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The Effects of Winter Forage Crop Grazing of Hillslopes on Soil Erosion in South Otago

A thesis submitted in partial fulfilment of the requirements for the Degree of Master of Natural Resources Management and Ecological Engineering

at Lincoln University

by

Veronica May Penny

Lincoln University

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Agricultural development has led to deforestation, intensification and increased erosion worldwide. In New Zealand, increasing cow numbers has led to greater demand for forage crops to feed stock off-farm in winter. Expansion of dairying on flat land has pushed wintering systems on to rolling to steep land, particularly in the Southland and South Otago regions.

While the impacts of forage crop grazing on soil compaction and overland flow of sediment and nutrients has been studied, there has been no previous work done on the direct influence of this farming practice on soil transport. This study used a novel technique to quantify the volume of soil transported downslope beneath the hooves of cows that were grazing kale over the 2015 winter period. Steel ball bearings were buried in the soil prior to grazing, and the distance they had moved was determined after winter, and used to infer soil transport.

A linear relationship was found between soil transport flux and slope gradient of up to 0.25 m m\(^{-1}\), with stock track formation on steeper slopes causing greater spatial variability of soil transport rates and non systematic dependence of soil transport hillslope gradient; further research is required to describe this relationship. The steep slope of the relationship for gradients <0.25 indicates that rapid downslope transport occurs relative to gradient under forage crop grazing. This soil transport results in erosion on convex sites, at rates that exceed soil production rates, leading to unsustainable soil loss in these areas.

Soil transport under conventional cultivation was also determined in this study, using the same methodology. No linear relationship was found between transport rates and gradient. However,
despite the lack of relationship, downslope soil transport rates under cultivation exceeded those under cow grazing, indicating that significant soil transport results from this practice. The combination of soil transport under grazing and cultivation allows the impact of the forage crop grazing system as a whole to be understood.

**Keywords:** winter cropping, forage crops, brassica, erosion, sediment, soil transport, soil creep, cattle, wintering systems, cultivation, ploughing, contour ploughing
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Chapter 1

Introduction

Soil provides physical support and a growing medium for food crops, and regulatory services such as water storage, flood mitigation, nutrient cycling and carbon storage (Dominati et al., 2010). Soil erosion results in the thinning of soil, reduced productivity and loss of soil services, while transport of soil and adhered nutrients to waterways causes eutrophication and damage to aquatic ecosystems downstream (Pennock et al., 2015).

Anthropogenic activities have been found to accelerate erosion and its detrimental effects; a major cause of this has been agricultural intensification (Montgomery, 2007). Deforestation of native bush for farmland has caused significant erosion in New Zealand over the last two centuries, with mass erosion being a large problem in the Central North Island (Dymond et al., 2010). 53% of New Zealand's land area is used for agricultural purposes, 29% of which is pastoral, with agricultural products from this land contributing to over half of the nation's total merchandise exports (Beef + Lamb New Zealand, 2016). An increase in global demand for meat and dairy products has led to intensification of New Zealand pastoral systems, and an increase in dairy cow numbers from 3.84 million in 1994 to 6.70 million in 2014 (Statistics New Zealand, 2014). This increase in cow numbers has led to an increase in demand for off-farm wintering systems, to provide feed for stock over the cool winter months when there is little pasture growth (Morris, 2013).

Due to the pastoral farming systems in New Zealand, stock feed availability is heavily influenced by climatic conditions enabling plant growth. The gap in pasture growth over winter is filled through the feeding of preserved pasture (silage) and the use of forage crops, grown over the summer months and fed in-situ over winter. Due to the high energy content of forage crops, they are grazed at a high stocking density for prolonged periods, often under wet soil conditions (Thorrold, 2000).

The impact of intensive pastoral agriculture on soil properties such as compaction and nutrient loss has been well studied over the last two decades. Grazing of wet soils in spring causes high levels of soil compaction and is particularly damaging to soil macropores and pore continuity, resulting in impaired infiltration and drainage rates (Houlbrooke & Laurenson, 2013; McDowell & Houlbrooke, 2008). Nutrient loss of negatively charged minerals, such as nitrate, occurs primarily through leaching and is thus a significant problem on free-draining soils. Loss of cations and specifically absorbed nutrients, such as phosphorus, takes place mainly through transfer of sediment, which is enhanced
on disturbed soils with impaired drainage or saturated conditions that lead to overland flow (McDowell et al., 2009). Accordingly, there has been a recent focus on soil erosion via overland flow, particularly in regard to winter forage cropping, and pastoral systems under irrigation (McDowell & Houlbrooke, 2009; Orchiston et al., 2013). Grazing of forage crops progressing in a downslope direction has been shown to reduce erosion by overland flow, compared to grazing upslope, due to the filtration-effect of ungrazed crop, and the avoidance of critical sediment source areas in gullies (Orchiston et al., 2013). Despite numerous studies on the effect of grazing on erosion via overland flow and of deforestation on mass erosion, there is a scarcity of literature on the direct transport of soil downslope beneath the hooves of stock, or on the transport of soil via cultivation.

The use of conventional cultivation for the establishment of a seedbed for planting crops has been found to contribute to soil transport downslope, and increase susceptibility to erosion via overland flow (Govers et al., 1996). In New Zealand, there have been few studies quantifying the effect of cultivation on soil transport, and those that exist have reported the combined effect of direct soil transport by the plough, overland flow, and wind erosion (Basher & Ross, 2002; Basher et al., 1995). While there is some international data on the effect of conventional cultivation on soil transport (Frauenfeld & Klik, 2002; Govers et al., 1994), these effects are not well understood or documented in New Zealand.

A review of the literature has identified a knowledge gap regarding the relationship between slope gradient and soil transport, and erosion that occurs under pastoral agriculture. Specifically, there was no literature found on rates of cattle-induced soil creep, worldwide. There is also a lack of understanding of the effects of cultivation on soil transport under New Zealand climatic and soil conditions.
1.1 Aims and Objectives

The aim of this research is to determine the relationship between gradient and soil transport on hillslopes under winter forage crop grazing (including post-grazing cultivation), and to use this relationship to calculate erosion rates. An assessment of the sustainability of winter forage grazing will then be made by comparing erosion rates and soil production rates. The ultimate aim is to identify areas where soil loss under current practice is unsustainable, and where implementation of mitigation strategies should be focused to reduce erosion in the future.

These goals will be realised by achieving the following objectives:

1. To generate a digital elevation model of the research area, to allow slopes and curvatures to be determined;
2. To quantify soil transport on a range of gradients over the winter forage crop grazing period;
3. To quantify soil transport on a range of gradients under post-grazing cultivation;
4. To characterise empirically the relationship between soil transport flux and slope gradient, from which soil erosion can be calculated.

1.2 Hypotheses

It is hypothesised that:

1. Soil transport will have a positive linear relationship with hillslope gradient and;
2. The rate of soil transport will decrease with soil depth and;
3. Cultivation will generate faster transport than cows grazing forage crop.
Chapter 2
Review of the Literature

2.1 Introduction

Soil erosion is a significant environmental issue and has been shown to occur worldwide. Although erosion is a natural process that occurs in all landscapes, it is often accelerated by agriculture and other anthropogenic influences, resulting in erosion rates that are unsustainable (Montgomery, 2007; Reusser et al., 2015). Modifications to hillsides such as cutting sections of the slope to create flat surfaces for buildings or roads, reduces slope stability and, coupled with the additional weight of building structures or vehicles, the risk of slope failure is increased significantly (Basher, 2008; Desai et al., 1995; Roberds, 2005). While these risks are known to affect people, property and infrastructure, risks associated with erosion in an agricultural setting are more difficult to assess and are thus often much harder to quantify. As well as potential risks to human settlements or infrastructure where large landslides may occur, erosion of fertile topsoil reduces the productivity of agricultural land and increases fertiliser costs, as lost nutrients must be replaced (Basher, 2008; Montgomery, 2007). Lost soil and nutrients typically end up in waterways, with deposition of sediment in surface waters increasing the risk of flooding after heavy rainfall and adding water pollution, eutrophication and stream habitat degradation to the costs of erosion (Reusser et al., 2015).

