converted into pasture, and such failures may occur in multiple locations within a catchment following one large storm event or earthquake (DeRose *et al.*, 1995; Crozier, 2005). The occurrence of hillslope mass wasting can then potentially lead to further erosion, which in turn leads to system productivity decline. Landslides may be economically detrimental to landowners depending on the scale and extent of damage to the landscape and the type of land use being undertaken (Reid & Page, 2002; Crozier, 2005; De Rose, 2013; Heaphy *et al.*, 2014).

Landslides transport large quantities of topsoil downslope that contain P, C, and N along with other nutrients required for productive soil and plant growth. A landslide will leave an exposed scar in the landscape that is almost completely devoid of nutrients, requiring the exposed soil to recover over time (Sparling *et al.*, 2003).

### **2.2.2. Soil regeneration after hillslope failure**

Following a landslide event, the erosion scar where soil was lost needs to recover and the rate of soil recovery is greatly influenced by soil parent material and localised factors such as climate and relief (Trustram & De Rose, 1988; Smale *et al.*, 1997; Schaetzl & Anderson, 2005). An indication of healthy soils (those which have essentially recovered from the erosion event and are now functioning to a large degree as they did pre-erosion), can be evaluated by measuring the amount of accumulated organic matter in the form of C and N (Sparling *et al.*, 2003). The rate at which soil

recovers can therefore be determined using a chronosequence (Hugget, 1998), analysing a number of landslides of varying ages by observing topsoil depths and total C and N and pasture production (Trustring & De Rose, 1988; Smale *et al.*, 1997; Sparling *et al.*, 2003).

Within New Zealand, studies have been conducted on sites that have been subject to hillslope mass wasting and soil recovery, and include for example Lambert *et al.* (1984); Sparling *et al.* (2003); Rosser & Ross, (2011); De Rose, (2013); and Parfitt *et al.* (2013). The studies were generally carried out on soft rock parent materials such as mudstones and siltstones (Sparling *et al.*, 2003; Rosser and Ross 2011). Landslides will occur on harder substrates such as greywacke (De Rose, 1995); however, documentation on soil recovery of such landslides within New Zealand is limited. The reports generally concluded that soil recovery is a slow process and the likelihood of soil recovering greater than 80 % of undisturbed controls is unlikely (Lambert, *et al.*, 1984; Sparling *et al.*, 2003; Rosser & Ross, 2011).

Sparling *et al.* (2003) found that through chronosequencing of slips that had occurred at Te Whanga station in the Wairarapa, southern North Island, soil recovery was initially rapid with organic C increasing exponentially over time before plateauing at about 80 % of that which was present before the slip. Furthermore, concluding that for the rate of soil recovery to reach that 80 % of previous undisturbed levels, it can take approximately 18 to 80 years. However, after the initial rapid recovery, during the first ~20 years, the rate slowed and there was little to no further recovery. What Sparling *et al.* (2003) inferred was that biochemical regenerating properties such as C and N accumulation within soil occurred at a rate faster than other mechanisms for soil recovery. The results of Sparling, *et al.* (2003) were comparable with other more recent

research conducted on other slip sites within New Zealand by Rosser & Ross, (2011), De Rose, (2013) and Parfitt, *et al.*, (2013). However, in some instances the degree of destruction of the landslide directly effected soil recovery, as was observed by the Rosser & Ross, (2011) study where Taranaki soil slides removed all overlying material leaving harder sandstone bedrock parent material exposed. In this case soil recovery was consequently slower than at sites with softer regolith remaining.

## **2.3. Nitrogen form and function**

### **2.3.1. The nitrogen cycle**

Nitrogen is one of the main essential nutrients required for plant growth, and it is one of the major limiting factors for pasture production (Parfitt *et al.*, 2005). The primary driver of the N cycle world wide is the agricultural industry (Bodirsky *et al.*, 2012).

There are many forms of N on Earth and within its atmosphere. In soil approximately 95 % of total N is found in soil organic matter and not readily available for use by plants. N needs to undergo N mineralisation to release the N from organic matter and into a mineral form available to plants (McLaren & Cameron, 1996). Further forms of N can be found as mineral N within soil solution, with 1 to 2 % in solution in the form of nitrate, nitrite, and ammonium with approximately 1 to 6 % of the ammonium N bound by clay minerals, such as smectites and vermiculites which protect the ammonium from nitrification (McLaren & Cameron, 1996; Mengel *et al.*, 2001). N fixation occurs by either chemical development processes or by microbes present in soil (McLaren & Cameron, 1996; Ollivier *et al.*, 2011). The N cycle (Figure 2.1) converts organic N into plant useable inorganic form such as ammonium ( $\text{NH}_4^+$ ) through the mineralisation of soil organic matter by microbes, fertiliser

inputs, and symbiotic legume fixation by rhizobia through the nitrification process  $\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$  (McLaren & Cameron, 1996; Lupwayi *et al.*, 2006). Nitrate ( $\text{NO}_3^-$ ) whilst useable by plants, if in excess in the soil solution, is at risk of leaching through the soil profile (Di & Cameron, 2002). Through the denitrification process, N may be lost from the system through volatilisation into gasses such as molecular nitrogen ( $\text{N}_2$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and ammonia ( $\text{NH}_3$ ) (McLaren & Cameron, 1996).

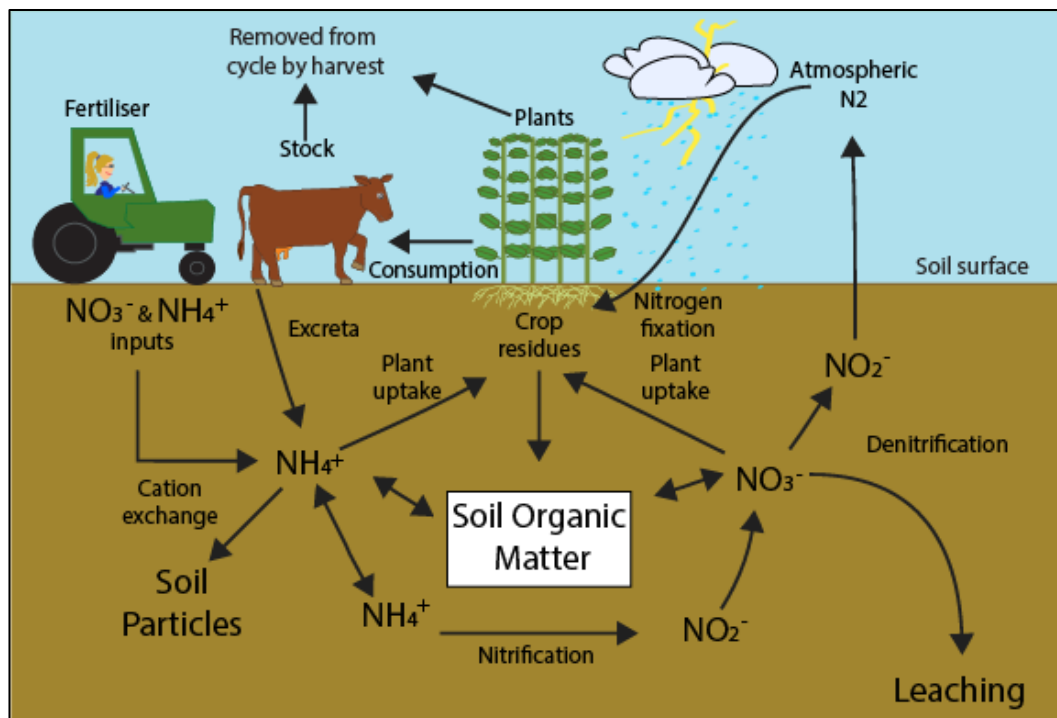


Figure 2.1: The agricultural nitrogen cycle (adapted from McLaren & Cameron, 1996).

### 2.3.2. Plant available nitrogen – uses and deficiency

N is an essential element required for plant growth and photosynthesis (Chapin *et al.*, 1987; McLaren & Cameron, 1996; Lupwayi *et al.*, 2006), N is taken up by plants in the form of  $\text{NH}_4^+$  or  $\text{NO}_3^-$ . Once nitrate is taken up by the plant it is reduced to  $\text{NH}_3$  and then converted into useable low molecular weight amino acids and high molecular weight proteins and nucleic acids (McLaren & Cameron, 1996). Plants need large quantities of

N, with the greatest quantities of N taken up and used by plants during their early growth stages, holding between 1 to 6 % of N within dry weight depending on plant variety and growing environment (Chapin *et al.*, 1987, McLaren & Cameron, 1996). When plants are not receiving enough N they hydrolyse older leaves which breaks down chloroplasts, causing leaf yellowing, necrosis, and abscission. Plants with N deficiency have diminished shoot and root growth in favour of early maturation (McLaren & Cameron, 1996; Raven *et al.*, 2003).

The application of P based fertilisers to pastures aides in the intensification of legumes such as white clover (*Trifolium repens*) which allows an increase of N fixation through the symbiotic mycorrhizal relationship existing between rhizobia and plant root (Edmeades *et al.*, 1984; Lupwayi *et al.*, 2006)

## **2.4. Carbon form and function**

### **2.4.1. Carbon function within soil**

Total C is the measureable quantity of soil organic matter found in detritus, root exudates, and soil biota. Soil organic carbon is beneficial for plant growth and productivity as well as soil fertility, structure and stability of aggregates. By maintaining soil structure, organic carbon aids in the reducing soil erodibility and increasing the soils ability to store water. Organic carbon is also an important factor in nutrient cycling and overall soil condition (McBratney *et al.*, 2014).

### **2.4.2. Organic matter and soil formation**

Soil organic matter losses or gains from soil are primarily controlled by the balance of inputs and outputs (Schipper *et al.*, 2010). Inputs into soil by way of re-deposition of organic C, translocation of photosynthates through the phloem of plant roots and shoots, along with the rate of decay

of the organic matter; and outputs from soil by way of product export, erosion, and microbial respiration (Batjes, 1996; Schipper *et al.*, 2010).

As plant detritus accumulate on the soil surface it is altered through interactions with soil organisms, in particular meso-fauna such as earthworms and nematodes, and micro-organisms such as bacteria, fungi, and protozoa (McLaren & Cameron, 1996). Such soil organisms are responsible for the mineralisation of organic matter and humus formation (Batjes, 1996). The organic content increases as soils develop. The rate in which soil formation occurs and the organic matter accumulates depends on variations of the factors of; climate, soil acidity, soil drainage, parent materials, and human activity (McLaren & Cameron, 1996).

### **2.4.3. Carbon sink and land use management**

Carbon in soil is the largest terrestrial global sink, holding in the top one metre of soil 2000 Pg of C, a quantity more than double that held in the atmosphere (750 Pg) and threefold larger than in above-ground biomass (500 Pg) (Kutsch *et al.*, 2009; Barnett *et al.*, 2013; McBratney *et al.*, 2014). Since the early 2000s the interest in soil organic carbon (SOC) has grown exponentially, largely related to SOC's potential for reducing climate change through acting as a net sink for greenhouse gases through carbon sequestration in soil (McBratney *et al.*, 2014). Carbon sequestration in soil is the act of removing carbon dioxide (CO<sub>2</sub>) from the atmosphere by way of transfer into soil organic matter (SOM) thereby reducing accumulation of atmospheric CO<sub>2</sub> (McBratney *et al.*, 2014).

However, land use and land management practices influence the rate at which organic matter and SOC accumulate or decrease in soils (Schipper *et al.*, 2010). As a result of the clearance of indigenous forest in New Zealand by the early Polynesians and European settlers, an estimated 3.4 Pg of C

was lost from the soil systems (Tate *et al.*, 2005). The cleared areas were then used for grazing of beef and sheep, which re-introduced small quantities of SOC back into the systems; however, as discussed the land clearance can leave the soils vulnerable to erosion and thus continued losses of topsoil and SOC (De Rose *et al.*, 1995; Crozier, 2005; Tate *et al.*, 2005).

## 2.5. Phosphorus

### 2.5.1. The phosphorus cycle

The process of P cycling occurs in soil through mineralization and immobilization of P working simultaneously. The cycling of P, and P distribution in soil, therefore relies on chemical and physical mechanisms (Figure 2.2). The P cycle lacks a gaseous phase and thus cycles more slowly than nitrogen. The mechanisms for P cycling are driven by plant uptake, microbial activity, mycorrhizal relationships and colloidal sorption of P (Stewart & Tiessen, 1987).

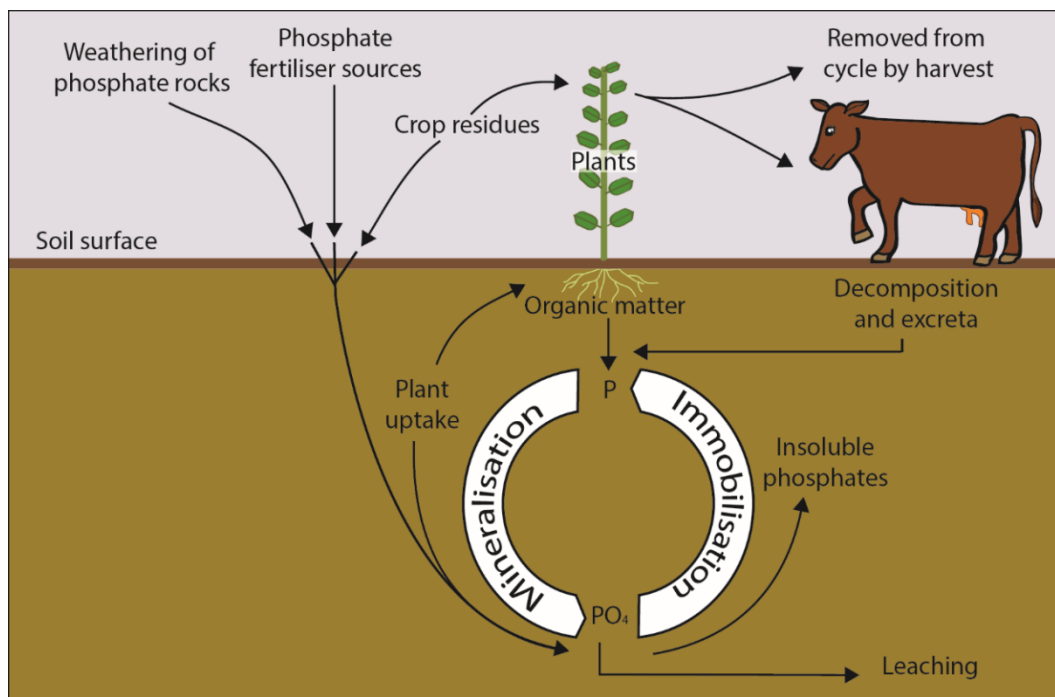


Figure 2.2: The phosphorus cycle (Adapted from Marston, 1989).

Phosphorus ions in soil can be in one of three states during soil development. The states range from primary ( $\text{H}_2\text{PO}_4^-$ ) dihydrogen phosphate, secondary ( $\text{HPO}_4^{2-}$ ) mono-hydrogen phosphate, and the tertiary ( $\text{PO}_4^{3-}$ ) orthophosphate form (McLaren & Cameron, 1996). Plant available P is readily accessible in the primary and secondary states. The combined organic and inorganic states are considered to be labile within soil, meaning they are easily moved into soil solution through mineralisation. However secondary state ions are taken up at a slower rate than  $\text{H}_2\text{PO}_4^-$ . The form of P present is determined by the acidity of the soil. Acidic soils will generally have primary state P dominated by  $\text{H}^+$  ions, whilst alkaline soils will tend to have P in its secondary state dominated by  $\text{OH}^-$  anions (Pierzynski *et al.*, 1994; McLaren & Cameron, 1996).

### **2.5.2. Plant requirements and use of phosphorus**

Phosphorus is one of two main nutrients required for plant growth. As discussed in section 2.3.1, the first is N and secondly P, in the form of inorganic P (Parfitt *et al.*, 2005). Plants will take up P from soil solution through the roots. Once taken up by plants, P is used as an energy source and structural components of macromolecular cells (Duff *et al.*, 1994). Phosphorus is found largely in nucleic acid in plant cells, the nucleic acid being a constituent of DNA and RNA. Plants convert absorbed inorganic P to organic P to be used within plant cells as building blocks required for cell formation during growth. P is found in high quantities in meristems where growth is concentrated (Marschner, 2008).

Phosphorus availability for plants is impacted by a number of factors such as soil age, fertility, and degradation through weathering processes (Parfitt *et al.*, 2005), along with fertiliser inputs. Inorganic phosphate ions predominantly account for plant available P in soil solution; it is unclear

how much organic P is readily available to plants (McLaren & Cameron, 1996).

### **2.5.3. Organic phosphorus**

Organic P is phosphorus that is held bound in organic matter derived from plant matter, animal wastes and microbes, and can account for between 20 and 80 % of total phosphorus in soil depending on stages of soil development (McLaren & Cameron, 1996; Condrón, 2005). As plants take up and use P it may be lost from the system by crop harvest or returned through plant death in the form of detritus or through animal excreta (Pierzynski *et al.*, 1994). Organic P turnover is determined by mineralisation and immobilisation rates. Mineralisation is responsible for the conversion of organic P to the plant useable form, inorganic P ( $\text{PO}_4$ ). Inorganic P is taken up by plants and then returned to the soil as organic P which is derived from plant detritus and animal excreta (Condrón, 2005). Organic P is not directly available to plants for uptake. For organic P to be used by plants it must undergo mineralisation so that the P ions are released from the organic matter and may be taken up from soil solution by plants (Messiga *et al.*, 2014). When phosphates are in their organic form, for example, in the form of phosphate rock, detritus or excrement, P undergoes the mineralisation process converting organic P into inorganic P by weathering of soil parent material through processes that are dependent largely on climate and soil pH (McLaren & Cameron, 1996).

### **2.5.4. Inorganic phosphorus**

Inorganic P is readily available to plants for uptake in soil, and contributes to 50 to 70 % of total P (Pierzynski *et al.*, 1994). In moderate to non-weathered soils, P is predominantly bound up in calcium, phosphates, iron, or aluminium phosphates (McLaren & Cameron, 1996). The

inorganic P becomes available in soil solution through weathering of soil parent material following mineralisation of organic P (McLaren & Cameron, 1996). As the inorganic P becomes freely accessible the P ions are then available to bind and form hydrous oxide minerals as P ions combine with soluble forms of iron and aluminium (McLaren & Cameron, 1996). Weathering of calcium phosphate parent materials leads to calcium leaching into soil solution and thereby lowers the pH of the soil. Such weathering of soil minerals allows ions to become immobilised, doing so by entering solution and binding with soluble iron and aluminium. Hydrous oxide minerals such as ferrihydrite form from binding with iron, and allophane from binding with aluminium. The newly formed hydrous oxides become insoluble, locking away the P, rendering it unavailable for plants (McLaren & Cameron, 1996). However, the binding with aluminium or iron is solely dependent on the acidity of the soil. Too low an acidity, hydrous oxides occur while high pHs will cause the inhibition of Ca both leading to the unavailability of P, thus there is a narrow potential for inorganic P to be available for plant uptake at rates of pH 4.5 to 7.5 (Figure 2.4) (Pierzynski *et al.*, 1994).

### **2.5.5. Phosphate retention**

Phosphate retention occurs when labile P is converted into non-labile P through interaction with soluble iron and aluminium minerals (Saunders, 1965; McLaren & Cameron, 1996). In New Zealand, P retention is largely related indirectly to soil parent material through its mineralogical and chemical composition after weathering (Saunders, 1965). Many soils in the North Island of New Zealand are derived from tephra and are classed as Allophanic Soils (Hewitt, 2010), especially within the Waikato, western Bay of Plenty, and Taranaki regions (Figure 2.3). These soils have high P

retention, thus limiting P availability and thereby limiting plant uptake of P (Saunders, 1965).

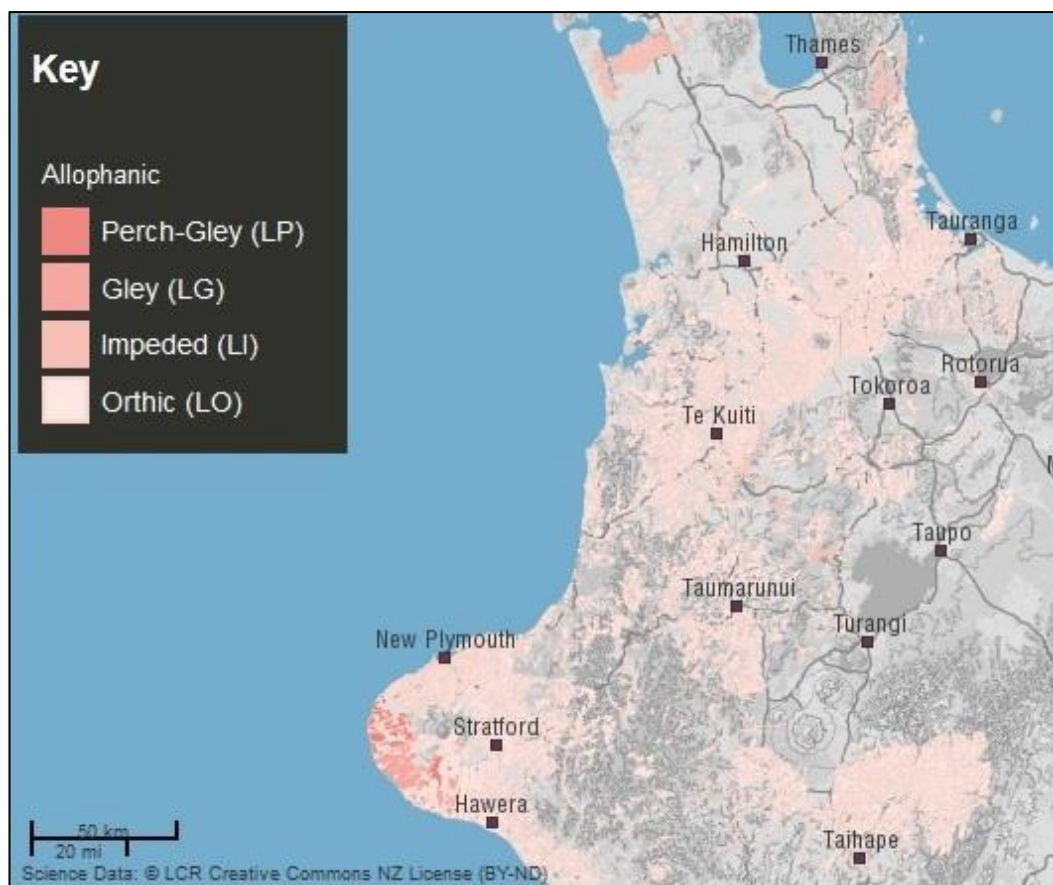


Figure 2.3: Allophane distribution within New Zealand. Image adapted from Landcare Research (2014).

The reversion of non-labile to labile P is a slow process and in the case of allophanic soils relatively irreversible; however, Saunders (1965) showed that in laboratory studies that there are variations in subsoil and topsoils in relation to P retention. The study concluded that increasing organic matter containing tartrate, citrate and oxalates reduced P retention caused by aluminium and iron hydrous oxides at least in the case of the laboratory trials.

### 2.5.6. Means of testing soil phosphorus

There are a number of techniques used to extract and measure P from soil samples depending on soil composition and pH (Messiga *et al.*, 2014). Tests such as extraction methods including Bray P, Mehlich-3, and Olsen P tests are evaluated colorimetrically after dry soil samples are combined with their required solutions for a set time and centrifuged (Ebeling *et al.*, 2006). As it is widely used in New Zealand (and in this thesis), the Olsen P test is discussed in more detail.

#### *a) Olsen P – measurement and use*

The Olsen P test was developed in 1954 and was designed specifically to test alkaline soils (Watson & Mullen, 2007). Olsen P testing uses an extraction solution of 0.5M sodium bicarbonate ( $\text{NaHCO}_3$ ) and a component that calibrates the soil to a pH 8.5 and centrifuging for 30 minutes, colorimetric analysis is then carried out to determine P quantities within the soil sample (Saunders, 1987; McLaren & Cameron, 1996; Sagger *et al.*, 1999). While readily used as a method of soil analysis, the Olsen P test has limitations as it was designed to measure plant available phosphorus in alkaline soils. The Olsen P test will, therefore, often underestimate P in soils that have been recently limed and overestimate P content in acid soils (Saunders, 1987). The over, or under, estimation of P is due to the extraction method accounting for inorganic P available to plants and does not take into account organic P within the soil as well as the  $\text{NaHCO}_3$  being unable to completely dissolve phosphate rock during extraction which would occur naturally during the P cycle (Sagger *et al.*, 1999). The Olsen P method has proven to be adequate for most New Zealand soils for determining plant available inorganic P. The method forecasts well for fertiliser requirements in crop and pasture respectively and when used in conjunction with the P retention test it is adequate

enough for farmers needs for understanding how much plant available P there is within their soils for maximum yields (McLaren & Cameron, 1996).

## **2.6. Carbon interactions with nitrogen and phosphorus**

### **2.6.1. C:N ratio**

Depending on plant species, their growth stage and soil nutrient health the C:N ratio of plants can vary substantially, ranging from 20:1 to 100:1, conversely the C:N ratio of soil biomass is lower and relatively stable with ratios between 4:1 and 9:1 (McLaren & Cameron, 1996). The C:N ratio may be used to determine the decomposition rate and quality of organic matter within soil, along with indicating the amount of N a soil can accommodate before reaching maximum capacity (Batjes, 1996; Schipper *et al.*, 2004). Globally the mean average C:N ratio of topsoil is rarely less than ~10 or exceeding ~30 (Batjes, 1996). Differences in land use may often influence the C:N ratio of soil. Wilson *et al.*, (2011) deduced that topsoil biomass displayed the greatest differences in the C:N ratio in their study conducted on varying sites in New South Wales, Australia. Finding that the highest C:N ratios were located in woodland soils, under pasture the ratio was lower, with cultivated cropland soil having the lowest C:N ratio and total C and N. However, with increasing use of N fertilisers and N fixing legumes pastures are seeing a decline in the C:N ratio as N accumulates in the soil (Schipper *et al.*, 2004). New Zealand pasture soils have C:N ratios of approximately 11.5 with forested areas having C:N ratios of about 16 (Schipper *et al.*, 2004). Following landslides the C:N ratio recovers at the fastest rate recovering to 90 % of undisturbed soils within five years (Sparling *et al.*, 2003).

### **2.6.2. Phosphorus and carbon interaction**

The interaction between organic P and organic C is vital for fertile soils, and the productivity of the interactions between organic P and C are depends on a number of factors that include soil type, vegetation, land use and management along with environmental impacts (Condrón, 2005). In relatively untouched environs the interactions between organic P and organic C are limited but as a result of the nature of P in both inorganic and organic forms the cycle continues slowly allowing plants to grow at their own pace. It was not until the introduction of intensive farming and the increase in food requirements globally that that need for P began to have an impact on farm management (Condrón, 2005; Dodd *et al.*, 2012). In managed environments the addition of P based fertilisers influence the dynamics of inorganic P and organic P by way of amount and accumulation within soil systems. Therefore the P:C ratio is highly variable between ecosystems especially when compared with the carbon to nitrogen or sulphur ratios (Condrón, 2005). Although both sulphur and nitrogen in most part are bound with C and react through biological means during soil development, organic P reaction with organic C occurs through biochemical mineralisation (Condrón, 2005).

## **2.7. General soil properties**

### **2.7.1. Soil acidity and alkalinity**

The measure of the acidity of soil is measured using the pH scale and relates to the balance concentration of hydrogen ions (H<sup>+</sup>) and hydroxyl ions (OH<sup>-</sup>) within soil solution (McLaren & Cameron, 1996) and may be expressed by the following equation:

$$\text{pH} = -\log_{10}[\text{H}^+]$$

*Equ: 2.1*

where  $[H^+]$  equates to the concentration of  $H^+$  ions in moles  $l^{-1}$ .

When  $H^+$  concentrations exceed that of  $OH^-$  ions the soil is regarded as acidic ( $pH < 7.0$ ), when  $OH^-$  concentrations exceed  $H^+$  ions the soil is regarded as alkaline ( $pH > 7.0$ ), when both ion concentrations are in equilibrium the soil is neutral (7.0) (McLaren & Cameron, 1996). For a variety of plants to effectively use P and N the soil needs to be between  $\sim pH$  5.5 to 7.5 (Figure 2.4), for example white clover requires soil to be pH 5.6 to 7.0 and ryegrass pH 5.5 to 6.5 (McLaren & Cameron, 1996). Soil acidity affects both P and N availability. In soils that are too acidic, some microbial activity slows limiting N mineralisation and P is immobilised by Fe and Al minerals, if soil is too alkaline P is bound up with Ca reducing plant availability (McLaren & Cameron, 1996).

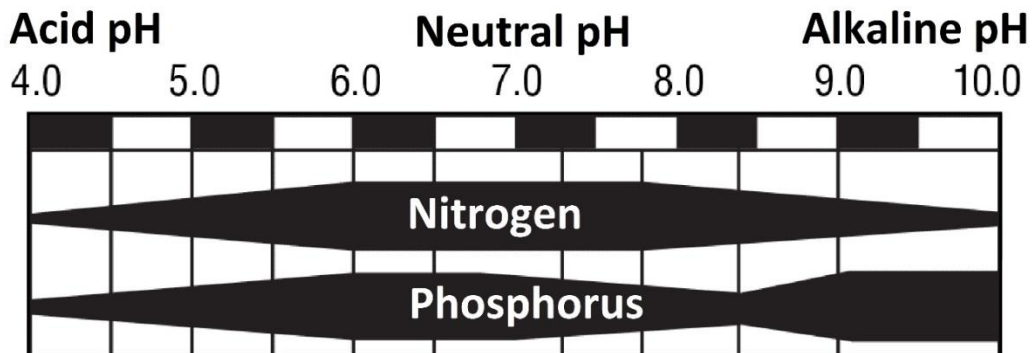


Figure 2.4: Nitrogen and phosphorus pH optimums for plant availability (adapted from: *Better Ground*, 2015).

### 2.7.2. Soil bulk density

Soil dry bulk density is the proportion of dry soil per total soil volume expressed in  $g^{-1} cm^3$  (McLaren & Cameron, 1996). Bulk density is expressed in this manner as it takes into consideration the inherent factors within the volume of soil including pore space, organic matter, water and air, thus is used to quantify compaction of soil (da Silva *et al.*, 1997). Soil

compaction has a negative effect on the soil's abilities for water retention and infiltration capacities along with plant rooting depth and nutrient delivery systems (Rawls, 1983). The bulk density of a healthy soil varies considerably depending on soil texture (Håkansson & Lipiec, 2000). For example, a high sand content soil that naturally has lower permeability and porosity will have a greater bulk density than a silty or clayey soil. However, considerations need to be taken into account such as soil productivity, aggregation and soil depth. As soil depth increases, soil aggregation and organic matter decreases, thus increases in bulk density are observed with depth. Directly related to soil bulk density are water-filled pore space and porosity. If a soil's ability to hold water exceeds field moist conditions the soil begins to become anaerobic. Under anaerobic conditions soil respiration ceases and denitrification occurs releasing  $N_2O$  gas into the atmosphere (USDA, Accessed May, 2015).

### **2.7.3. Particle size**

Soil particle size relates to the size of 'primary' (i.e. not aggregated) grains in soil. Sand is classified as 0.2 to 0.05 mm, silt 0.05 to 0.002 mm and clay particles at <0.002 mm (using the international scale). The particle size analysis then may be used to determine the fractions of sand, silt and clay within a soil, enabling a soil texture to be attained (Figure 2.5).

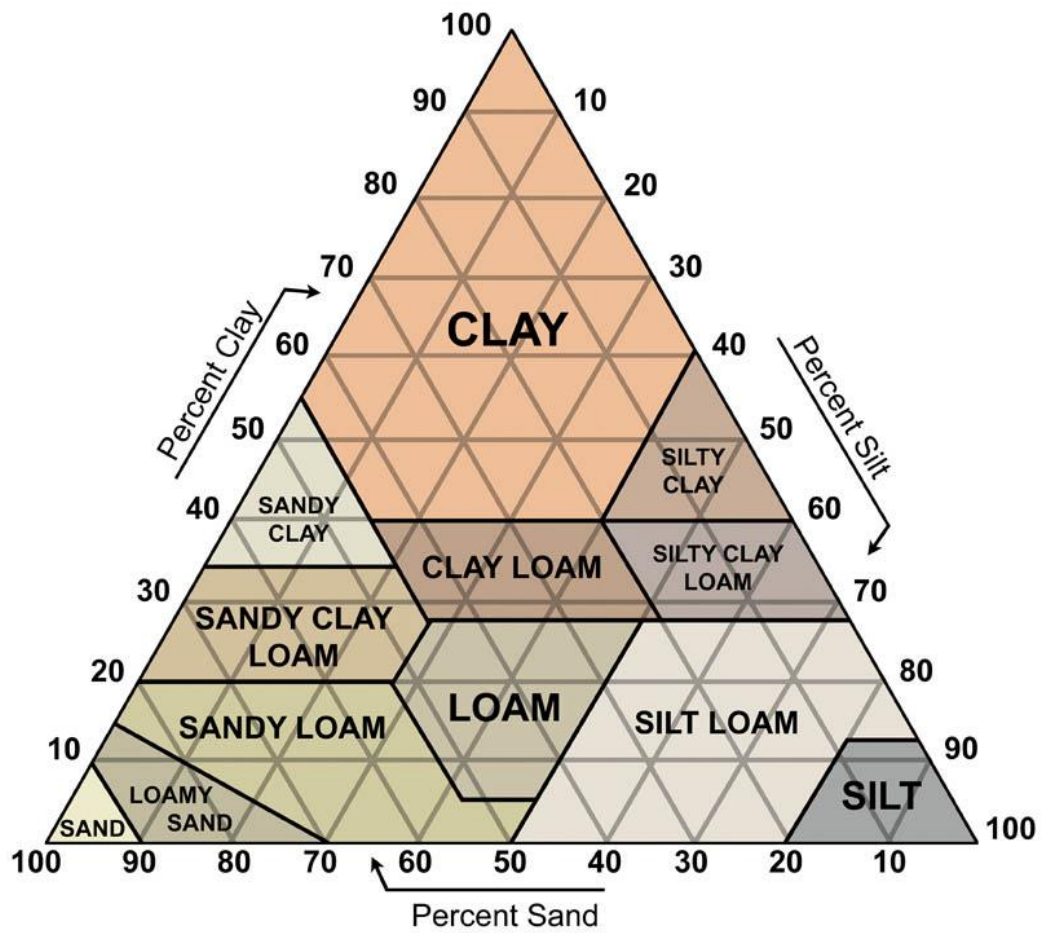


Figure 2.5: Sand, silt, clay textural triangle (Source: SoilSensor.com, 2015).

## **2.8. Environmental concern**

### **2.8.1. Soil management practices**

A number of studies have been conducted on soil management, cultivation, tillage versus non-tillage, stocking rate and differences between dry and dairy stock and how the differences in land-use influence soil structure and nutrient availability. Many studies have concluded that intensive cultivation and stocking degrade soil integrity (Urioste *et al.*, 2006; Kimble, 2007; Barnett *et al.*, 2013). However, with better management practices such as using low tillage and agronomy residue applications, soil structure is maintained and soil C levels will increase, as well as lowering CO<sub>2</sub> emissions (Smith *et al.*, 2008)

### **2.8.2. Environmental concerns**

As the global population continues to grow there is an increasing need for food. For efficient plant growth and crop sustainability and output the plants require nutrients such as P and N and others. As the need for sustainable food and nutrients grow the finite resource of rock P declines, therefore better management practices need to be implemented to ensure both viable food production and resource protection (Dodd *et al.*, 2012). Along with depletion of a finite resource there are several environmental concerns related to P, such as leaching, run-off, and eutrophication of waterways as well as accumulation of other elements in soil that are associated with phosphate fertilisers such as cadmium, uranium and fluoride (Loganathan *et al.*, 2001; Schipper *et al.*, 2011).

### **2.8.3. Eutrophication of water ways**

Eutrophication of water ways through the leaching and runoff of excess N and P lead to potential problems. The excess nutrients then increase the growth of autotrophic organisms, particularly cyanobacteria and algae. With the increased populations of autotrophic communities there is an

increase of respiration rates which put strain on aquatic ecosystems forming anoxic zones. The anoxic zones increasing in size as the waterways are deoxygenated, eventually resulting in faunal death (Correll, 1998; Turner, 2005).

#### **2.8.4. Accumulation of elements related to long-term P fertiliser use**

The main source of P for phosphate fertilisers is rock phosphate. Consequently it will be bound with trace elements and metals such as cadmium, fluorine, and uranium (Schipper *et al.*, 2011). The trace elements remain in soil and potentially increase levels of toxicity as they accumulate through long-term application of P based fertilisers.

## 2.9. Summary and conclusions

Hillslope mass movement transports large quantities of soil from the faces of hills that are structurally unstable. The mass wasting landslides in New Zealand are particularly prevalent on areas (especially of Tertiary mudstones) that have been deforested and converted into pastures for livestock farming, often triggered by high rainfall events when soils become saturated. Topsoil and subsoil materials, along with nutrients including P, N, and C, are transported downslope leaving a scar in the landscape. The scar site then has to recover to become a functioning soil for productive pasture growth. Research conducted in New Zealand on the regeneration of soil following landslide events show that soil recovery occurs largely through biochemical mechanisms, particularly through C and N increases. The research also concluding that soil recovery following landslides is initially rapid in the first several years, generally slowing after a period of greater than 20 years, and after approximately 60 years the soil will not recover further. What was also observed from the studies was that soil recovery following landslides will rarely reach 80 % of surrounding undisturbed soil levels.

Phosphorus and nitrogen are important elements required to maintain plant growth whilst carbon is needed to maintain soil structure. All three are important factors for a healthy fertile soil. P and N both are present in both inorganic and organic forms, organic P being largely unavailable to plants while inorganic P and mineralised N are readily available to plants between pH ~5.5 to 7.5. Excessive use of fertilisers used for agricultural purposes can lead to losses of P and N into waterways particularly following landslides and losses of topsoil into streams and rivers, and thus cause eutrophication of water bodies along with being potentially toxic to animals from the additional elements found in fertilisers including

cadmium. During hillslope mass wasting there is potential for accumulated toxins found in some fertilisers, for example uranium and cadmium, to become localised and cause exacerbated environmental concerns after deposition.



## Chapter 3: Methods

### 3.1. Introduction

Chapter 3 describes methods used for the field survey and laboratory analyses to measure general soil properties and plant available phosphorus, carbon, and nitrogen.

### 3.2. Field survey methods

Field surveying was conducted from of December 2014 to May 2015. Landslides were initially located using aerial photographs from AgResearch archives and Google Earth to determine areas where there were exposed soil sites and potentially mass wasting erosion. The dates of landslides were determined from the aerial photographs creating a 60-year chronosequence of landslide events that dated from pre-1953 to 2014. The sites were visited for ground truthing and landslides were located using GPS (Table 3.1).

*Table 3.1: Approximate years of landslide activation, determined through aerial photography and ground surveys.*

Landslide No.	GPS	Date									
		1953	1979	1993	1998	2004	2008	2009	2012	2013	2014
1	S37°47'14.99" E175° 4'6.49"	✓	V	V	V	V	V	V	P	V	V
2	S37°47'16.47" E175° 4'5.09"	?	✓	?	✓	V	✓	B	B	X	✓
3	S37°47'16.94" E175° 4'3.73"	✓	B	V	V	V	V	V	V	V	V
4	S37°47'17.50" E175° 4'2.40"	V	V	V	V	V	✓	B	V	V	V
5	S37°47'19.81" E175° 4'0.64"	✓	?	V	V	V	✓	B	V	V	✓
6	S37°47'7.27" E175° 4'3.24"	V	✓	P	✓	B	V	✓	V	V	V

*Key to table*

V – Vegetated – no bare soil	✓ – Landslide event	P – Probable new movement
? – Possible erosion - photo too grainy to tell	B – Bare ground	

Following initial reconnaissance survey, 16 potential landslides sites were identified for further study. From the initial 16 landslides, six were then chosen to sample, based on their morphology, dates of activation and

location. The landslide soils were investigated using a Dutch auger to determine soil horizonation, solum depth (i.e. depth of soil to the base of the B horizons) and key characteristics including soil texture, and colour to determine soil type. Full soil profile descriptions were made for the three soil variants observed in the field area across all six landslides. The main soil types were Kaawa hill soil, Waingaro steeppland soils and Dunmore hill soils.

Each landslide area was divided into five zones: shear zone, transitional zone, intact accumulation zone, re-deposition zone, and control zone. Zones were determined by geomorphological assessment of visual characteristics and physical position in the erosion scar.

### **3.3. Soil sample collection methods**

Soil samples were collected in June 2015. Two bulked samples were collected from each zone of each landslide using a 2.5 cm diameter bucket core sampler (Figure 3.1).



Figure 3.1: Soil samples were collected by using a bucket core sampler (February, 2016).

Each sample consisted of 10 to 12, 10-cm-long cores along a transect at about one metre intervals in each of the five zones within each landslide area. The direction of sampling along each transect depended on the shape and size of the zone. Control zones taken from side ridges to the right of each slide (except Landslide 1 where sampling was undertaken from the left ridge) were divided into two for their samples, a top control and a bottom control, to capture any variation possibly resulting from the previous fertiliser trials (Gillingham *et al.* 1990). The resulting samples then totalled to 10 samples per slide giving a total of 60 samples for soil analysis. Landslide 3 has only three of the zones (no intact accumulation zone) and so two extra samples were collected, one from the head scarp

and one from the transitional zones. Three bulk density cores were taken in each zone of each landslide by removing the plant surface matter and then hammering the 5-cm deep cores into the topsoil.

### 3.4. Laboratory analysis methods

The soil samples collected were used to measure

- ❖ soil dry bulk density, particle density and particle size
- ❖ soil pH and electrical conductivity
- ❖ Olsen P
- ❖ total C and N

#### 3.4.1. Soil preparation

As soil samples were collected they were crumbled inside their labelled bags to combine the cores and then emptied into labelled aluminium tins for air drying (Figure 3.2).



Figure 3.2: Soil samples drying in aluminium tins for analysis (July 2015).

The plant stems and roots were removed as samples dried. Once air dried the samples were passed through a 2 mm sieve. Because of the high clay

content the soil had to be crushed to allow sieving to take place (Figure 3.3). During sieving further organic matter was removed by hand and the samples were then weighed and bagged.



Figure 3.3: a) Crushing soil aggregates in metal tins. b) Sieving soil aggregates to <2 mm size for analysis (June 2015).

### 3.4.2. Glassware preparation

To ensure that glass and plasticware were free from potential contaminants all glass and plasticware was soaked in a mix of 340 ml of 37 % hydrochloric acid with 8 L of distilled water for several hours before being rinsed with tap water and then triple rinsed with distilled water and left to air dry. The dried glass and plasticware were then stored in plastic containers to prevent contamination.

### 3.4.3. Chemical preparation for Olsen P analysis

#### *a) NaHCO<sub>3</sub> extract reagent preparation*

860 ml of distilled water was added to a 1000 ml beaker with 42 g or NaHCO<sub>3</sub>. The beaker was placed on an HPS630 Wigger hauser magnetic stirrer. A magnetic flea was placed into the beaker to aide in the NaHCO<sub>3</sub> dissolution. Once dissolved the pH of the reagent was adjusted to pH 8.5 ± 0.05 by adding 50 % sodium hydroxide one drop at a time. Once the pH was within range, 1 ml of 0.2 % superfloc was added to the solution. The

extract reagent was then transferred into two 500 ml volumetric flasks and topped up with distilled water to the line measured from the bottom of the fluids meniscus. The reagent was then transferred back to the beaker for ease of pipetting.

*b) Murphy and Riley A preparation*

Murphy and Riley A solution of 1.2 % solution of ammonium molybdate  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}\cdot 4\text{H}_2\text{O}$  was combined with 0.1 mg/ml antimony in 2.5 M  $\text{H}_2\text{SO}_4$  for Olsen P analysis, using the Blakemore et al. (1987) method where

60 g of ammonium molybdate was dissolved in 1 litres of distilled water.

1.3343 g of antimony potassium tartrate was dissolved in 250 ml of distilled water.

Both reagents were then combined in 2.5 litres of 5 M  $\text{H}_2\text{SO}_4$  and mixed thoroughly and then made up to 5 litres with distilled water and then put into dark bottles for storage.

*c) Standard phosphorus preparation*

***Stock solution ( $\mu\text{g P/ml}$ ) 500ml***

For preparation of stock P solution 0.220 g of potassium dihydrogen phosphate ( $\text{KH}_2\text{PO}_4$ ), A.R., was dissolved in distilled water and then 0.5 ml of toluene was added as a preservative and made up to 500 ml in a volumetric flask.'

***Working Stock ( $1 \mu\text{g P/ml}$ )***

To create working stock for Olsen P analysis 5 ml of stock solution was pipetted into a 500 ml volumetric flask and diluted with distilled water up to 500 ml.

### 3.4.4. Equipment calibration

#### *a) Jenway (3510) pH meter calibration*

Calibration for the Jenway (3510) pH meter was completed before each run using the equipment instructions as follows:

The pH meter was turned on at the wall and left to stabilise for 30 minutes before calibration.

To calibrate the meter the CAL button was pressed to set daily calibration. The main display on the Jenway displayed CAL1. The electrode was then immersed into a pH 7 buffer and stabilised for 10 seconds. Once stabilised the pH was recorded into a note book and the STO key pressed. The display then read CAL OK. The slope value was also shown on the display screen. The electrode was then rinsed with deionised water and blotted dry. Display then displayed CAL2. Using a pH 4 buffer the previous steps were repeated as per CAL1. A successful calibration had a slope between 75 to 100 %. The electrode was then rinsed again and retested in a new pH 7 buffer and recorded along with the temperature and slope.

For measuring samples pH the electrode was rinsed with deionised water and blotted dry between each sample being tested. When not in use the electrode was placed into storage solution.

#### *b) Spectrometer calibration*

For each run to measure the plant available Olsen P the spectrometer required calibration, as follows.

The wavelength was checked to ensure it was set at 880 nm.

The spectrometer was then zeroed with a cuvette of distilled water, and zeroed again using the 0 standard of phosphorus (distilled water). Each cuvette was gently tapped to remove any air bubbles.

The standards were run and light absorbance recorded and the data entered into a premade spreadsheet and compared with previous known standard calibrations. The  $R^2$  was checked to ensure it was higher than 0.985 and standards were linear.

### 3.4.5. Chemical analysis methods

#### *a) Phosphorus analysis: Olsen P*

Olsen P was determined following Blakemore *et al.* (1987) on all soil samples. The method was devised by Murphy and Riley in 1962 and adapted by Watanabe and Olsen (1965) who compared colorimetric samples to standards created simultaneously during the chemical processing phase of analysis. Standards were prepared to generate a calibration curve for comparison for all samples run; blanks were also run alongside samples to ensure that no contamination had occurred during the sampling process.

The Blakemore *et al.* (1987) method was as follows.

1.5 g of soil (air-dried  $\leq 2$  mm) was added to a 50 ml centrifuge tube with an extract reagent of  $\text{NaHCO}_3$  and 1 ml of 0.2 % superfloc at a pH of  $8.5 \pm 0.05$ . The pH of the reagent was adjusted to 8.5 using a 50 % sodium hydroxide solution drop by drop. The  $\text{NaHCO}_3$  extract reagent needed to be created fresh daily as a result of having a 24 hour shelf life before the solution became unsuitable for analysis.

The centrifuge tubes were shaken at 50 r.p.m. for 30 minutes (Figure 3.4).

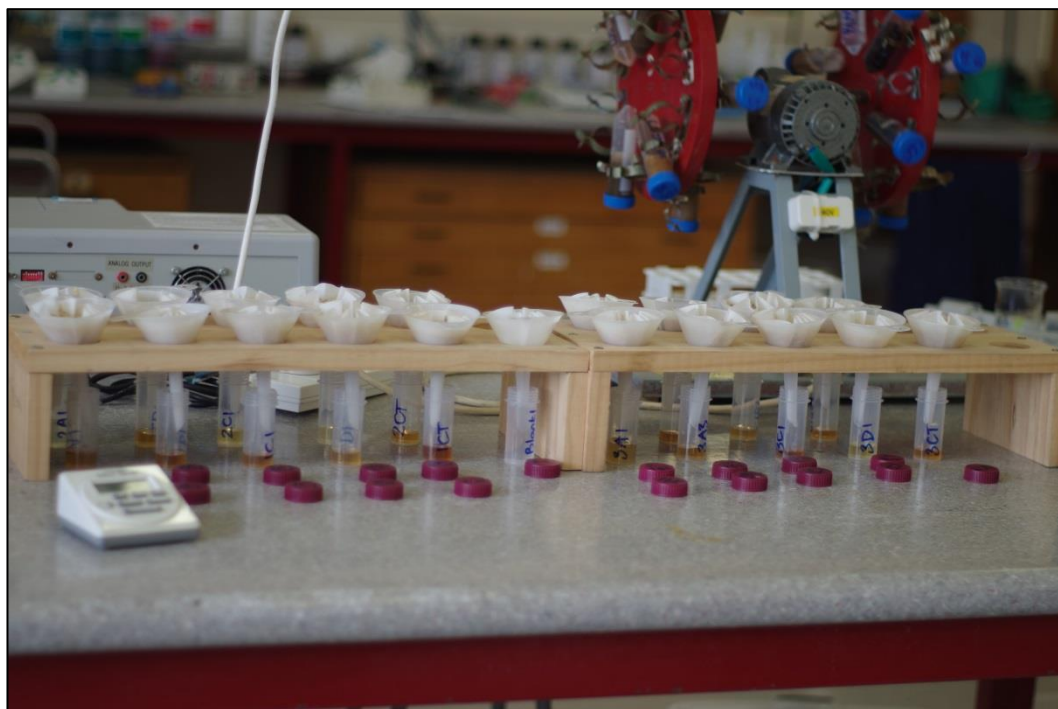


Figure 3.4: Samples being filtered in the foreground of the image; in the background on the right hand side of the image is a set of samples being shaken on a rotating machine during run 3 (September 2015).

The samples were then filtered through number 42 Whatman filter paper and 18 ml of extract collected (Figure 3.4). From the 18 ml of extract 10 ml was used for the analysis stage. For this stage, the Murphy and Riley A (M&R A) reagent was combined with 2.112 g of ascorbic acid to create M&R B. The M&R B reagent had to be made daily as it is a light sensitive chemical. 8 ml of M&R B reagent was mixed with the 10 ml of extractant and 70 ml of water in a 100 ml volumetric flask in a fumehood. Using 3 ml of 0.5 M  $\text{H}_2\text{SO}_4$  the extractant and M&R B mix pH was brought down to a range of pH 4.5 to 5.5. Each flask was then capped and inverted and degassed, the lids were then left off to prevent further gas building up in the flasks (Figure 3.5).



Figure 3.5: Samples and standards in the fumehood, as colour development was occurring during a trial run of Olsen P testing (August 2015).

The Olsen P solution was then left to stand and develop for 10 minutes; this solution remains stable for 24 hours. The solution was then pipetted into cuvettes and run through the spectrometer at 882 nm and the recorded results compared to the calibration curves created by the standards.

#### *b) Carbon and nitrogen analysis*

For an accurate measurement of C and N in soil, the dry combustion method was used. The 60 samples were ground to a fine powder to increase surface area for combustion using an agate mortar and pestle. To minimise cross contamination of samples, the mortar and pestle were wiped with a clean tissue and then rinsed in distilled water and left to air dry. Nine of the samples were selected to use as trial runs in the elemental analysis machine. The initial trial samples were selected to provide the lightest, darkest, reddest and mid-range in colour thus giving a range of the soil collected from the research station. For the initial nine samples 10 mg was weighed into aluminium cups and run through the Elementar - vario EL cube. From the data collected from the trial samples the best Xg

of soil was determined as providing optimal results from the elemental analysis machine.

Carbon and nitrogen were measured by combusting 10 to 70  $\mu\text{m}$  (paler soils requiring larger sample size) of each ground soil sample at about 900 °C using the Elementar – vario EL cube (Figure 3.6). As the soil heats  $\text{CO}_2$  and  $\text{NO}_2$  are released as a by-product and then measured. The portion of  $\text{CO}_2$  and  $\text{NO}_2$  measured was recorded as a percentage of the soil sample giving results of total soil carbon, organic carbon, and nitrogen.



Figure 3.6: Elementar analyser (Elementar - vario EL cube) (November 2014).

### 3.4.6. General soil properties

#### *a) Soil dry bulk density and field moisture content*

The dry bulk density was measured using the Gradwell & Birrell (1979) method where a core of soil was taken by pushing a metal cylinder of

known volume into the soil at each site. The cylinder containing the soil core was then wrapped in clingwrap and labelled for transportation. Once in the laboratory, the samples were levelled and any holes in the soil core that were not representative of the natural aggregation state of the soil were filled with a measurement of sand in millilitres and recorded to accurately determine the volume of soil. The sand was then gently removed from the samples to ensure that weight was not added to the soil cores from the sand. The samples were then crumbled into pre-weighed labelled tins, weighed and then placed in a 105 °C oven for 24 hours. Following the 24 hour period the samples were placed in a desiccator to cool then re-weighed and then returned to the oven for a further 24 hours. After 48 hours the samples were cooled in a desiccator and re-weighed to ensure constant mass had been achieved and the soil bulk density was determined using the following equation

$$\frac{\text{Mass of oven dried soil (g)}}{\text{Volume of cylinder (cm}^3\text{)}} = \text{Bulk density (g cm}^{-3}\text{)}$$

*Equ. 3.1*

From the weights obtained from the soil bulk density cores and the final oven dry weight the field moisture of each site was also determined:

$$\frac{\text{Mass of field moist soil (g)} - \text{Mass of oven dried soil (g)}}{\text{Mass of oven dried soil (g)}} * 100$$

*Equ. 3.2*

### *b) Soil pH*

Soil pH was measured following the Blakemore *et al.* (1987) using a soil to distilled water ratio of 1:2.5. 5 g ± 0.005 of air dry soil was weighed into labelled 30 ml plastic containers and 12.5 ml of distilled water was added. The slurry was stirred using a high speed electric mixer. Samples were then left to stand for 24 hours. After the 24 hour settling period the

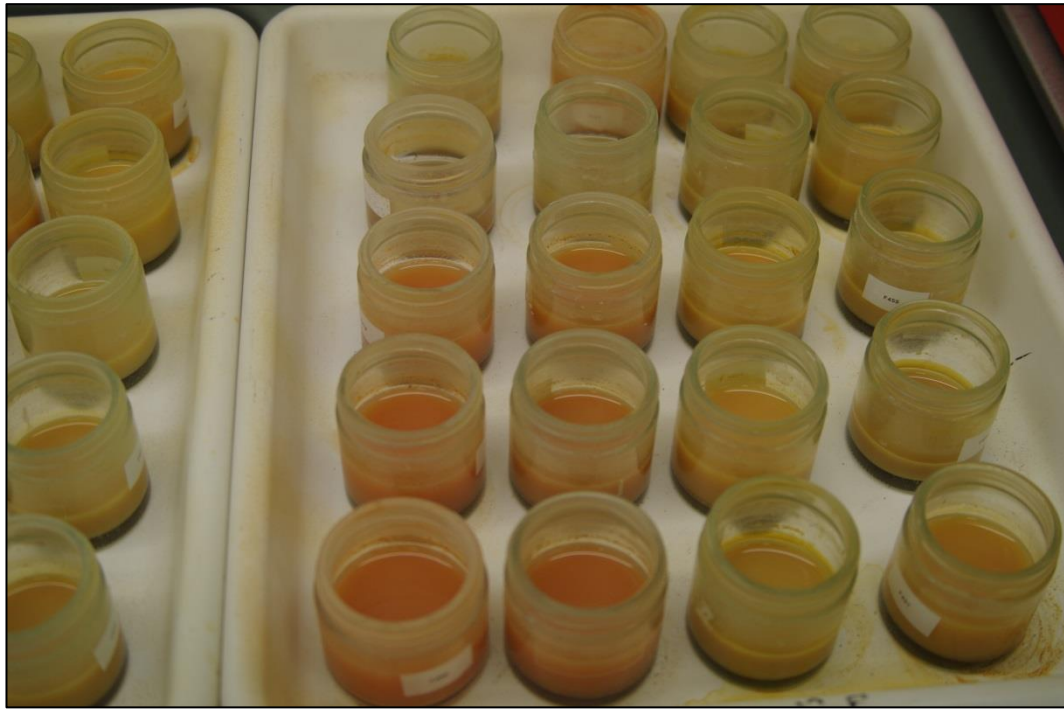
samples were tested using a pH Jenway electrode probe. The electrode probe was calibrated following the method discussed in section 3.4.4. Equipment calibration a) Jenway (3510) pH meter calibration (Figure 3.7).



Figure 3.7: Measuring soil pH following the settling period of 24 hours using the Jenway (3510) pH electrode probe.

### *c) Particle size analysis*

Particle size was determined by adding about 5 g of soil into a small glass jar, the samples were then placed in the fumehood for digestion. Each sample then had 10 to 20 ml of 30 % hydrogen peroxide solution added. The hydrogen peroxide solution was added to break down the organic matter present in the soil samples (Figure 3.8).



*Figure 3.8: Samples in the fumehood with hydrogen peroxide mix used to break down organic matter for particle size analysis (December 2015).*

The samples were topped up morning and evening to ensure that the hydrogen peroxide was not completely evaporated. After two weeks the samples were then heated on a hot plate during the day in 1.5 to 3 hour blocks at 70 °C to speed up the digestion process. The digestion of organic matter within the soil samples took three weeks. The samples were then processed by pipetting the soil slurry dropwise into the water filled laser-sizer receptacle and a pre-calibrated program for soil analysis was used to measure the soil particle size of each sample in the Malvern Mastersizer 2000 laser sizer; duplicate assays were conducted on each sample. The duplicate results for each sample were then averaged to give the clay (<0.002  $\mu\text{m}$ ), silt (0.05 to 0.002  $\mu\text{m}$ ), and sand (0.2 to 0.05  $\mu\text{m}$ ) fractions of each sample (Figure 3.9).



Figure 3.9: Particle laser sizer machine (Malvern Mastersizer 2000), University of Waikato (December 2015).

#### *d) Moisture factor*

The moisture factor of the soil samples was determined using the Blakemore *et al.* (1987) method. Air dry soil samples were weighed into aluminium tins. The tins were initially weighed and then the scales were tared to 0.000 and about five grams of soil was added to the tins and weighed. The samples were placed in a 105 °C oven for 48 hours. Once taken out, the samples were placed into a desiccator for cooling and reweighed. Each sample then had the tin weight subtracted from the oven dry weight and then the initial air-dried weight was divided by the oven dry weight to determine the moisture factor expressed to three decimal places for analytical purposes for calculating Olsen P.

$$MF = \frac{\text{air dried soil}}{\text{oven dried soil}}$$

*Equ. 3.3*

### **3.4.7. Statistical Analysis**

Paired t-tests were undertaken on data using Excel, along with statistical analysis carried out by Dr Ray Littler to determine the differences in landslide zones for total C using the Student-Newman-Keuls test.

## Chapter 4: Field sites and slide morphology

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### 4.1. Introduction

#### 4.1.1. Location and geomorphology of Whatawhata Research Station

Whatawhata Hill Country Research Station is located approximately 20 km west of Hamilton in the Waikato Region, North Island, New Zealand (Figure 4.1). Many of soils in the field area at the research station are derived from weathered Mesozoic siltstones and sandstones, argillite and greywacke (Kear and Schofield, 1964; Edbrooke, 2005). Waingaro steep-land soils (Mottled Yellow Ultic Soils) occur on slopes ~30 to 40° and Kaawa hill soils (Mottled Yellow Ultic Soils) on the moderate slopes (18 to 30°). The undulating to strongly rolling hills host Quaternary tephra deposits derived from the strongly weathered, clayey Hamilton ash beds (aged between c. 350,000 years and c. 80,000 years old) overlain by a patchy mantle of composite late Quaternary tephras (aged  $\leq$  c. 50,000 years old) forming Dunmore hill soils (Typic Orthic Allophanic Soils) (Bruce, 1978; Lowe, 1988; Lowe, *et al.*, 2001; Hewitt, 2010). Elevation of the catchment ranges from 374 m a.s.l in the planted forest behind the field area to about 59 m at the base of tributary streams. The field area lies within what is called Barkers Block on the station.

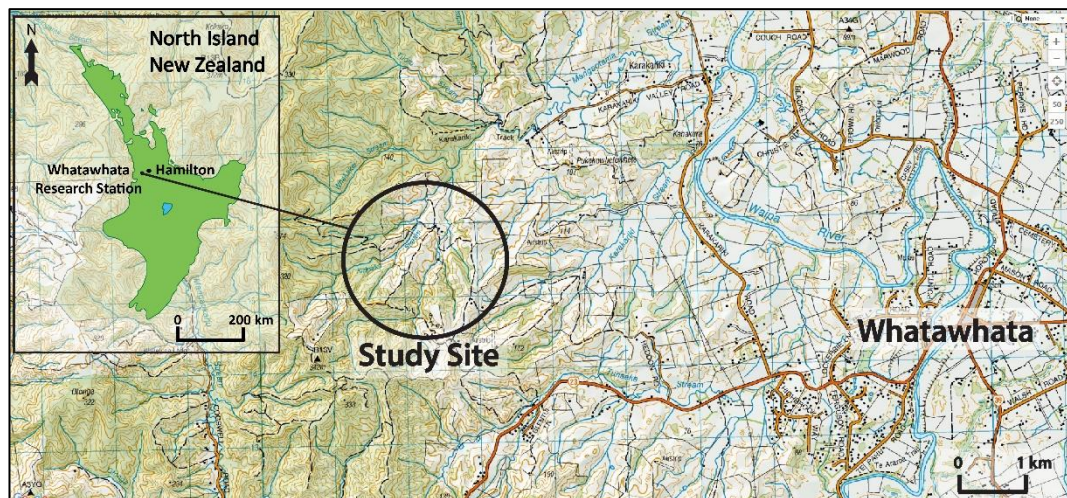


Figure 4.1: North Island of New Zealand, with location of study area in relation to Hamilton, and Whatawhata (adapted from NZTopo maps and Google Earth, 2015).

Temperature and rainfall have been measured at the station (climate station 25162) since 2003 and the climate station was still operational in 2015. The mean annual temperature at the research station is 14.3 °C with a mean annual rainfall of 1607 mm (NIWA, 2015). In terms of *Soil Taxonomy*, these represent mesic and udic temperature and moisture regimes, respectively (Soil Survey Staff, 2014).

#### 4.1.2. History and landuse of Raglan County and the Whatawhata Research Station

The first European settlers, Mr W.P. Cogswell and family, arrived in Raglan (Whaingaroa Harbour) in 1854. The land, including the hill country and steplands, was cleared with the felled trees being burned during the summer months so pasture grasses and wheat could be sown in the autumn (Bruce, 1978).

By the late 19<sup>th</sup> century New Zealand's sheep industry was becoming lucrative, for both wool export and meat. The hills throughout the North Island were further cleared of their native forests to accommodate growing sheep flocks (Farrelly, 1986).

In 1892, the Department of Agriculture was established and from the establishment of the department came experimental farms, studying the effects of animals, soils and cropping, with Ruakura farm being purchased in 1902 (Farrelly, 1986).

In 1949, 1328 acres of land was purchased to create the Ruakura Hill Station (Whatawhata Hill Country Research Station), chosen because of its similar hilly topography to much of that of North Island, New Zealand. The farm was established to observe livestock production and management in hill country in New Zealand.

Much of the land at the station was cleared of forest prior to World War II. However, it is difficult to pinpoint an exact date (Farrelly, 1986; Smale *et al.*, 2008). Prior to the settling of Europeans the land at the Whatawhata Research Station was dominated by podocarp forests, including tawa (*Beilschmiedia tawa*) and kohekohe (*Dysoxylum spectabile*), along with a few mangleo (*Litsea calicaris*) and mamaku (*Cyathea medullaris*) with pukatea (*Laurelia novae-zealandiae*) located in the gullies (Smale *et al.*, 2008).

The first experiments worked around farm development and stocking increases using methods that were both economical and productive. Since its establishment the station has hosted a number of farming research studies, for example, researching the pasture response to varying application rates of superphosphate fertilisers (Farrelly, 1986; Dodd *et al.*, 2008a).

### **4.1.3. Fertiliser trials**

The fertiliser trials conducted on the Mangaotoma catchment at Whatawhata Research Station were carried out using superphosphate fertiliser between 1980 to 1984 (Figure 4.2a) at rates of 10, 20, 30, 50 and 100 kg ha<sup>-1</sup> applied in February/March (I. Power 2015, personal

communication, December 11, 2015). In 1984, the trial ceased application rates on 18 paddocks, but application rates on the remaining eight paddocks were continued (Figure 4.2b). In 1990 the fertiliser being applied to the paddocks was changed to triple super and applications were continued until ~2013/2014 (I. Power 2015, personal communication, December 11, 2015). The fertiliser trials were of particular interest to this research project as five of the six landslides studied were located within the paddocks where the fertiliser trial was conducted (Figure 4.2).

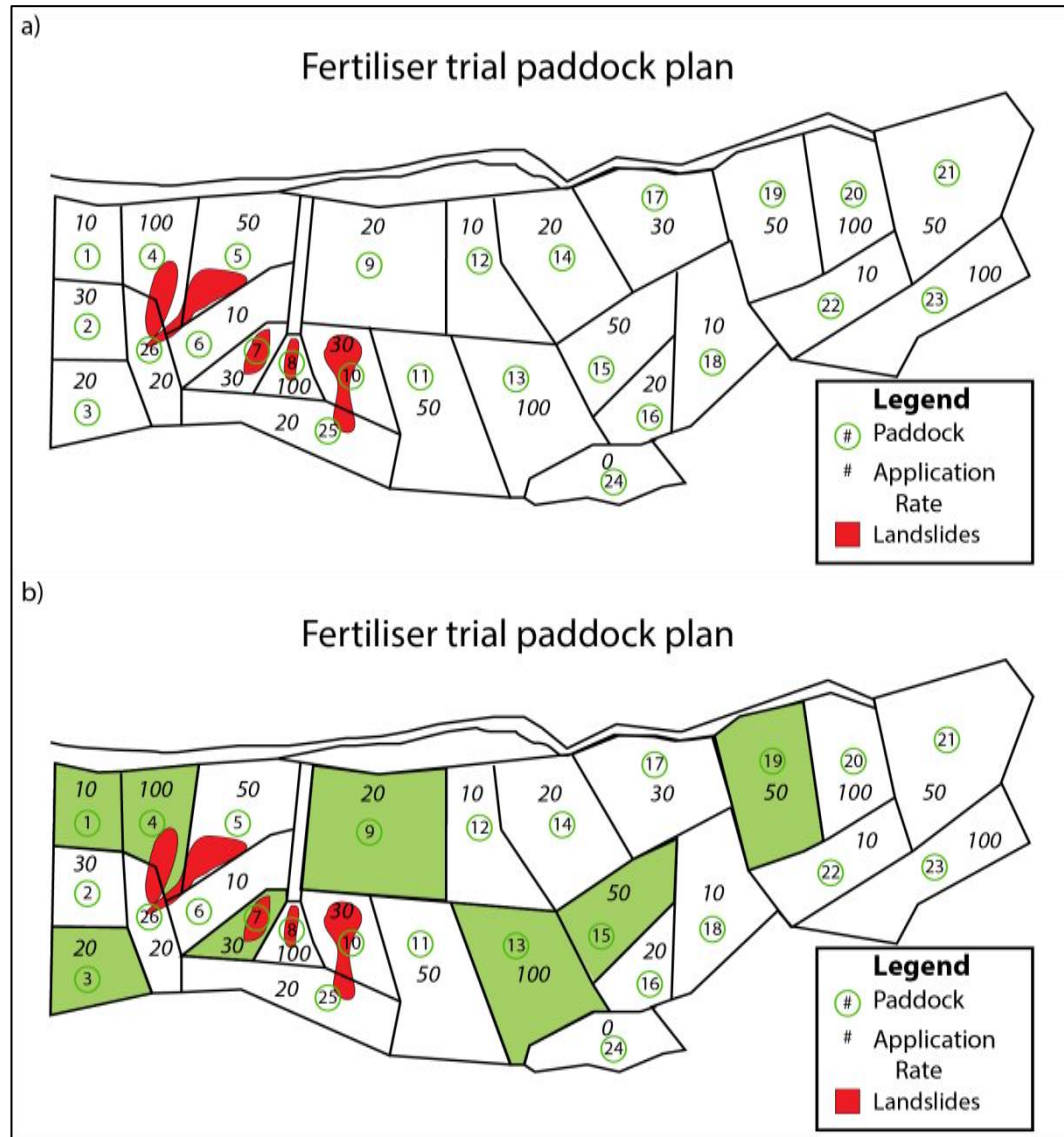


Figure 4.2: Fertiliser trials at Whatawhata Research Station. a) Original trial application rates with landslides positioned on top. b) Maintenance paddocks shaded in green (adapted from: I Power, n.d.).

#### 4.1.4. Current farm management

The farm is managed as a hill country sheep and beef farm. In May 2015, approximately 100 kg/ha of diammonium phosphate (DAP) was applied to the entire station (B. Carlson, personal communication, February 3, 2016). During the months of surveying, the paddocks where the study was undertaken were grazed with both sheep and cattle at various times.

Observation of the landscape shows that in areas where severe landsliding and erosional events have occurred, the hills have either been returned to pasture with poplar stabilisation on the moderate to steep slopes (about 1000 mixed clone species), or left to regenerate naturally, or have been planted in native species (Dodd *et al.*, 2008b).

Sediment prevention measures have been implemented by way of planting radiata pine (*Pinus radiata*) on the steepest slopes along with excluding stock from the waterways as a result of the hillslopes' susceptibility to erosion. A native tree planting replanting initiative was set up by the Waikato Regional Council, NIWA, and Landcare Research, called the Whatawhata Biodiversity Restoration Project (as part of a sustainable land management plan, est. 2001 at the station), within small sub-catchments (2.5 ha in total) on some of the steeper slopes. *Agathis australis* (kauri), *Podocarpus totara* (totara), *Dacrydium cupressinum* (rimu) and *Knightia excelsa* (rewarewa) single species' stands were planted (Dodd *et al.*, 2008b).

Additionally there were many species of plants both invasive and native at the station. The pastures include rye-grass (*Lolium perenne*) and white clover, with juncus (*Juncus acutus*), foxgloves (*Digitalis purpurea*), Scotch thistle (*Cirsium vulgare*), and gorse (*Ulex europaeus*) spread throughout, shrubs were mainly manuka (*Leptospermum scoparium*) varieties (Figure 4.3).



Figure 4.3: Examples of some of the plant species at the Whatawhata Research Station. a) *Juncus s*, b) foxglove, c) scotch thistle, d) foxglove in flower, e) manuka, f) poplar tree.

#### 4.1.5. Soils of field area of Whatawhata Hill Country Research Station

##### *a) Introduction*

Soils in the field area control zones at the research station were moderately well drained and three main soil types were identified, including Waingaro steepland soils (Mottled Yellow Ultic Soil) on the steepest slopes, Dunmore hill soils (Typic Orthic Allophanic) on upper flat to gently sloping areas, and Kaawa hill soils (Mottled Yellow Ultic Soil) generally on the moderately steep slopes.

Within the landslides zones, the soils were often either Recent or Raw soils depending on the zone and position.

*b) Kaawa hill soil*

The Kaawa hill soils developed from deeply weathered greywacke-argillite sedimentary parent materials (Figure 4.4). The Kaawa hill soil is a dark yellowish-brown clay loam over yellowish brown clays located on moderately sloping hills, 18 to 30° (Bruce, 1978). Parent materials at the base of the soil profiles were often a pinkish colour to a bright reddish hue possibly as a result of the weathering of the greywacke and argillite in a climate warmer than that of today (Bruce, 1978). With increasing depth within the profile, saprolite and remnant rock fragments are present. Soil acidity was approximately 5.6 in the A horizons consistent with the observations of Bruce (1978).



Figure 4.4: (Left) Example of a Kaawa hill soil profile at Whatawhata Research Station in the Barkers Block (January 2016). (Right) Soil auger samples displaying the red hues common to the lower subsoil of the Kaawa hill soil (March 2015).

**Kaawa hill soil***Table 4.1: Typical soil profile for a Kaawa hill soil at Whatawhata Research Station.*

<i>Site location</i>	Inside top of LS5, on an upper terracette at the top of the intact accumulation zone (explained in section 4.4.2.b)
<i>GPS co-ordinates</i>	S37°47'20.4", E175°04'02.2"
<i>Slope</i>	~20° northwest
<i>Altitude</i>	122 m a.m.s.l
<i>Drainage</i>	Moderately well drained
<i>Vegetation</i>	Pasture grasses including; ryegrass and clovers, cocksfoot grass, and scotch thistles; poplar trees
<i>Parent material</i>	Deeply weathered argillaceous greywacke
<i>Soil classification</i>	Mottled Yellow Ultic Soil

*Soil profile description*

Ap – 0 - 20 cm	dark brown (10YR 3/4) sandy clay loam; friable to slightly firm; moderately developed earthy granular microfine to fine, blocky/polyhedral peds; moderately plastic, slightly sticky; many roots; distinct wavy boundary
Bw 20 - 80 cm	yellowish brown (10YR 5/6) clay loam; abundant semi-deformable, moderate to strongly developed, medium breaking to very fine blocky/polyhedral peds; very plastic, slightly sticky; 5 % bright brown (7.5YR 5/8) mottles; few roots; indistinct boundary
C 80 - 100 cm	bright brown (7.5YR 5/8) clay; many firm, deformable, strongly developed, coarse breaking to medium, blocky/polyhedral peds; very plastic, very sticky; 40 % bright reddish brown (5YR 5/8) mottles; few roots

*c) Waingaro steepeland soil*

Of similar development to the Kaawa hill soil, the Waingaro steepeland soil is generally located on the steepelands (30 to 40°) (Figure 4.5). The Waingaro steepeland soil has a shallower soil profile and included saprolite and rock fragments are more abundant in the lower subsoil than observed in the Kaawa hill soil. The Waingaro steepeland soil was slightly more acidic than the Kaawa hill soil with pH 5.2 in the A horizon (Bruce 1978).