Due to the extensive use of hill country, the amount of erosion, and its relative effect on soil function is difficult to quantify via localised measurements, and therefore its impact is difficult to assess. Different farm management practices, cultivation techniques, soil types, organic matter content, slope angles and climates are all known to influence soil erosion (Basher, 2008; Montgomery, 2007; Reusser et al., 2015). However, not only is the relative contribution and interactions of each of these factors not fully understood, data on these factors are only known to a very broad and generalised level in the extensively used areas that are the most susceptible to erosion (Basher, 2008). The identification of a threshold in terms of their susceptibility to erosion would allow for the development and adoption of prevention techniques. As detailed information on soil properties affecting susceptibility to erosion is highly labour intensive to obtain, this information is often given by predictions, which make assumptions and interpolations of data. Although these assumptions and generalisations increase the uncertainty surrounding output data, they allow for the prediction of erosion rates across large areas. An example of such an approach is the national map on soil erosion in New Zealand (Dymond et al., 2010).
This literature review gives an overview of current knowledge on different erosion processes, and methods of erosion measurement that are presently available.

2.2 Erosion Processes

2.2.1 Forms of Erosion

The term erosion refers to the gradual destruction of something by natural forces: the process by which something is worn away. In Geological science, a commonly accepted definition of erosion is that by Bates and Jackson (1987); "the general process whereby the materials of the earth's crust are loosened, dissolved or worn away and simultaneously moved from one place to another". This definition is similar to that of transportation by the American Geological Institute (2005), "the movement by natural agents (such as flowing water, ice, wind, or gravity) of sediment or of any loose material, either as solid particles or in solution, from one place to another on or near the Earth's surface". However, these definitions don't allow for a clear distinction between soil transport processes (movement of soil within an area) and soil erosion (removal of soil from an area). For the purposes of this literature review and thesis, the term soil transport will refer to the movement of soil, and the term erosion will refer to the divergence of soil flux from the area of concern. In soil erosion, this refers to the transport of soil particles or sediment from an area of interest which results in a net loss or thinning of the soil. Soil transport (i.e. the relocation of soil particles) on its own does not necessarily result in erosion. If influx of sediment from upslope equals loss of sediment downslope, then soil thickness remains the same and thus erosion is not considered to have occurred. In many regards this definition is similar to that of “denudation” in the geological literature, although the latter concept includes the notion of wearing away of the land by chemical as well as physical processes (American Geological Institute, 2005).

The main erosion processes are a result of gravity and water, or wind moving soil particles. Gravity, assisted by water, is the dominant erosive force on hillslopes (Amundson et al., 2015; Anderson & Anderson, 2010; Bierman & Montgomery, 2014b; Chaplot & Le Bissonnais, 2003; Heimsath et al., 1997; Hughes et al., 2009; McLaren & Cameron, 1996; Montgomery, 2007; Paton, 1978). This may be in the form of diffusive processes (see below) such as rainsplash and sheetwash, which act to reduce relief (Dunne et al., 2016). Alternatively, erosion may occur by concentrated flow within rills, gullies or streams, which tends to increase local relief; these processes are referred to as advective, and are discussed in further detail below.

The ability of water to erode soil depends on the energy, or erosivity, of the water in relation to the stability of the soil. Soil stability is influenced by its cohesion and friction; cohesion is increased by the presence of clay, soil organic matter (OM) and iron oxides, while friction is dependent on normal
stress of the slope (Anderson & Anderson, 2010; Bierman & Montgomery, 2014b; Montgomery, 2007). The erosivity of water depends on the velocity and depth of flow, and the amount of sediment load that is already entrained, with water velocity and thus erosion risk being increased on steep land (Bierman & Montgomery, 2014b; Dietrich et al., 1993). A threshold exists for the amount of sediment that is able to be carried by water, depending on the power of the water flow compared to the amount of energy required to carry the sediment particles. As inclination lessens at the foot of a slope, the effect of gravity on the water and therefore its velocity and power lessens, causing sediment deposition to occur as the sediment transport threshold is crossed (Bierman & Montgomery, 2014b; Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993; Montgomery, 2007). The volume of water will also affect how much soil is able to be transported, with greater volumes of runoff capable of carrying more sediment (Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993).

The volume of water runoff that occurs depends on the infiltration rate of the soil, the precipitation rate, and the initial water content of the soil; as well as how much water has accumulated at that point from the area upslope. If the soil has a low water content, then the initial infiltration rate will be greater as water is absorbed into the pores of the soil (sorptivity). When the soil is saturated, the infiltration will match saturated hydraulic conductivity or the percolation rate. Soils that are near field capacity have less ability to hold water and therefore, if the precipitation rate is in excess of the percolation rate, runoff will occur (Anderson & Anderson, 2010; Bierman & Montgomery, 2014b). The percolation rate of an individual soil also depends on a number of soil factors, such as structure (pore size distribution), hydrophobicity, the presence of slowly permeable layers or a pan, surface crusts, and the positioning of the water table, which may contribute to the occurrence of overland flow (Anderson & Anderson, 2010).

A greater depth and flow rate of water has more potential to entrain and carry sediment and therefore has greater erosivity; higher volume and more intensive rainfall runoff events are likely to cause more erosion than smaller events. The characteristics of precipitation, coupled with the resistance of the soil, influences the occurrence of erosion; position in the landscape influences the form of erosion that is likely to occur. Mass, inter-rill and gully processes dominate further from the divide or range, where water has accumulated from upslope (Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993; Dunne et al., 2016); diffusive erosion processes are prevalent closer to the divide and near the top of slopes (Anderson & Anderson, 2010; Bierman & Montgomery, 2014b). As the initiation of rill erosion is relative to depth of overland flow, rill erosion may also occur where water flow converges, such as at the foot of the slope (Anderson & Anderson, 2010).
2.2.2 Soil erosion processes

The main transport process influencing soil formation on hillslopes is **colluvial**, which involves the movement of soil particles down slope as a result of gravitational potential, often aided by water. Repetitive erosion events will result in layering downslope, and deposition may occur via diffusive erosion processes, advective processes, or in short, catastrophic mass erosion events (Bierman & Montgomery, 2014a).

**Mass movement erosion**

Mass movement erosion processes involve the transport of large volumes of sediment down the slope simultaneously, along a generally well-defined failure surface (Bierman & Montgomery, 2014b). Soil **falls** occur on very steep slopes, such as cliffs or stream banks, and involve sediment falling or toppling through the air. **Slides** involve movement of blocks of material along a well-defined failure plane, with the structure of the surface remaining relatively intact. Movement may be rotational (concave plane) or translational (plane parallel to surface) in form. When **flows** occur, the shape and form of the original surface is lost and material is mixed as it flows down the slope.

![Mass movement processes](image)

**Figure 2.1** Mass movement processes; a) fall b) slide c) flow. Adapted from Leyva (2006).

If the sum of factors affecting shear stress (namely gravity, the weight of the soil, and the slope gradient) is greater than the factors affecting shear strength (cohesion, soil density, internal resistance), then slope failure will occur. Generally, saturated water conditions are prevalent with mass erosion events, as positive pore water pressure reduces effective stress of the soil. This may cause the stress/strength threshold to be crossed, initiating mass soil movement (Bierman & Montgomery, 2014b; Crozier, 2010; Dietrich et al., 1993; Dymond et al., 2010). The stress/strength threshold may also be crossed due to an increase in driving shear stress, such as from seismic activity or loading from roads, buildings, trees, the weight of water when saturated, and of the soil itself (Bollati et al., 2012; Crozier, 2010; Dietrich et al., 1993; Goff & McFadgen, 2002; Kaitna, 2014b).

These factors all add stresses to the soil, increasing the likelihood of mass movement. Mass erosion sediment transport is the dominant erosion process on steep hillslopes (Crozier, 2010; Dietrich et al., 1993), particularly where a clear boundary between topsoil and dense subsoil/bedrock exists (Kaitna,
Diffusive erosion processes involve the gradual movement of sediment, without the concentrated flow of water, wind or ice. Diffusive erosion processes are termed as such because they lead to the diffusion of topography: i.e. erosion of highs and infilling of lows, leading to the loss of relief (Bierman & Montgomery, 2014b). The rate of diffusive transport (\( q_s \) m\(^3\) of soil m\(^{-1}\) contour y\(^{-1}\)) is typically reported to be proportional to the gradient of the hillslope (S - dimensionless), with sediment being transported downslope at faster rates on steeper slopes (Equation 2.1) (Bierman & Montgomery, 2014b; Dunne et al., 2016). Rate of transport is modulated by the transport coefficient (\( K \) – m\(^2\) y\(^{-1}\)), which is influenced by factors such as soil texture, water content and organic matter content (Anderson & Anderson, 2010). Diffusive processes dominate near the top of slopes because accumulation of water is limited and the opportunity for overland or concentrated flow is minimal (c.f. advective erosion processes). An exception is sheetwash occurring near hill crests in intense rainfall events that exceed infiltration rates (Dunne et al., 2016). Intense, short-lived events can induce sediment transport but the transport distance is sufficiently short that the time-integrated flux of sediment is slope-dependent (i.e. diffusive) (Dietrich et al., 1993; Dunne et al., 2016). Sediment is typically deposited at the foot of slopes where gradient lessens, and gravity has less power to transport sediment (Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993; Montgomery, 2007).

\[
\text{Equation 2.1:} \quad q_s = KS
\]

\[
\text{Equation 2.2:} \quad E = K \frac{\delta^2 z}{\delta x^2}
\]

Whether or not diffusive transport is erosive (\( E - m \ y^{-1} \)), is determined by the curvature of the slope (Equation 2.2), and is a function of the soil transport law, and the conservation of mass (Anderson & Anderson, 2010; Smith & Bretherton, 1972). Change in soil thickness (i.e. erosion) is proportional to slope curvature, the second spatial derivative of elevation \( \frac{\delta^2 z}{\delta x^2} \), in one dimension - m\(^{-1}\), and is dependant only on the slope, not the distance down slope (Anderson & Anderson, 2010). This diffusive erosion smooths topography by thinning soil fastest on areas of high positive curvature (bumps), and thickening soil on high negative curvature (dimples).