Figure 4.5: (Left) Example of a Waingaro steepeland soil profile at Barkers Block (January 2016). (Right) Soil auger samples representing a Waingaro steepeland soil (April 2015).

## Waingaro steepland soil

Table 4.2: Typical soil profile for a Waingaro steepland soil at Whatawhata Research Station.

<i>Site location</i>	Centre of intact accumulation zone of LS2, on a lower teracette
<i>GPS co-ordinates</i>	S37°47'16.9", E175°04'05.3"
<i>Slope</i>	North-north-east
<i>Altitude</i>	98 m a.m.s.l
<i>Drainage</i>	Moderate to well drained
<i>Vegetation</i>	Pasture grasses including; ryegrass and clovers, cocksfoot grass; and poplar trees
<i>Parent material</i>	Highly weathered argillaceous greywacke
<i>Soil classification</i>	Mottled yellow Ultic Soil
Ap – 0 - 3cm	dark brown (10YR 3/4) clay loam; friable, firm moderately developed abundant, fine to medium polyhedral peds; moderately plastic, slightly sticky; common to many roots, no mottles; distinct wavy boundary,
Bw1 – 3 - 30 cm	yellowish brown (10YR 5/6) clay loam; many firm, friable, weak to moderately developed polyhedral breaking to apedal earthy, peds; slight to moderately plastic, moderately sticky; 2 - 5 % bright brown (7.5 YR 5/8) mottles; few roots; indistinct boundary,
Bw2 – 30 - 61 cm	bright yellowish brown (10YR 6/6) clay loam; many weak, semi-deformable, moderately to strongly developed, very fine to medium polyhedral peds; very plastic, moderately sticky; 25 % light grey (7.5YR 8/2) gleyed mottles combined with orange (7.5YR 6/6) redox mottles; few roots; strong NaF reaction; indistinct boundary
CR - 61 - 100 cm	bright yellowish brown (10YR 6/8) silty clay; many firm, semi-deformable, blocky/polyhedral, fine to medium moderately developed peds; very plastic, not sticky; 40 % reddish pink mottles, imperfectly drained, no roots; strong NaF reaction; hard weathered rock fragments and saprolite present

*d) Dunmore hill soil*

Derived from Late Quaternary tephras (previously referred to as “Mairoa Ashes”; Lowe, 1988), the Dunmore hill soils are Typic Orthic Allophanic Soils located on rolling hills to steep slopes across the Raglan region. The Dunmore hill soil is allophanic and with a dark brown friable topsoil over yellow brown clay (Bruce, 1978) (Figure 4.6).



Figure 4.6: (Left) An example of a Dunmore hill soil profile in a road cutting at Whatawhata Research Station (January 2016). (Right) augured material of a Dunmore hill soil (January 2015).

**Dunmore hill soil***Table 4.3: Typical soil profile for a Dunmore hill soil at the Whatawhata Research Station.*

Site location	Whatawhata Research Station – Barkers block, left of LS5 looking towards farm track, mid-slope, on a flattish terrace
GPS co-ordinates	S 37°47'18.1", E 175° 04'02.8"
Slope	13° west
Altitude	~110 m
Vegetation	Pasture grasses including; ryegrass and clovers, cocksfoot grass, dandelions and scotch thistles
Parent material	Weathered volcanic tephras “Mairoa ashes” over argillaceous greywacke
Soil classification	Typic Orthic Allophanic Brown

**Soil profile description**

Ap – 0 - 20 cm	brownish black (10YR 3/2) silt loam; friable; weak - moderately developed, many very fine - fine blocky sub-angular peds breaking apedal earthy; many very fine to fine roots; distinct smooth boundary
Bw – 20 - 60 cm	yellowish brown (10YR 5/8) silty clay; many weak, very friable, weak to moderately developed polyhedral peds; moderately plastic, slightly sticky; very few microfine roots,
C – 60 - 90 cm	yellowish brown (10YR 5/6) silty clay; slightly firm, semi-deformable, weakly developed polyhedral peds; moderately plastic, moderately sticky; very few microfine roots,
2C – 90+ cm	yellowish brown (10YR 5/8) clay; massive, moderate to strongly developed structure; moderate to very plastic, very sticky

## **4.2. Location and geomorphology of landslides**

### **4.2.1. Landslide location**

An initial survey of the research station identified 16 landslides (Figure 4.7). Six landslides, three earthflows and three translational landslides, were then selected for detailed study, focusing on landslides activated in the last 20 years.

- ❖ Landslides 1 and 3 dating pre-1953.
- ❖ Landslides 2 and 5 activated multiple times over the last 60 years, evidence of erosion was observed through aerial photography (approximately 2004–2008) and, a portion of both slides triggered in 2014.
- ❖ Landslide 4 most recently activated in 2007.
- ❖ Landslide 6 moved during a large landslide event in 1995.

Landslides 1 to 5 were located within one paddock whilst Landslide 6 was located on an adjacent ridge. The six landslide sites were augered, determining sampling zones, soil type, soil solum depth and depth of A horizons, along with soil textural analysis.



Figure 4.7: Landslide locations: red circled numbers are the landslides studied, black squares are other identified landslides in the area (adapted from: Google Earth, 2015).

### 4.2.2. Landslide zones

Each landslide was divided into four geomorphic zones (shear, intact accumulation, transition and re-deposition) and an adjacent control (Figure 4.8). The zones were identified by their placement within the landslide scar, geomorphic shape, and soil characteristics.

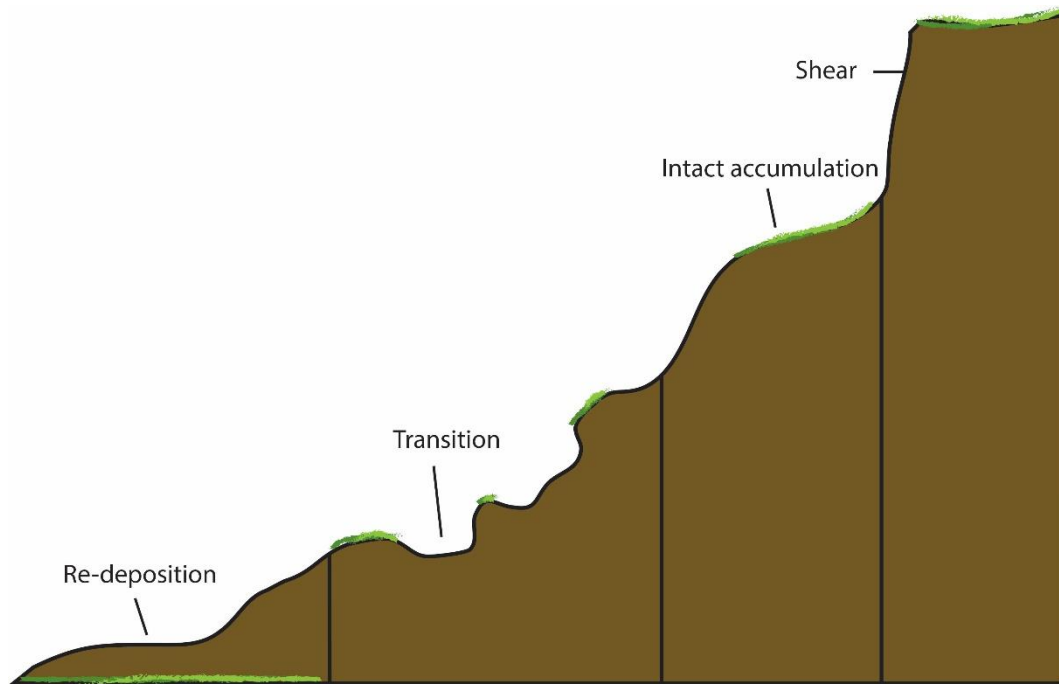


Figure 4.8: Schematic example of zone positions within a landslide.

*a) Shear zones*

The scarp and exposed shear zones (shear zone) were areas within the landslide with steep to near vertical surfaces where all topsoil had been removed during the landsliding event (Figure 4.9). The shear zone also included areas within the landslide where exposed surfaces were left after the landslide event, where entire soils were removed down to and including weathered parent materials (ash-derived clays and saprolite).



Figure 4.9: Landslide 6 with dashed line outlining the head scarp of the landslide (photo: M. Balks, 1996).

*b) Intact accumulation zones*

The intact accumulation zones were areas within the landslides that had moved downslope in large predominantly >2 m size blocks of soil (Figure 4.10). The intact accumulations were often located near the top of landslides. However, Landslide 3 did not have an intact accumulation zone and in Landslide 4 the intact accumulation zone was located at the bottom of the landslide.



Figure 4.10: Landslide 5 with dashed line outlining the intact accumulation zone (photo: D. Kelly, 2015).

*c) Transition zones*

The transition zones of the landslides were areas where there was a combination of re-worked materials along with small areas of exposed subsoils and smaller (<1 m-wide) blocks predominantly of intact soil

(Figure 4.11).



Figure 4.11: An example of the transition zone of Landslide 5 marked by the dashed line (photo: D. Kelly, 2015).

*d) Re-deposition zones*

The re-deposition zones were areas at the foot of the landslide where re-worked materials were deposited during landsliding events often with a shallow or non-existent A horizon followed by the reworked materials over a buried A horizon. (Figure 4.12). In the case of Landslide 6 (LS6), large quantities of soil were washed down the small stream in the valley floor at the bottom of the slip (Figure 4.13).



*Figure 4.12: The re-deposition zone of LS5 marked by dashed line.*



Figure 4.13: Sediment from LS6 that was washed down stream following the 1995 event (photo: M. Balks, 1996).

At the base of the other five landslides, there was also a small stream which probably carried some sediment away from the sites at the time of landsliding or soon after.

#### *e) Control zones*

Control zones were areas adjacent to each landslide representative of the soil and hill slopes pre-landslide.

### **4.2.3. Zone proportions within each landslide**

Each zone was sketched over photographs and then cut out and weighed to determine an estimated proportion of each landslide zone. The weights of each landslide were summed by adding the weight of each zone. Each zone was then divided by the total and multiplied by 100 to work out the proportion as a percent.

The smallest zones were the shear and re-deposition zones, approximately 10 to 20 % of total landslide area. The largest zones were the transition

zone, about 35 to 55 % of total area. The intact accumulation zones were variable proportionally depending on the landslide morphology, ranging from 10 to 35 % of total landslide area (Figure 4.14).

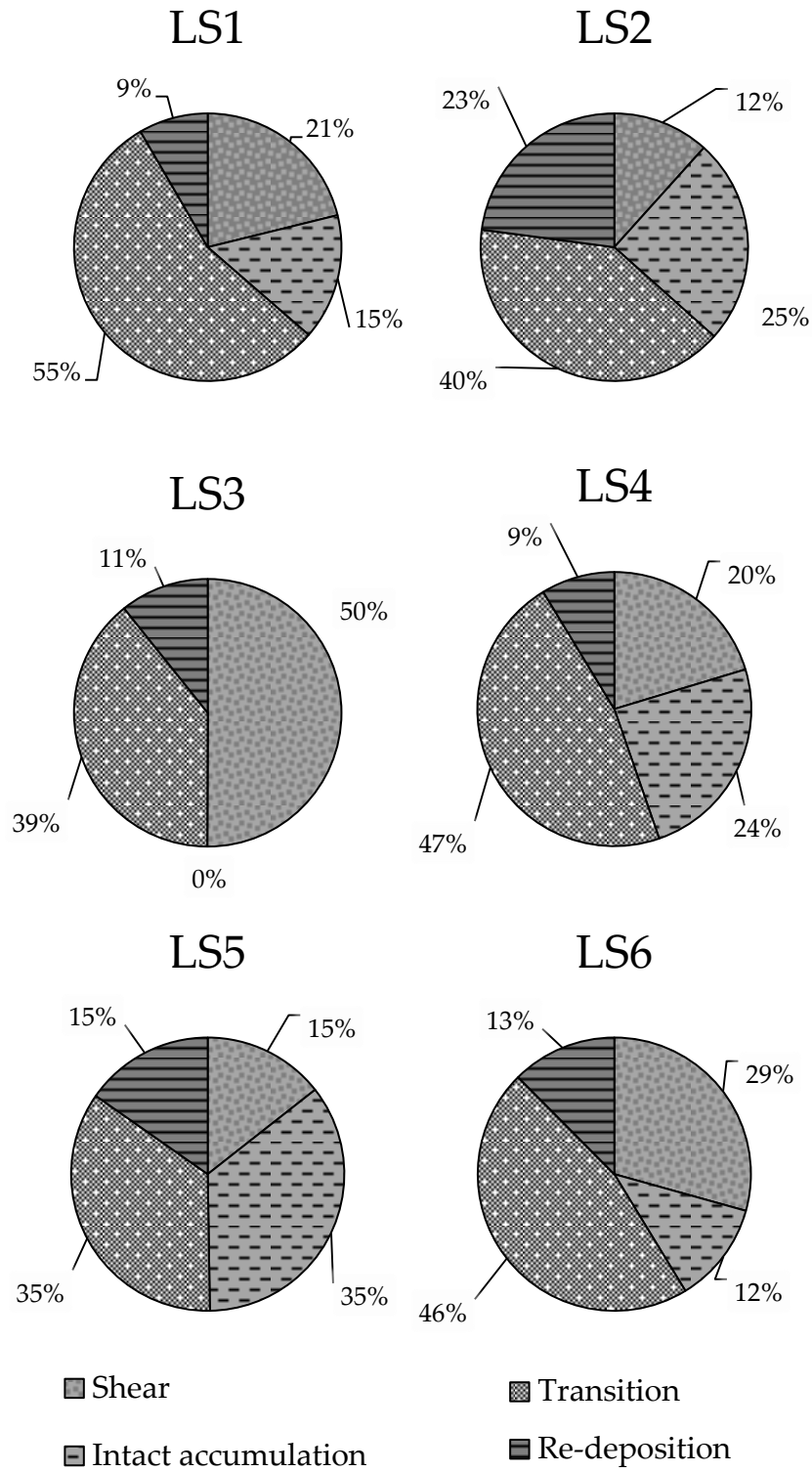
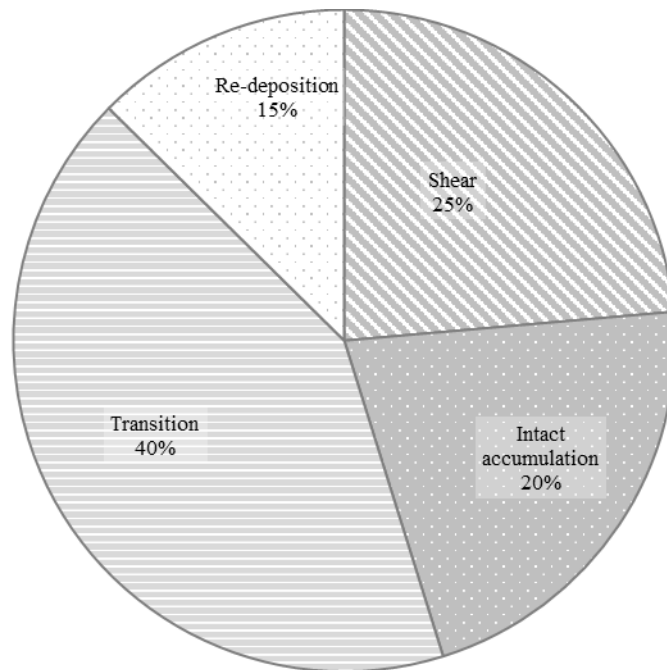


Figure 4.14: Landslide proportion of each zone within LS1-6.

Overall, the largest portion of the landslides (about 40 %) comprised the transition zones (Figure 4.15). The shear zones equated to about 25 % of the total landslide area. The re-deposition zones made up the smallest portion of the landslide (10 %) and the intact accumulation zones were about 20 % of total landslide area.



*Figure 4.15: Estimated proportion of total area for each zone across six landslides in the field area.*

#### 4.2.4. Landslide 1 (LS1)

LS1 is an earthflow slide situated at GPS coordinates S37°47'15.6", E 175°04'06.8". The slide was >60 years old at the time of study and was evident on the oldest aerial photograph available (1953). The aspect of LS1 is 301° with a slope of about 21°. The top of the landslide was 97 m a.s.l with the toe of the slide about 79 m a.s.l. LS1 has been stabilised by a small poplar stand at the apex of the transition zone and within the re-deposition zone (Figure 4.16). The vegetation is dominated by pasture with rushes in the transition zone gully.

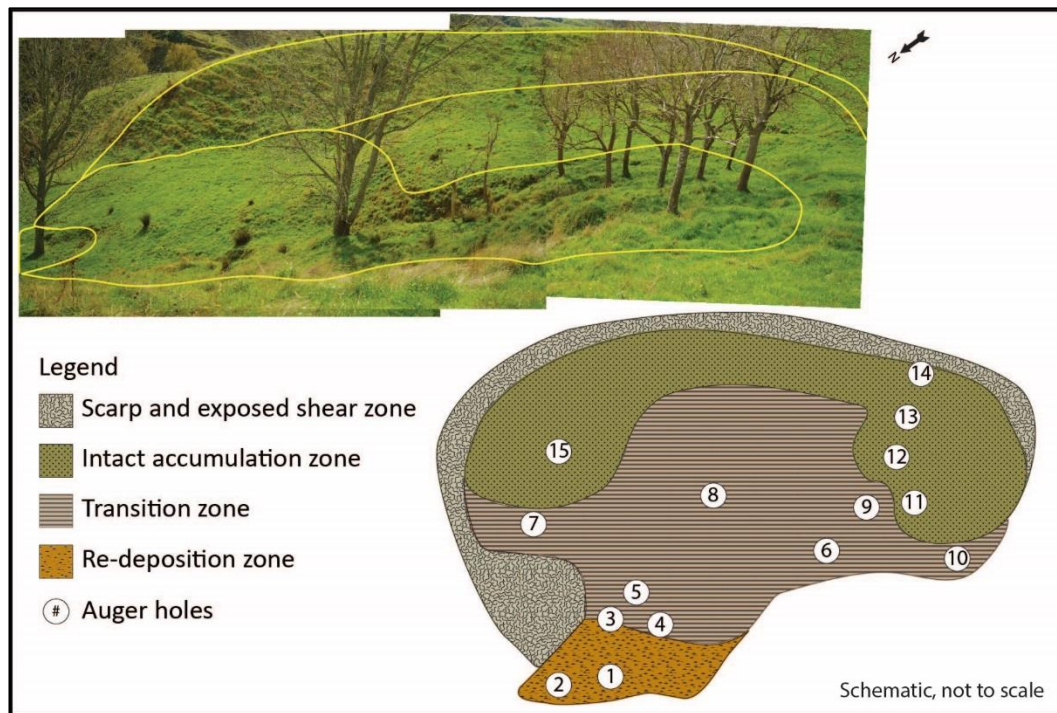


Figure 4.16: Stylised schematic of Landslide 1 with the four morphological zones drawn in. The north arrow is pointing to the direction the earthflow mass movement had occurred.

### 4.2.5. Landslide 2 (LS2)

Located at S37°47'16.6", E175° 4'05.3", LS2 is an earthflow landslide (Figure 4.17). LS2 has activated several times since 1953 with the most recent activation occurring between May and July 2014. The slide is approximately 70 m in vertical length and 42 m at the widest point horizontally with a slope of approximately 19° with a steeper gradient in the recent transition zone. LS2 has an aspect of 354° with the top of the landslide at 103 m a.s.l and the toe 83 m a.s.l. The slide is dominated by pasture and has a large run of poplars down its eastern face. A 'stabilisation' tree was toppled during the most recent activation, leaving a large root mound structure in the centre of the transition zone. The landslide has potential to fail further, with many cracks present throughout the landslide.

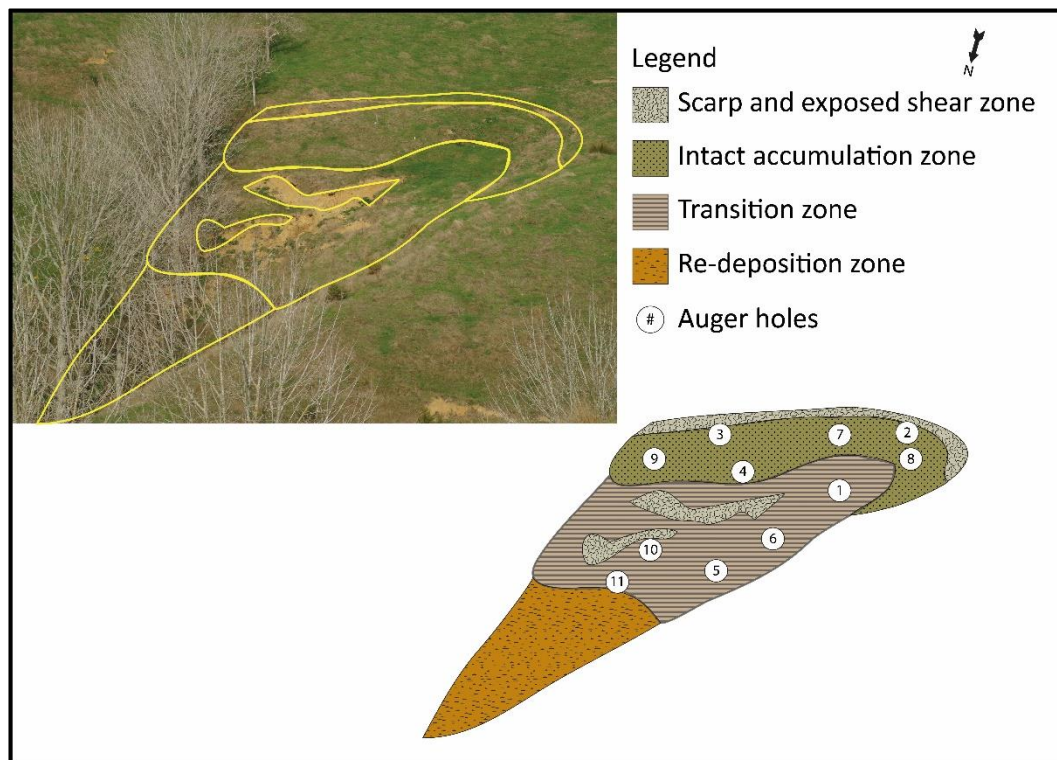


Figure 4.17: Landslide 2 divided into the four morphological zones.

### 4.2.6. Landslide 3 (LS3)

LS3 is located at S37°47'16.25", E175° 4'3.23" and is a translational landslide. It has an aspect of 319° and a slope of 24°. At the widest point, the landslide is 20 m wide and estimated to be more than 40 m in length, and the toe of the landslide is approximately 80 m a.s.l with the apex at 85 m a.s.l. LS3 is a well-recovered slide that occurred pre-1953. As a result of the long interval of time the slide has had to recover, it was hard to determine exact zone divisions (Figure 4.18). The pasture vegetation is ryegrass and within the scar there are manuka and poplars acting as hillslope stabilisers.

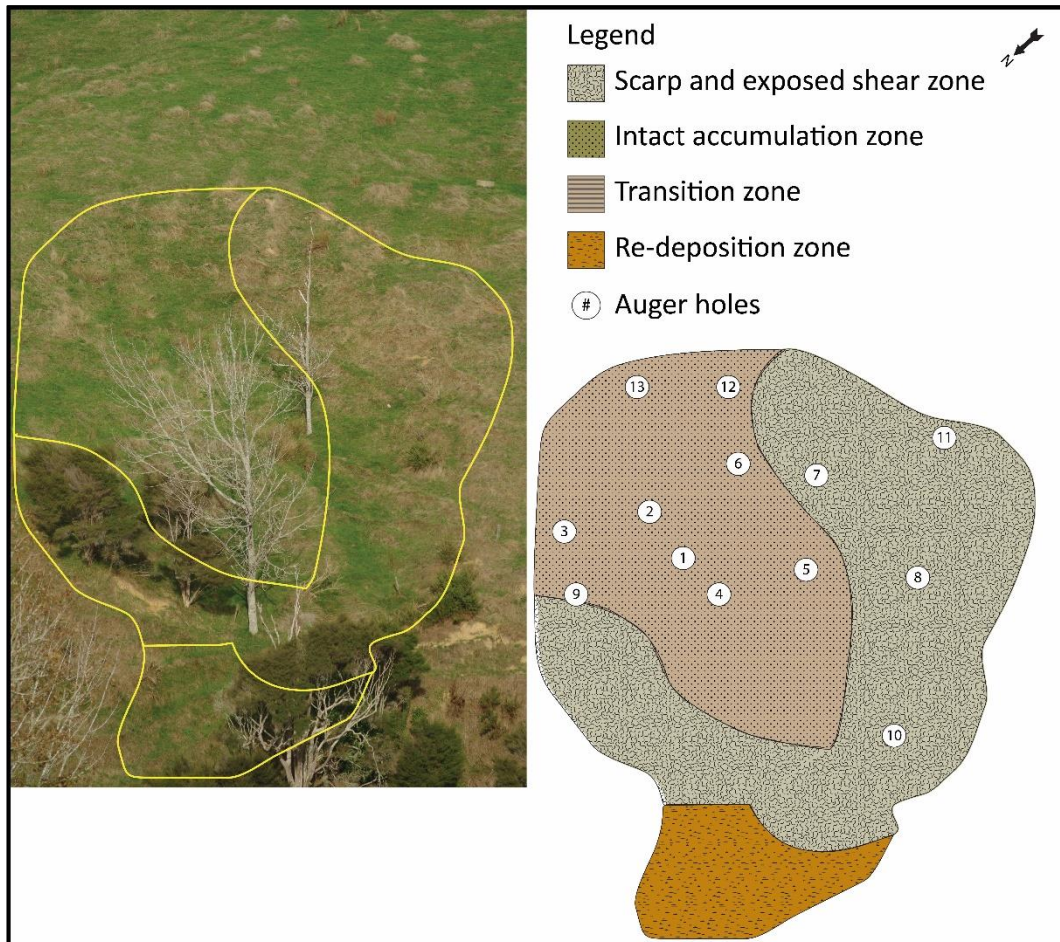


Figure 4.18: Landslide 3 with three of the morphological zones indicated.

### 4.2.7. Landslide 4 (LS4)

The second of the three translational landslides is LS4, which is situated at  $S37^{\circ}47'17.50''$ ,  $E175^{\circ}4'2.40''$ . The aspect of the slide is  $320^{\circ}$  with a slope of  $25^{\circ}$ . At its widest horizontal point, LS4 is 14.8 m with a vertical length of about 40 m, and it is 85 m a.s.l at the apex and 78 m a.s.l at the toe. LS4 was most recently active in 2007 following a large storm event in February (Quinn & Basher, 2007). The event caused soil removal down to bedrock in places (Figure 4.19). Vegetation recovery within LS4 is varied compared with that of older slides and is being re-vegetated by *Paesia scaberula* (ring fern), manuka, and ryegrass pasture.

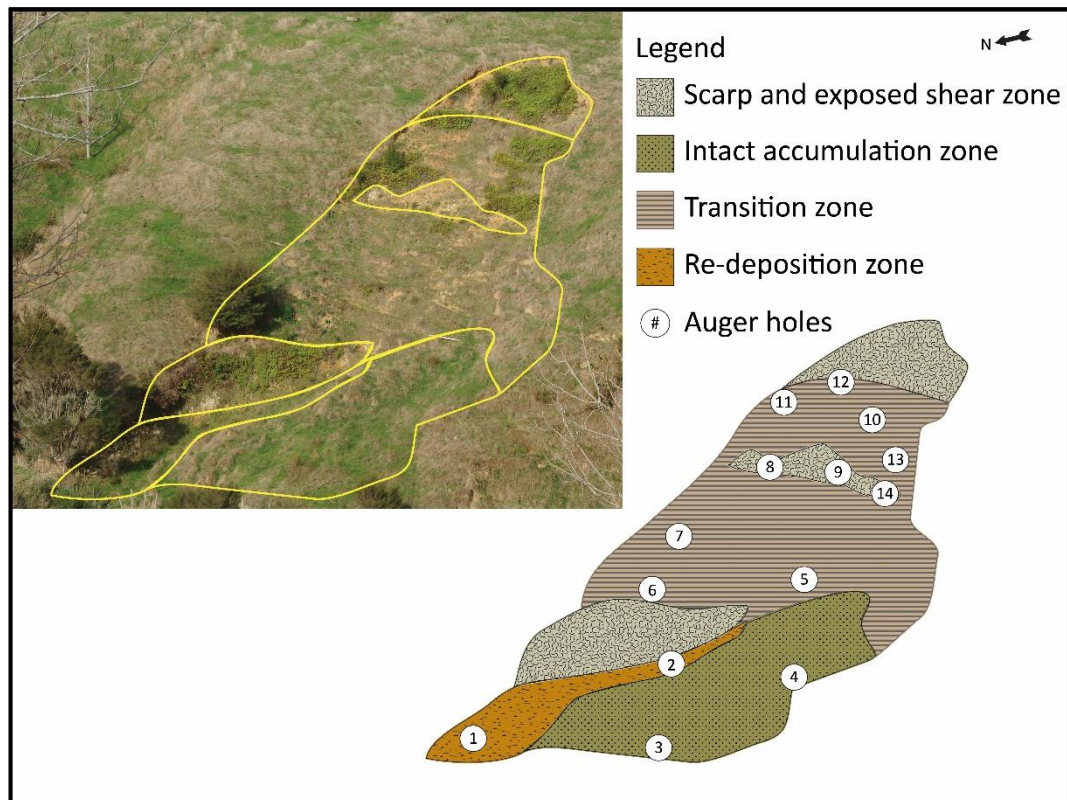


Figure 4.19: Landslide 4, separated into the four morphological zones.

#### 4.2.8. Landslide 5 (LS5)

LS4 is an earthflow landslide situated at S37°47'19.81", E175°04'02.40". The landslide spans 36 m horizontally at its widest point with the narrowest horizontal width spanning about 5 m. The topographic ground length is 123 m, with a slope of 25° from top to bottom, and with a steeper slope from the transition zone to the re-deposition zone. The top of LS4 is 114 m a.s.l with the toe of the slide being 77 m a.s.l. The aspect of the slide is ~287° WNW. The slide is divided into four distinct zones of mass movement (Figure 4.20). Initial activation of LS4 appears to have occurred prior to 1953. Many of the intact blocks were moved downslope in ~1988 during or soon after cyclone Bola, forming very deep crevices (>3 m) between blocks in areas (I. Power, personal communication, December 11, 2015). More reactivation occurred between 2004 and 2008, most recently activating between May and July 2014. Efforts to stabilise the hillslope were evident with poplars planted around the landslide edge and inside the landslide spanning the intact accumulation and transition zones in the late 1980s (I. Power, personal communication. December 11, 2015). The 2014 event uprooted a middle stabilisation tree, transporting it to the bottom of the transition zone. The fallen tree trunk caused a two-tier re-deposition zone, with initial topsoil failure beneath the tree extending to the base of the landslide and then further re-deposition on top of the toppled tree.

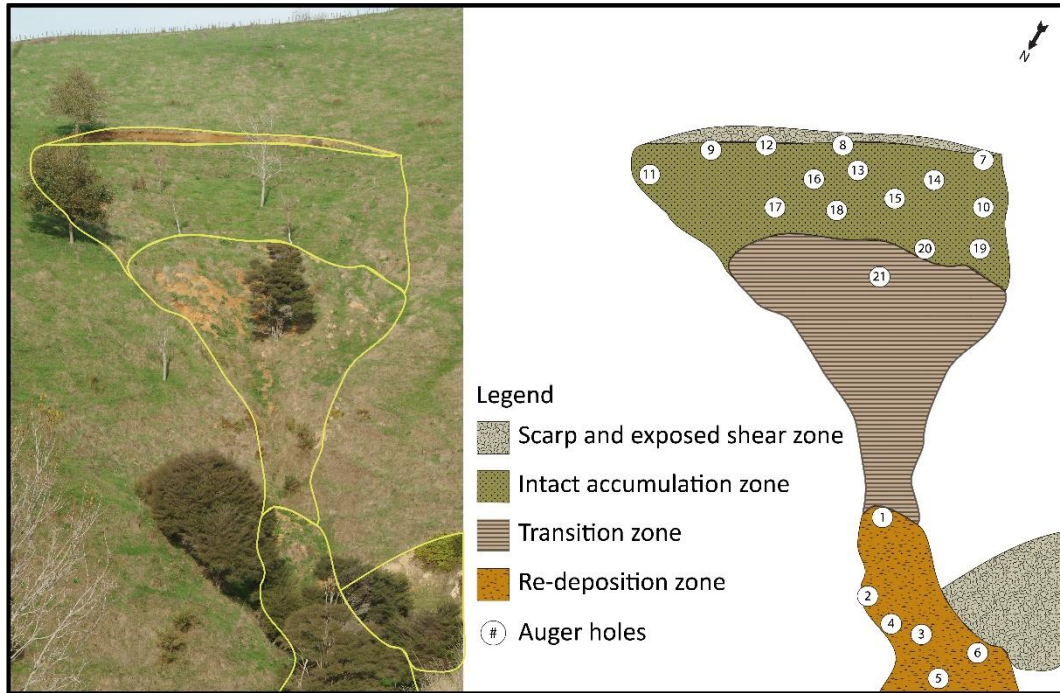


Figure 4.20: Landslide 5, divided into the four morphological zones.

#### 4.2.9. Landslide 6 (LS6)

Located at S37°47'7.37", E175° 4'3.65", LS6 is a large translational landslide with an aspect of 346° and an overall slope of 25°. The top of the landslide is 101 m a.s.l with the bottom of the slide 79 m a.s.l. LS6 slope failure occurred in the winter of 1995 (Davies-Colley, 1997) and was left to re-vegetate naturally (Figure. 4.21). The vegetation within the slip site comprised a range of native and invasive plant species. The invasive species included gorse and Himalayan honeysuckle (*Leycesteria formosa*). Native species within the slip site included silver fern (*Cyathea dealbata*), manuka, and other New Zealand fern varieties. The understory of the landslide has numerous gorse bushes. However, ferns and manuka had begun to establish alongside the gorse on the exposed soil. Although vegetation has been established on the landslide scar there are still patches

of exposed earth. The landslide scar is on the western face of the hill and is very steep at the top of the scar – in some places almost vertical.

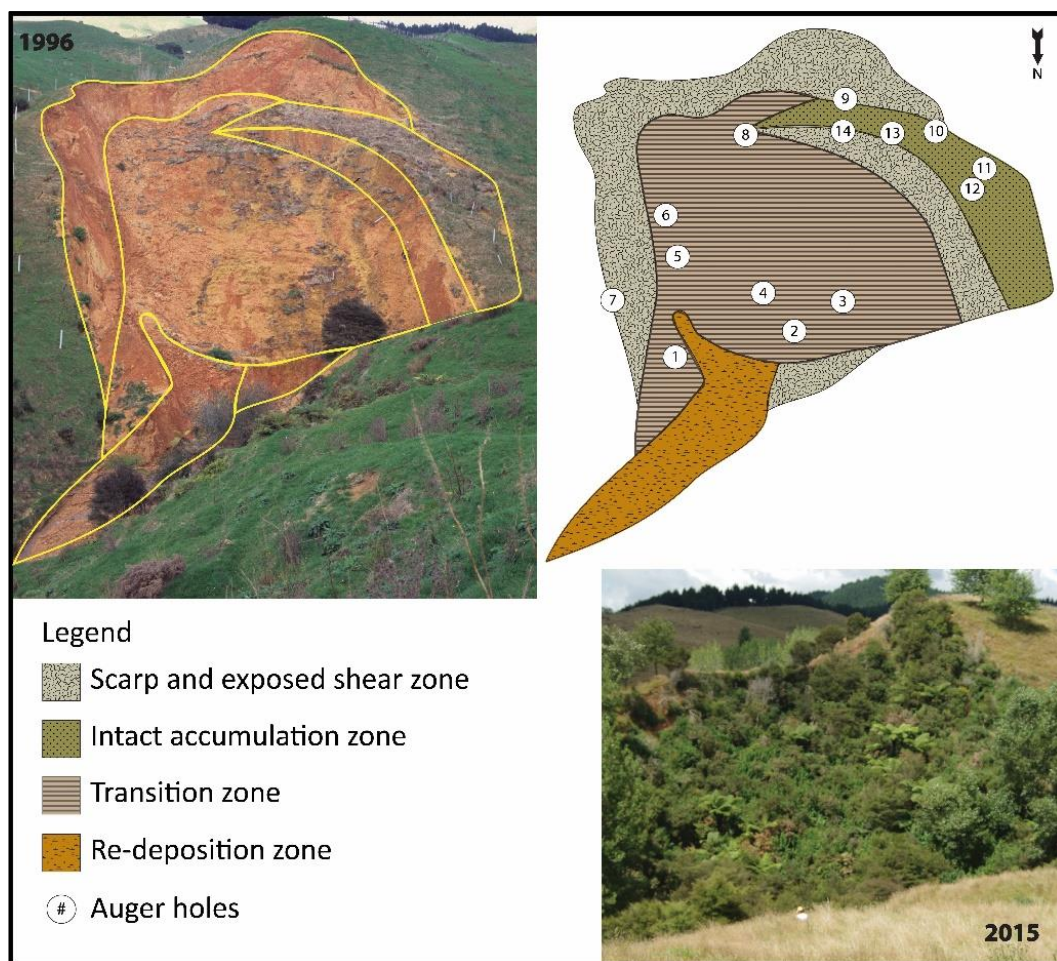


Figure 4.21: Landslide 6 showing how landslide appeared in 1996 compared with 2015.

#### 4.2.10. Soil A horizons and solum depth

A horizons were shallow and poorly developed in the shear and re-deposition zones, whereas the transition zones were variable depending on landslide age and small block (>1 m) distribution (Table 4.4). Soil horizon thicknesses in intact accumulation zones were similar to those of the control zones, but variable with some parts lacking soil between the intact blocks.

Table 4.4: Soil properties for landslides at Whatawhata Hill Country Research Station.

Zone	A horizon depth (cm)		Solum depth (cm)		Typical A horizon colour	Root depth (cm) <sup>1</sup>
	Mean	Range	Mean	Range		
Shear	2	0-7	24	0-100+	10YR 4/6 brown	ND <sup>2</sup>
Intact accumulation	17	5-25	91	40-100+	10YR 3/4 dark brown	53
Transition	7	1-20	72	17-100+	10YR 4/3 dull yellowish brown	46
Re-deposition	2	0-5	90	50-100+	10YR 3/4 dark brown	26
Control	20	15-30	>100	80-100+	10YR 3/4 dark brown	ND

1. Mean rooting depth across the six landslides. 2. ND = Not determined

The solum depth (i.e. depth of soil to the base of the B horizons) was greatest in the control, intact accumulation and re-deposition zones. The soils in the re-deposition and transition zones often hosted buried horizons of variable depths.

## Chapter 5: Laboratory results

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### 5.1. Introduction

Chemical and physical soil analyses were undertaken on two bulked samples collected from each zone in each of the six landslides described in Chapter 4. Soil samples were analysed for C, N, and P content, soil pH, soil moisture factors, soil dry bulk density, water filled pore space, and particle size following methods described in Chapter 3.

Soil C, N, and P values were rated as high, medium, and low (Table 5.1).

*Table 5.1: Blakemore et al. (1987) rating values for C, N and C:N ratio.*

	<i>Total C (%)</i>	<i>Total N (%)</i>	<i>C/N ratio</i>
High	10-20	0.6-1.0	16-24
Medium	4-10	0.3-0.6	12-16
Low	2-4	0.1-0.3	10-12
Very low	<2	<0.1	<10

### 5.2. Chemical analysis

#### 5.2.1. Carbon and nitrogen results

##### *a) Total C and N % by zone*

Total C ranged from very low to high (1–12) across the landslides (Figure 5.1, Table 5.2), and total N ranged from very low to high (0.1 to 1.0) (Figure 5.2, Table 5.2).

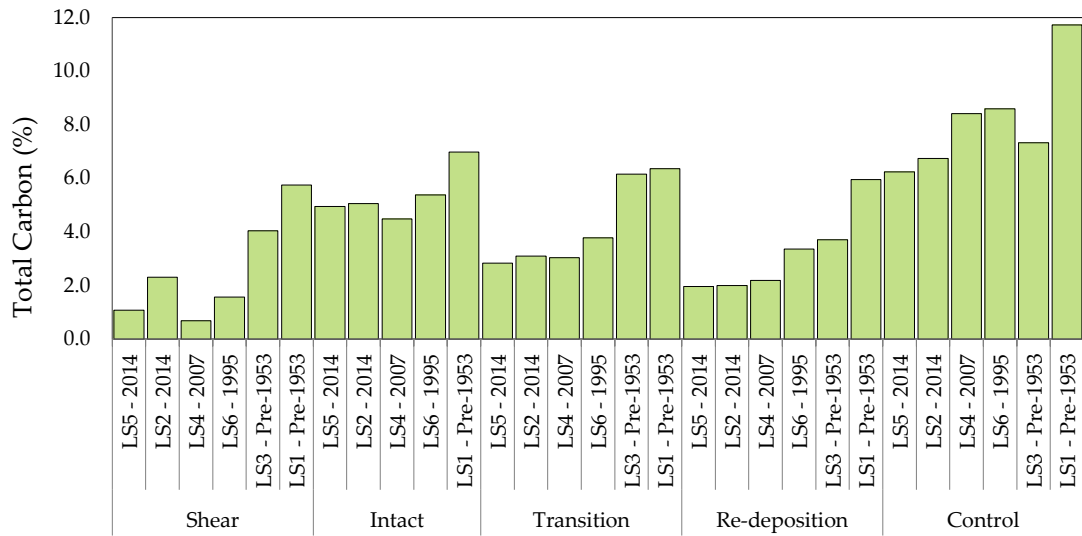


Figure 5.1: The total C (%) of each landslide zone ordered chronologically youngest to oldest.

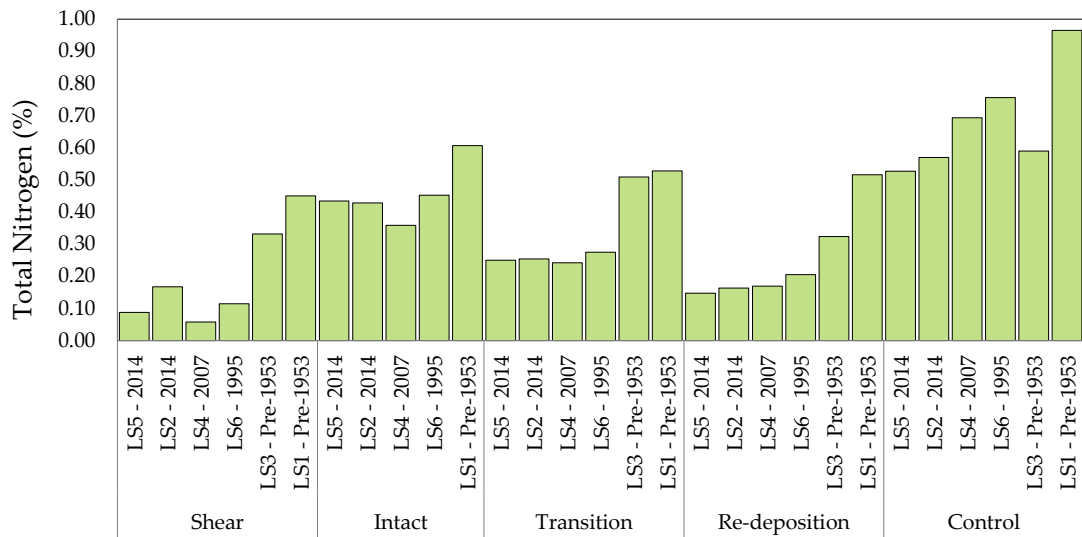


Figure 5.2: The total N (%) of each landslide zone ordered chronologically youngest to oldest.

Table 5.2: Mean C and N content (%) of each landslide zone, including zone mean for each zone.

<i>Zone</i>	<i>Landslide</i>						<i>Zone (mean)</i>
	<i>LS1</i>	<i>LS2</i>	<i>LS3</i>	<i>LS4</i>	<i>LS5</i>	<i>LS6</i>	
<i>Carbon (%)</i>							
Shear	5.7	2.3	4.0	0.7	1.1	1.6	2.6
Intact accumulation	7.0	5.1	-	4.5	4.9	5.4	5.4
Transition	6.4	3.1	6.2	3.0	2.8	3.8	4.2
Re-deposition	6.0	2.0	3.7	2.2	2.0	3.4	3.2
Control	11.7	6.7	7.3	8.4	6.2	8.6	8.2
<i>Nitrogen (%)</i>							
Shear	0.4	0.2	0.3	0.1	0.1	0.1	0.2
Intact accumulation	0.6	0.4	-	0.4	0.4	0.5	0.5
Transition	0.5	0.3	0.5	0.2	0.2	0.3	0.3
Re-deposition	0.5	0.2	0.3	0.2	0.1	0.2	0.3
Control	1.0	0.6	0.6	0.7	0.5	0.8	0.7

The total C in the shear zone was very low in LS4 and LS5 to low in LS2 and LS6. The C content in the shear zone was higher (medium total C levels) in the older two landslides, LS1 and LS3. Total N in the shear zone was low in LS2, LS4, LS5 and LS6 with medium levels in LS1 and LS3.

The intact accumulation zones all had medium total C, however, total N was high in LS1, whilst the other five landslides had medium total N contents.

The C content in the transition zone was variable, with LS1, LS3 and LS6 having medium levels of accumulated C. LS2, LS4 and LS5 had low total C in the transition zone. Total N was medium in LS1, LS2, LS3, and LS6, but low in LS4 and LS5.

The re-deposition zones had low levels of total C and N in LS2, LS4, LS5, and LS6 and medium total C and N in LS1 and LS3.

Control zones had medium total C levels in LS2 – LS6 and high only in LS1. Total N in the control zones was high in LS1, LS2, LS3, LS4 and LS6 and medium total N was recorded in LS5.

There was no significant difference between the shear and re-deposition zones, but all the other landslide zones were significantly different ( $P < 0.05$ ) from one another. The controls had the highest total C (11.7 %) and the shear zone the lowest C (1.1 % in LS5 to 5.7 % in LS1).

Conversely total N statistically differed in all zones ( $P < 0.05$ ) from each other.

*b) Total C and N vs. % of controls*

The proportion of C for each of the landslides zones ranged from 8 % of control for LS4 in the shear zone to 84 % of the control for LS3 in the transition zone. The total N proportion of control ranged from 8 % in the shear zone for LS4 to 86 % in the transition zone for LS3.

*Table 5.3: Proportion of total C and N of landslide zone to control zone.*

<i>Zone</i>	<i>Landslide</i>					
	<i>LS1</i>	<i>LS2</i>	<i>LS3</i>	<i>LS4</i>	<i>LS5</i>	<i>LS6</i>
<i>Carbon (% of control)</i>						
Shear	49	34	55	8	17	18
Intact accumulation	59	75	-	53	79	63
Transition	54	46	84	36	45	44
Re-deposition	51	30	51	26	31	39
Control	100	100	100	100	100	100
<i>Nitrogen (% of control)</i>						
Shear	47	29	56	8	17	15
Intact accumulation	63	75	-	52	83	60
Transition	55	45	86	35	47	36
Re-deposition	53	29	55	24	28	27
Control	100	100	100	100	100	100

*c) Total C and N vs. Landslide age*

The C and N results obtained from each landslide zone were divided into zones and ages of landslide activation, then graphed as total C vs. age and total N vs. age. Linear trend lines were attached to each zone to determine the slope relationship for each zone for soil C and N increases and landslide age (Figures. 5.3 & 5.4).

Shear zones had the least total C and N increases with time when compared to those of the other zones and had an  $R^2 = 0.4814$  of the linear trend line slope, which was not significant when compared to the other zones which had  $R^2$  values of about 0.7 (Figure 5.3). However, the slopes of the lines were very low as changes over time were small.

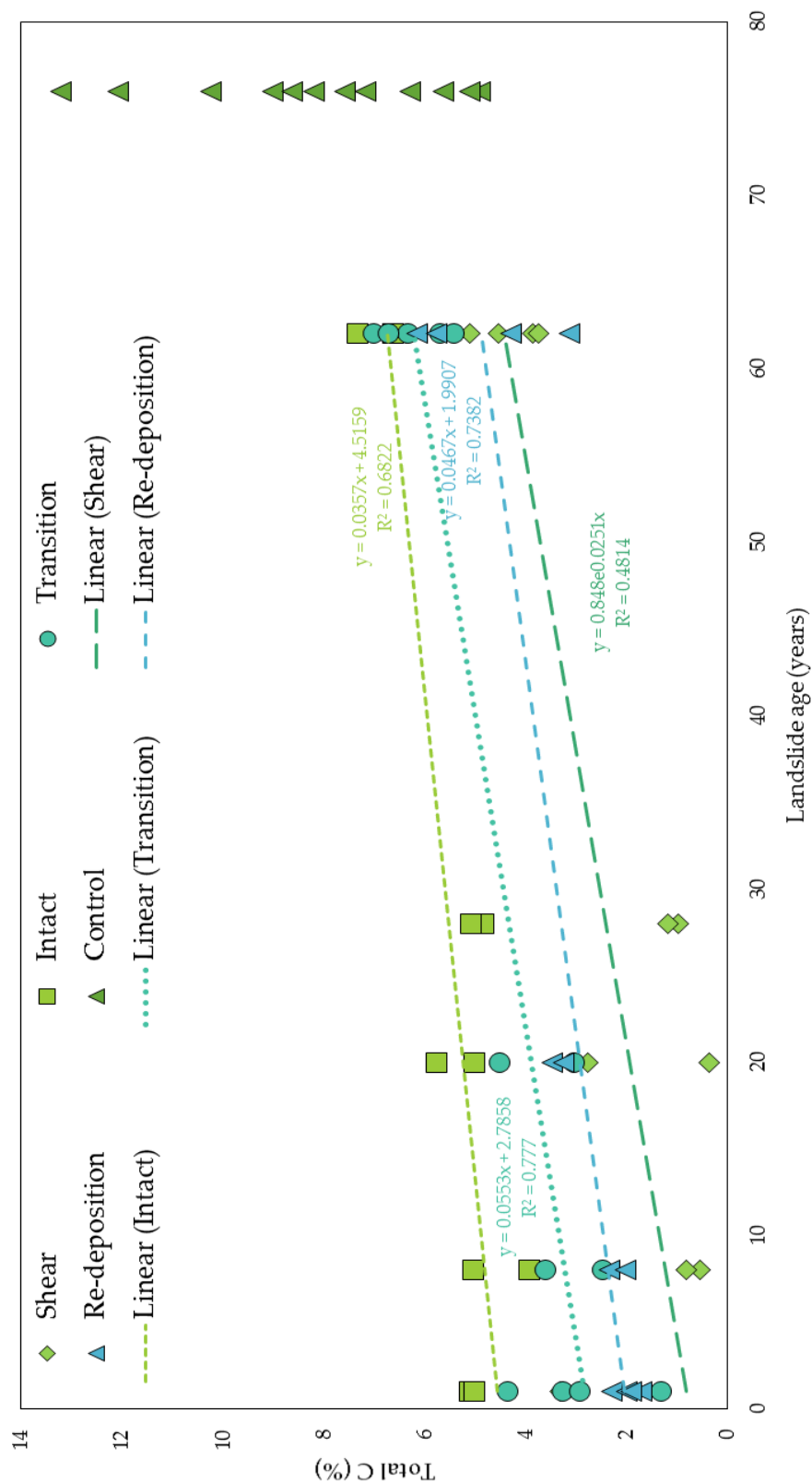


Figure 5.3: Total C (%) of all landslides divided by zone and age of landslide zone activation, with adjacent controls.

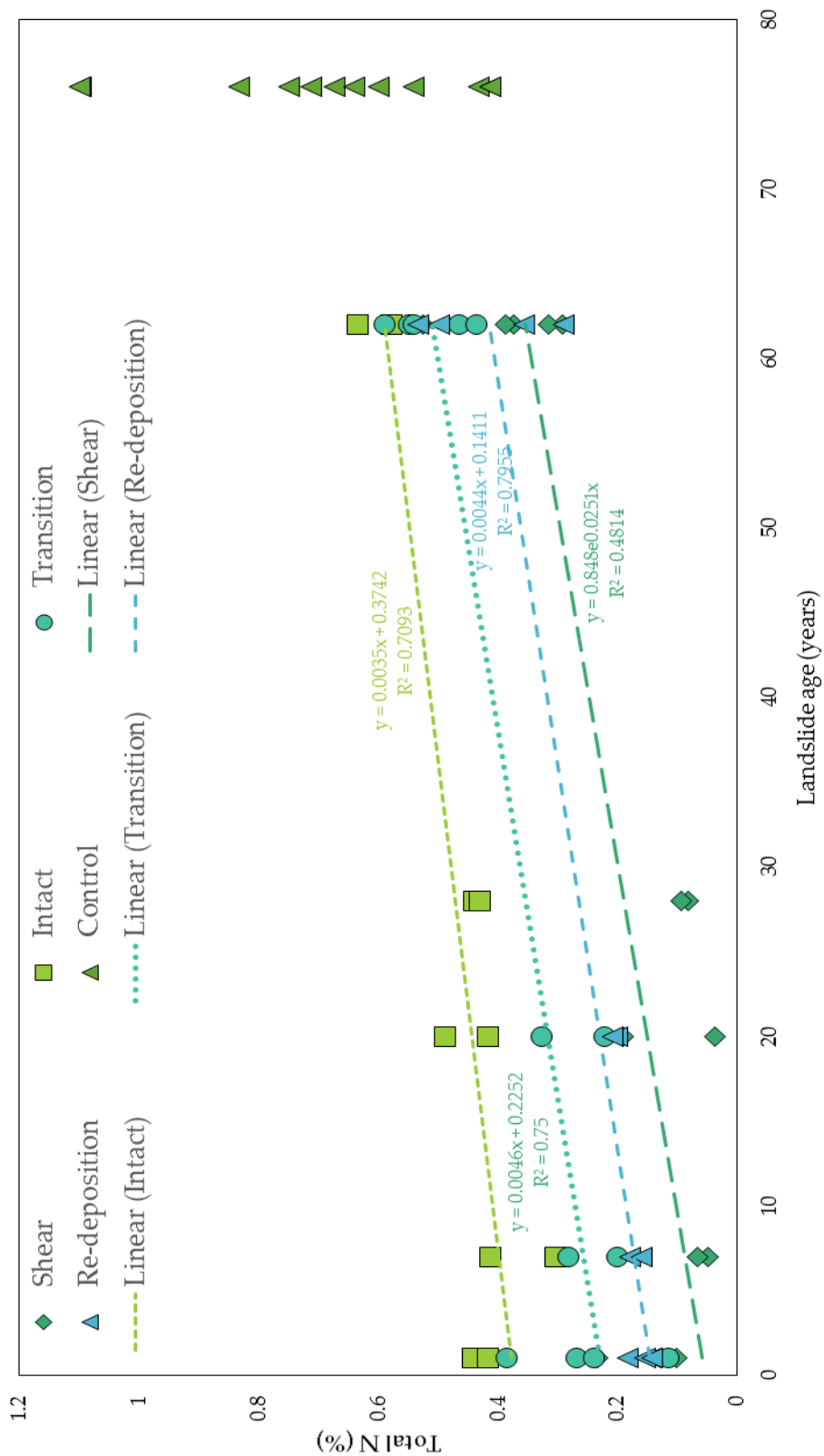


Figure 5.4: Total N (%) of all landslides divided by zone and age of landslide zone activation, with adjacent controls.

*d) C and N relationship*

The C:N ratio ranged from 11 to 16 (Figure 5.5) across the landslides (low to high). The soil samples collected and analysed for soil C and N from the field area supported the relationship when compared to each other with an  $R^2$  of 0.9883 (Figure. 5.6). The shear and re-deposition zones generally had the lowest C and N values with increasing C and N in the transition and intact accumulation zones. The controls have some overlap but generally had the greatest C and N contents.

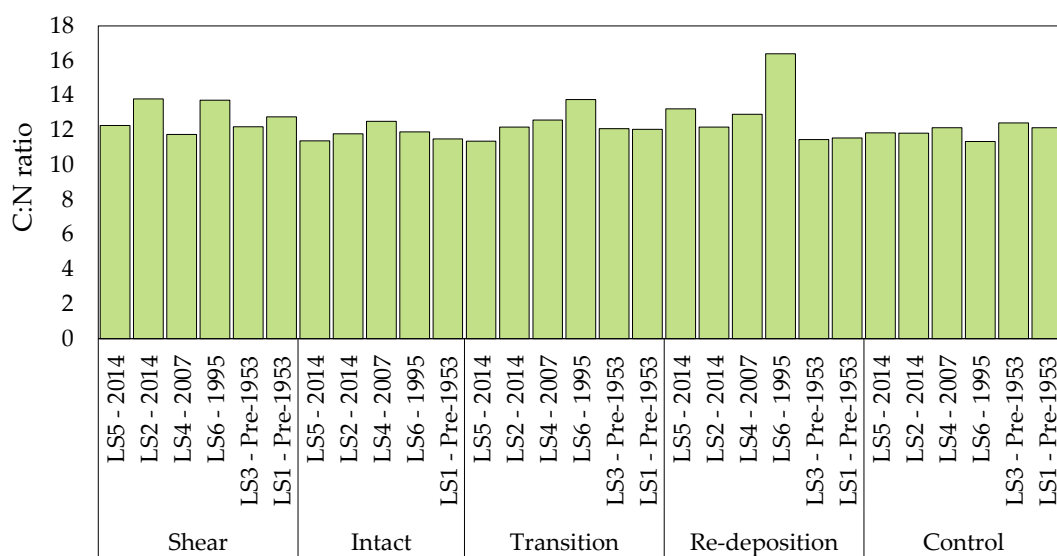


Figure 5.5: C:N ratio of all landslides, ordered by zone chronologically youngest to oldest.

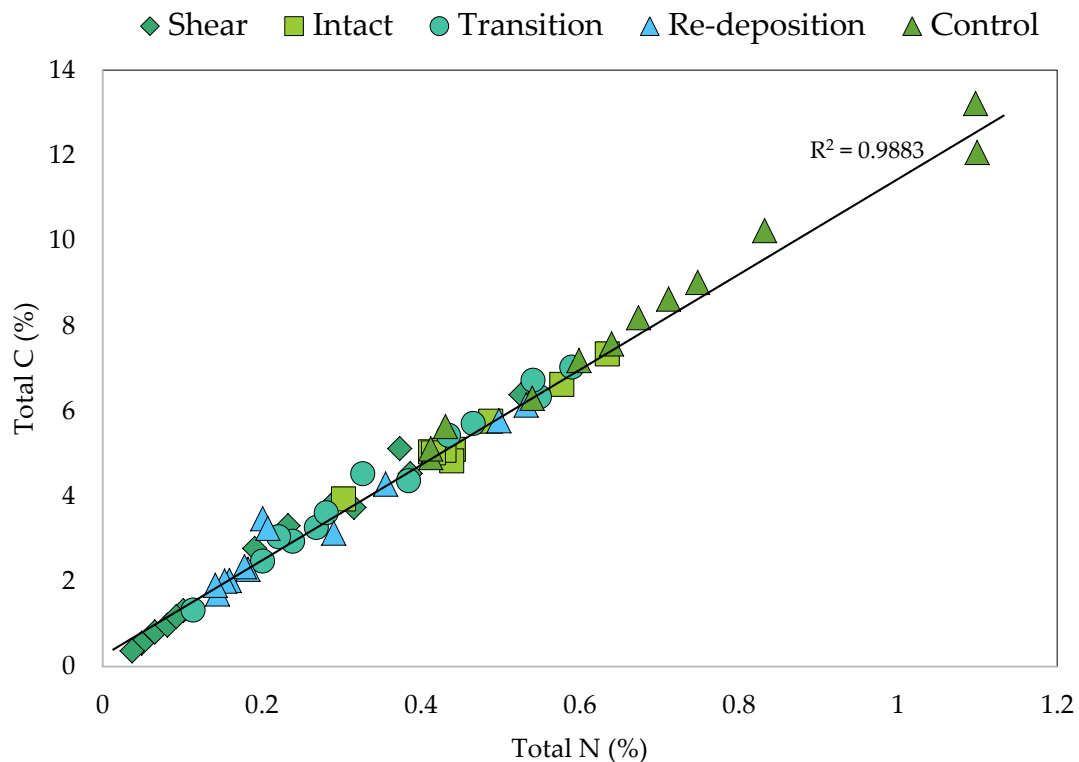


Figure 5.6: Relationship between soil C and N of soil samples taken from all six landslides in the field area, divided into landslide zones.

### 5.2.2. Olsen P

The shear and re-deposition zones had the least plant available P (Figure 5.6). The Olsen P in the shear zone was lower than the intact accumulation, transition, and control zones ( $P < 0.05$ ). The re-deposition zone was lower only than the control ( $P < 0.05$ ) LS2 to LS6 had lower Olsen P levels when compared to those of LS1 (Figure 5.7).

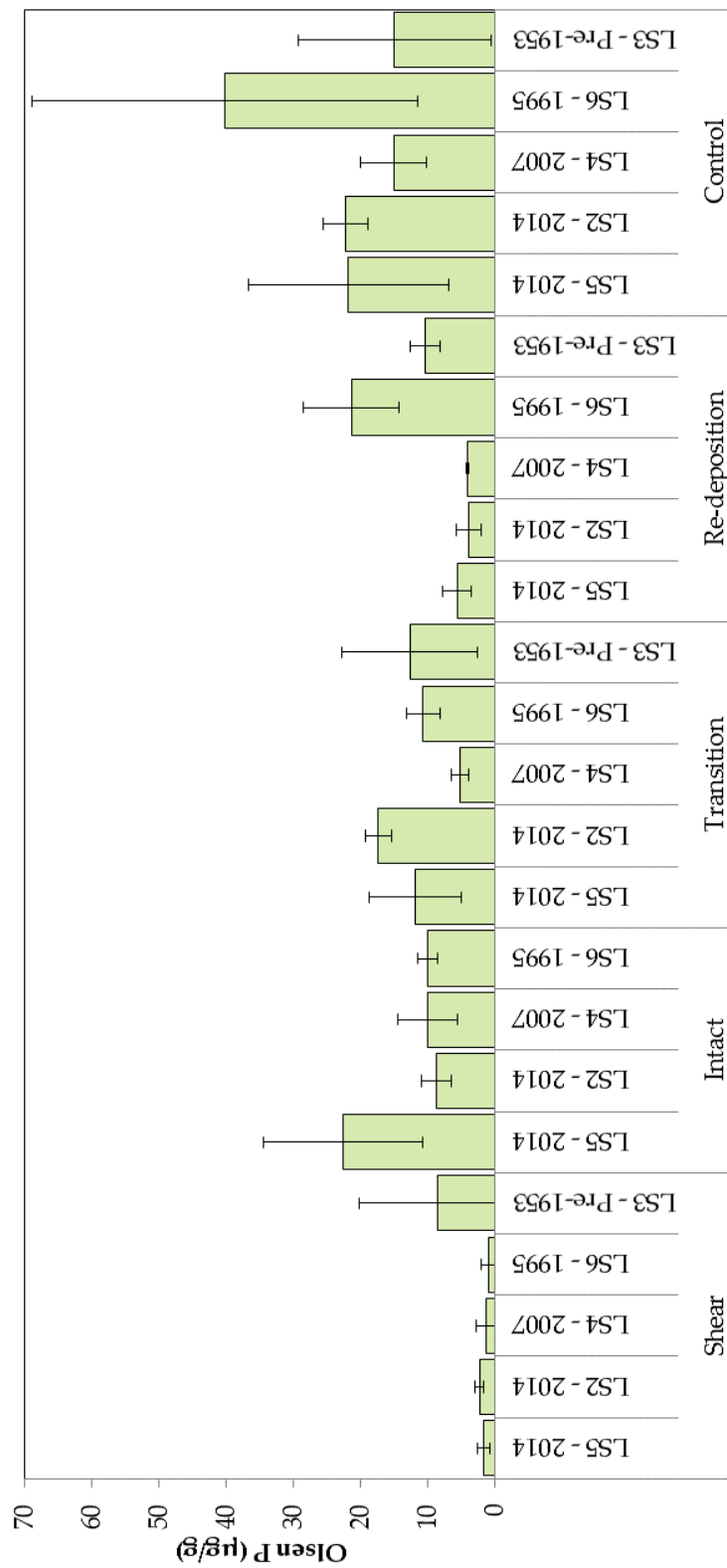


Figure 5.7: LS2 to LS6 Olsen P values for each zone in landslide chronological order, oldest to youngest landslide events.

The Olsen P ranged from 15 to 40 in the control zones (Figure 5.7). Large errors on measurements were related to field and laboratory variability. Field variability within zones was often greater than the laboratory replicates. LS1 had markedly higher Olsen P values than those of other sites (Figure 5.8). The Olsen P values within LS1 had unusually high Olsen P levels across all zones that were much higher than those expected in hill country soils (Figure 5.8). The measurements of the shear zone of LS1 had wide errors as a result of the zone being sampled from a semi-recovered slope together with a near vertical head scarp above the intact accumulation zone (i.e. There is a demonstrably wide variability in the field properties). The control zone of LS1 had assays similar to the Olsen P results from the other five control sites.

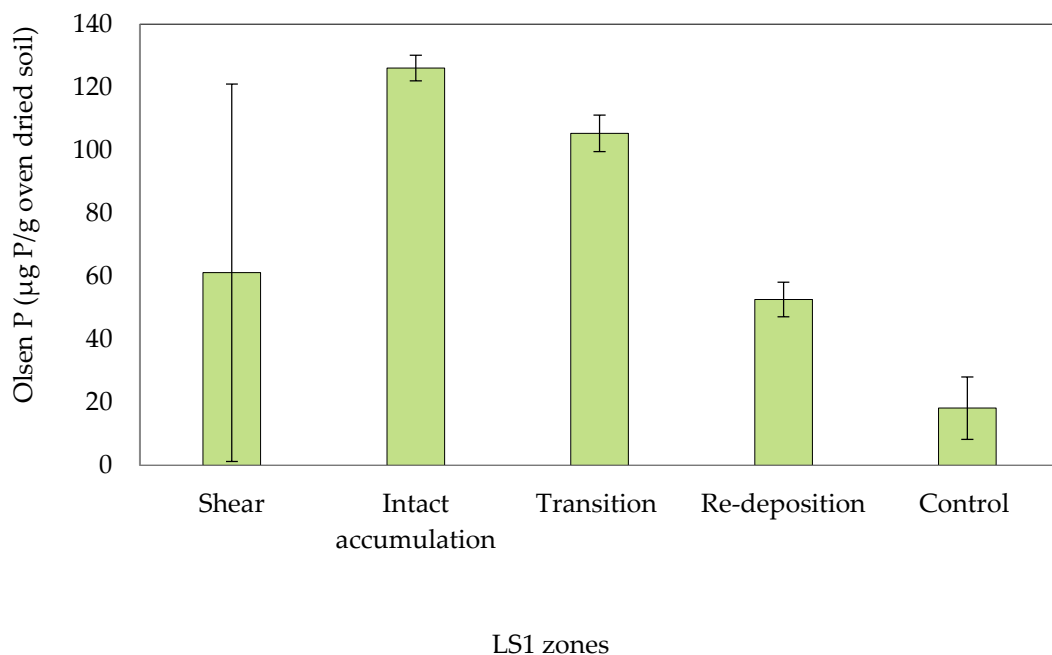


Figure 5.8: LS1 had high Olsen P levels in all zones except the control zone.

When the Olsen P data were plotted against total C there was potentially a small correlation with an  $R^2 = 0.5401$  for the landslides analysed when omitting LS1 (Figure 5.9).

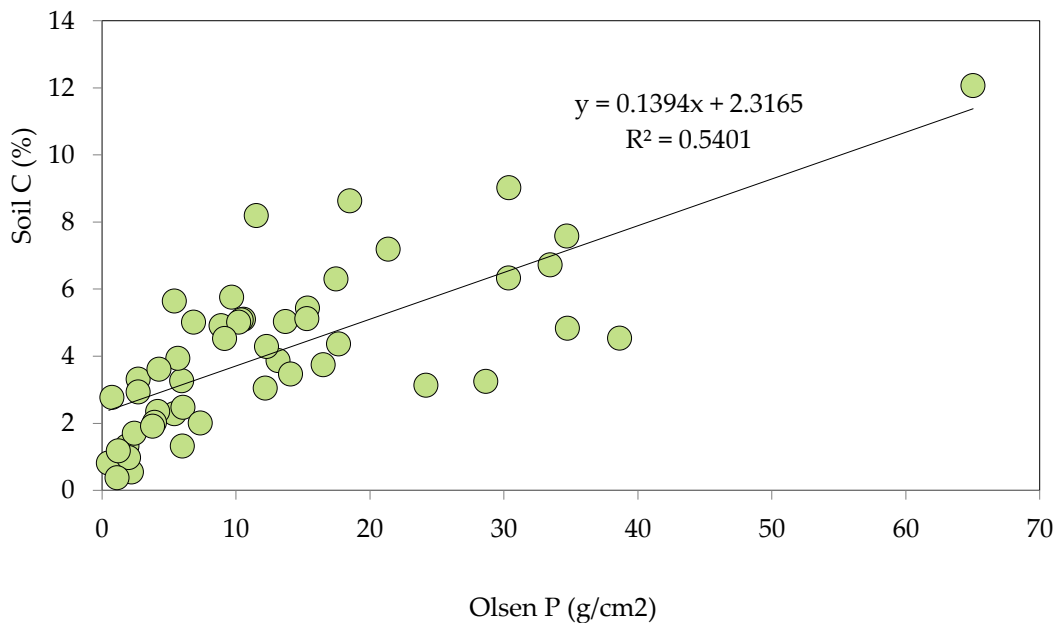


Figure 5.9: Correlation between total C (%) and Olsen P with LS1 omitted from analysis.

### 5.2.3. Soil pH

Soil pH ranged from 4.7 to 5.6 with no significant differences between landslides or zones (Figure 5.10). The ranges of soil pH measured in the A horizon in the controls and within the landslides were consistent with results from Bruce (1978) for three soil types in the area: Waingaro steepland, 5.2, Dunmore silt loam, 5.5, and Kaawa hill soils, 5.6. The lowest pH levels were recorded in LS6 within the transition and re-deposition zones (pH 4.8 and 4.7), which were areas under the revegetating native shrubs.

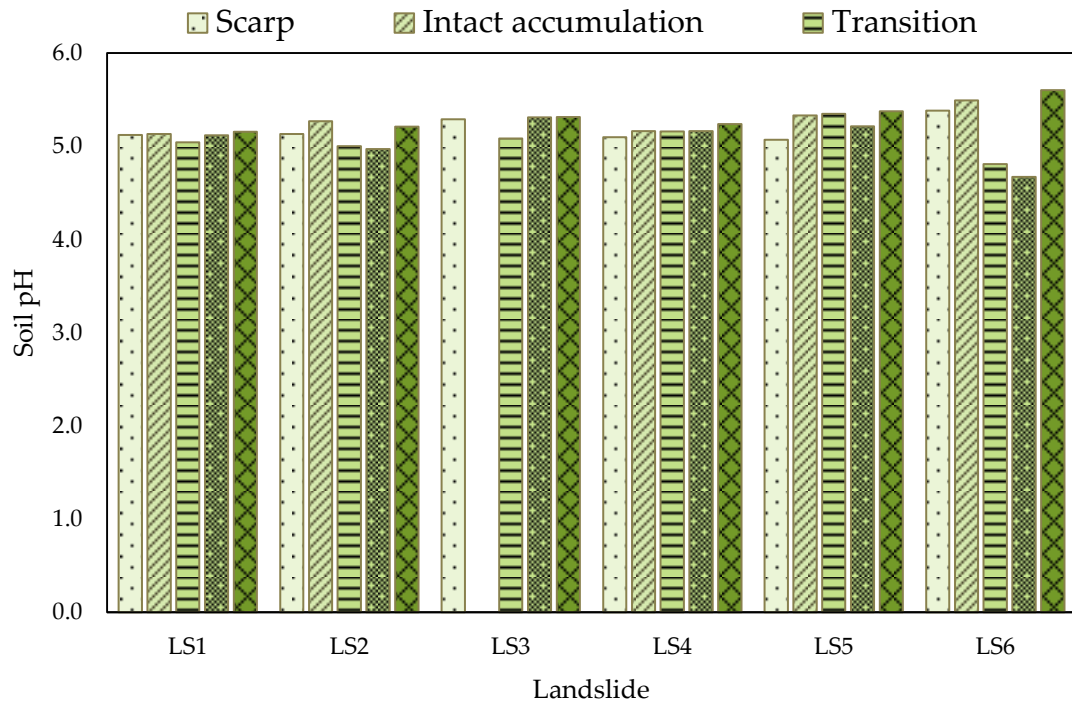


Figure 5.10: Soil pH for all six landslides with majority of pH 5 to 5.6 with lowest pH soils recorded in LS6.

### 5.3. Physical soil properties

#### 5.3.1. Soil dry bulk density and associated properties

The soil dry bulk density across all landslides and zones was variable (Figure 5.11). The lowest soil dry bulk densities were in the friable allophanic Dunmore hill soils. Higher values were attributed to the Waingaro stepland soil and the Kaawa hill soils (Figure 5.11).