Creep is the gradual downslope movement of soil resulting from processes such as heave, tree-throw and displacement by burrowing animals. Heave involves the expansion of soil perpendicular to the soil surface, due to wetting of clays or ice expansion for example; and settling in a vertical downward movement due to gravity when clays dry and shrink, or ice melts (Anderson & Anderson,
Creep is directly proportional to low gradients, but a non-linear relationship prevails at steeper gradients (Roering et al., 1999).

**Rainsplash** is the impact of raindrops directly onto the soil surface, which disrupts and dislodges soil particles. On hillslopes, this results in net downhill transport as ejected particles travel much further downslope before colliding with the soil surface, compared to particles ejected in an upslope direction (Bierman & Montgomery, 2014a; Chaplot & Le Bissonnais, 2003; Morgan et al., 1986). Soil particles that have been dislodged by rainsplash erosion are typically small and sitting loose on the soil surface, and are thus easily entrained and eroded if precipitation exceeds infiltration rate and overland flow occurs. However, rainsplash erosion generally only occurs when surface water is shallow or not present, as deeper water will protect the soil surface from raindrop impact (Bierman & Montgomery, 2014b; Chaplot & Le Bissonnais, 2003). Similarly, vegetation cover will protect the soil surface from raindrop impact and thus this process is only prevalent where soil surface is exposed, such as recently grazed or cultivated fields and semi-arid environments (Dunne et al., 2016; Montgomery, 2007).

**Advective erosion**

Advective erosion processes are those which are influenced by the upslope drainage area. These processes are considered advective because entrained material is carried (or advected) by flows that increase downslope from the divide (Bierman & Montgomery, 2014b; Dietrich & Perron, 2006). Advective erosion acts to incise valleys and therefore create relief, and consists of sheetwash, or overland flow, erosion.

**Sheetwash** refers to advective erosion resulting from overland flow when water is not concentrated into channels. This only occurs when the rate of precipitation exceeds the infiltration rate, which occurs commonly on agricultural soils that have been disturbed or compacted, and where plant cover is low (Amundson et al., 2015; Baxter et al., 2013; Bierman & Montgomery, 2014b; Chaplot & Le Bissonnais, 2003; Morgan et al., 1986). Under natural conditions, this process is more common in areas where plant cover, soil organic matter and therefore infiltration rates are low (Amundson et al., 2015; Bierman & Montgomery, 2014b; Dietrich & Perron, 2006). Soil cohesiveness and strength help to resist sheetwash erosion, and vegetation protects the soil surface, slowing water flow, enhancing infiltration, filtering any entrained sediment and adding strength to the soil with its roots (Zaimes & Schultz, 2015). Sheetwash erosion is generally considered to maintain concave landforms, as the larger area (and thus discharge) downslope is counter-balanced by steeper upslope sections, leading to equal erosion rates and a decline in slope downhill (Bierman & Montgomery, 2014b; Kirkby, 1971). However, some studies have shown that the occurrence of sheetwash induces the
formation of convex hillslope profiles, due to the increase in volumetric flow rate (and thus transport capacity) in a downslope direction, particularly in arid landscapes (Dunne, 1991; Dunne et al., 2016).

As overland flow of water occurs on hillslopes, water and entrained sediment move downhill and are deposited in basins at the foot of the slope, where low gradients slow or stop water flow (Bierman & Montgomery, 2014b). However, in areas where concentrated volumes of water continue to flow, formation of rills and channels may occur, enabling advective transport of entrained sediment to surface water bodies (Anderson & Anderson, 2010; Bierman & Montgomery, 2014b).

**Channel erosion** and rills occur where water converges (and thus depth of flow increases) due to the shape of slope and/or where water accumulates resulting from a change in gradient (Anderson & Anderson, 2010). The greater depth /flow rate-interaction in these areas leads to more erosive power, causing the water to incise and erode the soil (Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993). Over time, these incisions deepen and widen and may develop from rill to channel to stream, and contribute to the formation of gullies over longer time periods (Crozier, 2010; Dietrich et al., 1993; Hancock & Evans, 2010). The continued incision of the rill or channel increases the local relief, accelerating erosion and facilitating transport of sediment by increasing relief and therefore velocity of overland flow (Bierman & Montgomery, 2014b). If this occurs at the foot of a slope, it may undercut the slope, reduce its support and trigger mass movement processes (Bierman & Montgomery, 2014b; Crozier, 2010; Hancock & Evans, 2010).

**Wind**

Wind erosion susceptibility is largely controlled by the weight of soil peds, which is influenced by their size and water content. Larger particles weigh more and therefore require more energy to transport (Bolte et al., 2011). Consequently, soils are more susceptible to wind erosion during or after cultivation, as soil clods are broken up into smaller peds, and there is a lack of vegetation protecting the soil surface (Baxter et al., 2013; Bolte et al., 2011). The size and weight of particles will also influence the form of transport that occurs, with small dust-like particles being suspended in the air, whilst larger particles move along the ground surface via saltation (Bierman & Montgomery, 2014b; Bolte et al., 2011). Deposition of dust particles results in the formation of loess under prolonged dry conditions such as glacial periods, with depth of deposited material decreasing with distance from its source (Anderson & Anderson, 2010; Bierman & Montgomery, 2014b). **Saltation** (transportation of particles by 'bouncing' along the soil surface) typically occurs with heavier evenly-sized particles, such as sand grains, and results in the formation of dunes along coastlines and in deserts (Nabi et al., 2013).
Wind speed also affects the amount of erosion that occurs, with stronger winds having greater capacity to transport soil particles; larger peds or grains will be picked up, and peds will be moved further (Bierman & Montgomery, 2014b; Bolte et al., 2011). Additionally, the water content of the soil will affect its weight, meaning that wet particles are not as easily transported by wind as dry particles. Water content also influences cohesion between soil particles and peds, resulting in a greater shear stress threshold; i.e. more energy being required to dislodge them from the surface (Bolte et al., 2011). As a consequence, wind erosion is a greater problem during a drought when soils are dry.

2.3 Measuring soil transport and erosion rates

It is widely recognised that erosion under agriculture is greater than erosion under natural landscapes (Montgomery, 2007). There is a need to quantify erosion to assess the level of impact agriculture is having on erosion and consequently on the environment (onsite & offsite effects). It is therefore also important to understand how much erosion occurs under natural conditions, to serve as a ‘benchmark’ to compare to and understand what the ‘background’ rates of erosion are. Understanding soil erosion processes also helps to identify why there is more erosion under agricultural landscapes, and how the contribution of agriculture to erosion can be reduced (Amundson et al., 2015; Wiaux et al., 2014). This section covers some of the common methods and knowledge of existing erosion research.

2.3.1 Direct measurements

To calculate the volumes of soil eroded, direct physical measurements of the dimensions of areas eroded or sediment mobilised and redeposited can be made. When dimensions of an erosion scar are obtained the volume of soil that has eroded can be calculated, whilst if the dimensions of the debris or sediment deposition are used, there is a higher degree of error. This increase in error is due to the possibility of a) not all of the eroded material being present, such as may occur if some of the sediment becomes suspended in a stream, b) additional material having been entrained as the debris moved down the slope (Kaitna, 2014a), or c) erosion debris having a different bulk density to the soil. Direct measurements of erosion require prior knowledge of the shape of the land surface that was eroded or deposited on, or an assumption to be made that the surface was planar, to enable the volume of the eroded material to be calculated. Alternative methods for measuring different forms of erosion are described in the following tables.