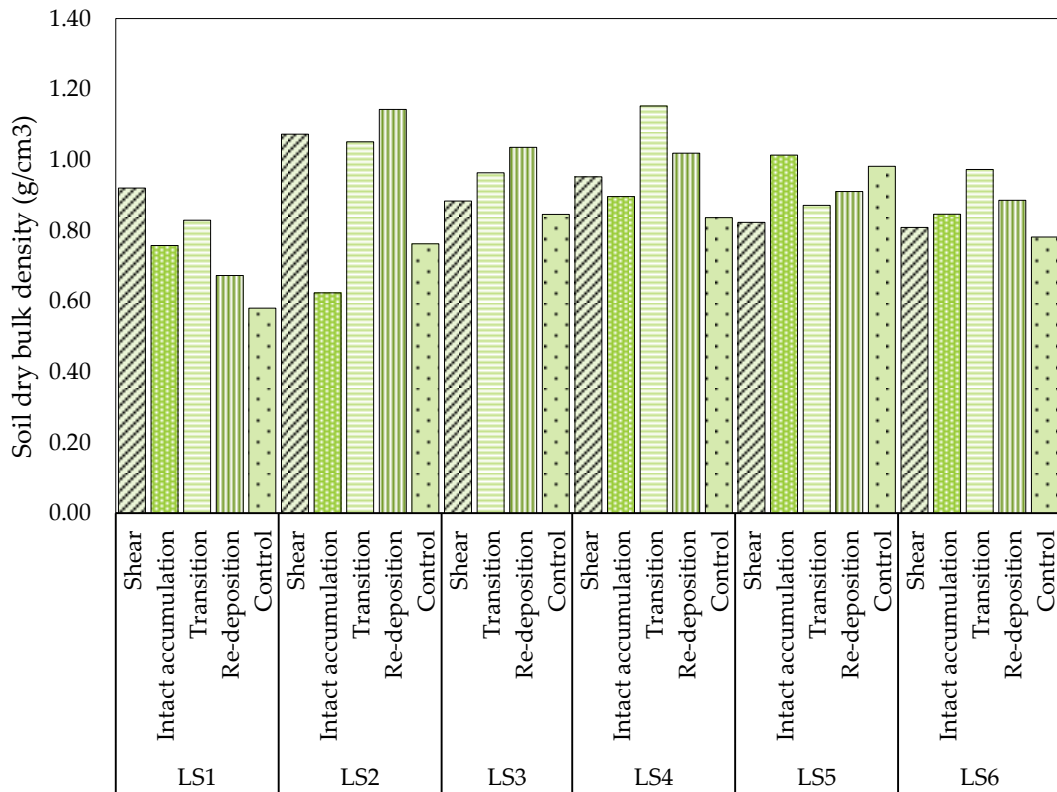


Figure 5.11: Soil dry bulk density, by landslide ordered into zones.

The soil dry bulk density had a negative correlation with C ( $R^2 = 0.329$ ) (Figure 5.12).

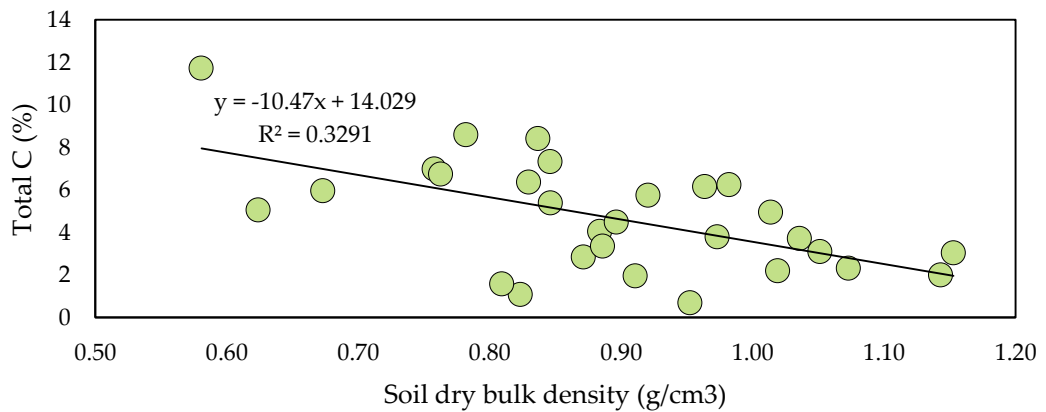


Figure 5.12: Correlation between soil dry bulk density and total C.

### 5.3.2. Particle size

The particle size data did not differentiate between landslides, with most soils falling under the category of clay loams (Figure. 5.13). The shear zone in LS4 had low clay content compared to that of almost all other sites, with higher sand and silt contents, thus classifying it as a sandy loam. A few other sites were classified as loams due to their composition and particle size.

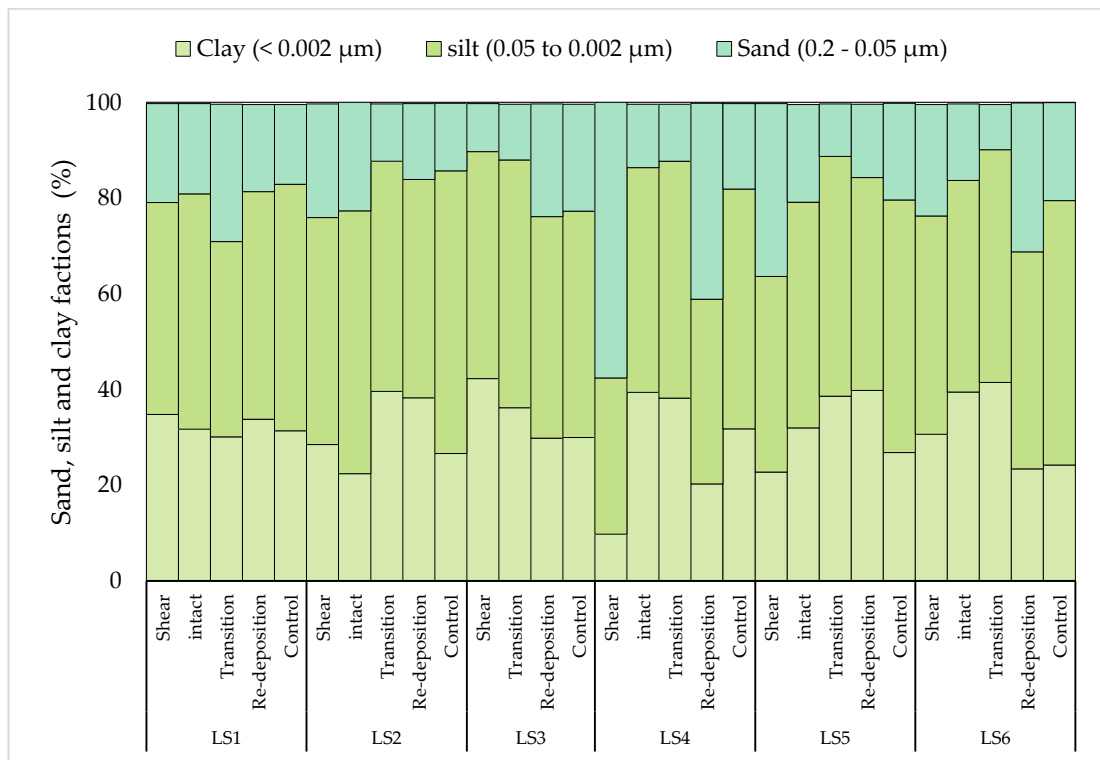


Figure 5.13: Particle size of all of the zones across the six landslides studied.



## **Chapter 6: Discussion and conclusions**

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### **6.1. Introduction**

This chapter reviews key findings of this thesis and discusses some of the findings, focusing on factors that may be influencing the rate of soil recovery and topsoil development following landslides in the field area at the Whatawhata Research Station including the landscape and landuse influences, landslide ages, landslide zones, along with the physical and chemical properties of the soil collected from within the landslides and their respective zones. My hypothesis is addressed, possibilities for future research are discussed and key conclusions are drawn.

### **6.2. Review of key findings**

#### **6.2.1. Summary of key findings**

My thesis investigated soil recovery following landslides in hill country and steepland in a field area on the Whatawhata Research Station 25 km west of Hamilton, North Island. Six landslides were studied, ranging in activation time from pre-1953 to 2014. Based on geomorphological analysis, the landslides were divided into five zones: shear zones (mean of 25 % of landslide area), intact accumulation zones (20 %), transition zones (40 %), and re-deposition zones (15 %), plus an adjacent control zone. Soil physical and chemical properties including solum depth, A horizon depth, particle size, and soil dry bulk density, along with, soil C, N, P, and pH, were determined for soils on each zone of each landslide.

The rate of soil recovery (defined here as the ability of a soil to attain profile depth features and physio-chemical properties that generally accord with those of equivalent soils in the non-landslide control zones) and development between landslides of varying ages and their respective

zones varied. The differences in soil development, and in C, N, and P, between zones within landslides were greater than the differences between the landslides of different ages.

Shear zones take the longest to recover following landslides; they generally had the shallowest A horizons, shallowest depth of solum, and lowest C, N, and P levels. However, they occupy only about 25 % of the landslide area.

Intact accumulation zones were similar to control zones, but more variable and some had areas of exposed bare subsoil (or pre-soil regolith) which take longer to recover than soils in all the other zones. The re-deposition and transition zones were areas where soil accumulated and, once stabilised, such zones are expected to be reasonably productive.

A horizon depths in the shear (1.2 cm) and re-deposition (2 cm) zones were shallower ( $P < 0.05$ ) than those in the intact accumulation, transition, and control zones. The A horizon depths in the intact accumulation zones (mean 16 cm) were the most similar to depths of the control zones (approximately 21 cm). The transition zones had variable A horizon depths (mean 7 cm).

Solum depth in the shear zone was shallowest (mean 24 cm), whilst the intact accumulation and re-deposition zones were most like the controls having solum depths  $> 90$  cm. The solum depths of the transition zone were variable (range average 17 to  $> 100$  cm).

### **6.2.2. Age and occurrence of landslides at in the field area at Whatawhata Research Station**

Multiple landslides occurring in one catchment is not uncommon in New Zealand hill country, particularly following periods of intense rainfall (e.g. Reid & Page, 2002; Crozier, 2005). The Barkers Block (where this study

was carried out) was not dissimilar. For example, multiple landsliding events at the Whatawhata Research Station were evident in a 2008 image (Figure 6.1).

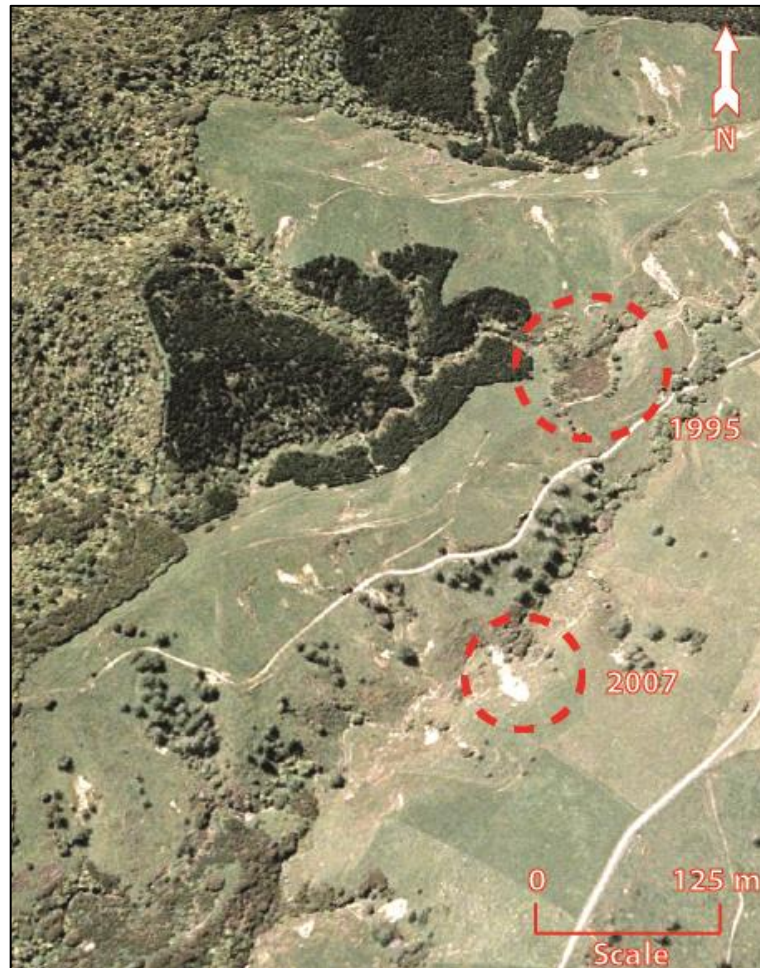


Figure 6.1: A large number of erosion sites are visible within the above image from 2008 at the Whatawhata Research Station. Circled are two landslides studied in this thesis, LS6 (1995) and LS4 (2007) (image: Google Earth, 2015).

The hills of the Whatawhata Research Station have been subjected to multiple hillslope mass movement events and the landscape hosts an array of landslides in varying states of recovery as a result of time of landslide activation and re-activation (pre-1953 to 2014). For example, Landslide 5 (LS5) appeared to initially start moving before 1953 (aerial photograph, 1953), but recovered and was then re-activated during

Cyclone Bola in 1988 (I. Power, personal communication, December 11, 2015) and again in 2014 (Google Earth, 2015).

### **6.2.3. Landslide recovery**

My results indicate that the soil recovery rate at Whatawhata Research Station was similar to that reported in other parts of New Zealand where the oldest landslides had recovered to between 51 to 84 % of their respective undisturbed controls for C and 47 to 86 % for total N (Sparling *et al.*, 2003; Rosser & Ross, 2011). However, my results did not indicate that C and N accumulation was increasing markedly over time (probably as a result of low sample numbers and high variability) when compared to non-eroded sites, unlike prior research into landslide C and N soil recovery (Sparling *et al.*, 2003; Rosser & Ross, 2011).

Previous research measuring landslide recovery generally analysed landslide scars as a whole unit, investigating soil recovery in terms of solum depths, soil physical and chemical properties, and pasture productivity through chronosequences (Trustram & De Rose, 1988; Smale *et al.*, 1997; Sparling *et al.*, 2003; Rosser & Ross, 2011). In contrast my research investigated different zones within the landslides, along with age to ascertain if some parts of the landslide recovered faster than others through time. Consistent with past studies (Sparling, *et al.*, 2003; Rosser & Ross, 2011) on landslide soil recovery, my findings showed that the soil chemical properties could be used as indicators of soil recovery following landslides, for example total N and C content and, topsoil development.

The slope of the landslide was discussed in De Rose (1995), who found that pasture productivity and mean annual herbage declined in soils on hillslopes  $\geq 28^\circ$ . Whilst I did not investigate herbage in my study, the C

and N showed noticeably lower accumulation levels in the shear zones which were often steeper than slope angles in other zones.

#### **6.2.4. Zones within the landslides**

I divided the landslides into geomorphic zones to determine how well soil was recovering. Each landslide zone had different characteristics and was either an attrition zone (eg. shear zone) or a combination of both receiving and attrition environments, such as the transition, intact accumulation, and re-deposition zones. Each zone had different influencing factors, for example slope, size, position within the landslide and, whether it was a receiving or attrition environment. Thus each the soils in zone were expected to recover at different rates.

The zones captured variations within each landslide, indicating that some zones such as the intact accumulation and transition zones recovered faster. The transition and intact accumulations had higher ( $P < 0.05$ ) C and N concentrations and greater topsoil depths than those of the shear and re-deposition zones and were therefore likely to be more productive.

The least productive and least recovered zone across all six landslides was the shear zone. The shear zones were generally steep-faced exposed surfaces within the landslides comprising about 25 % of the total landslide areas. They were the slowest to recover. The C and N levels were generally lower in soils within the shear zone than in soils of other zones or of the controls.

The intact accumulation zones made up about 20 % of the landslide area and were similar to the control zone as the soil had remained largely intact during landslide activation. Thus the intact accumulations had potential for rapid soil recovery. However, large cracks occurred between the blocks of intact soil these blocks of soil tended to have slower recovery

rates because small areas in the crack of exposed subsoil lacked topsoil development. For example the accumulation of soil in the cracks between blocks in the intact accumulation zone of Landslide 5 has taken approximately 30 years to reach depths of about 1 metre through infilling and degradation of the intact blocks.

The transition zones (about 40 % of landslide area) were dominantly a place of soil accumulation whilst also being a zone of attrition and were highly variable. Within the transition zone, small intact blocks of rafted materials or areas where not all topsoil had been lost, tended to be better recovered than areas that had lost soil down to exposed subsoil and parent material.

The re-deposition zone (about 15 % of landslide area) tended to recover more quickly than the shear zone as both a receiving and attrition environment.

Therefore, because the transition, intact accumulation, and re-deposition zones were receiving environments they tended to have higher C and N contents and thus were likely to be relatively productive once they reached a stable state.

#### **6.2.4. Soil properties within the zones**

##### *a) Carbon contents*

The soil recovery over time, as measured by C and N contents, was variable, with highest C and N in the pre-1953 landslides and in the intact accumulation zones in all slides. The 1995 to 2014 landslides had the least recovery of soil C and N in the shear zones (8 to 34 % of control), and had only recovered to about 30 % of the control values in the re-deposition zones.

The shear zone across all landslides had the slowest soil recovery rate following landsliding and had considerably lower total C than the other zones (Figure 6.2). For example, C accumulation in the shear zones had recovered to only 8 % of that of the controls after 9 years since LS4 was activated in 2007. The shear zone had accumulated 18 % of the C of the levels of the control zone after 20 years and then took about 60 years to reach the 50 % levels of the control sites.

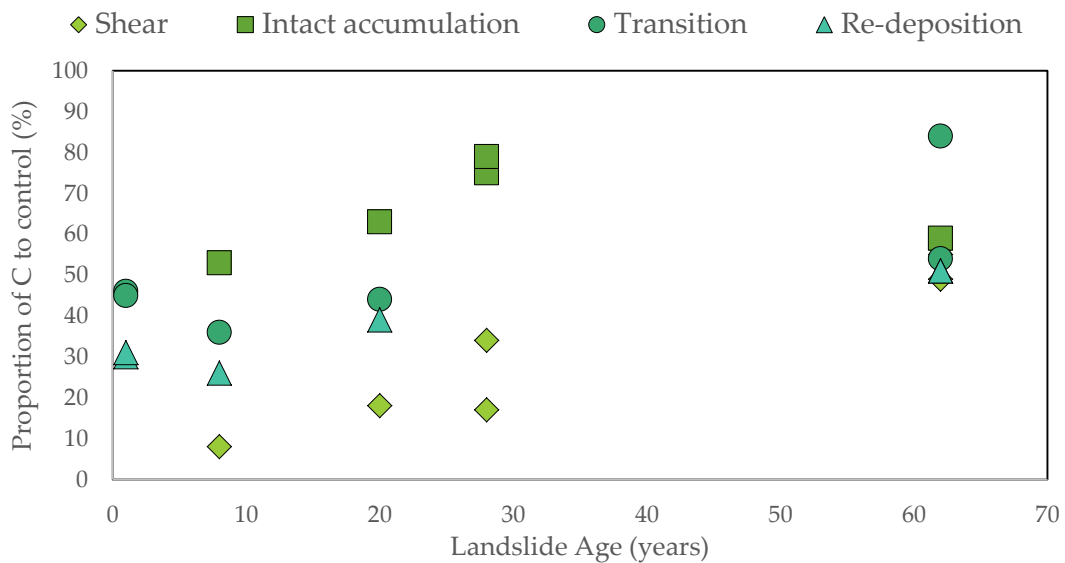


Figure 6.2: Percent of carbon in soils in each landslide zone relative to those for soils in the adjacent controls.

The C content in the transition zones was variable spatially, and with time, most likely because of the soils comprised a combination of rafted materials along with exposed subsoils. The least recovered transition zone was from LS4 which was a translational landslide. Re-activation of the steeper rapidly occurring landslide could potentially explain why it had lower C accumulation than the two earthflow landslides (LS2 and LS5) which, whilst only occurring in 2014 had higher percentages of the C of the control (at 54 and 45 % respectively) compared with the C content of

LS4 which had about 35 % of the C of the control. LS6, also a translational landslide, had 44 % C in the transition zone of its control, suggesting that soils on it were recovering also at a slower rate than those on the earthflow landslides. Contrary to that explanation are LS1 (54 % of control, earthflow) and LS3 (84 % of control, translational). Both LS1 and LS3 were estimated to have been activated about 62 years ago. However, exact dates were unobtainable for either landslide. LS3 had higher C contents in the soils of the transition zone of the control than the content of LS1, suggesting that LS3 may be older than the 62 year estimated activation date on the basis of the C content being 84 % of that of the control.

As the re-deposition zones all represent areas of soil accumulation following landsliding, the type of landslide may not need to be taken into consideration. The youngest re-deposition zones (LS2 and LS5) had accumulated about 30 % of C of the controls, whilst in LS4 the C content in the re-deposition zone was 26 % of the control. The re-deposition zone for LS4 was close to the stream, a much smaller landslide, with a narrow funnelling re-deposition zone which may explain the marginally lower C % compared to LS2 and LS5. As LS2 and LS5 have activated on a number of occasions some parts of the area may have been more recovered than others. LS6 (the 20 year old landslide), had 39 % of C of the control in the re-deposition zone. Whilst much of the topsoil and subsoil was probably lost to the stream at the time of the landslide the landslide has been reverting to native bush, which may be trapping further sediments from being lost from the system. Leaf litter may also be contributing to the C accumulation within the soil.

The intact accumulation zones all had C levels all above 50 % of control (53 to 79 %). The lower C contents measured in the intact accumulation zones compared to their controls were most likely attributed to samples

being combined with raw/recent soils in the crevices between blocks. The intact accumulation zone in LS4 (the 8 year old slide) had the lowest C levels whilst unusually LS2 and LS5 (which are assumed to have had the intact zones activate about 1988 during cyclone Bola) had the highest percent of accumulated C when compared to that of the controls. Generally, with time, soil C increased. Overall the mean soil C contents of the intact accumulation zones were higher than those in soils in the other landslide zones but lower than those in the controls.

#### *b) Nitrogen contents*

The C:N ratio remained constant (Figure 5.5), thus N levels behaved in much the same way as the C contents, with the same patterns evident. Soil total N was variable across the zones of the landslides with the oldest landslides and the soils in the intact accumulation zones having the highest contents of N. The N contents of soils in all zones differed ( $P < 0.05$ ) from one another.

#### *c) C:N ratio*

In the youngest landslides the C and N contents were low but the C:N ratio was balanced (Figure 5.6). All zones and landslides measured had largely balanced C:N ratios. Therefore my findings are in general concurrence with Sparling *et al.*, (2003) who reported that the C:N ratio recovered to levels similar to those of the controls within 5 years and that soil C had recovered to about 80 % of adjacent non-eroded areas after 80 years.

#### *d) Topsoil development and solum depth*

The topsoil depths varied between zones but were generally within the range reported by Trustram & De Rose (1988) on New Plymouth hill soils following landsliding. Although Trustram & De Rose (1988) did not

distinguish between landslide zones they did recognise rafted material that would be equivalent to the intact accumulation and transition zones in my study.

A horizon development (as measured by thickness) in the shear zone was poor. Shear zones had shallow A horizons (mean of 2 cm), and shallow solum depths (mean of 24 cm). The shallow A horizons in the shear zones were attributed to their occurrence on steeper slopes and in many cases had lost the entire soil profile, exposing the parent material.

Intact accumulation zones had deeper ( $P < 0.05$ ) A horizons (mean of 17 cm) than those of other zones within the landslides which was attributed to the soil moving downslope in undisturbed blocks that therefore retained the original topsoil.

Due to the substrate variability of the transition zone it was difficult to determine A horizon soil development. The transition zones had mean A horizon depths of 7 cm and mean solum depths of 70 cm.

The re-deposition zone A horizon depths were similar to those in the shear zone. The re-deposition zones had shallow A horizons (mean of 2 cm) with the youngest landslides often having no, or minimal, topsoil. However, as was evident in the transition zone, the re-deposition zones are areas where soil accumulation occurs, sharing similar solum depths (about 90 cm) and thus these soils are likely to recover more quickly and to be more productive than the soils in the shear zones.

#### *e) Soil P, pH and soil dry bulk density*

The plant available P, soil dry bulk density and soil pH results obtained during this study were not directly associated with topsoil recovery following a landslide, nor with the age of landslide, which is consistent

with results of soil recovery reported by Sparling *et al.*, (2003); Rosser & Ross, (2011); De Rose, (2013); and Parfitt *et al.*, (2013).

### *Olsen P*

Soil Olsen P levels varied between landslides and controls, and the results were possibly influenced by the large scale fertiliser trial conducted at the research station during the 1980s and 1990s as noted earlier (Gillingham *et al.*, 1990). Landslides 1 to 5 (LS1 to LS5) are likely to have been influenced to some extent as a result of the trials. Particularly high Olsen P values were likely to be a result of the fertiliser trial. LS1 was situated within the boundaries of a paddock that had received 100 kg ha<sup>-1</sup> yr<sup>-1</sup> of superphosphate fertiliser throughout the trial (1984 to about 2013). Soil measurements for the 100 kg ha<sup>-1</sup> yr<sup>-1</sup> sites recorded Olsen P values above 80 in 1988 (Gillingham *et al.*, 1990), whilst in 2003 the paddock had Olsen P values exceeding 120 (Power, n.d.). Landslide LS2 (50 kg ha<sup>-1</sup> yr<sup>-1</sup>), LS4 (100 kg ha<sup>-1</sup> yr<sup>-1</sup>), and LS5 (30 kg ha<sup>-1</sup> yr<sup>-1</sup>) were in paddocks in which fertiliser application ceased after 1990, whilst LS3 was also in a maintenance paddock that received 30 kg ha<sup>-1</sup> yr<sup>-1</sup> (I. Power, personal communication, December 11, 2015). These three paddocks did not reflect the fertiliser application rates because LS1 had probably resulting from the cessation of fertiliser application from 1990.

Because of LS1's exceptionally high Olsen P values it was removed from statistical analyses. Once LS1 was removed from analysis the Olsen P values were lower ( $P < 0.05$ ) than those in the controls in only the shear and re-deposition zones. The intact accumulation and transition zones were not significantly different from the control with regard to Olsen P values. Thus it was concluded that Olsen P has little association to physical soil recovery and topsoil development.

### ***Soil pH***

Soil pH was consistent across all landslides except for Landslide 6. LS6 had lower pHs in the transition (pH 4.8) and re-deposition (pH 4.7) zones that were under recovering native bush and invasives. Rosser and Ross (2011) reported that slip sites in the Wairarapa had high soil pH (6.8 and 8.2) in the youngest landslide scars, which decreased significantly with landslide age. Their research was conducted on poorly consolidated calcareous siltstone parent material which would influence soil pH. With time, Rosser and Ross (2011) observed a decrease in soil pH (5.5) in landslide scars older than 60 years which had returned to uneroded levels (i.e. recovered). However, in comparison the landslide scars I analysed generally had low soil pH, likely a result partly of the high rainfall (hence strong leaching) and the greywacke parent material which lacks the calcareous components that were found in the siltstones analysed by Rosser and Ross (2011). Thus my findings assume that pH was not a factor of soil recovery and that the soil pH was most likely associated with soil type. The lowest soil pH usually occurred in the Waingaro steep-land soil with marginally higher soil pH in the Kaawa hill and Dunmore soils (Bruce, 1978).

### ***Soil dry bulk density***

When the soil dry bulk density was plotted with age of landslide there was no trend ( $R^2 = 0.1326$ , Figure 6.3). My results were not consistent with those of Sparling *et al.* (2003) who reported that as landslide age increased there were decreases in soil dry bulk density, taking 50 years to reach uneroded levels.

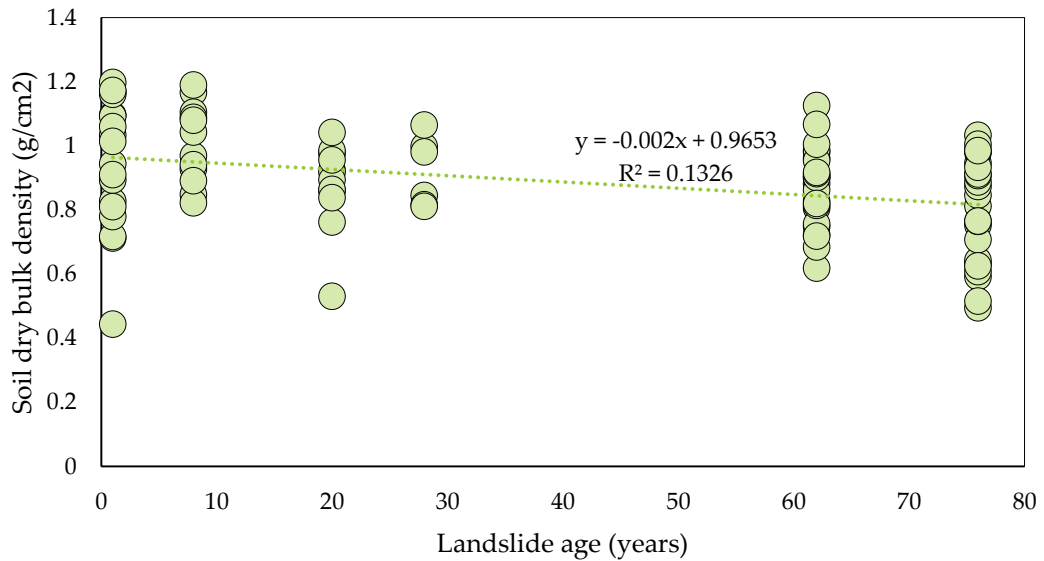


Figure 6.3: Correlation between soil dry bulk density and landslide activation age.

### 6.3. Review of hypothesis

My hypothesis was that topsoil will have increased in depth and organic matter content with time since disturbance, and that soils on more gently sloping landslide areas will show greater recovery (i.e. greater degree of similarity with the soils and soil properties of the control zones) than those on steeper slopes.

The statement that topsoil depth and organic content will increase with time can be generally accepted apart from in the shear and re-deposition zones where topsoil depths were generally shallow and had lowest C content ( $P < 0.05$ ).

The statement that soils on the more gently sloping areas will show greater recovery than the steeper slope may also be accepted, however it must be rejected in the case of the re-deposition zones. Although these zones are on gently sloping land, they did not show greater recovery than the intact accumulation or transition zones.

## 6.4. Soil productivity

At similar sites to ours in the Taranaki region, De Rose, *et al.*, (1995) reported that pasture production recovered fastest in the first 40 years after landslides and fully recovered after 80 years, whereas Rosser and Ross (2011) suggested that most pasture productivity recovers in the first 20 years with only slow further gains thereafter. Our observations suggest that in the intact accumulation, transition, and redeposition zones at Whatatwhata, pasture production will recover well within 20 years but that in the shear zones may take considerably longer to recover.

## 6.5. Further research

Further work to measure pasture production within the varying zones of the landslide, along with management such as targeted fertiliser applications to maximise pasture recovery in the most responsive zones, could improve efficiency of management response following landslides. Another property that might deserve further analysis is that of soil-water holding capacity.

## 6.6. Summary and conclusions

My research investigated soil recovery following landsliding at the Whatawhata Hill Country Research Station 25 km west of Hamilton. Six landslides of varying ages (pre-1953 to 2014) were identified through aerial photographs and ground truthing. The landslides were divided into four zones: shear zones, intact accumulation zones, transition zones, and re-deposition zones, together with an adjacent control zone that represented the undisturbed soil pre-landslide. The landslides were then analysed to determine their soil physical and chemical properties including: solum depth, A horizon development, particle size and dry bulk density, along with, soil C, N, P, and soil pH. These parameters were

then compared with those of similar soils in adjacent uneroded land (control zones) to evaluate the degree of recovery of the soils in the landslide zones.

The overall conclusion was that the differences in soil development, and in C, N, and P, between zones within landslides were greater than the differences between landslides of varying ages. Soils were well-developed in the control and intact accumulation zones and least recovered in the shear and re-deposition zones. Mean A horizon depths ranged from 2 cm in the shear and re-deposition zones to 7 cm in the transition zones, 17 cm in the intact accumulation zones, and 20 cm in the control. Mean solum depths ranged from 24 cm in the shear zones, 91 cm in the intact accumulation zones, 72 cm in the transition zones, 90 cm in the re-deposition zones and >100 cm in the control zones.

The soils in the controls had higher ( $P<0.05$ ) C contents than in any of the soils in the zones within the landslides, and the soil in the intact accumulation zones had higher ( $P<0.05$ ) C contents than those in the shear, transition or re-deposition zones. Mean soil C contents ranged from 8.2 % in the controls through 5.4 % (intact accumulation zones), 4.2 % (transition zones), 3.2 % (re-deposition zones) to 2.6 % in the shear zones.

Similarly, the total N was higher in the soils in the controls than in the soils in the landslide zones ( $P<0.05$ ). Mean N content ranged from 0.2 % in soils in the shear zones, 0.3 % in soils in the transition and re-deposition zones, 0.5 % in the intact accumulation zones to 0.7 % in soils in the control zones.

The shear zone, on average made up 25 % of the total landslide area, and its soils had the lowest C, N, and P and generally had the shallowest A

horizon and solum depths, and took the longest to recover following landsliding. The shear zones had the steepest slopes and all soil material had been removed by landsliding and so soil formation commenced in newly exposed (exhumed) parent material. In other zones, pre-existing soil materials were present; therefore recovery was faster in the intact accumulation, transition and re-deposition zones than in the shear zones.

The soils of the intact accumulation zones were most similar to those of the controls and occupied about one quarter of the total landslide area. They were variable compared to the controls, with some areas of exposed bare soil which take longer to recover. However, because most of the area comprising intact blocks of soil, the intact accumulation zone would remain relatively productive.

The transition zone and the re-deposition zone make up approximately 55 % of the total landslide area and are zones of soil and nutrient accumulation and once they have stabilised they are expected to be reasonably productive.

Soil Olsen P was lower ( $P < 0.05$ ) in the soils in the shear and re-deposition zones than those in the control, intact accumulation, and transition zones. The results were variable with no discernible differences observed between the soils of the intact accumulation, transition or control, with the results likely attributed to variable fertiliser distribution. Soil pH was generally low across all six landslides and soil dry bulk densities were variable. Thus soil pH, dry bulk density and Olsen P were assessed as not strongly correlatable with soil recovery and development.

Measuring the total C and N of a soil gave a good indication of how well a soil had recovered following erosion and landsliding, particularly when investigating landslides of known age. Dividing the landslides studied

into zones gave me an indication of how different portions of a landslide were recovering. Whilst the shear zones remain relatively unproductive as a result of soil loss and their steep slopes, the soils of the other zones of the landslide generally recovered faster. Further research into pasture productivity in each of the zones would be beneficial.



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# Appendix A

## Soil recovery following landslides at Whatawhata Research Station, Waikato, New Zealand: preliminary results

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### Abstract

This research investigates soil recovery following landslides at the Whatawhata Research Station 20 km west of Hamilton. Six landslides were studied, ranging in age from pre-1953 to 2014. The landslides were divided into four zones: shear zones (mean of 25% of landslide area), intact accumulation zones (20%), transition zones (40%), and re-deposition zones (15%), along with a control. Soils were well-developed in the control and intact accumulation zones and least recovered in the shear and re-deposition zones. Mean A horizon depths ranged from 2 cm in the shear and re-deposition zones to 7 cm in the transition zone, 17 cm in the intact accumulation zone, and 20 cm in the control. Mean soil carbon contents were lower ( $P < 0.05$ ) in the landslide zones (range of 3.2–5.2%) than in controls (8.2%). Older landslides showed greater recovery; however, the differences between zones within the landslides were greater than the differences between landslides.

**Keywords:** mass movement, soil carbon, hill country

### Key statements

- Four geomorphic zones were identified within landslides
- Soil recovery varied more between zones than between landslides of different ages
- The least recovered shear zones comprised less than 25% of the landslide area.

### Introduction

More than 40% of New Zealand is moderately to very steep, forming extensive hill country (21–25°) and steeplands (>26°) (Leathwick *et al.* 2003). Such landforms are prone to slope failure resulting in landslides, particularly during periods of high rainfall which often triggers earth movement (Crozier 2005; De Rose 2013). Landsliding (mass movement) results in soil materials and nutrients being transported down-slope leaving an exposed surface that then needs time for soil to regenerate to be productive once more (Sparling *et al.* 2003; Rosser & Ross 2011; Heaphy *et al.* 2014).

Studies on a number of sites in New Zealand have measured the impacts of landslides on soil carbon (C), nitrogen (N), Olsen P, soil pH, CEC, bulk density,

porosity, soil depth and pasture productivity through time. The findings often concluded that, following landslide events, soil C content increases over time, on average taking ~60 years to recover to ~80% of total C in adjacent undisturbed areas (Lambert *et al.* 1984; Sparling *et al.* 2003; Rosser & Ross 2011; De Rose 2013). Unlike soil C, the soil pH and total phosphorus (P) changes over time were not associated with landslide age (Sparling *et al.* 2003). The C:N ratio recovered more quickly than physical soil properties when compared to non-slip sites (Sparling *et al.* 2003). The overall aim for this research was to improve understanding of soil recovery following landslides. The specific objectives were to:

- Identify and map landslides on the hill country and steeplands of Whatawhata Research Station, and to characterise selected landslides based on geomorphology, age, and soil characteristics
- Determine topsoil depth, colour, horizon development, and C, P, and N contents of four defined zones within each of the chosen landslides as well as a control zone for each site
- Develop a chronosequence of the soil properties using landslides of varying ages.