Change in surface level

Localised erosion can be determined through the measurement of changes in soil level, over either time or space. This may consist of soil surface measurements at two different periods in time, to
measure erosion that has occurred at a point over time (Table 2.1). Alternatively, the difference in two surface levels can be measured, such as with stock tracks or rills on a hillslope, if the original surface shape is assumed to be uniform (Figure 2.2). As these methods measure the soil surface level only, they are not appropriate for soils where settling may have occurred, such as arable soils (Hudson, 1993).

Table 2.1  Methods of direct volume measurements of erosion via change in level of the soil surface

<table>
<thead>
<tr>
<th>Method</th>
<th>Target parameter</th>
<th>Limitation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in surface level</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Point measurements</td>
<td>Surface level at a single point</td>
<td>Individual measurements vary</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Erosion pins</td>
<td>Surface relative to top of pin</td>
<td>May interfere with overland flow, causing scouring</td>
<td>(Hudson, 1993; Nellesen et al., 2011)</td>
</tr>
<tr>
<td>Paint collars</td>
<td>Surface relative to rock/root</td>
<td>Different erosion rates as runoff flows around object</td>
<td>(Rapp et al., 1972, as cited in Hudson, 1993)</td>
</tr>
<tr>
<td>Tree mounds</td>
<td>Soil height under tree, due to protection of surface</td>
<td>May be due to root density or increased insect activity</td>
<td>(Biot, 1990)</td>
</tr>
<tr>
<td>Pedestals</td>
<td>Soil height under stone or root</td>
<td>Measures splash erosion only</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Profile meters</td>
<td>Surface level along a cross section</td>
<td>Assumes no change in neighbouring surface</td>
<td>(Hudson, 1993)</td>
</tr>
</tbody>
</table>

Figure 2.2  A simple profile meter. Taken from Hudson (1993).

Surface runoff measurements

Surface erosion can occur through the displacement of soil particles by the impact of raindrops falling directly onto the soil surface (rainsplash), or by entrainment of the soil particles into water flowing over the soil surface (Chaplot & Le Bissonnais, 2003; Van Dijk, Bruijnzeel, & Eisma, 2003).
Rainsplash occurs through the transfer of energy from a raindrop to the soil surface as it lands, causing soil particles to be dislodged and allowing them to be eroded by surface runoff or wind much more easily (Asadi et al., 2007; Bierman & Montgomery, 2014a; Bremenfeld et al., 2013; Klik, 2014a). The impact energy of raindrops increases with droplet size as they have a greater mass and fall at higher terminal velocity and therefore have greater kinetic energy, causing more displacement (Klik, 2014a; Van Dijk, Bruijnzeel, & Eisma, 2003). Distrometers are instruments that measure size and velocity of raindrops by converting their momentum to an electric pulse, by recording them on 2D video, or with a laser based optical system (Klik, 2014a).

Alternatively, rainfall kinetic energy can be estimated using rainfall intensity and kinetic energy load (Van Dijk, Bruijnzeel, & Eisma, 2003). The direct impact of rainsplash on erosion can be measured using sediment traps on paired plots where one plot has soil that is exposed to raindrop impact and the other plot is protected from rainsplash but still experiences surface runoff (Asadi et al., 2007; Bremenfeld et al., 2013; Klik, 2014a; Van Dijk, Bruijnzeel, & Eisma, 2003). Sheetwash erosion occurs when overland flow of water is not concentrated into channels; the effects of which can be measured using techniques described in 'Change in surface level' above. The effects of rainsplash and sheetwash combined with the effects of rill erosion can be determined using the methods in Table 2.2. Quantification of sediment leaving a catchment area allows an average erosion rate of the catchment to be calculated, though this estimate does not identify critical source areas that contribute the sediment. Sediment that is being eroded from a catchment can be measured by calculating stream flow, the suspended sediment load and bedload transport (Ertl, 2014; Hudson, 1993; Klik, 2014b; Rodriguez-Blanco et al., 2013).

Figure 2.3 Illustrations of confined and unconfined sediment traps. Taken from Klik (2014).
<table>
<thead>
<tr>
<th>Method</th>
<th>Target parameter</th>
<th>Limitation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface runoff</td>
<td>Sediment in overland flow. Can utilise rainfall</td>
<td>Rainsplash, sheetwash and rill combined</td>
<td>(Asadi et al., 2007; Bremenfeld et al., 2013; Klik, 2014a)</td>
</tr>
<tr>
<td>Sediment traps</td>
<td>Sediment in overland flow. Can utilise rainfall</td>
<td>Rainsplash, sheetwash and rill combined</td>
<td>(Asadi et al., 2007; Bremenfeld et al., 2013; Klik, 2014a)</td>
</tr>
<tr>
<td>Mesh bag</td>
<td>Collect sample of soil distribution downhill</td>
<td>Doesn't indicate how far soil transported</td>
<td>(Hsieh et al., 2009)</td>
</tr>
<tr>
<td>Channel erosion</td>
<td>Width x depth x length</td>
<td>Site-specific, no spatial representation</td>
<td>(Rodriguez-Blanco et al., 2013)</td>
</tr>
<tr>
<td>Cross section</td>
<td>Surface level along a cross section</td>
<td>Assumes no change in neighbouring surface</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Profile meter</td>
<td>Surface level along a cross section</td>
<td>Assumes no change in neighbouring surface</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Suspended sediment</td>
<td>Time for dye to travel measured distance</td>
<td>Cross section must be constant</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>-Stream flow</td>
<td>Determines velocity by shape of ripples</td>
<td>Must combine with depth reading</td>
<td>(Ertl, 2014)</td>
</tr>
<tr>
<td>Velocity x area</td>
<td>Restricts flow to known area, measure depth</td>
<td>Requires stream alteration</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Radar flow</td>
<td>Restricts flow to known area, measure depth</td>
<td>Requires stream alteration</td>
<td>(Ertl, 2014; Hudson, 1993)</td>
</tr>
<tr>
<td>Flume</td>
<td>Injects salt solution, measures time until detection</td>
<td>Doesn't allow for lateral diffusion</td>
<td>(Planchon et al., 2005)</td>
</tr>
<tr>
<td>Salt velocity gauge</td>
<td>Time for dye to travel measured distance</td>
<td>Cross section must be constant</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>-Sediment concentration</td>
<td>Take samples by hand</td>
<td>May be at irregular intervals</td>
<td>(Ertl, 2014; Hudson, 1993)</td>
</tr>
<tr>
<td>Spot sampling</td>
<td>Manually take samples daily</td>
<td>May miss rapid changes in loading</td>
<td>(Ertl, 2014; Hudson, 1993)</td>
</tr>
<tr>
<td>24-hour sampling</td>
<td>Samples automatically, set time/flow intervals</td>
<td>May run out of space under heavy flow</td>
<td>(Ertl, 2014; Hudson, 1993)</td>
</tr>
<tr>
<td>Pumping samplers</td>
<td>Sediment load measured by light absorption, recorded</td>
<td>Light readings may be disrupted by algae</td>
<td>(Ertl, 2014; Hudson, 1993; Rodriguez-Blanco et al., 2013)</td>
</tr>
<tr>
<td>Continuous measurement</td>
<td>Measure, weigh sediment that drops into hole in stream</td>
<td>Differences in transport across streambed</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Bedload transport</td>
<td>Measure, weigh sediment that drops into hole in stream</td>
<td>Differences in transport across streambed</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Direct measurement</td>
<td>Sediment load measured by light absorption, recorded</td>
<td>Estimations only</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Sampler basket</td>
<td>Captures sample in basket</td>
<td>Changes hydraulic conditions</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Radioactive tracers</td>
<td>Form similar to bedload sediment, detected downstream</td>
<td>Introduces radioactive material to stream</td>
<td>(Hudson, 1993)</td>
</tr>
<tr>
<td>Empirically</td>
<td>Based on bedload texture, suspended texture and</td>
<td>Reliability debated</td>
<td>(Hudson, 1993)</td>
</tr>
</tbody>
</table>
Deposition of sediment on stream banks or floodplains in the catchment area may result in sediment eroded from the landscape not being detected in suspended sediment monitoring or bedload transport estimations. Erosion pins may be used to monitor stream deposition, as described in the section 'Change in surface level' above (Nellesen et al., 2011; Zaimes & Schultz, 2015). Nicholas & Walling (1997) have developed a model to predict flood sediment deposition based upon suspended sediment concentration, relative sediment particle size, and floodplain geometries. The sum of sediment deposition volumes, suspended sediment and bedload transport measured by the above techniques can be used to estimate soil eroded from a catchment area.