### Methods

#### Site description

The Whatawhata Research Station is a sheep and beef farm situated about 20 km west of Hamilton, New Zealand. The soils on steeper hills are derived from Mesozoic siltstones, sandstones, argillite and greywacke (Kear & Schofield 1964). Waingaro steepland soils (Mottled Yellow Ultic Soils) occur on steeper slopes (30–40°) and Kaawa hill soils (Mottled Yellow Ultic Soils) form on the moderate slopes (18–30°). The undulating to strongly rolling hills host tephra derived from the Mairoa and Hamilton ashes, forming Dummore hill soils (Typic Orthic Allophanic Soils) (Bruce 1978). Elevation in the catchment ranges from about 60 to 375 m a.s.l. The mean annual temperature is 14.3 °C with a mean annual rainfall of 1 607 mm (NIWA, 2015).

#### Field methods

Field surveying was conducted between December 2014 and May 2015. Landslides were initially located

using aerial photographs (from AgResearch archives and Google Earth) to identify areas where probable landslide deposits and exposed soils were evident. The dates of landsliding were determined from the aerial photographs, creating a chronosequence of landslide events that dated from pre-1953 to 2014. The sites were visited for ground truthing and landslides were located using GPS. Following initial reconnaissance survey, 16 landslides were identified for further study. From the initial 16, six landslides were then chosen for detailed study and sampling, based on their morphology, dates of activation, and location (Table 1). Landslides 1–5 (LS1–5) were located within one paddock whilst Landslide 6 (LS6) was located on an adjacent ridge. Soils were investigated using a Dutch auger to determine soil horization and other profile characteristics.

Each landslide was divided into four zones (scarp zone, transitional zone, intact accumulation zone, and re-deposition zone, and an adjacent control zone). Zones were determined by visual assessment of geomorphic characteristics and physical position of the scarp zone (Figure 1). The scarp zone was characterised by near vertical faces with exposed saprolite and, at best, incipient shallow topsoils. The transitional zones consisted of 3–20 cm deep topsoils with small <1 m diameter intact blocks ('floaters' of intact soil). Intact accumulation zones were areas of the landslide where large blocks (>2 m wide) of soil had remained intact although they had moved down-slope. The re-deposition zones were areas of re-deposited soil materials resting at the foot of the landslide. Re-deposition zones often had

a shallow or non-existent A horizon overlying mixed soil materials. The control zones were located adjacent to, but outside, the landslide scar and represented the non-slipped landscape before failure.

#### Soil sample collection methods

Soil samples were collected in June 2015. Two bulked samples were collected from surficial materials in each zone of each landslide using a 3 cm diameter, 10 cm deep, core-sampler. Each sample consisted of 10 to 12 cores collected at the soil surface along a transect at about 1 m intervals in each of the five zones within each landslide area. The direction of sampling along each transect depended on the shape and size of the zone. The addition of samples from the control zones taken from side ridges adjacent to each slide gave a total of 60 samples. LS3 had only three of the zones (no intact accumulation zone was present) and so two extra samples were collected from the scarp and transitional zones.

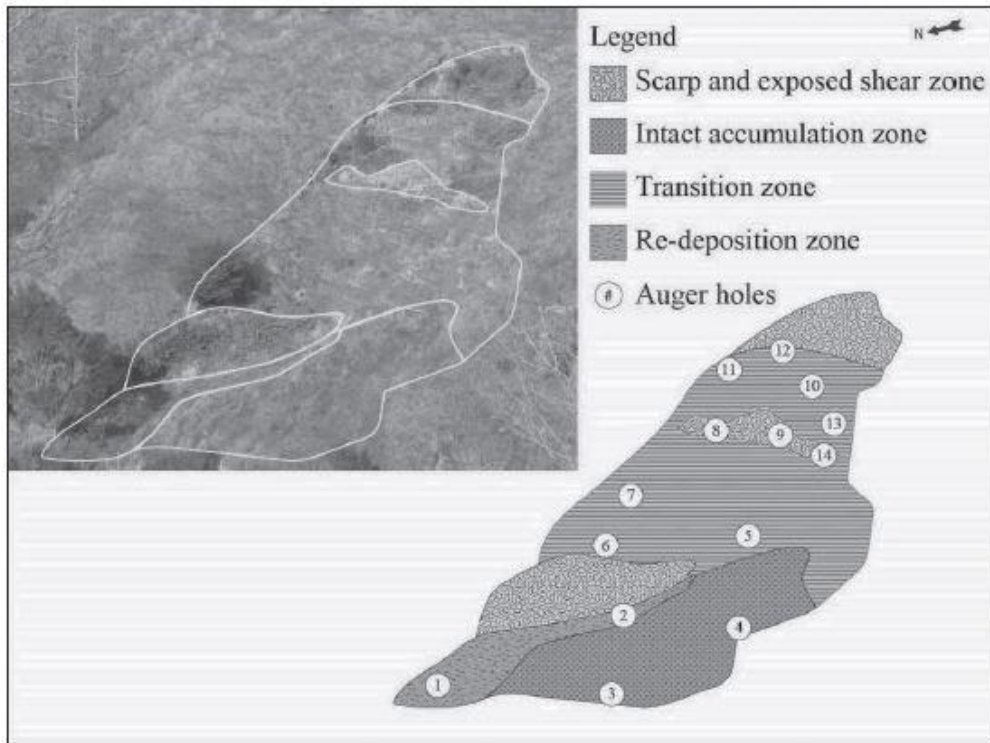
#### Laboratory methods

Soil P, C, and N, along with soil pH and moisture factors, were determined on <2 mm air dried soil fractions. To measure plant available P, the Olsen P method was used following Blakemore *et al.* (1987), but modified to increase soil from 1 g per 20 ml of NaHCO<sub>3</sub> reagent to 1.5 g and 30 ml of the reagent. Total C and total N were determined on finely-ground soil samples using the dry combustion method in an Elementar-vario EL cube furnace. Soil pH was measured in distilled water

Table 1 Site locations and photo dates when landslides were evident.

Landslide No.	GPS	Pre 1953	Date								
			1953 - 1979	1979 - 1993	1993 - 1998	1998 - 2004	2004 - 2008	2008 - 2009	2009 - 2012	2012 - 2013	2013 - 2014
1	S37°47'14.99" E175° 4'6.49"	✓	V	V	V	V	V	V	P	V	V
2	S37°47'16.47" E175° 4'5.09"	?	✓	?	✓	V	✓	B	B	X	✓
3	S37°47'16.94" E175° 4'3.73"	✓	B	V	V	V	V	V	V	V	V
4	S37°47'17.50" E175° 4'2.40"	V	V	V	V	V	✓	B	V	V	V
5	S37°47'19.81" E175° 4'0.64"	✓	?	V	V	V	✓	B	V	V	✓
6	S37°47'7.27" E175° 4'3.24"	V	✓	P	✓	B	V	✓	V	V	V

Key to table  
 V – Vegetated – no bare soil  
 ✓ – Landslide event  
 P – Probable new movement  
 ? – Possible erosion - photo too grainy to tell  
 B – Bare ground



**Figure 1** Example of landslide zones using schematic from Landslide 4, most recently activated in 2008. Soil descriptions were conducted on auger samples for typical areas within each zone on each landslide. Soil properties, including soil horization, texture, and colour, were recorded to determine soil type and to characterise the varying zones in each landslide.

at a 1:2.5 soil-to-water ratio using a Janway glass electrode probe. Soil C, N, and P values were rated as high, medium, and low following the definitions of Blakemore *et al.* (1987).

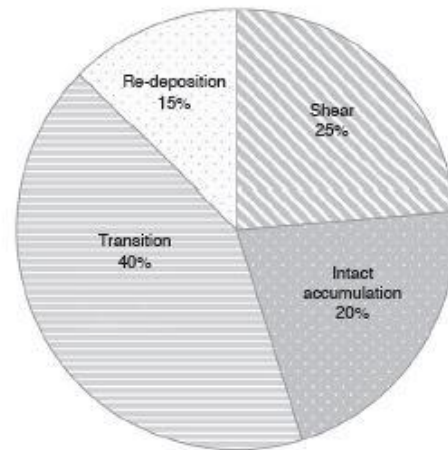
**Results**

The largest portion of the landslides (about 40%) comprised the transition zone (Figure 2). The shear zone equated to about 25% of the total landslide area.

A horizons were shallow and poorly developed in the shear and re-depositions zones, whereas the transition zones were variable depending on landslide age and floater distribution (Table 2). Intact accumulation zones were similar to control zones, but variable with some parts lacking soil between the intact blocks.

Soil pH ranged from 4.7 to 5.6 with no significant differences between landslides or zone, total C was low to medium (1–12) across the landslides, and total N was low to medium (0.1–1.0) (Table 3). The C:N ratio ranged from 11–16 across the landslides. Shear zones had the least soil recovery in terms of total C and N. Soil C and N were lower ( $P < 0.05$ ) in each of the landslide zones compared to the control zones.

LS1 had unusually high Olsen P levels across all zones that were much higher than those expected in



**Figure 2** Mean area of each zone, as a proportion of total landslide area.

# Appendix A

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Table 2 Soil depths, plant root depth, and A horizon colour for landslides at Whatawhata Hill Country Research Station.

Zone	A horizon depth (cm)		Solum depth (cm)		Typical A horizon colour	Root depth (cm)
	Mean	Range	Mean	Range		
Shear zone	2	0-7	24	0-100+	10YR 4/6 brown	ND
Intact accumulation zone	17	5-25	91	40-100+	10YR 3/4 dark brown	53
Transition zone	7	1-20	72	17-100+	10YR 4/3 dull yellowish brown	46
Re-deposition zone	2	0-5	90	50-100+	10YR 3/4 dark brown	26
Control	20	15-30	>100	80-100+	10YR 3/4 dark brown	ND

\* ND = Not determined

Table 3 Mean Olsen P and soil pH and soil Total N, Total C, C:N ratio and proportions of C and N relative to controls for each zone in six landslides.

Landslide	Zone	Proportion of landslide area	Olsen P <sup>2</sup>		Soil pH <sup>3</sup>	Total N <sup>3</sup>	Total C <sup>3</sup>	C:N	Proportion of N to control	Proportion of C to control
			%	Mean	Std. Dev.	Mean	%	%	%	%
1 (pre-1953) <sup>1</sup>	Shear	21	61	59.9	5.1	0.4	6	13	47	49
	Intact accumulation	15	126	4.1	5.1	0.6	7	12	63	59
	Transition	55	105	5.8	5	0.5	6	12	55	54
	Re-deposition	8	53	5.4	5.1	0.5	6	12	53	51
	Control	-	18	9.9	5.2	1.0	12	12	-	-
2 -2014	Shear	12	2	0.7	5.1	0.2	2	14	29	34
	Intact accumulation	25	9	2.2	5.3	0.4	5	12	75	75
	Transition	40	17	1.9	5	0.3	3	12	45	46
	Re-deposition	23	4	1.9	5	0.2	2	12	29	30
	Control	-	22	3.1	5.2	0.6	7	12	-	-
3 (pre-1953)	Shear	50	8	12.6	5.3	0.3	4	12	56	55
	Transition	-	13	10.1	5.1	0.5	6	12	86	84
	Re-deposition	39	10	9.3	5.3	0.3	4	11	55	51
	Control	11	15	14.4	5.3	0.6	7	12	-	-
4 -2008	Shear	20	1	1.2	5.1	0.1	1	12	8	8
	Intact accumulation	24	10	4.7	5.2	0.4	4	13	52	53
	Transition	47	5	1.2	5.2	0.2	3	13	35	36
	Re-deposition	9	4	0.2	5.2	0.2	2	13	24	26
	Control	-	15	4.9	5.2	0.7	8	12	-	-
5 -2014	Shear	14	2	1	5.1	0.1	1	12	17	17
	Intact accumulation	35	23	16.4	5.3	0.4	5	11	83	79
	Transition	35	12	6.8	5.3	0.2	3	11	47	45
	Re-deposition	15	6	2.1	5.2	0.1	2	13	28	31
	Control	-	22	14.9	5.4	0.5	6	12	-	-
6 -1995	Shear	29	1	1.1	5.4	0.1	2	14	15	18
	Intact accumulation	22	10	1.5	5.5	0.5	5	12	60	63
	Transition	44	11	2.5	4.8	0.3	4	14	36	44
	Re-deposition	13	21	9	4.7	0.2	3	16	27	39
	Control	-	40	28.7	5.6	0.8	9	11	-	-

<sup>1</sup> Dates denote year of most recent landslide activation.

<sup>2</sup> Mean of four replicates.

<sup>3</sup> Mean of two field replicates.

hill country, thus they were omitted from subsequent statistical analysis. Olsen P was lower ( $P < 0.05$ ) than the control only in the shear and re-deposition zones.

### Discussion

The shear zones were generally steep-faced exposed surfaces within the landslides comprising about 25% of the total landslide areas and were the slowest to recover. They had shallow A horizons (mean of 2 cm), shallow (mean of 24 cm) solum depths and low Olsen P values. The C and N were generally lower within the shear zone than other zones or the controls.

The intact accumulation zones made up about 20% of the landslide area. Intact accumulation zones had the deepest A horizons (mean of 17 cm) within the landslides which was attributed to the soil moving down-slope in undisturbed blocks retaining the original topsoil. The mean soil C and N contents of the intact accumulation zones were higher than other landslide zones but lower than the controls. Olsen P values were variable but generally lower than the controls.

The transition zones (about 40% of landslide area) were a place of soil accumulation. They had thicker A horizons (mean of 7 cm) and deeper solum depths (mean of 72 cm) than shear zones therefore making them zones where soils will recover relatively quickly. C and N were medium to low with low Olsen P values.

The re-deposition zones (about 15% of landslide area) had shallow A horizons (mean of 2 cm) with the youngest landslides often having no, or minimal, topsoil. However, they are akin to the transition zone where soil accumulation occurs, with deeper solum depths and thus are likely to recover more quickly and be more productive than shear zones.

The soil recovery over time, as measured by C and N contents, was variable, with highest C and N in the pre-1953 landslides and in the intact accumulation zones in all slides. The 1995–2014 landslides had the least recovery of soil C and N in the shear zones (8–34% of control), and had only recovered to about 30% of the control values in the re-deposition zones. This finding is in general concurrence with Sparling *et al.* (2003) who reported that the C:N ratio recovered to similar to controls within 5 years and that soil C had recovered to about 80% of adjacent non-eroded areas after 80 years.

The topsoil depths varied between zones but were generally within the range reported by Trustram & De Rose (1988) though they didn't distinguish between the landslide zones they did recognise rafted material that would be equivalent to our intact accumulation and transition zones.

At similar sites, De Rose *et al.* (1995) reported that pasture production recovered fastest in the first 40 years after landslides and fully recovered after 80 years, while Rosser & Ross (2011) suggest that most pasture

productivity recovers in the first 20 years with only slow gains thereafter. This research suggests that in the intact accumulation, transition, and redeposition, zones pasture production will recover well within 20 years, however, the shear zones may take considerably longer to recover. Further work to measure pasture production within the varying zones of the landslide, along with management such as targeted fertiliser applications to maximise pasture recovery in the most responsive zones, could improve efficiency of management response following landslides.

### Conclusions

Soil C and N were lower in each of the landslides zones than the control ( $P < 0.05$ ). Olsen P was lower ( $P < 0.05$ ) than the control only in the shear and re-deposition zones.

The differences in soil development, and in C, N, and P, between zones within landslides were greater than the differences between landslides of varying ages. Shear zones take the longest to recover following landslides; they generally had the shallowest A horizons, shallowest depth of solum, and lowest C, N, and P levels, however, they occupied only about 25% of the landslide area. Intact accumulation zones are similar to control zones, but more variable as some with areas of exposed bare soil take longer to recover. The re-deposition and transition zones are areas where soil accumulates and, once stabilised, they are expected to be productive.

Plant-available P and soil pH were not correlated with soil development nor age of the landslides. Soil total C and N recovery were variable across the zones of the landslides with the oldest landslides and the soils in the intact accumulation zones having the highest contents of C and N.

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## **Appendix B**

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### **Landslide characteristics and physical properties**

Notes are highly variable depending on the person I took into the field with me for the day. Some GPS co-ordinates were so far out they have had to be estimated using Google Earth and sketches of landslides and auger hole locations in my field work book. Complete soil profiles were only conducted when a new soil type was located, full soil descriptions for the three main soil types are in Chapter 4.

## Appendix B

### B1. Landslide 1

#### *B1.1 Auger holes and profile descriptions*

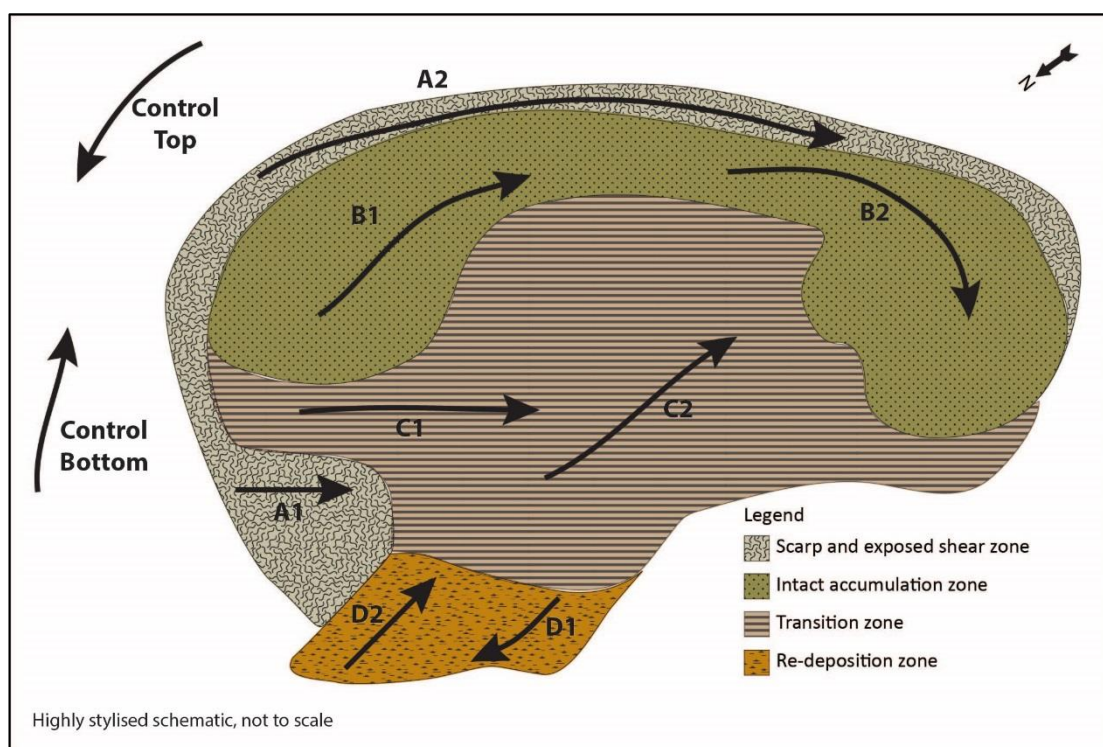
<i>Landslide 1</i>	<i>GPS Co-ordinates</i>	<i>Description</i>
Hole 1 – Re-deposition zone – soil has same properties/ characteristics of LS2 so only mini soil profiles have been conducted Waingaro Steepland soil	S37°47'15.40" E175°04'06.1"	Horizon: A – 0-3 cm Colour: Peds: Moderate – strong pedality Failure: Friable Mottles: None Roots: Many – Organic matter layer on top of soil 1.5 cm depth
		Horizon: Bw – 4-15 cm (transition layer between newly formed A horizon and bA horizon) Colour: 10YR 5/6 yellowish brown Peds: Moderately developed breaking to apedal earthy. Mn present Failure: Friable Roots: ?
		Horizon: bA – 16-30 cm Colour: 10YR 5/8 yellowish brown Peds: Moderately developed breaking to apedal earthy Failure: Friable Mottles: 2% Roots: Few tree roots present
		Horizon: bBw1 – 31-50 cm Colour: 10YR 5/8 yellowish brown Peds: Moderate – weakly developed peds Failure: Semi-deformable – deformable Roots: Few tree roots
		Horizon: bBw2 – 51-80 cm Colour: 10YR 5/6 yellowish brown Peds: Moderate – weakly developed peds Failure: Semi-deformable – deformable Roots: Very fine tree roots
		Horizon: bBw1 – 31-50 cm Colour: 10YR 5/8 yellowish brown Peds: Moderate – weakly developed peds Failure: Deformable Roots: None
Hole 2 Re-deposition zone	S37°47'15.4" E175°04'05.8"	1.5 cm – Organic matter Horizon: A – 0-2 cm Horizon: A/B – 3-9 cm (mixed topsoil) Horizon: bA – 10-30 cm Horizon: bBw – 31-50 cm Horizon: C – 51-100 cm
Hole 3 Re-deposition zone/Transition zone	S37°47'15.3" E175°04'05.8"	2 cm – Organic matter Horizon: A – 0-5 cm Strong to moderate development breaking to apedal earthy Roots: Common  Horizon: Bw/C – 6-20 cm (mixed soil with saprolite pieces) Roots: Few tree roots

## Appendix B

			Horizon: bAp – 21-40 cm (Questionable)
			Horizon: Bw/C – 41-80 cm (transition layer)
			Roots: Few
			Horizon: C – 81-100 cm
			Roots: Very few
Hole 4	S37°47'15.5"		Horizon:Horizon:Horizon:As hole 3
Re-deposition zone/Transition zone	E175°04'06.2"		
Hole 5	S37°47'15.4"		Horizon:Horizon:As holes 3 and 4
Re-deposition zone/Transition zone	E175°04'06.5"		
Hole 6	S37°47'15.7"		1.5 cm – Organic matter
Shear zone within transition zone	E175°04'06.2"		Horizon: A – 0-7 cm Horizon:Horizon:Horizon: C – 8-40 cm – Did not dig deeper than 40 cm. Mottled clay
Hole 7	S37°47'15.7"		2 cm – Organic matter
Shear zone within transition zone	E175°04'06.6"		A – 0-2 cm – Developing, not as developed in hole 6. Roots: Common Horizon: C - 3-50 cm – Did not go past this point
Hole 8	S37°47'15.7"		A – 0-1 cm – Some nicely developing peds, moderate development
Transition zone	E175°04'06.7"		Horizon: Bw - 2-35 cm (mixed rubble) Horizon: C – 36-70 cm – Did not dig deeper as continued to bring out same soil horizon
Hole 9	S37°47'16.0"		2.5 cm – Organic matter
Transition zone	E175°04'06.2"		Horizon: Ap – 0-10 cm Roots: Many - abundant Horizon: B – 11-30 cm (mixed rubble) Horizon: C 31 – 70 cm – Stopped digging, very few roots
Hole 10	S37°47'15.5"		3 cm – Organic matter
Transition zone	E175°04'06.1"		Horizon: A – 0-20 cm Roots: Abundant Horizon: C – 21+ Roots: Very few
Hole 11	S37°47'16.2"		1 cm – Organic matter
Shallow A horizon intact accumulation	E175°04'06.6"		Horizon: Ap – 0-5 cm – common roots Horizon: Bw – 6-35 cm – few roots Horizon: C – 36-90 cm – very few roots
Hole 12	S37°47'16.4"		As hole 11
Transition	E175°04'07.0"		
Hole 13	S37°47'16.6"		Horizon: A – 0-3 cm
Transition	E175°04'07.0"		Horizon: Bw – 4-14 cm
Hole 13 cont.			Horizon: C – 15-50 cm Horizon: Saprolite - 50+ cm
Hole 14	S37°47'16.6"		Horizon: Ap – 0-3 cm
Shear	E175°04'07.0"		Horizon: Bw – 4-40 cm Horizon: C – 40+ cm
Hole 15	S37°47'15.4"		2 cm – Organic matter
	E175°04'07.7"		Horizon: Ap – 0-15 cm– roots common Horizon: Bw – 16-40 cm – few roots Horizon: C1 – 41-60 cm Horizon: C2 – 61-90 cm – Mn layer Horizon: C3 – 91-100 cm

## Appendix B

### B1.2. Bucket sampling transects



#### Transect co-ordinates

Sample	GPS - Start	GPS - End
A1	S37° 47'14.6" E175°04'07.0"	S37° 47'14.9" E175°04'06.0"
A2	S37° 47'15.6" E175°04'07.9"	S37° 47'15.6" E175°04'07.4"
B1	S37° 47'15.2" E175°04'07.7"	S37° 47'15.6" E175°04'08.0"
B2	S37° 47'15.6" E175°04'08.1"	S37° 47'16.3" E175°04'07.8"
C1	S37° 47'14.9" E175°04'06.5"	S37° 47'15.4" E175°04'06.5"
C2	S37° 47'15.4" E175°04'06.8"	S37° 47'15.5" E175°04'06.8"
D1	S37° 47'15.2" E175°04'06.1"	S37° 47'15.2" E175°04'05.7"
D2	S37° 47'15.2" E175°04'06.0"	S37° 47'15.1" E175°04'05.7"
Control Top	S37° 47'14.5" E175°04'08.7"	S37° 47'14.7" E175°04'08.8"
Control Bottom	S37° 47'14.1" E175°04'06.5"	S37° 47'13.8" E175°04'06.7"

### B1.3. Soil dry bulk density and other soil properties

Sample	GPS Location	Tin weight (g)	Sand added (mls)	Cylinder Diameter (cm)	Cylinder length (cm)	Volume of cylinder $\pi r^2 \times \text{length}$ (cm <sup>3</sup> )	Amended Volume of cylinder	Sample + Tin weight (g)	Sample only (field moist)	Weight after oven 48 (g)	Sample only (oven-dried) 48 hours	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Soil Moisture content (g/g)	Soil Porosity (g)	Volumetric water content (g/cm <sup>3</sup> )	Water filled pore space (%)
LS1 - A1	S37° 47' 15.3" E175° 04' 08.6"	10.75	5.00	6.0	5.0	141.37	136.37	199.81	189.06	144.49	133.74	0.98	41.26	0.41	0.62	0.40	65.59
LS1 - A2	S37° 47' 15.9" E175° 04' 08.6"	10.90	5.20	6.0	5.1	144.20	139.00	197.55	186.65	133.45	122.54	0.88	52.17	0.52	0.66	0.46	70.15
LS1 - A3	S37° 47' 14.6" E175° 04' 07.2"	10.92	10.40	6.0	5.1	144.20	133.80	192.61	181.70	131.25	120.33	0.90	50.73	0.51	0.65	0.46	70.33
LS1 - B1	S37° 47' 15.2" E175° 04' 07.9"	10.94	9.20	6.0	5.1	144.20	135.00	185.76	174.81	119.51	108.57	0.80	61.02	0.61	0.69	0.49	71.55
LS1 - B2	S37° 47' 15.8" E175° 04' 08.1"	10.76	1.00	6.0	4.9	138.54	137.54	172.02	161.26	110.08	99.33	0.72	62.19	0.62	0.72	0.45	62.55
LS1 - B3	S37° 47' 16.4" E175° 04' 07.5"	10.70	0.20	6.0	5.1	144.20	144.00	199.65	188.95	118.35	107.65	0.75	75.26	0.75	0.71	0.56	79.47
LS1 - C1	S37° 47' 15.8" E175° 04' 06.4"	10.61	4.20	6.0	5.1	144.20	140.00	204.95	194.33	137.49	126.88	0.91	53.05	0.53	0.65	0.48	74.42
LS1 - C2	S37° 47' 15.5" E175° 04' 06.7"	10.77	1.80	6.0	4.9	138.54	136.74	182.73	171.96	114.17	103.40	0.76	66.25	0.66	0.70	0.50	71.10
LS1 - C3	S37° 47' 14.9" E175° 04' 06.6"	10.91	1.20	6.1	5.1	149.05	147.85	205.12	194.21	133.11	122.20	0.83	58.64	0.59	0.68	0.48	71.57
LS1 - D1	S37° 47' 115.2" E175° 04' 05.9"	10.95	12.00	6.0	5.0	141.37	129.37	151.39	140.44	90.94	79.99	0.62	75.32	0.75	0.76	0.47	61.40
LS1 - D2	S37° 47' 15.0" E175° 04' 05.9"	10.91	2.40	6.0	5.1	144.20	141.80	163.47	152.56	107.83	96.92	0.68	57.20	0.57	0.73	0.39	53.34
LS1 - D3	S37° 47' 15.1" E175° 04' 05.8"	10.78	9.20	6.0	5.2	147.03	137.83	175.24	164.45	109.67	98.88	0.72	66.12	0.66	0.72	0.47	65.91
LS1 - CT1	S37° 47' 15.7" E175° 04' 08.8"	11.07	0.60	6.0	5.2	147.03	146.43	175.93	164.86	103.51	92.43	0.63	77.95	0.78	0.75	0.49	65.31
LS1 - CT2	S37° 47' 15.2" E175° 04' 09.0"	10.82	1.60	6.1	5.0	146.12	144.52	163.99	153.17	96.15	85.34	0.59	78.77	0.79	0.77	0.47	60.46
LS1 - CB1	S37° 47' 13.9" E175° 04' 06.8"	10.84	0.00	6.0	5.0	141.37	141.37	151.98	141.14	80.68	69.84	0.49	101.35	1.01	0.81	0.50	62.05
LS1 - CB2	S37° 47' 13.3" E175° 04' 06.7"	10.88	3.40	6.0	5.1	144.20	140.80	169.03	158.15	96.37	85.49	0.61	84.18	0.84	0.76	0.51	67.00

## B2. Landslide 2

### B2.1. Auger holes and profile descriptions

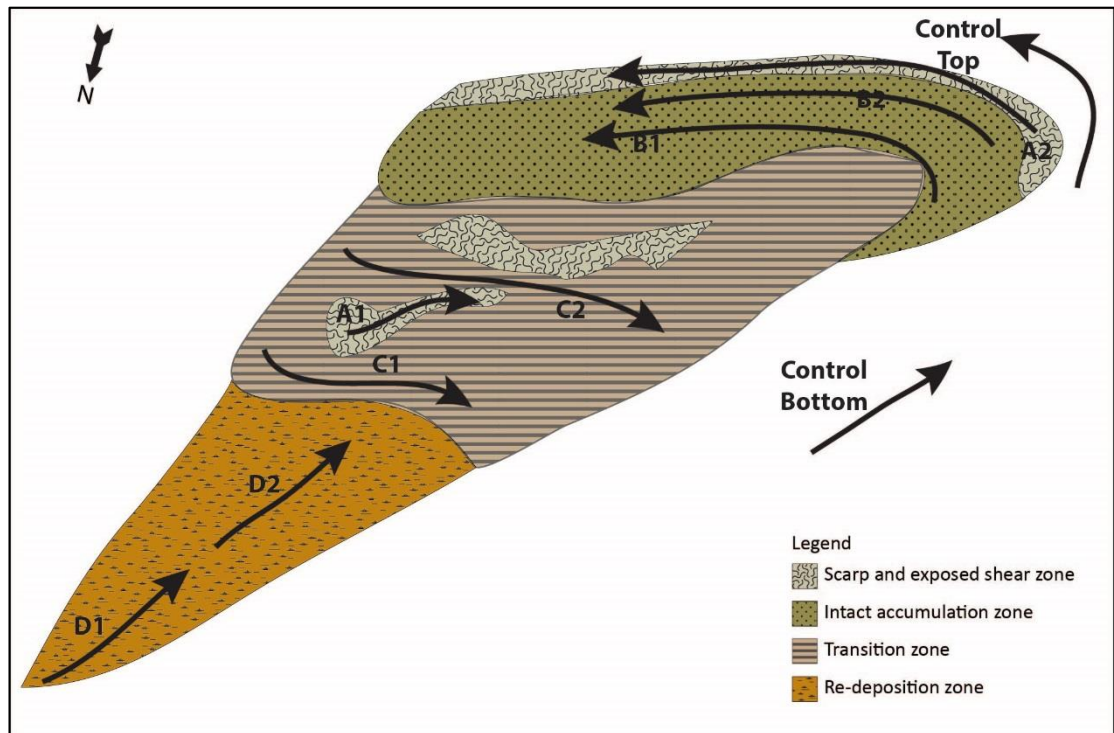
Landslide 2	GPS Co-ordinates	Description
Hole 1	S37°78 803	A 0-3 cm 10YR 3/4 dark brown, friable, very fine polyhedral peds, clay loam, firm, moderately plastic, slightly sticky, no mottles, imperfect drainage, abundant roots, NaF: None
Transition zone	E175°068.14	Bw1 4-30 cm 10YR 5/6 yellowish brown, clay loam, friable, strong, abundant very fine to medium polyhedral peds, slightly firm, very plastic, imperfectly drained, 5% mottles, common roots, NaF:weak Bw2 31-70 cm 10YR 6/6 bright yellowish brown, very fine – medium, moderate to strong polyhedral peds, few roots. Slightly firm, very plastic, semi deformable, imperfect drainage, mottles 40%
Hole 2 – Transition zone – micro-profile as horizons have similar characteristics to first auger hole and consequent holes	S37°47'17.41" E175° 04'04.58"	Horizon: A – 0-4 cm Colour: 10YR 4/3 dull yellowish brown Peds: Weakly developed breaking to apedal earthy polyhedral microfine – fine peds Texture: Clay loam Roots: Abundant  Horizon: Bw1 – 5-25 cm Colour: 10YR 4/4 brown Peds: Weakly developed breaking to apedal earthy microfine – fine polyhedral peds Roots: Few fine roots  Horizon: Bw2 26-35 cm Colour: 10YR 5/6 yellowish brown Peds: Weak – moderately developed very fine – medium polyhedral peds Texture: Silty clay loam Strength: Firm Roots: Very few  Horizon: C 36-100 cm Colour: 10YR 5/6 yellowish brown Peds: Moderately developed fine – medium polyhedral peds Roots: Very few
Hole 3	S37°47'16.96"	Horizon: A – 0-10 cm
Intact accumulation zone – test hole	E175° 04'05.79"	Horizon: Bw1 – 11-40 cm Horizon: Bw2 41+ cm not full auger
Hole 4	S37°47'16.69"	Horizon: A – 0-15 cm
Intact accumulation zone test hole	E175° 04'05.34"	Horizon: Bw – 16-40 cm Horizon: C – 41-100 cm
Hole 5	S37°47'16.17"	Horizon: A – 0-3 cm
Transition zone – test hole	E175° 04'04.87"	Horizon: AB – 4-20 cm – Soil mixed Horizon: bBw1 – 21-30 cm Horizon: bBw1 – 31-60 cm Horizon: C – 61-100 cm
Hole 6	S37°47'16.29"	Horizon: A – 0-4 cm

## Appendix B

Transition zone – test hole	E175°04'05.21"	Horizon: AB – 5-10 cm – Soil mixed Horizon: Bw – 11-30 cm – Soil slightly mixed with A horizon soil Horizon: C – 31-100 cm
Hole 7	S37°47'17.40"	Horizon: A – 0-20 cm
Intact accumulation zone	E175°04'05.31"	Horizon: Bw1 – 21-36 cm Horizon: Bw2 – 37-42 cm Horizon: C – 43-100 cm
Hole 8	S37°47'17.08"	Horizon: A – 0-7 cm
Intact accumulation zone	E175° 04'04.67"	Horizon: Bw1 – 8-20 cm – Soil mixed Horizon: Bw2 – 21-35 cm Horizon: C – 36-100 cm
Hole 9	S37°47'16.85"	Horizon: A – 0-20 cm
Intact accumulation zone	E175° 04'05.74"	Horizon: Bw1 – 21-35 cm Horizon: C – 36-100 cm
Hole 10	S37°47'16.62"	Horizon: B/C – 0-7 cm (topsoil rubble) Very few – few roots
Transition zone	E175° 04'05.66"	Horizon: C – 8-25 cm Redox present, clayey and gleyed. Tree roots  Horizon: C2 – 26 – 80 cm Mottles: 50% Weakly developed with Mn and Fe <sup>3+</sup> oxidation  Horizon: C3 – 81-100 cm - Heavily gleyed with redox fracturing lines, apedal earthy, weakly developed. Very few Mn fragments present.
Hole 11	S37°47'16.26"	Horizon: B/C – 0-25 cm (soil rubble)
Re-deposition zone	E175° 04'05.55"	Horizon: C3 – 26-36 cm (like from Hole 10)  Horizon: bA/B – 37-47 cm (topsoil mixture) Organic matter present along with roots  Horizon: bBw1 – 47-100 cm Mottles: 20% Strength: Very deformable, weakly developed
Hole 12	S37°47'16.05"	Horizon: A – 0-0.5 cm
Re-deposition zone	E175° 04'05.26"	Roots: Few to common Horizon: A/B – 1-5 cm Roots: Few Horizon: bAp – 6-10 cm Roots: Common - Many Horizon: bBw1 – 11-60 cm Roots: Very few Horizon: C – 61-90 cm (gley) Horizon: C – 91-100 cm (weathered parent material)
Hole 13	S37°47'17.59"	Horizon: A – 0-35 cm
Control zone? (notes say Bw looks like C horizon, could be recovered shear zone or badly written notes)	E175° 04'06.77"	Roots: Common – few in top 10 cm Horizon: Bw1 – 36-100 cm Roots: Few large tree roots

## Appendix B

### B2.2. Bucket sampling transects



#### Transect co-ordinates

Sample	GPS - Start	GPS - End
A1	S37° 47'16.5" E175°04'05.8"	S37° 47'16.9" E175°04'05.4"
A2	S37° 47'17.7" E175°04'04.9"	S37° 47'17.0" E175°04'05.6"
B1	S37° 47'16.8" E175°04'05.1"	S37° 47'16.9" E175°04'05.5"
B2	S37° 47'17.2" E175°04'05.1"	S37° 47'17.2" E175°04'05.6"
C1	S37° 47'16.5" E175°04'05.9"	S37° 47'16.4" E175°04'05.4"
C2	S37° 47'16.2" E175°04'05.4"	S37° 47'16.3" E175°04'05.1"
D1	S37° 47'15.8" E175°04'05.8"	S37° 47'15.8" E175°04'05.7"
D2	S37° 47'16.1" E175°04'05.7"	S37° 47'16.3" E175°04'06.2"
Control Top	S37° 47'17.4" E175°04'04.2"	S37° 47'17.5" E175°04'04.5"
Control Bottom	S37° 47'16.5" E175°04'04.2"	S37° 47'16.4" E175°04'04.5"

### B2.3. Soil dry bulk density and other soil properties

Sample	GPS Location	Tin weight (g)	Sand added (mls)	Cylinder Diameter (cm)	Cylinder length (cm)	Volume of cylinder $\pi r^2 \times$ length (cm <sup>3</sup> )	Amended Volume of cylinder	Sample + Tin weight (g)	Sample only (field moist)	Weight after oven 48 (g)	Sample only (oven-dried) 48 hours	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Soil Moisture content (g/g)	Soil Porosity (g)	Volumetric water content (g/cm <sup>3</sup> )	Water filled pore space (%)
LS1 - A1	S37° 47'16.3" E175° 04'05.8"	10.72	7.00	6.0	4.9	138.54	131.54	211.89	201.17	154.73	144.01	1.09	39.56	0.40	0.57	0.43	75.65
LS1 - A2	S37° 47'16.5" E175° 04'05.7"	10.75	21.80	6.0	5.1	144.20	122.40	209.85	199.11	144.41	133.66	1.09	48.79	0.49	0.57	0.53	92.91
LS1 - A3	S37° 47'17.0" E175° 04'05.8"	10.74	7.50	6.0	5.1	144.20	136.70	183.61	172.87	151.92	141.18	1.03	22.31	0.22	0.60	0.23	38.62
LS1 - B1	S37° 47'17.3" E175° 04'05.3"	10.66	2.40	6.0	5.1	144.20	141.80	171.96	161.30	111.56	100.90	0.71	59.75	0.60	0.72	0.43	58.89
LS1 - B2	S37° 47'17.1" E175° 04'05.4"	10.86	6.20	6.0	5.0	141.37	135.17	160.98	150.12	107.75	96.89	0.72	54.69	0.55	0.72	0.39	54.44
LS1 - B3	S37° 47'16.9" E175° 04'05.4"	10.98	0.00	6.0	5.2	147.03	147.03	136.40	125.43	76.18	65.20	0.44	92.13	0.92	0.83	0.41	49.42
LS1 - C1	S37° 47'16.4" E175° 04'05.9"	11.08	9.60	6.0	5.0	141.37	131.77	178.42	167.34	119.99	108.91	0.83	53.43	0.53	0.68	0.44	65.22
LS1 - C2	S37° 47'16.4" E175° 04'05.7"	10.90	3.00	6.0	5.0	141.37	138.37	244.50	233.60	172.51	161.61	1.17	44.38	0.44	0.54	0.52	95.32
LS1 - C3	S37° 47'16.5" E175° 04'06.1"	10.83	10.00	6.0	5.0	141.37	131.37	221.14	210.31	163.22	152.39	1.16	37.81	0.38	0.55	0.44	80.19
LS1 - D1	S37° 47'15.8" E175° 04'05.7"	11.02	1.00	6.0	5.1	144.20	143.20	256.58	245.56	182.46	171.44	1.20	43.03	0.43	0.53	0.52	96.77
LS1 - D2	S37° 47'16.2" E175° 04'05.6"	10.87	1.20	6.0	5.1	144.20	143.00	239.14	228.27	162.40	151.53	1.06	50.47	0.50	0.59	0.53	91.24
LS1 - D3	S37° 47'16.1" E175° 04'05.5"	10.82	1.80	6.0	4.9	138.54	136.74	234.70	223.88	171.16	160.34	1.17	39.43	0.39	0.54	0.46	85.30
LS1 - CT1	S37° 47'17.5" E175° 04'04.2"	10.86	0.40	6.0	5.0	141.37	140.97	190.56	179.70	116.88	106.02	0.75	69.17	0.69	0.71	0.52	73.66
LS1 - CT2	S37° 47'17.7" E175° 04'04.5"	10.91	0.40	6.0	5.0	141.37	140.97	196.03	185.12	125.38	114.46	0.81	61.58	0.62	0.68	0.50	73.23
LS1 - CB1	S37° 47'16.6" E175° 04'04.9"	10.73	11.00	6.0	5.1	144.20	133.20	165.11	154.38	96.26	85.53	0.64	80.40	0.80	0.75	0.52	68.91
LS1 - CB2	S37° 47'16.4" E175° 04'04.3"	10.96	2.00	6.0	5.1	144.20	142.20	183.62	172.67	131.15	120.20	0.85	43.51	0.44	0.67	0.37	54.90

## B3. Landslide 3

### B3.1. Auger holes and profile descriptions

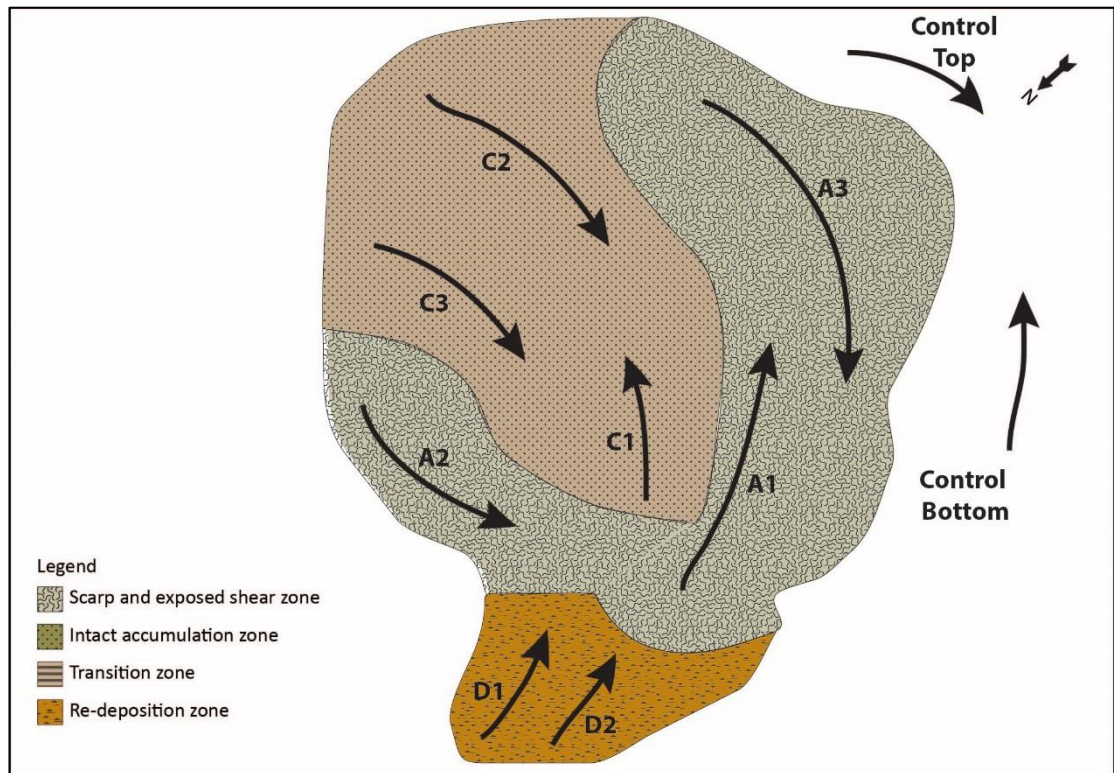
<i>Landslide 3</i>	<i>GPS Co-ordinates</i>	<i>Description</i>
Hole 1	S37°47'16.1"	Horizon: A 0 – 10 cm
Transition zone	E175°04'03.3"	Colour: 10YR 3/4 dark brown
Flattish area left side inside scar		Bw1 11-40 cm 10YR 5/8 & 5/6 yellowish brown Bw2 41-85 10YR 6/8 bright yellowish brown C 86-100+ cm 10YR 6/6 bright yellowish brown, gleying
Hole 2	S37°47'16.1"	A 0-15 cm
Transition zone	E175°04'03.4"	A/Bw 16-35 cm C 81- 90 cm Solum Depth: 91-100+ cm 2.5Y 7/4 light yellow and 10YR6/6 bright yellowish brown
Hole 3	S37°47'15.9"	A 0-7 cm
Transition zone	E175°04'03.4"	Bw1 8 – 20 cm Bw2 21-50 cm C 51-90 cm Solum Depth: 91-100+ cm, 7.5YR 5/8 bright brown, ample manganese or carbon tree roots present
Hole 4	S37°47'16.14"	Horizon: - Ap – 0-8 cm
Transition zone	E175°04'03.24"	Roots: Many Horizon: Bw1 – 9-40 cm Roots: Few Horizon: Bw2 – 41-80 cm Roots: Very few Horizon: C – 81-100 Roots: None
Hole 5	S37°47'16.25"	Horizon: Ap – 0-10 cm
Transition zone	E175°04'03.23"	Roots: Common Horizon: Bw1 – 11-30 cm Roots: Few Horizon: Bw2 – 31-85 cm Roots: Very few Horizon: C – 86-100 cm Roots: Minimal
Hole 6	S37°47'16.50"	Horizon: Ap – 0-9 cm
Transition zone	E175°04'03.53"	Roots: Common Horizon: Bw1 – 10-30 cm Roots: Few Horizon: Bw2 – 31-80 cm Roots: Very few Horizon: C – 81-100 cm Roots: None
Hole 7	S37°47'16.67"	Horizon: A – 0-4cm
Head scarp	E175°04'03.41"	Roots: Common Horizon: Bw1 – 5-30 cm Roots: Few Horizon: Bw2 31-80 cm Roots: Very few Horizon: C – 81-100cm – Weak pedality, weak development, weathered parent material Colour: 5YR 6/4 dull orange
Hole 8	S37°47'16.56"	Horizon: A – 0-3cm
Head scarp	E175°04'03.05"	Colour: 10YR 4/6 brown
Waingaro Steepland Soil		Texture: Clay loam Peds: Moderately developed, subangular fine- medium abundant peds Strength: Firm Failure: Friable

## Appendix B

	Plasticity: Slightly Stickiness: Slightly Mottles: None Drainage: Imperfectly drained Roots: Common – many NaF reaction: Non-reactive  Horizon: Bw – 4-50 cm Colour: 10YR 5/8 yellowish brown Texture: Clay loam Peds: Many weak to moderately developed, polyhedral – subangular peds breaking to apedal earthy Strength: Firm Failure: Friable Plasticity: Slightly – moderately Stickiness: Moderately Mottles: 2-5 % Drainage: Imperfectly drained Roots: Few NaF reaction: Non – very weak  Horizon: C – 51-61 cm Colour: 10YR 6/8 bright yellowish brown Peds: Many moderately developed microfine – fine polyhedral peds breaking to apedal earthy Strength: Weak Failure: Semi-deformable with hard parent material present Plasticity: Very Stickiness: Moderately Mottles: 25 % Drainage: Imperfectly drained Roots: Few NaF reaction: Non-reactive - Very weak  Horizon: C2 – 62-100 cm Colour: 10YR 4/6 brown Texture: Sandy clay (think this must be parent material) Peds: Weakly developed microfine –fine apedal earthy Strength: Very weak - weak Failure: Very friable Plasticity: Moderately Stickiness: Moderately Mottles: 50 % Drainage: Imperfectly drained Roots: None NaF reaction: Non-reactive – very weak Mn present and Fe redox
Hole 9 Trans	A 0-9
Hole 10 Shear	A 0 -3
Hole 11 shear	A 0 - 2
Hole 12	A 0-7

## Appendix B

### B3.2. Bucket sampling transects



#### Transect co-ordinates

Sample	GPS - Start	GPS - End
A1	S37° 47'15.7" E175°04'02.6"	S37° 47'15.9" E175°04'02.8"
A2	S37° 47'16.3" E175°04'03.1"	S37° 47'16.2" E175°04'03.2"
A3	S37° 47'16.6" E175°04'02.9"	S37° 47'16.9" E175°04'03.5"
C1	S37° 47'16.2" E175°04'03.2"	S37° 47'16.4" E175°04'02.9"
C2	S37° 47'16.1" E175°04'02.9"	S37° 47'16.1" E175°04'03.4"
C3	S37° 47'15.8" E175°04'03.3"	S37° 47'16.1" E175°04'03.1"
D1	S37° 47'15.7" E175°04'02.0"	S37° 47'15.9" E175°04'01.8"
D2	S37° 47'15.9" E175°04'02.2"	S37° 47'16.0" E175°04'02.4"
Control Top	S37° 47'17.0" E175°04'03.2"	S37° 47'16.8" E175°04'03.6"
Control Bottom	S37° 47'16.7" E175°04'03.1"	S37° 47'16.9" E175°04'03.0"

## Appendix B

### B3.3. Soil dry bulk density and other soil properties

Sample	GPS Location	Tin weight (g)	Sand added (mls)	Cylinder Diameter (cm)	Cylinder length (cm)	Volume of cylinder $\pi r^2 \times \text{length}$ (cm <sup>3</sup> )	Amended Volume of cylinder	Sample + Tin weight (g)	Sample only (field moist)	Weight after oven 48 (g)	Sample only (oven-dried) 48 hours	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Soil Moisture content (g/g)	Soil Porosity (g)	Volumetric water content (g/cm <sup>3</sup> )	Water filled pore space (%)
LS1 - A1	S37° 47'15.8" E175° 04'01.9"	10.973	0	6	5	141.37	141.37	210.756	199.783	146.74	136	0.96	47.01	0.47	1	0.47	69.76
LS1 - A2	S37° 47'16.1" E175° 04'02.9"	10.870	0.01	6	5	141.37	141.36	205.639	194.769	132.59	122	0.86	59.93	0.60	1	0.25	36.07
LS1 - A3	S37° 47'16.2" E175° 04'03.8"	10.747	0	6	5.2	147.03	147.03	198.071	187.324	130.34	120	0.81	56.54	0.57	1	0.34	49.17
LS1 - A4	S37° 47'16.8" E175° 04'03.3"	10.642	0.2	6	4.9	138.54	138.34	190.750	180.108	135.21	125	0.90	44.57	0.45	1	0.34	54.93
LS1 - C1	S37° 47'16.2" E175° 04'03.2"	11.050	0.1	6	5.1	144.20	144.10	205.065	194.015	153.11	142	0.99	36.41	0.37	1	0.32	51.46
LS1 - C2	S37° 47'16.0" E175° 04'03.6"	10.880	0	6.1	5	146.12	146.12	206.088	195.208	144.18	133	0.91	46.34	0.46	1	0.34	58.97
LS1 - C3	S37° 47'16.5" E175° 04'03.9"	10.897	0	6	5.2	147.03	147.03	219.903	209.006	151.02	140	0.95	49.15	0.49	1	0.49	75.31
LS1 - C4	S37° 47'16.3" E175° 04'04.2"	10.946	0	6	5.1	144.20	144.20	223.498	212.552	155.73	145	1.00	46.80	0.47	1	0.46	65.80
LS1 - D1	S37° 47'16.2" E175° 04'02.5"	10.717	1	6	4.9	138.54	137.54	206.440	195.723	136.80	126	0.92	55.21	0.55	1	0.51	80.26
LS1 - D2	S37° 47'16.2" E175° 04'01.9"	10.753	0.01	6	5.1	144.20	144.19	240.477	229.724	172.95	162	1.12	41.47	0.42	1	0.46	76.90
LS1 - D3	S37° 47'16.1" E175° 04'01.9"	10.778	0.8	6	5	141.37	140.57	229.209	218.431	160.63	150	1.07	45.64	0.46	1	0.55	85.68
LS1 - CM	S37° 47'16.7" E175° 04'03.5"	10.847	0.8	6	5.2	147.03	146.23	197.798	186.951	130.65	120	0.82	55.76	0.56	1	0.45	65.15
LS1 - CT1	S37° 47'17.0" E175° 04'03.3"	11.042	0	6.1	5.1	149.05	149.05	172.830	161.788	116.42	105	0.71	53.34	0.54	1	0.27	43.14
LS1 - CT2	S37° 47'16.9" E175° 04'03.4"	10.776	1.8	6	5	141.37	139.57	198.599	187.823	132.52	122	0.87	54.28	0.54	1	0.42	68.41
LS1 - CB1	S37° 47'16.6" E175° 04'02.7"	10.822	0	6.1	5.1	149.05	149.05	211.111	200.289	142.88	132	0.89	51.66	0.52	1	0.25	38.88
LS1 - CB2	S37° 47'16.7" E175° 04'02.8"	10.964	0	6.1	5	146.12	146.12	209.661	198.697	149.08	138	0.95	43.86	0.44	1	0.36	60.40

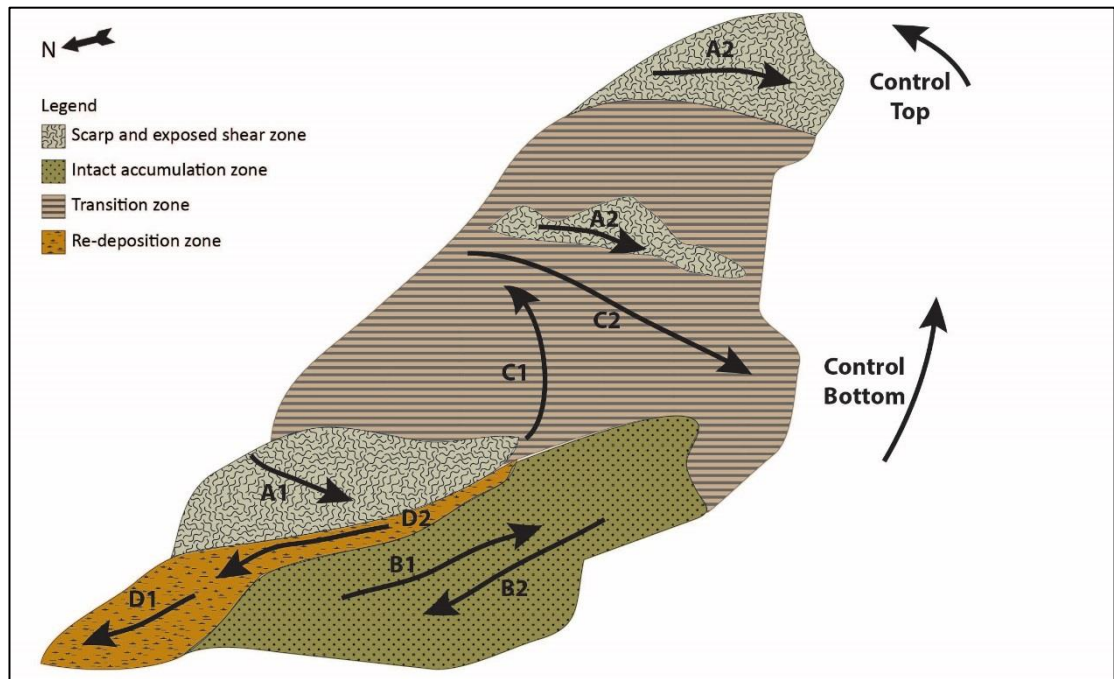
## B4. Landslide 4

### B4.1. Auger holes and profile descriptions

<i>Landslide 4</i>	<i>GPS ordinates</i>	<i>Co-</i>	<i>Description</i>
Hole 1 Re-deposition zone Typical soil characteristics of this series of landslides	S37°47'16.30" E175° 4'01.6"		Organic Matter: 1.5 cm Horizon: 0 -4 cm of mixed rubble mainly C horizon and saprolite Roots: Many to common  Horizon: bAp - 5 – 15 cm Roots: Common  Horizon: bBw - 16 – 26 cm  Horizon: C - 27 – 100 cm → weathered saprolite
Hole 2 Shear zone	S37°47'16.40" E175° 4'01.7"		Organic Matter: 0 – 3 cm Horizon: C – 4 cm → weathered saprolite
Hole 3 Intact accumulation	S37°47'17.0" E175° 4'01.3"		Horizon: A – 0 – 20 cm Horizon: Bw – 21 – 50 cm Horizon: C – 51 →
Hole 4 Shear zone	S37°47'17.1" E175° 4'01.5"		No A horizon only clay
Hole 5 Transition zone	S37°47'16.8" E175° 4'01.8"		Floater within transition zone
Hole 6 Transition zone	S37°47'16.9" E175° 4'02.1"		Really random sample. No clear horization
Hole 7 Transition zone	S37°47'17.0" E175° 4'02.1"		Horizon: Ap – 0 – 3 cm Horizon: Bw – 4- 24 cm (A horizon pieces within horizon) Horizon: Mixed C/B – 25 – 50 cm Horizon: bAp – 51 – 70 cm Horizon: 71 →
Hole 8 Shear zone	S37°47'17.1" E175° 4'02.3"		Bare exposed saprolite
Hole 9 Shear zone	S37°47'17.2" E175° 4'02.1"		Bare exposed saprolite
Hole 10 – Transition zone	S37°47'17.2" E175° 4'02.4"		No notes in field notebook other than transition zone soil so assuming it was similar to Hole 7
Hole 11 Transition zone	S37°47'17.4" E175° 4'02.4"		No notes in field notebook other than transition zone soil so assuming it was similar to Hole 7
Hole 12 Transition zone	S37°47'17.4" E175° 4'02.3"		No notes in field notebook other than transition zone soil so assuming it was similar to Hole 7
Hole 13 Transition zone	S37°47'17.4" E175° 4'02.1"		No notes in field notebook other than transition zone soil so assuming it was similar to Hole 7
Hole 14 Shear zone	S37°47'17.1" E175° 4'01.9"		Bare exposed saprolite

## Appendix B

### B4.2. Bucket sampling transects



*Transect co-ordinates*

<i>Sample</i>	<i>GPS - Start</i>	<i>GPS - End</i>
A1	S37° 47'16.5" E175°04'01.4"	S37° 47'16.6" E175°04'02.1"
A2 – Middle scarp	S37° 47'17.2" E175°04'02.2"	S37° 47'17.0" E175°04'02.3"
Upper most scarp	S37° 47'17.3" E175°04'02.1"	S37° 47'17.5" E175°04'02.4"
B1	S37° 47'16.7" E175°04'01.6"	S37° 47'16.8" E175°04'01.5"
B2	S37° 47'16.7" E175°04'01.6"	S37° 47'16.9" E175°04'01.5"
C1	S37° 47'16.4" E175°04'01.7"	S37° 47'16.7" E175°04'01.6"
C2	S37° 47'16.7" E175°04'02.1"	S37° 47'16.7" E175°04'02.2"
D1	S37° 47'16.7" E175°04'02.0"	S37° 47'16.2" E175°04'01.4"
D2	S37° 47'16.3" E175°04'01.5"	S37° 47'16.2" E175°04'01.4"
Control Top	S37° 47'17.9" E175°04'01.5"	S37° 47'17.8" E175°04'01.6"
Control Bottom	S37° 47'17.2" E175°04'01.3"	S37° 47'17.7" E175°04'01.0"

### B4.3. Soil dry bulk density and other soil properties

Sample	GPS Location	Tin weight (g)	Sand added (mls)	Cylinder Diameter (cm)	Cylinder length (cm)	Volume of cylinder $\pi r^2 \times \text{length}$ (cm <sup>3</sup> )	Amended Volume of cylinder (g)	Sample + Tin weight (g)	Sample only (field moist)	Weight after oven 48 (g)	Sample only (oven-dried) 48 hours	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Soil Moisture content (g/g)	Soil Porosity (g)	Volumetric water content (g/cm <sup>3</sup> )	Water filled pore space (%)
LS1 - A1	S37° 47'16.3" E175° 04'01.7"	11.011	0	6	5.1	149.05	149.05	203.012	192.001	137.27	126	0.85	52.07	0.52	1	0.47	69.76
LS1 - A2	S37° 47'16.8" E175° 04'01.8"	10.918	0	6	5	146.12	146.12	203.953	193.035	152.39	141	0.97	36.45	0.36	1	0.25	36.07
LS1 - A3	S37° 47'16.6" E175° 04'02.3"	10.863	0	6	5.1	149.05	149.05	232.567	221.704	166.15	155	1.04	42.77	0.43	1	0.34	49.17
LS1 - B1	S37° 47'16.6" E175° 04'01.7"	10.924	0	6	4.9	143.20	143.20	160.718	149.794	128.55	118	0.82	27.35	0.27	1	0.34	54.93
LS1 - B2	S37° 47'16.6" E175° 04'01.3"	10.686	0	6	5	146.12	146.12	215.170	204.484	146.21	136	0.93	50.89	0.51	1	0.32	51.46
LS1 - B3	S37° 47'17.0" E175° 04'01.4"	10.819	0	6	5	146.12	146.12	187.197	176.378	148.23	137	0.94	28.36	0.28	1	0.34	58.97
LS1 - C1	S37° 47'16.8" E175° 04'01.7"	10.893	3.1	6	5.1	149.05	145.95	229.348	218.455	181.03	170	1.17	28.40	0.28	1	0.49	75.31
LS1 - C2	S37° 47'16.8" E175° 04'01.6"	10.782	0	6	5	146.12	146.12	209.890	199.108	172.12	161	1.10	23.41	0.23	1	0.46	65.80
LS1 - C3	S37° 47'16.8" E175° 04'01.8"	10.902	0	6	5.1	149.05	149.05	250.192	239.290	188.08	177	1.19	35.06	0.35	1	0.51	80.26
LS1 - D1	S37° 47'15.9" E175° 04'01.9"	10.806	0	6	5	146.12	146.12	227.184	216.378	169.82	159	1.09	36.08	0.36	1	0.46	76.90
LS1 - D2	S37° 47'16.2" E175° 04'01.7"	10.631	0	6	5	146.12	146.12	216.847	206.216	168.28	158	1.08	30.81	0.31	1	0.55	85.68
LS1 - D3	S37° 47'16.4" E175° 04'01.6"	10.886	0	6	5	146.12	146.12	203.737	192.851	141.07	130	0.89	48.14	0.48	1	0.45	65.15
LS1 - CT1	S37° 47'18.6" E175° 04'03.9"	10.809	0.2	6	5	146.12	145.92	186.858	176.049	143.16	132	0.91	33.02	0.33	1	0.27	43.14
LS1 - CT2	S37° 47'17.8" E175° 04'02.9"	10.958	0	6	5.1	149.05	149.05	163.260	152.302	124.85	114	0.76	33.73	0.34	1	0.42	68.41
LS1 - CB1	S37° 47'17.8" E175° 04'00.8"	10.774	0	6	5.1	149.05	149.05	184.278	173.504	124.78	114	0.76	52.19	0.52	1	0.25	38.88
LS1 - CB2	S37° 47'17.8" E175° 04'00.9"	10.879	0	6	4.8	140.28	140.28	178.324	167.445	138.74	128	0.91	30.96	0.31	1	0.36	60.40

## B5. Landslide 5

### B5.1. Auger holes and profile descriptions

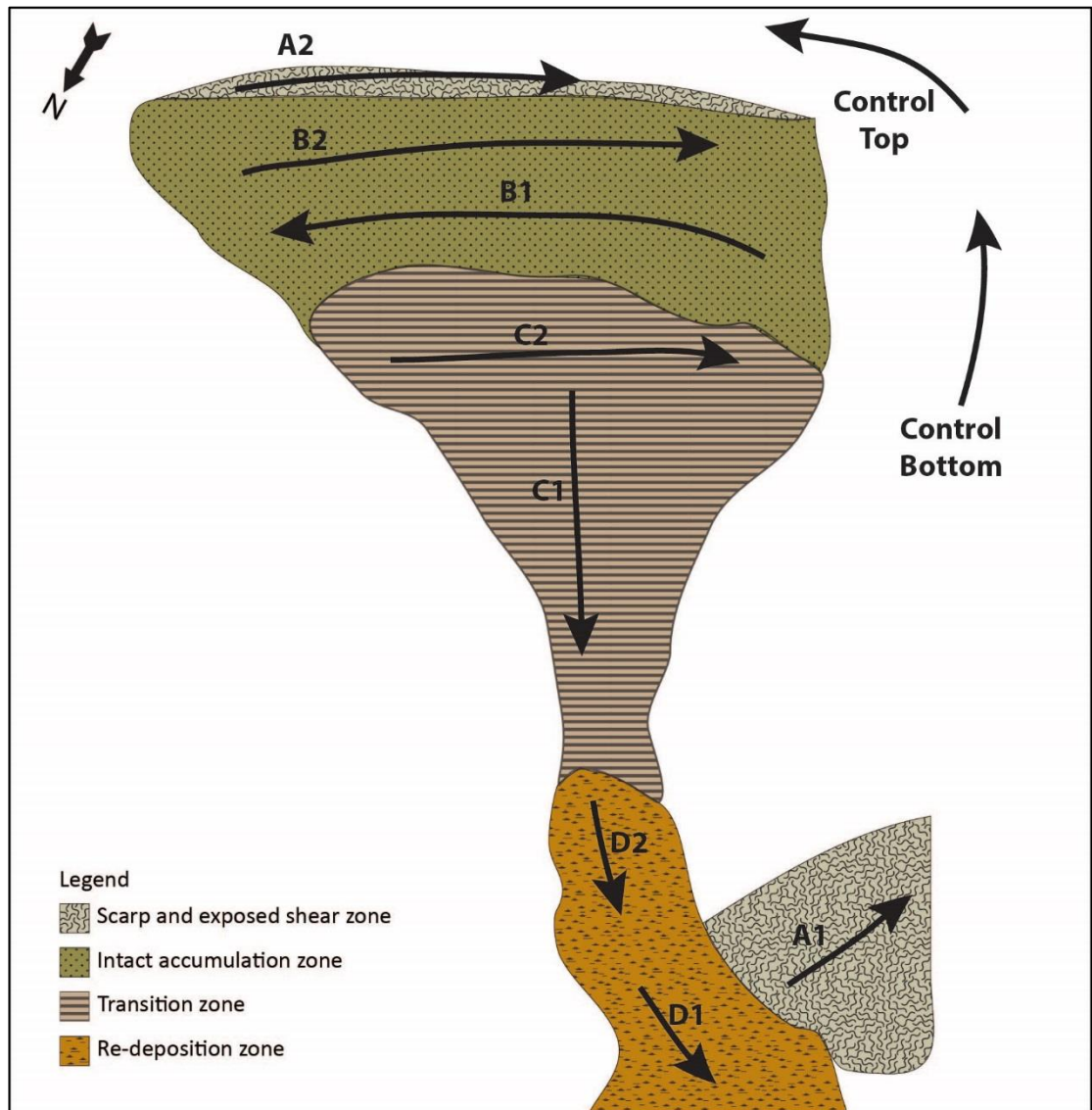
<i>Landslide 5</i>	<i>GPS Co-ordinates</i>	<i>Description</i>
Hole 1 Re-deposition zone Typical soil characteristics of this series of landslides	S37°47'18.3" E175° 03'59.8"	No clear horizonation, all soil types jumbled to 1 m depth
Hole 2 Re-deposition zone	S37°47'18.2" E175° 03'59.6"	No clear horizonation, all soil types jumbled to 1 m depth
Hole 3 Re-deposition zone	S37°47'18.3" E175° 03'59.3"	As above - 60 cm 61 → Saprolite
Hole 4 Re-deposition zone	S37°47'18.1" E175° 03'59.4"	As holes 1 & 2
Hole 5 Re-deposition zone	S37°47'17.6" E175° 03'59.9"	As above
Hole 6 Re-deposition zone	S37°47'18.2" E175° 04'00.2"	As above
Hole 7 Intact accumulation zone Dunmore	S 37°47'20.24" E 175° 4'1.45"	Horizon: Ap – 0 – 25 cm Colour: 10YR 3/4 Dark brown Roots: Very few  Horizon: Bw1 – 26 – 50 cm Colour: 10YR 5/8 Yellowish brown Roots: Very few  Horizon: Bw2 – 51 – 75 cm Colour: 10YR 5/8 Yellowish brown Roots: Very few  Horizon: C – 76 – 100 cm Colour: 10YR 6/8 Bright yellowish brown Roots: None
Hole 8 Intact accumulation zone Dunmore soil	S 37°47'20.37" E 175° 4'1.69"	Horizon: Ap – 0 – 7 cm Colour: 10YR 3/4 Dark brown Roots: Few  Horizon: Bw1 – 8 – 22 cm Colour: 10YR 5/4 Dull yellowish brown Roots: Few  Horizon: Bw2 – 23 – 50 cm Colour: 2.5YR 4/4 Olive brown Roots: Very few  Horizon: C1 – 51 – 80 cm Colour: 10YR 5/6 Yellowish brown Roots: Very few  Horizon: C2 – 81 – 100 cm Colour: 10YR 4/6 Brown Roots: Few
Hole 9 – Intact accumulation zone	S 37°47'20.06" E 175° 4'02.26"	Horizon: Ap – 0 – 15 cm Colour: 10YR 4/4 Brown Roots: Common  Horizon: Bw1 – 16 – 30 cm Colour: 10YR 4/6 Brown Roots: Few

## Appendix B

		Horizon: Bw2 – 31 – 70 cm Colour: 10YR 5/6 Brown Roots: Very few
		Horizon: C – 71 – 100 cm Colour: 7.5YR 5/6 Bright brown Roots: Very few
Hole 10	S 37°47'20.09" E 175° 4'1.61"	Horizon: Ap – 0 – 15 cm Colour: 10YR 3/4 Dark brown Roots: Many
Intact accumulation zone Dunmore soil		Horizon: Bw1 – 16 – 50 cm Colour: 2.5YR 4/6 Olive brown Roots: Few
		Horizon: Bw2 – 51 – 80 cm Colour: 10YR 5/8 Yellowish brown Roots: Very few
		Horizon: C – 81 – 100 cm Colour: 7.5YR 5/6 Bright brown Roots: None
Hole 11	S 37°47'19.7" E 175° 4'02.5"	No notes in field notebook assuming similar to Holes 7 – 10
Intact accumulation zone		
Hole 12	S 37°47'19.8" E 175° 4'02.4"	As above
Intact accumulation zone		
Hole 13	S 37°47'20.0" E 175° 4'02.3"	Slight mixed A horizon → 20 cm but Bw1 and below as above
Intact accumulation zone		
Hole 14	S 37°47'20.1" E 175° 4'02.2"	As Holes 7 – 10
Intact accumulation zone		
Hole 15	S 37°47'20.2" E 175° 4'02.3"	As above
Intact accumulation zone		
Hole 16	S 37°47'19.7" E 175° 4'02.2"	As above
Intact accumulation zone		
Hole 17	S 37°47'19.3" E 175° 4'01.9"	As above
Intact accumulation zone		
Hole 18	S 37°47'19.7" E 175° 4'01.7"	As above
Intact accumulation zone		
Hole 19	S 37°47'19.9" E 175° 4'01.4"	As above
Intact accumulation zone		
Hole 20 -	S 37°47'19.3" E 175° 4'01.3"	Shallow A horizon – 0 – 10 cm 10 cm → as above
Intact accumulation zone		
Hole 21	S 37°47'19.1" E 175° 4'01.0"	No field notes, recently activated landslide
Transition zone		

Additional holes were dug in the transition zone to determine topsoil depth, however the GPS co-ordinates were misplaced depths can be found in the A horizon summary tables