**Creep**

Reported measurements of soil creep rates have used changes in surface elevation, as described in the sections below, or have used instruments specifically tailored for measuring creep. These instruments include:

- The strain probe, as described by Yamada (1999). The probe consists of a 50 cm long spring steel strip with strain gauges along its length, which was inserted into the soil perpendicular to the surface (Figure 2.4). As the probe was bent due to soil creep, the strain is measured on the gauges, and recorded automatically by a data logger. Soil water content and temperature were also monitored to determine their effect on creep.

- Finlayson (1981) developed a device that is tripod-mounted above a flexible plastic tube inserted vertically into the soil. The 100 cm long tube has a light source at the bottom and four sets of cross wires, and movements of these cross wires is used to calculate change in their positions and therefore that of the surrounding soil. A modified theodolite telescope (Figure 2.5) is used to measure positions of the upper three cross wires relative to the bottom cross wire, which is assumed not to have moved.

- Finlayson (1977) measured soil creep at a stream bank using another technique, illustrated in Figure 2.6. In this method, a hole is drilled into the bedrock of a streambed, and is used to support an upright metal pipe with a fulcrum attached to it. A plastic footplate is attached to the nearby bank using six-inch nails, and a steel rule attached to a wooden rod is used to measure the distance between the footplate on bank and the upright pipe. Repeated measurements will give indication of movement of the bank.

- Anderson & Cox (1978) compare six instruments for measuring soil creep, which are described as follows:
An inclinometer, which allows precise measurements of angles. This can be used to measure movement of a peg in the ground, though this can only measure the net movement of the length of the peg, and assumes the peg to pivot at its base.

A tube with a steel rod in its centre that is driven into the bedrock, fixing the base. Movements of the tube relative to the rod can be measured, determining its soil movement at different depths.

Aluminium pillars were inserted into the soil, and their movement relative to the fixed rods used in the method above was measured using callipers.

Pits were dug into shallow soil, and thin rods were inserted into the soil at different depths. A plumb line was used to template the placement of the rods and the pits were re-filled. The pits were later re-excavated and the plumb line was aligned to the lowest rod and used to determine movement of the remaining rods (Selby, 1966).

A borehole technique using dowelling pillars, where 25 mm lengths of 15 mm diameter dowelling were placed in a borehole of the same diameter.

A borehole technique using Cassidy’s tubes, where the PVC tubes with a closed base were used. This technique and the one above were examined by excavating half of the circumference of the borehole and fitting a flexicurve to their shape, allowing their curve and thus soil creep to be measured.

Figure 2.4 The strain probe and bridge circuit used by Yamada (1999).
Roering et al. (2002, 2004) and Hughes et al. (2009) used changes in concentration of and depth to tephra tracers to determine rates of soil creep via bioturbation and tree throw, over millennial time scales. Soil creep over long periods can also be estimated through repeated imagery of a landscape, such as aerial photography or measurements of elevation using different methods of surveying. These methods are explained in further detail in the following sections.

### 2.3.2 Tracers

Soil transport and erosion can be estimated by measuring the movement or change in concentration of tracers. The use of tracers to infer soil transport requires the assumptions that the tracer and bulk soil are inextricably linked, tracer movement is representative of soil transport, and the tracer is
conservative. Tracers used can be objects placed in the soil then recovered, or specific isotopes or elements whose concentration in the soil indicate certain conditions or changes in soil surface level.

Objects
The movement of physical tracers can be measured directly, and used to infer soil movement. This is most commonly done by determining the location of the tracer before and after a specified time period or event. Commonly, physical tracers used are metal or partially metal to enable easy recovery using a metal detector, and individually numbered to accurately determine the movement of each specific tracer (Frauenfeld & Klik, 2002; Govers et al., 1994; Lindstrom et al., 1992). The initial and final positions of each individual tracer can be recorded with a highly sensitive GPS measurement, such as with an automatic theodolite, or by measuring the position of the tracer relative to the boundaries of a plot area. This tracer method has been used to determine soil transport over a relatively short period of time, such as under cultivation (Frauenfeld & Klik, 2002; Govers et al., 1994; Lindstrom et al., 1992). This methodology measures soil transport occurring via disturbance mechanisms such as cultivation, though it is not able to encapsulate movement of finer soil particles or peds, such as occurs with rainsplash or overland flow erosion.

Isotopes
Soil erosion can also be quantified through the collection of soil samples and analysing them in the laboratory, such as through the measurement of nuclides caesium ($^{137}\text{Cs}$), beryllium ($^{7}\text{Be}$) or lead ($^{210}\text{Pb}$). This can be done with samples taken from sediment suspended in stream flow, sediment deposits, or samples taken directly from the soil profile.

To estimate erosion by measuring a soil’s $^{137}\text{Cs}$ content, the amount of $^{137}\text{Cs}$ present must be compared to the level present at a local reference site, which has had little to no disturbance or erosion. In areas where no significant accumulation of $^{137}\text{Cs}$ from the Chernobyl fallout occurred, all $^{137}\text{Cs}$ present can be assumed to be derived from bomb testing in the 1960’s, thus changes in $^{137}\text{Cs}$ content can be attributed to erosion that has occurred since this period once decay has been accounted for (Porto et al., 2003). At the reference site and at undisturbed sample sites, soil samples are taken at depth increments to determine their $^{137}\text{Cs}$ content. At disturbed sites, such as where ploughing or tree harvest has occurred, soil cores are taken to analyse the total $^{137}\text{Cs}$ in the disturbed layer (Porto et al., 2003). Values measured in samples are compared to the reference site, to determine the difference in $^{137}\text{Cs}$ content and therefore infer the erosion that had occurred at that site since the bomb testing caused the $^{137}\text{Cs}$ fallout to occur (Porto et al., 2003). The same theory and laboratory techniques can be used to measure $^{137}\text{Cs}$, $^{7}\text{Be}$ and $^{210}\text{Pb}$ in suspended sediment samples from waterways (Smith et al., 2014; Wilson et al., 2012). $^{210}\text{Pb}$ is a derivative of gaseous radon ($^{222}\text{Rn}$), which is a decay product of uranium ($^{238}\text{U}$), whilst $^{7}\text{Be}$ is produced from nitrogen and oxygen atoms
being separated by cosmic rays in the atmosphere. Both $^7$Be and $^{210}$Pb are transported to the soil surface with rainfall and are confined to the top few centimetres of soil (Wilson et al., 2012). The length of time that the soil surface has been exposed can therefore be estimated by the concentration of these isotopes in the soil, and their concentration in suspended sediment can indicate the proportion of sediment load originating from slope surfaces or stream bank collapse (Fülöp et al., 2015; Smith et al., 2014; Wilson et al., 2012).

Fülöp et al. (2015) described methods for measurement of $^{10}$Be and $^{14}$C (produced in-situ during soil production) for the purpose of estimating soil erosion. As the relative concentration of $^{14}$C/$^{13}$C or $^{10}$Be/$^{9}$Be are indicative of soil production rates, they can only be used to estimate soil erosion when the soil age is already known and therefore there is an expected concentration of $^{10}$Be and $^{14}$C (Fülöp et al., 2015). The difference between expected and measured isotope concentrations is used to estimate erosion, under the assumption that isotopes have not moved vertically or laterally in the soil profile and were removed with the soil particles that they were adhered to. Fülöp et al. (2015) and Granger & Riebe (2014) describe the estimation of erosion through the examination of $^{10}$Be concentrations throughout the soil depth profile by plotting a concentration curve. Granger & Riebe (2014) describe how erosion can be estimated in soils where mixing has occurred, as illustrated in Figure 2.7 below.

![Figure 2.7](image-url)

**Figure 2.7** Beryllium ($^{10}$Be) concentrations in soil profiles where mixing has occurred. Bold lines represent actual $^{10}$Be concentrations and dashed lines represent $^{10}$Be concentration in a matching unmixed soil profile. Figure taken from Granger & Riebe (2014).

**Tephra**

Volcanic glass derived from tephra can be used to estimate soil movement, using the same approach as for $^{137}$Cs. Changes in the depth to tephra from a known eruption event implies soil erosion or aggradation, while differences in concentration indicates bioturbation and, if the total amount of tephra is lower, soil erosion (Roering et al., 2002, 2004). Changes in tephra concentration through
the soil profile can also indicate what forms of soil transport mechanisms have occurred, with particle-based soil transport mechanisms, such as freeze-thaw, displaying different distribution to disturbance dominated transport, such as tree throw (Figure 2.8).

**Figure 2.8** Schematic soil velocity profiles for A) particle-based soil transport models, and B) disturbance-based models. Taken from Roering et al. (2002).

### 2.3.3 Aerial photography / satellite

Repeated aerial photography or satellite imagery is used to compare landscape change over a known time length. The position of landscape features such as bluffs, knolls or gullies can be aligned against steady control points such as houses, fence lines or roads (Day et al., 2013; Frankl et al., 2015). This allows the extent of movement of features such as the edge of bluffs to be determined, and the area of a slip scar and/or deposited material, and distance moved to be calculated (Day et al., 2013; Debella-Gilo & Kaab, 2012). Frankl et al. (2015) developed a system to produce 3D elevation models of gullies from photographs taken in the field. A similar concept was used by Debella-Gilo & Kaab (2012) and Kaab, Haebeli & Gudmundsson (1997), who used repeated high resolution aerial and satellite photos to produce models of surface displacement of rock glaciers and rockslides.

Aerial photography can be combined with light detection and ranging (LiDAR), Interferometric Synthetic Aperture Radar (InSAR), digital elevation models (DEM) or site measurements of erosion/deposition depth to calculate the volume of sediment moved (Akbarimehr et al., 2013; Bielecki & Mueller, 2002; Day et al., 2013). Methods such as InSAR or LiDAR may be used in combination with aerial photography to compare and validate results, particularly when looking at data spanning several decades and prior to the establishment of modern scanning techniques (Day et al., 2013). Alternatively, these methods may be used independently to measure changes in landscape characteristics over shorter timeframes, and when historical landscape change is not considered (Bielecki & Mueller, 2002; Frankl et al., 2015).
InSAR produces an interferogram from two or more synthetic aperture radar (SAR) images, which are taken from planes or satellites in orbit around the earth. When images are taken from multiple positions in the same pass it allows a DEM to be created, while images taken from the same position on different passes will allow any change in landform over time to be determined (Akbarimehr et al., 2013; Bierman & Montgomery, 2014a; Burgmann et al., 2000). This is done by measuring differences in the phase of the returning electromagnetic wave, which is relative to the change in elevation (Bierman & Montgomery, 2014a; Burgmann et al., 2000). Comparison of DEMs created on different passes of the satellite will allow changes in the landscape to be recognised and soil erosion to be estimated (Akbarimehr et al., 2013; Burgmann et al., 2000; Chen et al., 2014).

2.3.4 Surveying

Multiple surveying techniques are available, including LiDAR, InSAR, terrestrial laser scanning (TLS), total stations, real time kinematic global positioning system (RTK GPS) and 'topography meter' (Bielecki & Mueller, 2002; Bierman & Montgomery, 2014a; Day et al., 2013; Debella-Gilo & Kaab, 2012; Xu et al., 2015).

LiDAR systems can be ground-based but are much more commonly airborne, attached to an aircraft or satellite in orbit around earth (Mallet & Bretar, 2009). The components of an airborne LiDAR system include a laser transmitter and receiver, a mechanical scanner, a positioning system, and a storage and operating system. This operating system synchronizes measurements and processes data to obtain geo-referenced points (Mallet & Bretar, 2009). The device sends out a laser signal, and detects the echo that returns, calculating the distance to the ground surface by the time it takes for the signal to return, and is able to detect the height of different objects by the different return times for signals (Mallet & Bretar, 2009). LiDAR systems can have a large 'footprint' (10-85 m diameter) resulting in the echoed pulse being an integration of multiple objects, or a small footprint (0.15-3 m diameter) giving a higher point density and more precise altimetric description (Figure 2.9), but at the cost of not knowing whether the ground surface has been reached under dense vegetation, and of the system being labour-intensive for mapping large areas (Mallet & Bretar, 2009).
Figure 2.9 Illustration of a) a small footprint LiDAR and (b) a large footprint LiDAR. With a small-sized footprint, all targets strongly contribute to the waveform shape but the laser beam has a high probability of missing the ground. When considering large footprints, the last pulse is bound to be the ground but each echo is the integration of several targets at different locations and with different properties. Taken from Mallet & Bretar (2009).

LiDAR can be used to detect erosion or soil transport through differences in repeated surveys taken of the same area (Bossi et al., 2015). Large footprint LiDAR can detect significant changes in landform, or identify signature land features from past erosion events while scanning large areas. The identified areas of interest can then be surveyed from the ground or using small footprint LiDAR to enable more precise measurements of the amount of erosion that has occurred (Bossi et al., 2015; Roering et al., 2013). Ground surveying techniques may include field measurements, or the creation of a DEM using TLS, Total Station, or RTK GPS equipment (Corsini et al., 2013; El-Ashmawy, 2015; Roering et al., 2013). TLS uses the same technology as LiDAR, but measurements are taken from a fixed point on the ground as opposed to from an aircraft, and generally have a small footprint and high accuracy of ±1 to 2.5 cm (Corsini et al., 2013; Day et al., 2013; El-Ashmawy, 2015). While providing high resolution data of surveyed areas, it is time-consuming in terms of data collection and processing, meaning that although ideal for smaller study areas, extrapolation of data is necessary for measurements of larger catchment areas (Day et al., 2013). Similarly, with LiDAR, TLS can be used to measure soil erosion by repeated scans of the same study site (Day et al., 2013; El-Ashmawy, 2015).

Total station and RTK GPS can also be used to measure soil erosion through repeated measurements of a site (El-Ashmawy, 2015; Lee et al., 2013; Roering et al., 2013). Both of these systems require a base station being set up on a known geo-referenced point, which interacts with a mobile device that can be used to measure specific points in the landscape by moving it around (El-Ashmawy, 2015). The mobile part of the total station system is a prism that reflects a laser signal from the base station.
back to it, where the signal is received. The base station uses the time taken for the signal to return
to calculate the distance to the prism, combined with the angle and direction of the signal to
determine the 3D location of the prism and therefore point measured (El-Ashmawy, 2015). The prism
is then moved around the landscape and the process is repeated, to obtain a DEM with reported
accuracies of ±1.2 to 10 cm (Lee et al., 2013 and El-Ashmawy, 2015, respectively). With the RTK GPS
system, both the base station and the mobile device (called a rover) receive GPS signals at the same
time, and transmit data to one another. As the base station is stationary and positioned above a
known reference point, any variation in the GPS signal is able to be accounted for. This information is
sent to the rover and used to correct the positioning of the points recorded (El-Ashmawy, 2015). As
with the total station system, the rover is moved around the landscape to obtain a grid of points to
create a DEM, with reported accuracies of ±1 to 23 cm (Lee et al., 2013 and El-Ashmawy, 2015,
respectively). The RTK rover can also be attached to a backpack or vehicle to give continuous
measurements (a measurement every second), which allows measurements over large areas to be
covered quickly, but with higher inaccuracies of ±2.6 cm and ±1.5 cm for backpack and ATV,
respectively (Lee et al., 2013).

Another 3-D surface measuring technique has been developed by Xu et al. (2015), which they have
called the ‘Topography Meter’. The Topography Meter consists of a camera, a laser source and a
position device. The laser source produces horizontal stripes at 3.0 cm intervals, shining onto the
hillslope surface (Figure 2.10). These lasers are recorded by a video camera facing perpendicular to
the laser beams, and positioning marks are at fixed positions within the frame of the camera, to give
reference to any change in the soil surface. The camera records the erosion process and snapshots
from the video can then be imported into GIS software, converted to 3D images and used to
calculate the eroded volume (Figure 2.11) (Xu et al., 2015). The Topography Meter has a monitoring
range of 3.0 x 2.0 meters, limiting its use to small-scale projects.

Repeated photographs are used to monitor soil erosion on larger scale areas through
photogrammetry (El-Ashmawy, 2015; Kaab et al., 1997). High-resolution aerial photographs are
taken from different angles with a high proportion of overlapping area. A computer programme is
used to compile the images and produce a 3D Digital Terrain Model, using control points of known
coordinates to orientate the images (Kaab et al., 1997). When this process is repeated, changes in
the digital terrain models produced can be used to determine changes in the landscape, such as soil
creep (Kaab et al., 1997) or landslide erosion (Bossi et al., 2015). Similarly, landscape changes can be
observed by the comparison of 3D models created using surveying techniques such as RTK-GPS (Lee
et al., 2013).
Direct measurements of erosion volumes can be used to calibrate other detection methods of soil erosion, such as aerial photography or the creation of a DEM using LiDAR or RTK GPS, or as the sole method of erosion measurement (Bollati et al., 2012; Chen et al., 2014). These direct techniques measure either the volume of soil eroded or the volume deposited, and the methods vary depending on the type of erosion that has occurred.