B5.2. Bucket sampling transects



## Appendix B

### *Transect co-ordinates*

<i>Sample</i>	<i>GPS - Start</i>	<i>GPS - End</i>
A1	S37° 47'17.9" E175°03'59.2"	S37° 47'18.4" E175°03'59.2"
A2	S37° 47'18.1" E175°03'59.2"	S37° 47'20.1" E175°04'03.3"
B1	S37° 47'19.0" E175°04'02.3"	S37° 47'20.0" E175°04'01.6"
B2	S37° 47'19.9" E175°04'02.7"	S37° 47'20.4" E175°04'01.6"
C1	S37° 47'18.3" E175°03'59.9"	S37° 47'18.6" E175°03'59.7"
C2	S37° 47'18.7" E175°04'01.5"	S37° 47'19.3" E175°04'00.9"
D1	S37° 47'18.1" E175°03'59.40"	S37° 47'17.7" E175°03'59.1"
D2	S37° 47'17.9" E175°03'59.4"	S37° 47'18.2" E175°03'59.7"
Control Top	S37° 47'20.7" E175°04'01.7"	S37° 47'20.5" E175°04'02.2"
Control Bottom	S37° 47'18.8" E175°04'01.3"	S37° 47'18.7" E175°04'01.6"

### B5.3. Soil dry bulk density and other soil properties

Sample	GPS Location	Tin weight (g)	Sand added (mls)	Cylinder Diameter (cm)	Cylinder length (cm)	Volume of cylinder $\pi r^2 \times$ length (cm <sup>3</sup> )	Amended Volume of cylinder	Sample + Tin weight (g)	Sample only (field moist)	Weight after oven 48 (g)	Sample only (oven-dried) 48 hours	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Soil Moisture content (g/g)	Soil Porosity (g)	Volumetric water content (g/cm <sup>3</sup> )	Water filled pore space (%)
LS1 - A1	S37° 47'20.2" E175° 04'02.5"	10.96	0	6	5	141.37	141.37	196.92	185.96	130.38	119.42	0.84	55.33	0.55	0.67	0.47	69.76
LS1 - A2	S37° 47'20.3" E175° 04'02.6"	10.95	1.4	6	5.1	144.20	142.80	162.68	151.73	127.39	116.44	0.82	30.15	0.30	0.68	0.25	36.07
LS1 - A3	S37° 47'20.4" E175° 04'02.2"	10.86	0	6	4.9	138.54	138.54	169.92	159.06	123.14	112.28	0.81	41.46	0.41	0.68	0.34	49.17
LS1 - B1	S37° 47'20.4" E175° 04'01.5"	10.67	0.1	6	5	141.37	141.27	199.49	188.82	151.55	140.88	1.00	33.63	0.34	0.61	0.34	54.93
LS1 - B2	S37° 47'20.1" E175° 04'01.7"	10.78	2.6	6	5	141.37	138.77	191.10	180.32	146.81	136.03	0.98	32.40	0.32	0.62	0.32	51.46
LS1 - B3	S37° 47'19.7" E175° 04'01.5"	10.86	0	6	5.1	144.20	144.20	214.34	203.48	164.31	153.45	1.06	32.38	0.32	0.58	0.34	58.97
LS1 - C1	S37° 47'19.3" E175° 04'01.4"	10.82	0	6	5	141.37	141.37	185.12	174.29	137.03	126.21	0.89	54.94	0.55	0.65	0.49	75.31
LS1 - C2	S37° 47'19.1" E175° 04'00.9"	10.83	0	6	5.1	144.20	144.20	211.60	200.77	123.11	112.28	0.78	58.80	0.59	0.70	0.46	65.80
LS1 - C3	S37° 47'19.1" E175° 04'00.9"	10.93	0	6	4.9	138.54	138.54	212.11	201.18	141.60	130.68	0.94	53.74	0.54	0.63	0.51	80.26
LS1 - D1	S37° 47'18.5" E175° 04'00.5"	10.75	0	6	4.8	135.72	135.72	211.65	200.91	148.22	137.48	1.01	45.88	0.46	0.60	0.46	76.90
LS1 - D2	S37° 47'18.1" E175° 03'59.9"	10.89	0	6	5.1	144.20	144.20	222.08	211.19	142.04	131.15	0.91	60.73	0.61	0.64	0.55	85.68
LS1 - D3	S37° 47'18.0" E175° 03'59.4"	10.71	0	6	5.1	144.20	144.20	192.06	181.36	127.49	116.78	0.81	55.00	0.55	0.68	0.45	65.15
LS1 - CT1	S37° 47'20.6" E175° 04'02.5"	10.62	2	6	5	141.37	139.37	184.36	173.74	147.01	136.40	0.98	27.23	0.27	0.62	0.27	43.14
LS1 - CT2	S37° 47'21.0" E175° 04'02.2"	10.73	1	6	5.1	144.20	143.20	212.26	201.52	151.75	141.02	0.98	42.74	0.43	0.62	0.42	68.41
LS1 - CB1	S37° 47'17.3" E175° 03'59.9"	11.01	0	6	5	141.37	141.37	178.19	167.18	142.87	131.86	0.93	26.50	0.26	0.64	0.25	38.88
LS1 - CB2	S37° 47'17.9" E175° 04'01.0"	10.86	0	6	5	141.37	141.37	208.88	198.03	156.82	145.96	1.03	34.91	0.35	0.60	0.36	60.40

## B6. Landslide 6

### B6.1. Auger holes and profile descriptions

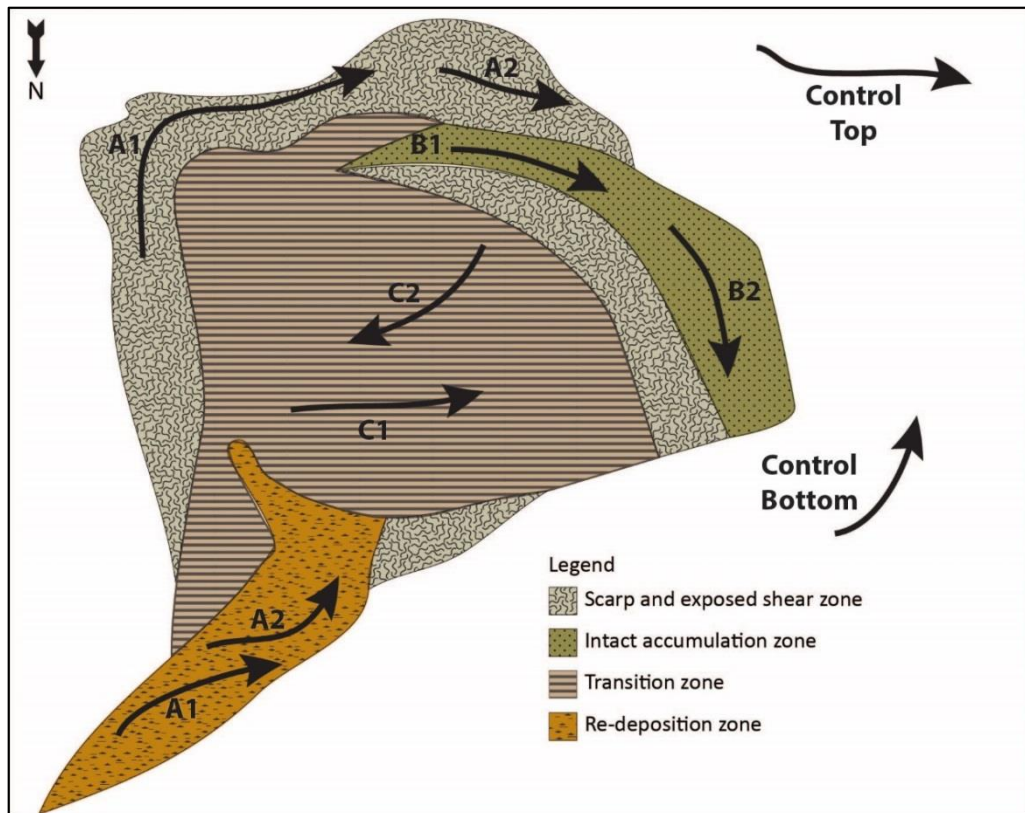
<i>Landslide 6</i>	<i>GPS Co-ordinates</i>	<i>Description</i>
Hole 1 - Transition zone	S37° 47'06.3" E175° 04'04.2"	Horizon: A – 0 – 7 cm mainly detritus Horizon: Mixed soils – 7 – 17 cm Horizon: 17 → Saprolite
Hole 2 - Transition zone	S37°47'06.3" E175° 04'04.4"	As above
Hole 3 - Transition zone	S37° 47'06.5" E175° 04'03.3"	Horizon: A – 0 – 5 cm mainly detritus Horizon: Mixed soils – 7 – 17 cm Horizon: 17 → Saprolite
Hole 4 - Transition zone	S37° 47'06.3" E175° 04'05.1"	As above
Hole 5 - Transition zone	S37° 47'05.5" E175° 04'03.4"	As above
Hole 6 - Transition zone	S37° 47'06.5" E175° 04'03.3"	As above
Hole 7 - Transition zone	S37° 47'06.6" E175° 04'04.1"	Horizon: A – 0 – 7 cm The rest of profile looks like Holes 1 - 7
Hole 8 – Intact accumulation zone/Transition zone boundary	S37° 47'08.1" E175° 04'03.6"	Horizon: A 0-7 cm Mix soil 8-17 cm Bw 18-30 cm C 31-50 cm Saprolite – 50+ cm
Hole 9 – Intact accumulation zone/ Shear zone boundary – Kind of like a re-deposition area between intact and shear	S37° 47'08.0" E175° 04'03.4"	Horizon: A 0-3 cm Mix soil 4-60 cm Saprolite – 61+ cm
Hole 10 Dunmore soil Intact accumulation	S37° 47'08.1" E175° 04'03.6"	Horizon: A 0-20 cm Colour: 10YR 3/4 dark brown Peds: Moderate Roots: Many NaF reaction: Weak Horizon: Bw 21-50 cm Colour: 5YR 5/8 bright reddish brown Peds: Weak Roots: None NaF reaction: Weak Horizon: C 51-80 cm Colour: 2.5YR 5/8 bright brown Peds: Weak Roots: None Solum Depth: 81-100+ cm. Saprolite
Hole 11 Outer edge intact accumulation	S37° 47'07.4" E175° 04'02.7"	As hole 8
Hole 12 Outer edge intact accumulation Waingaro Steepland soil	S37° 47'07.4" E175° 04'03.1"	Horizon: A 0-10 cm Colour: 10YR 4/4 brown Horizon: Bw1 11-30 cm Colour: 10YR 5/8 yellowish brown Horizon: Bw2 31-50 Colour 10YR 5/8 yellowish brown Horizon: C – mixed gley 51-80 cm Colour: 5YR 5/8 bright reddish brown Horizon: C2 81-100+ Colour: As above
Hole 13	S37° 47'07.7"	Horizon: A 0-20 cm

## Appendix B

Intact accumulation zone, outer edge	E175° 04'03.0"	AB mix 21-55 cm C 55+ cm
Hole 14 Intact accumulation	S37° 47'08.0" E175° 04'03.0"	As above

Appendix B

B6.2. Bucket sampling transects



Sample	GPS - Start	GPS - End
	S37° 47'17.9"	S37° 47'07.8"
	E175°03'59.2"	E175°04'03.4"
A2	S37° 47'07.4"	S37° 47'07.9"
	E175°04'02.7"	E175°04'02.8"
B1	S37° 47'07.9"	S37° 47'07.8"
	E175°04'03.6"	E175°04'03.2"
B2	S37° 47'07.5"	S37° 47'07.8"
	E175°04'02.8"	E175°04'03.7"
C1	S37° 47'06.4"	S37° 47'06.5"
	E175°04'04.2"	E175°04'03.9"
C2	S37° 47'06.8"	S37° 47'07.0"
	E175°04'03.7"	E175°04'03.8"
D1	S37° 47'06.2"	S37° 47'06.6"
	E175°04'04.1"	E175°04'03.7"
D2	S37° 47'06.3"	S37° 47'06.3"
	E175°04'03.6"	E175°04'03.8"
Control Top	S37° 47'08.1"	S37° 47'08.8"
	E175°04'02.7"	E175°04'02.3"
Control Bottom	S37° 47'07.5"	S37° 47'07.2"
	E175°04'02.7"	E175°04'01.9"

### B6.3. Soil dry bulk density and other soil properties

Sample	GPS Location	Tin weight (g)	Sand added (mls)	Cylinder Diameter (cm)	Cylinder length (cm)	Volume of cylinder $\pi r^2 \times$ length (cm <sup>3</sup> )	Amended Volume of cylinder	Sample + Tin weight (g)	Sample only (field moist)	Weight after oven 48 (g)	Sample only (oven-dried) 48 hours	Bulk Density (g/cm <sup>3</sup> )	Moisture Content (%)	Soil Moisture content (g/g)	Soil Porosity (g)	Volumetric water content (g/cm <sup>3</sup> )	Water filled pore space (%)
LS1 - A1	S37° 47'07.4" E175° 04'04.3"	10.92	0	6	5	141.37	141.37	209.72	198.79	148.85	137.92	0.98	43.99	0.44	0.62	0.43	69.34
LS1 - A2	S37° 47'08.0" E175° 04'03.2"	10.76	0	6	5.1	144.20	144.20	203.40	192.65	143.72	132.96	0.92	44.73	0.45	0.64	0.41	64.47
LS1 - A3	S37° 47'08.4" E175° 04'02.7"	10.92	0	6	5	141.37	141.37	122.12	111.20	85.83	74.91	0.53	47.93	0.48	0.79	0.25	32.03
LS1 - B1	S37° 47'08.0" E175° 04'02.9"	10.89	0	6	4.9	138.54	138.54	201.58	190.69	116.45	105.56	0.76	79.94	0.80	0.70	0.61	86.72
LS1 - B2	S37° 47'07.8" E175° 04'03.0"	10.69	0	6	5	141.37	141.37	199.67	188.98	132.11	121.42	0.86	55.27	0.55	0.66	0.47	71.43
LS1 - B3	S37° 47'07.6" E175° 04'02.8"	10.73	0	6	5.1	144.20	144.20	199.68	188.96	143.17	132.44	0.92	42.44	0.42	0.64	0.39	60.79
LS1 - C1	S37° 47'06.3" E175° 04'03.3"	10.81	0	6	5	141.37	141.37	218.91	208.10	149.97	139.15	0.98	49.24	0.49	0.62	0.48	78.74
LS1 - C2	S37° 47'06.7" E175° 04'03.7"	10.75	0	6	5.1	144.20	144.20	234.15	223.41	160.96	150.22	1.04	48.57	0.49	0.59	0.51	85.32
LS1 - C3	S37° 47'07.9" E175° 04'03.5"	10.89	0	6	5.1	144.20	144.20	194.51	183.61	139.73	128.84	0.89	42.22	0.42	0.65	0.38	57.94
LS1 - D1	S37° 47'06.2" E175° 04'04.2"	10.78	0	6	5	141.37	141.37	214.99	204.21	132.92	122.14	0.86	66.90	0.67	0.66	0.58	87.25
LS1 - D2	S37° 47'06.4" E175° 04'03.6"	11.05	0	6	5	141.37	141.37	218.61	207.56	146.18	135.13	0.96	53.43	0.53	0.63	0.51	81.50
LS1 - D3	S37° 47'06.2" E175° 04'04.0"	11.05	1	6	5	141.37	140.37	206.33	195.27	128.67	117.62	0.84	65.65	0.66	0.67	0.55	81.77
LS1 - CT1	S37° 47'08.5" E175° 04'02.7"	10.90	0	6	5	141.37	141.37	139.68	128.77	83.65	72.75	0.51	76.03	0.76	0.80	0.39	48.96
LS1 - CT2	S37° 47'08.8" E175° 04'02.4"	10.80	0	5.9	5.1	139.43	139.43	158.45	147.65	97.97	87.17	0.63	68.55	0.69	0.76	0.43	56.70
LS1 - CB1	S37° 47'07.1" E175° 04'02.3"	10.94	0.6	6	5.1	144.20	143.60	215.66	204.73	155.16	144.23	1.00	41.77	0.42	0.61	0.42	69.04
LS1 - CB2	S37° 47'07.3" E175° 04'01.7"	10.89	0	6	5	141.37	141.37	203.94	193.05	150.02	139.13	0.98	38.57	0.39	0.62	0.38	61.66

## Appendix B

### B7. Controls

#### B7.1. Auger holes and profile descriptions

<i>Control Zones</i>	<i>GPS Co-ordinates</i>	<i>Description</i>
LS1 Hollow above landslide 1 Kaawa Hill soil	S37°47' 16.4" E175° 04' 08.8"	Horizon: A 0-15 cm – Mid brown colouring Clayey bright brown subsoil with bright mottles Solum Depth: 80cm Dull brown subsoil with greying mottles developing
LS1 Left flattish mid-ridge Dunmore soil	S37°47' 14.5" E175° 04' 07.9"	Horizon: A 0-30 cm – Orangey brown, allophanic topsoil, friable and earthy. Subsoil – bright brown, no mottles, allophanic Solum Depth: 100+ cm
LS1 Moderate slope Kaawa Hill soil	S37°47' 13.9" E175° 04' 06.3"	Horizon: A 0-20 cm – Dark/mid brown, granular Horizon: B 21-50 cm – Clayey, bright brown matrix, no mottles Horizon: C 51-80 – pale mottling starting Solum Depth: 80+ cm – Saprolite beginning
LS2 Moderate slope Kaawa Hill soil Left ridge bottom	S37°47' 15.4" E175° 04' 04.4"	Horizon: A 0-10 cm – Midbrown blocky Subsoil interspersed with saprolite Solum Depth 50 cm
LS2 Flattish area Kaawa Hill soil	S37°47' 16.1" E175° 04' 04.2"	Horizon: A 0-20 cm – Midbrown Subsoil – Lighter brown B Solum Depth: 80+ cm
LS3 Kaawa Hill soil Strongly sloping	S37°47' 16.3" E175° 04' 03.5"	Horizon: A 0-15 cm – Midbrown Subsoil – Bright brown B, slightly allophanic Solum Depth: 80+ cm
LS3 Kaawa Hill soil Gently sloping	S37°47' 17.5" E175° 04' 03.3"	Horizon: A 0-20 cm – Midbrown Subsoil – Orangey brown B, no mottles Solum Depth: 80+ cm
LS4 Dunmore soil Moderately sloping	S37°47' 17.5" E175° 04' 01.7"	Horizon: A 0-25 cm – Orangey mid-brown, friable, apedal earthy Subsoil – 26-65 cm Bright brown, clayey, no mottles Solum Depth: 100+ cm
LS5 Bad control	S37°47' 19.4" E175° 03' 08.7"	Evidence of past movement in control site
LS5 Kaawa Hill soil Top flat – gently sloping gully – Rushes around landslide Kaawa Hill soil	S37°47' 19.4" E175° 04' 01.7"	Horizon: A 0-20 cm – Midbrown Subsoil – 21-40 cm B, clayey, bright brown mottles, imperfectly draining, sticky, brown matrix Solum Depth: 40+ cm
LS5 Dunmore soil Left ridge – stable, high elevation, moderate – gently sloping	S37°47' 18.8" E175° 04' 03.1"	Horizon: A 0-25 cm – Dark/Midbrown Subsoil – 26-70 heavier clay Solum Depth: 100+cm
LS6 Dunmore soil Flat ridge top right	S37°47' 08.5" E175° 04' 02.5"	Horizon: A 0-15 cm – Dark brown, friable, apedal earthy, allophanic Solum Depth: 100+ cm
LS6 Waingarō steepland soil Mid slope – Strong – steeply sloping	S37°47' 08.2" E175° 04' 02.4"	Horizon: A 0-15 cm – Midbrown/yellowish Solum Depth: shallow

## B8. Soil depth summary

### B8.1 A horizons summarised raw data

Zone	Landslide					
	LS1	LS2	LS3	LS4	LS5	LS6
<i>Shear</i>	7		4	3		
	2		3	0		
	1		3	0		
	3		2	0		
			7	0		
<b>Average</b>	3	0	3	1	0	0
<i>Intact accumulation</i>	15	10	N/A	20	25	7
		15			7	20
		20			15	7
		7			15	10
		20			15	20
					20	20
					18	
					18	
					18	
					10	
<b>Average</b>	15	14		20	16	14
<i>Transition</i>	10	4	8	3	10	7
	20	3	10	3	4	7
	3	4	9	3	5	5
	3	7	10	3	1	5
			15	3	0	5
			7	18		5
			9			7
					7	
<b>Average</b>	9	5	10	6	4	6
<i>Re-deposition</i>	3	0	4	4	0	0
	2	1	2		0	0
	5		6		0	0
	5		3		0	0
	5				0	0
<b>Average</b>	4	0	4	4	0	0
<i>Control</i>	15	35	20	25	20	15
	30	10	15		25	15
	20	20				
<b>Average</b>	22	22	18	25	23	15

Appendix B

**B8.2A horizon means**

	<i>LS1</i>	<i>LS2</i>	<i>LS4</i>	<i>LS5</i>	<i>LS6</i>	<i>LS3</i>	<i>Mean</i>	<i>Std. Dev.</i>
<i>Shear</i>	3.3	0.0	0.8	0.0	0.0	3.0	1.2	1.4
<i>Intact accumulation</i>	15.0	14.4	20.0	16.3	14.0	-	15.9	6.3
<i>Transition</i>	9.0	4.5	5.5	4.0	6.0	9.7	6.5	2.2
<i>Re-deposition</i>	4.0	0.3	4.0	0.0	0.0	3.8	2.0	1.9
<i>Control</i>	21.7	21.7	25.0	22.5	15.0	17.5	20.6	3.3

**B8.3A horizon t-tests**

<i>Zone</i>	<i>Shear</i>	<i>Intact</i>	<i>Transition</i>	<i>Re-deposition</i>	<i>Control</i>
<i>Shear</i>	-	0.000	0.000	0.158	0.000
<i>Intact</i>	-	-	0.003	0.000	0.010
<i>Transition</i>	-	-	-	0.001	0.001
<i>Re-deposition</i>	-	-	-	-	0.000
<i>Control</i>	-	-	-	-	-

# Appendix C

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Laboratory analysis raw data

## C1. Carbon and nitrogen analysis

<b>Total Carbon (%)</b>																
Landslide	Field replicate	Shear zone			Intact accumulation zone			Transition zone			Re-deposition zone			Controls		
		Total C (%)	Year of last activation	Years since activation	Total C (%)	Year of last activation	Years since activation	Total C (%)	Year of last activation	Years since activation	Total C (%)	Year of last activation	Years since activation	Total C (%)	Year of last activation	Years since activation
1	1	5.11	Pre-1953	62	7.33	Pre-1953	62	7.02	Pre-1953	62	6.14	Pre-1953	62	10.23	Pre-1939	76
	2	6.37	Pre-1953	62	6.62	Pre-1953	62	5.70	Pre-1953	62	5.77	Pre-1953	62	13.22	Pre-1939	76
2	1	1.31	2014	1	5.09	2014	1	3.26	2014	1	2.28	2014	1	6.30	Pre-1939	76
	2	3.31	2014	1	5.01	2014	1	2.93	2014	1	1.70	2014	1	7.18	Pre-1939	76
3	1	3.86	Pre-1953	62	-	Pre-1953	62	6.32	Pre-1953	62	3.13	Pre-1953	62	9.02	Pre-1939	76
	2	3.73	Pre-1953	62	-	Pre-1953	62	6.72	Pre-1953	62	4.28	Pre-1953	62	5.63	Pre-1939	76
	3	4.53	Pre-1953	62	-	Pre-1953	62	5.42	Pre-1953	62	-	Pre-1953	62	-	Pre-1939	76
4	1	0.54	1988	27	5.03	1988	27	2.47	2007	8	2.34	2007	8	8.62	Pre-1939	76
	2	0.81	1988	27	3.93	1988	27	3.60	2007	8	2.02	2007	8	8.19	Pre-1939	76
5	1	0.97	1988	28	4.82	1988	28	1.31	2014	1	2.00	2014	1	4.90	Pre-1939	76
	2	1.17	1988	28	5.07	1988	28	4.36	2014	1	1.90	2014	1	7.57	Pre-1939	76
6	1	0.37	1995	20	5.01	1995	20	3.04	1995	20	3.46	1995	20	12.06	Pre-1939	76
	2	2.77	1995	20	5.75	1995	20	4.52	1995	20	3.24	1995	20	5.11	Pre-1939	76
<b>Total Nitrogen (%)</b>																
Landslide	Field replicate	Shear zone			Intact accumulation zone			Transition zone			Re-deposition zone			Controls		
		Total N (%)	Year of last activation	Years since activation	Total N (%)	Year of last activation	Years since activation	Total N (%)	Year of last activation	Years since activation	Total N (%)	Year of last activation	Years since activation	Total N (%)	Year of last activation	Years since activation
1	1	0.37	Pre-1953	62	0.63	Pre-1953	62	0.59	Pre-1953	62	0.53	Pre-1953	62	0.83	Pre-1939	76
	2	0.53	Pre-1953	62	0.58	Pre-1953	62	0.47	Pre-1953	62	0.50	Pre-1953	62	1.10	Pre-1939	76
2	1	0.10	2014	1	0.44	2014	1	0.27	2014	1	0.18	2014	1	0.54	Pre-1939	76
	2	0.23	2014	1	0.42	2014	1	0.24	2014	1	0.14	2014	1	0.60	Pre-1939	76
3	1	0.29	Pre-1953	62	-	Pre-1953	62	0.55	Pre-1953	62	0.29	Pre-1953	62	0.75	Pre-1939	76
	2	0.32	Pre-1953	62	-	Pre-1953	62	0.54	Pre-1953	62	0.36	Pre-1953	62	0.43	Pre-1939	76
	3	0.39	Pre-1953	62	-	Pre-1953	62	0.44	Pre-1953	62	-	Pre-1953	62	-	Pre-1939	76
4	1	0.05	1988	27	0.41	1988	27	0.20	2007	8	0.18	2007	8	0.71	Pre-1939	76
	2	0.07	1988	27	0.30	1988	27	0.28	2007	8	0.16	2007	8	0.67	Pre-1939	76
5	1	0.08	1988	28	0.44	1988	28	0.11	2014	1	0.15	2014	1	0.41	Pre-1939	76
	2	0.09	1988	28	0.43	1988	28	0.38	2014	1	0.14	2014	1	0.64	Pre-1939	76
6	1	0.04	1995	20	0.42	1995	20	0.22	1995	20	0.20	1995	20	1.10	Pre-1939	76
	2	0.19	1995	20	0.49	1995	20	0.33	1995	20	0.21	1995	20	0.41	Pre-1939	76

## Appendix C

### *C1.1. Soil C t-test*

<b>Zone</b>	<i>Shear</i>	<i>Intact accumulation</i>	<i>Transition</i>	<i>Re-deposition</i>	<i>Control</i>
<i>Shear</i>	-	0.004	0.003	0.156	0.000
<i>Intact accumulation</i>	-	-	0.004	0.004	0.000
<i>Transition</i>	-	-	-	0.021	0.002
<i>Re-deposition</i>	-	-	-	-	0.000
<i>Control</i>	-	-	-	-	-

### *C1.2. Soil N t-test*

<b>Zone</b>	<i>Shear</i>	<i>Intact accumulation</i>	<i>Transition</i>	<i>Re-deposition</i>	<i>Control</i>
<i>Shear</i>	-	0.001	0.001	0.046	0.000
<i>Intact accumulation</i>	-	-	0.002	0.004	0.010
<i>Transition</i>	-	-	-	0.012	0.003
<i>Re-deposition</i>	-	-	-	-	0.000
<i>Control</i>	-	-	-	-	-

## Appendix C

### C1.3. Dr. Ray Littler

#### C Analysis of variance comparing zones and treating landslides as blocks

Analysis of variance

=====

Variate: TotC

Source of variation v.r. F pr.	d.f. (m.v.)	s.s.	m.s.
Landslide stratum 16.23	5	54.9922	10.9984
Landslide.*Units* stratum Zone 43.78 <.001	4	118.6820	29.6705
Residual	19 (1)	12.8764	0.6777
Total	28 (1)	184.0271	

\* MESSAGE: the following units have large residuals.

Landslide 3      \*units\* 1                      -1.62      s.e. 0.66

Tables of means

=====

Variate: TotC

Grand mean    4.73

Zone	Control	Intact	Redeposit	Shear	Trans
	8.17	5.52	3.19	2.57	4.21

Standard errors of differences of means

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Table	Zone
rep.	6
d.f.	19
s.e.d.	0.475

(Not adjusted for missing values)

Student-Newman-Keuls test

=====

Zone

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	Mean	
Shear	2.567	a
Redeposit	3.189	a
Trans	4.210	b
Intact	5.521	c
Control	8.170	d

The interpretation is that we are 95% confident that all the means that have different letters differ in the population from

## C2. Soil pH

Soil pH												
Sample/Zone	Landslide 1		Landslide 2		Landslide 3		Landslide 4		Landslide 5		Landslide 6	
	Soil weight (g)	pH	Soil weight (g)	pH	Soil weight (g)	pH	Soil weight (g)	pH	Soil weight (g)	pH	Soil weight (g)	pH
A1 - Shear	5.0050	5.1	5.0004	4.9	5.0037	5.6	5.0001	5.2	5.0013	4.9	4.9986	5.1
A2 - Shear	5.0012	5.1	5.0032	5.4	5.0029	5.1	5.0011	5.0	4.9989	5.2	4.9997	5.6
A3 - Shear	-	-	-	-	4.9988	5.2	-	-	-	-	-	-
B1 – Intact accumulation	4.9990	5.1	4.9954	5.2	-	-	5.0050	5.2	4.9992	5.2	4.9982	5.4
B2 – Intact accumulation	5.0001	5.2	4.9998	5.3	-	-	5.0042	5.1	5.0007	5.5	4.9991	5.6
C1 - Transition	4.9991	5.0	5.0020	5.1	5.0019	4.9	5.0050	5.2	5.0026	5.2	5.0005	4.7
C2 - Transition	5.0026	5.1	5.0030	4.9	4.9994	5.1	5.0007	5.2	5.0045	5.5	4.9988	4.9
C3 - Transition	-	-	-	-	5.0010	5.2	-	-	-	-	-	-
D1- Re-deposition	5.0006	5.1	4.9975	5.0	5.0025	5.3	5.0036	5.1	4.9993	5.2	5.0000	4.6
D2 – Re-deposition	5.0042	5.1	4.9977	4.9	5.0000	5.3	5.0007	5.2	5.0002	5.2	4.9999	4.7
Control Top	5.0009	5.1	5.0041	5.3	5.0000	5.2	5.0000	5.3	5.0034	5.5	4.9993	5.7
Control Bottom	5.0007	5.2	5.0016	5.1	4.9997	5.4	5.0042	5.2	4.9993	5.3	5.0048	5.5

### C3. Olsen P

Olsen P

Landslide	Field replicate 1				Field Replicate 2					
	Zone	Run 1 <i>ug P/g oven dried soil</i>	Run 3	Mean	Zone	Run 2 <i>ug P/g oven dried soil</i>	Run 4	Mean	Mean of all 4	Std Dev.
1	Shear	10	9	9.4	Shear	118	108	113	61	59.9
	Intact	129	131	129.5	Intact	122	122	122	126	4.1
	Transition	103	99	101.1	Transition	113	106	110	105	5.8
	Re-deposition	59	55	57.0	Re-deposition	50	47	48	53	5.4
	Control Top 1	13	11	11.7	Control Bottom	11	33	22	17	9.9
2	Shear	1	2	1.9	Shear	2	3	3	2	0.7
	Intact	11	10	10.6	Intact	7	6	7	9	2.2
	Transition	6	6	6.0	Transition	3	3	3	4	1.9
	Re-deposition	6	5	5.4	Re-deposition	3	2	2	4	1.9
	Control Top 1	20	15	17.5	Control Bottom	19	22	21	19	3.1
3	Shear	14	12	25.9	Shear	16	17	17	23	12.6
	Shear	42	35		Transition	35	32			
	Transition	38	22	30.4	Transition	15	16	24	26	10.1
	Re-deposition	29	19	24.2	Re-deposition	6	18	12	18	9.3
	Control Top 3	31	30	30.4	Control Bottom	5	5	5	18	14.4
4	Shear	2	3	2.2	Shear	1	0	0	1	1.2
	Intact	15	13	13.7	Intact	6	5	6	10	4.7
	Transition	5	7	6.1	Transition	4	4	4	5	1.2
	Re-deposition	4	4	4.2	Re-deposition	4	4	4	4	0.2
	Control Top 1	22	15	18.5	Control Bottom	11	11	11	15	4.9
5	Shear	1	3	2.0	Shear	2	1	1	2	1.0
	Intact	45	24	34.8	Intact	10	10	10	23	16.4
	Transition	5	7	6.0	Transition	17	18	18	12	6.8
	Re-deposition	8	7	7.4	Re-deposition	4	3	4	6	2.1
	Control Top 1	10	8	8.9	Control Bottom	31	35	33	21	14.9
6	Shear	0	2	1.1	Shear	2	0	1	1	1.1
	Intact	12	9	10.2	Intact	11	9	10	10	1.5
	Transition	14	10	12.2	Transition	10	8	9	11	2.5
	Re-deposition	11	18	14.1	Re-deposition	30	27	29	21	9.0
	Control Top 1	66	64	65.0	Control Bottom	16	15	15	40	28.7

## Appendix C

### C3.1. Olsen *P* *t*-tests

#### With LS1

<i>Zone</i>	<i>Shear</i>	<i>Intact</i>	<i>Transition</i>	<i>Re-deposition</i>	<i>Control</i>
<i>Shear</i>	-	0.116	0.119	0.549	0.568
<i>Intact</i>	-	-	0.093	0.285	0.633
<i>Transition</i>	-	-	-	0.333	0.773
<i>Re-deposition</i>	-	-	-	-	0.614
<i>Control</i>	-	-	-	-	-

#### Without LS1

<i>Zone</i>	<i>Shear</i>	<i>Intact</i>	<i>Transition</i>	<i>Re-deposition</i>	<i>Control</i>
<i>Shear</i>	-	0.040	0.026	0.310	0.073
<i>Intact</i>	-	-	0.130	0.532	0.192
<i>Transition</i>	-	-	-	0.767	0.140
<i>Re-deposition</i>	-	-	-	-	0.023
<i>Control</i>	-	-	-	-	-

## C4. Landslide proportions

<i>Zone</i>	<i>Weight (g) by zone and landslide</i>					
	<i>LS1</i>	<i>LS2</i>	<i>LS3</i>	<i>LS4</i>	<i>LS5</i>	<i>LS6</i>
Shear	0.1653	0.0427	0.5118	0.0878	0.0765	0.1520
Intact accumulation	0.1190	0.0912	0.0000	0.1052	0.1878	0.0620
Transition	0.4317	0.1481	0.4008	0.2014	0.1858	0.2398
Re-deposition	0.0655	0.0838	0.1099	0.0375	0.0812	0.0645
<b>Totals</b>	<b>0.7815</b>	<b>0.3658</b>	<b>1.0225</b>	<b>0.4319</b>	<b>0.5313</b>	<b>0.5183</b>

<i>Zone</i>	<i>Landslide zone proportion (%)</i>						<i>Zone average (%)</i>
	<i>LS1</i>	<i>LS2</i>	<i>LS3</i>	<i>LS4</i>	<i>LS5</i>	<i>LS6</i>	
<i>Shear</i>	21	12	50	20	14	29	24
<i>Intact accumulation</i>	15	25	-	24	35	12	22
<i>Transition</i>	55	40	39	47	35	46	44
<i>Re-deposition</i>	8	23	11	9	15	12	13

## C5. Particle size data

Particle size notes from laser sizer - Notes: Samples run in duplicate, there are sometimes high peaks in the coarser grain sizes potentially attributed to organic matter.

<i>Landslide</i>	<i>Clay (&lt; 0.002 mm)</i>	<i>Silt (0.05 - 0.002 mm)</i>	<i>Sand (0.2 - 0.05 mm)</i>
LS1 Shear	34.78	44.31	20.64
LS1 Intact	31.76	49.15	18.85
LS1 Transition	30.13	40.77	28.75
LS1 Re-deposition	33.83	47.52	18.24
LS1 Control	31.43	51.47	16.66
LS2 Shear	28.53	47.44	23.75
LS2 Intact accumulation	22.44	54.90	22.66
LS2 Transition	39.59	48.16	11.97
LS2 Re-deposition	38.26	45.67	15.81
LS2 Control	26.64	59.10	14.09
LS3 Shear	42.32	47.37	10.05
LS3 Transition	36.20	51.79	11.64
LS3 Re-deposition	29.85	46.31	23.55
LS3 Control	29.98	47.30	22.35
LS4 Shear	9.82	32.63	57.55
LS4 Intact accumulation	39.40	47.01	13.20
LS4 Transition	38.21	49.51	11.89
LS4 Re-deposition	20.30	38.62	40.90
LS4 Control	31.82	50.05	17.88
LS5 Shear	22.76	40.87	36.13
LS5 Intact accumulation	32.02	47.14	20.40
LS5 Transition	38.58	50.14	10.95
LS5 Re-deposition	39.80	44.49	15.36
LS5 Control	26.86	52.76	20.21
LS6 Shear	30.68	45.63	23.29
LS6 Intact accumulation	39.49	44.22	15.99
LS6 Transition	41.51	48.63	9.42
LS6 Re-deposition	23.46	45.35	31.07
LS6 Control	24.21	55.28	20.46