Figure 2.10 A blue print and photos of the Topography Meter system. Parts include: 1: Rainfall simulator, 2i: Camera with a collimator, 2ii: Laser source, 3: positioning marks, 4: model slope and 5: horizontal laser projections. Taken from Xu et al. (2015)

Figure 2.11 Images of the model slope used for developing the Topography Model, from (a) prior to failure and (b) after failure. (c) and (d) are the 3D surface models produced of the white rectangle areas of images (a) and (b) respectively. Taken from Xu et al. (2015).
2.3.5 Modelling

Models help to explore and communicate understanding of relationships between system driving and response variables, and allow the extrapolation of data to accommodate prediction into the future and assessment of the impact of change of management techniques (Smith et al., 2014). The use of models to interpolate or extrapolate data at points that were not measured is less labour intensive and more practical than measuring everywhere (Smith et al., 2014). However, the extrapolation of data involves uncertainty and potential error, as assumptions and simplifications are made when developing a model. Therefore, modelling simulations must be used with caution, particularly if extrapolating beyond where models are calibrated (Hudson, 1993; Roberds, 2005; Smith et al., 2014; Zhang et al., 2015). Often, soil erosion model predictions are good at specific sites but under- or over-predict erosion in other areas, demonstrating the complexity of the relationship between factors influencing erosion, and that the interaction of these factors are not fully understood (Montgomery, 2007). Some of the inaccuracies are caused by simplification or standardisation of relationships to allow for easier data entry and calculations (Dymond et al., 2010; Wang et al., 2008).

Different types of soil erosion models exist, which allow the relationship of factors affecting erosion to be understood based upon different types of data. Statistical modelling is used in conjunction with the modelling methods below to determine the reliability of results, such as by verifying the effect of sampling distribution on variance in data (Funk et al., 2012; Li et al., 2015; Shi et al., 2014). The production of models themselves involves the use of statistics to determine relationships between factors, and allow for the extrapolation of data to make predictions. Some of the model types include:

**Empirical**

Erosion models can be formed from observational data, rather than based on logic or theory only. These models are the most commonly used for predicting erosion in large catchment areas and are only useful for predicting long-term average data and effects of management practices, rather than reflecting short-term effects or soil loss from a single flood event (Hudson, 1993; Kinnell, 2015). The most widely-known and used empirical model used is the universal soil loss equation (USLE), which was developed in the United States and has been used to predict erosion world-wide (Kinnell, 2015; Yoder et al., 2004). The equation predicts the average annual soil loss in tonnes per hectare and incorporates: the erosive forces of rainfall and runoff; a 'K' factor that reflects the susceptibility of the soil to erosion; slope length factor: slope gradient; a crop management factor; and a conservation practice factor (Hudson, 1993; Klik, 2014a). Updates of the USLE (RUSLE and RUSLE2) allow for more specific erosion models, such as a sediment budget model (Smith et al., 2014), or...
other empirical models may be developed based on local data and conditions (Dymond et al., 2010; Hicks & Anthony, 2001).

**Physical**

Physical models are produced using data from replicate plots of similar soil type, land use, climate, slope, size and shape, and are used to predict soil loss from areas of the same parameters (Bagarello et al., 2015). These models are used for comparison of treatments, and are an alternative to before / after measurements. Dietrich et al. (2003) describes the importance of using physical models to calibrate other model types, with the aim of minimising unexplained error between plots or between treatments for before / after measurements.

**Mechanistic mathematical**

Soil transport processes can be represented mathematically to calculate soil erosion from an area of given topographic and biophysical characteristics. Mathematical models may incorporate multiple sub-models to predict the effect of different factors that influence erosion, such as gradient, slope length, and rainfall intensity. Alternatively, they may quantify different forms of erosion that may be occurring on the same landscape, such as cultivation, overland flow, diffusive transport, and channel incision (Dunne et al., 2016; Furbish & Fagherazzi, 2001; Govers et al., 1996; Mudd & Furbish, 2007; Wiranatha et al., 2001; Yamada, 1999).

Dietrich et al. (1993) used a steady state runoff model to test two theories on thresholds for channel network erosion. Data on topographic contours and flow lines were used to produce their runoff model, which was run with a slope stability threshold model and a threshold model for erosion by saturated overland flow. They determined that steeper channel heads are largely controlled by slope instability, while critical shear stress is a dominant influence on channel networks where saturated overland flow is significant. Govers et al. (1996) similarly used a two-part model to compare soil redistribution by diffusive processes (rainsplash, creep and tillage) and overland flow. Their results indicated that both diffusive and overland flow erosion processes contribute to erosion in agricultural fields, with diffusive (namely tillage) having the dominant effect.

Diffusive transport may also be modelled against slope gradient, and calibrated using alternative methods of measuring soil transport (McKean et al., 1993; Roering et al., 1999; Yoo et al., 2005). McKean et al. (1993) modelled a linear relationship between soil creep rate and gradient in California, which they support by comparing to $^{10}$Be concentrations. Yoo et al. (2005) also produced a linear transport model on low-gradient slopes in California. However, their model was produced from knowledge on the energy expenditure of pocket gophers, and their population densities relative to soil thickness. Roering et al. (1999), meanwhile, produced a non-linear model for diffusive transport on slopes in California, though they did report a linear approximation at low gradients. They
calibrated their model using high resolution topographic data of hillslope morphology, produced using airborne laser altimetry.

These soil diffusive transport models were generated with the objective of understanding hillslope evolution over extended periods. They determine process changes and spatial distribution of forms of soil transport, and the effects or geomorphic signatures this will have on the landscape. However, they are not suited to determining soil erosion for specific events, and are thus unsuitable for determining erosion from agricultural landscapes over short time periods. A two-part runoff model (simulating soil erosion via overland flow and sediment yield) was developed at the USDA-ARS Southwest Research Watershed Centre, to describe overland flow erosion on rangelands. Cogle et al. (2003) test the suitability of this model under agricultural conditions in New Zealand, Australia and India. They determined that the model was applicable for a clay loam soil in New Zealand, but required calibration for a heavy clay soil in Australia and a sandy loam in India. This model is capable of determining sediment yield from individual runoff events, making it applicable to measuring erosion resulting from agricultural practices, though the design of the model limits it to simulating erosion by overland flow only.

2.3.6 Summary

Many different methods exist for the measurement of soil erosion, because there are many different processes driving erosion, and measurements can be made directly, or interpolation or simulation can be done using other predictor variables. Methods that comprise measurement of effects of erosion rather than erosion itself (e.g. Isotopes or modelling) run the risk of extrapolating errors or inconsistency into the results (Hudson, 1993; Roberds, 2005; Zhang et al., 2015). However, these methods are useful to overcome temporal and spatial limitations of time, resources and cost to conduct research.

Hudson (1993) highlights the need for care when undertaking before and after measurements in the field, due to the possibility of change being induced by outside factors that were not considered or not understood. When studying the effect of a factor or treatment, paired plots using a control site such as a nearby field that is under pasture or a lesser slope, are suggested as a safer alternative than repeated measurements (Bagarello et al., 2015; Hudson, 1993). On the other hand, if the level of erosion is being measured and the cause of it determined later, then technologies such as LiDAR and other survey techniques can quickly provide a detailed representation of the current state of the landscape which can easily be repeated at a later date for comparison (Frankl et al., 2015). This method would then provide data on the entire catchment area in question. Physical sampling is comparatively time consuming and only provides small samples of over a limited spatial extent to represent a much larger area. Therefore, there is a risk that processes that are stochastic in nature,
both temporally and spatially, are under- or over-represented. Moreover, many methods may be biased; for example the mesh bag method not retaining all suspended sediment (Hsieh et al., 2009), or catchment erosion estimated from stream sediment flux relying solely on suspended sediment and ignoring bedload transport (Rodriguez-Blanco et al., 2013). The conclusion of this section is that there is no one 'best method' for quantifying erosion, and when deciding upon a technique to use, factors to consider are the form of erosion being considered, budget and time-scale of the project, the physical size of the project and the need to extrapolate from the data to represent a larger catchment area.

2.4 Factors influencing soil erosion

The rate at which soil erosion occurs is influenced by many factors, including the climate, organisms, the landscape in which the soil is present, and the physical and chemical properties of the soil itself, and anthropogenic effects. Some factors act as both stress and resistance forces, such as soil density and gravity, and their net effect is determined by other factors, namely slope gradient and soil water content (Bierman & Montgomery, 2014b; Kaitna, 2014b). This section describes the key factors that are known to contribute to soil erosion, and explains how they affect erosion rates.

2.4.1 Hillslope gradient/hillslope position

Slope affects the balance of driving shear stress and resisting shear strength (Figure 2.12). Steeper slopes have more stress acting down the slope and less normal stress than lesser gradients, and therefore a soil mass on a steep hillslope is closer to the threshold of failure (Bierman & Montgomery, 2014b). Diffusive processes involve gradual movement of soil once disturbance mechanisms overcome the resisting frictional forces, and dominate on gentler hillslopes where mass movement is not prevalent. The resulting movement and sediment flux is dependent on the slope gradient. Position on a slope also affects the movement of soil water, which influences pore water pressure and thus the effective stress (normal stress - pore pressure) acting on the soil.

![Figure 2.12 Stresses acting on a hillslope. Adapted from Bierman and Montgomery (2014a).](image)

Definition of terms:
- \( Z_s \) = slab thickness
- \( h \) = water-table height
- \( \theta \) = failure plane angle
- \( =\) Effective normal stress
- \( =\) Pore pressure
- \( =\) Driving shear stress
- \( =\) Resisting shear strength
Water convergence above the soil surface influences the form of erosion that occurs, with sheetwash being dominant on steeper gradients, and rill erosion being dominant on the lower gradients where water from upslope accumulates and converges, yet continues to flow (Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993). Sediment deposition occurs where gradient lessens: as gravitational stresses reduce, water loses velocity and its power drops below the threshold required for soil transport (Chaplot & Le Bissonnais, 2003; Dietrich et al., 1993; Montgomery, 2007). Gradient also affects how quickly water moves away via overland flow before it can infiltrate (in addition to affecting velocity of subsurface flow), while precipitation rate determines the intensity of water entry into the site. Infiltration rate is influenced by soil physical properties (such as porosity), hydraulic conductivity and antecedent water content, with faster infiltration of unsaturated soil than saturated soil as water moves into the soil pores (Anderson & Anderson, 2010; Bierman & Montgomery, 2014a). Accumulation of water from upslope can occur via both subsurface flow and overland flow, with subsurface flow influencing soil water content and therefore infiltration rate, and overland flow contributing to influx of water above the soil surface.

### 2.4.2 Vegetation

The presence of vegetation increases infiltration by aiding water movement through the soil profile along plant stems and roots, while plant stems effectively increase surface roughness, reducing flow velocity and entraining sediment (Jian et al., 2015; Montgomery, 2007). Additionally, the decomposition of organic matter (OM) that is added to the soil by vegetation will improve soil structure, that in turn may facilitate drainage and therefore infiltration of water into the soil surface, as will the presence of plant roots. This increase in water infiltration reduces overland flow and consequent erosion by surface wash and/or rill formation (Anderson & Anderson, 2010; Bierman & Montgomery, 2014b; Jian et al., 2015; Montgomery, 2007).

Plant roots add apparent cohesion to soil, by holding particles together, particularly on slopes prone to erosion (Amundson et al., 2015; Crozier, 2010). For this reason, trees are often planted on steep slopes where recurring mass erosion is a problem (Amundson et al., 2015; Crozier, 2010). However, as the trees reach maturity, they add weight to the soil, which contributes to shear stress on the soil, and may trigger slope failure under saturated soil conditions (Kaitna, 2014b). Additionally, trees which have a greater canopy height than the surrounding surface will transfer wind energy to the soil at the base of the tree, and may initiate tree throw, transporting soil downslope (Amundson et al., 2015; Kaitna, 2014b).
2.4.3 Soil organisms

Organisms such as fungi and bacteria break down organic matter and secrete organic glues and/or filaments that help bind soil particles into peds. Organic glues add strength to the structure formed, and cohesion to soil particles, increasing soil strength and resistance to dislodgement and erosion (Baxter et al., 2013). However, Bremenfeld et al. (2013) found soil carbon to be preferentially removed during surface wash erosion, due to its low density and dominant presence at or above the soil surface. The net effect of the removal of carbon by erosion on the global carbon cycle is debated, due to different dynamics for erosion, deposition and transport and the influence of management practices on the fate of carbon (Bremenfeld et al., 2013; Dymond, 2010; Kirkels et al., 2014; Lal, 2003; Wiaux et al., 2014).

Movement of soil macro-fauna such as worms and beetles mixes soil, incorporating organic matter further down the soil profile, and aids in the formation of macropores that facilitate drainage, thus reducing erosion by overland flow (Houlbrooke et al., 2011). On the other hand, burrowing mammals such as moles, gophers and rabbits can induce soil transport and erosion by bringing soil to the surface and depositing it downhill of their burrow entrance (Gabet, 2000; Yoo et al., 2005). However, while burrowing they simultaneously mix organic acids and aerate closer to the soil/bedrock interface, amplifying soil production and somewhat counteracting their erosive impact (Yoo et al., 2005).

2.4.4 Soil water

Water held at negative matric potentials adds cohesion due to capillary forces of water along the surfaces of pores, holding the peds together, reducing their susceptibility to structural deformation, and of removal via erosion. Moist soils are also less prone to wind erosion due to the added weight of water. However, soil water can reduce strength of soil under saturated conditions due to positive pore water pressure pushing peds apart, reducing effective stress (Figure 2.12) (Bolte et al., 2011; Houlbrooke et al., 2006). Dry soils, on the other hand, can lead to an increase in surface wash erosion, due to hydrophobicity repelling water and preventing infiltration (Dunne, 1991).

2.4.5 Development of agriculture

It was recognised long ago that the activities of humans has a significant influence on soil erosion and the surrounding environment, dating back to the mid-Holocene (Lowdermilk, 1953; Marsh, 1869; Rosen et al., 2015). The effects of agriculture have shown to be particularly destructive on the landscape, and it is the destruction and loss of soil via erosion that has been implicated in the downfall of civilisations, including the Roman and Greek empires (Montgomery, 2007). Of the land that is not currently used for arable production but is potentially suitable for agricultural use, 60% is
covered in forests, protected areas or is under urban use (Bruinsma, 2003). As human populations continue to climb, realisation of the importance of conserving the land that we currently use has heightened in awareness. Research and understanding of how erosion processes occur, how humans influence them, and how our impact can be reduced are of increasing importance. The key points of existing knowledge on erosion in agricultural landscapes are described in this section.

Change in land cover
Worldwide, most agricultural systems are sited on lands that have been cleared of native vegetation, such as forests, native grass or shrublands, to clear land for growing crops and pasture for animals. Accelerated rates of erosion have been recorded under agriculture, particularly where frequent cultivation occurs, when compared to background erosion rates (Amundson et al., 2015; Crozier, 2010; Dymond et al., 2010; Hicks & Anthony, 2001; Montgomery, 2007; Reusser et al., 2015). These higher rates of erosion have been attributed to the direct effects of tree removal, and to decreased interception of rainfall, exposure of the soil surface to atmospheric processes, reduced soil organic matter, and increased soil disturbance.

Interception of rainfall by trees results in less water reaching the ground, and thus less runoff occurs under forest systems than crop or pasture species. The high leaf area of forests captures rainfall, which then drips from the leaves, trickles down the branches and tree trunk, or remains on the leaves and bark until it is evaporated (Jian et al., 2015; Klik, 2014a; Yi & Wang, 2013; Zimmermann et al., 2007). The water remaining on bark and leaves is considered to be 'intercepted', and Jian et al. (2015) report average interception rates of more than 20% of annual rainfall for three different tree and shrub species studied. Jian et al. (2015) also report a significant difference in interception rates between species with smooth and rough bark, with rough bark retaining more water. In addition to some water being retained on leaf and bark surfaces, the water that reaches the ground does so with lower velocity, as the water takes more time to trickle down the trunk than it does to fall directly to the soil surface as it does in agricultural systems. Water is also stored in leaf litter and moss after it reaches the ground surface, further slowing the rate of water movement and increasing interception (Klik, 2014a). This effectively reduces the intensity of the rainfall, meaning that the infiltration rate is less likely to be exceeded and runoff is less likely to occur, compared to agricultural systems (Jian et al., 2015; Klik, 2014a).

Exposed soil surface leaves soil vulnerable to erosion processes, with leaf litter under forests protecting the soil surface from raindrop impact and surface wash. In agricultural systems the soil surface is more exposed due to less canopy, and the absence of leaf litter exposes the soil surface to raindrop impact which dislodges particles and can lead to capping (Van Dijk, Bruijnzeel, & Wiegman, 2003). Surface capping, fewer and shallower rooting systems, and soil structure compaction
associated with agricultural soils can reduce infiltration rates, resulting in a greater amount of surface runoff that can erode soil and entrain soil particles that have been dislodged (Chaplot & Le Bissonnais, 2003; Klik, 2014a, 2014b; Nciizah & Wakindiki, 2015). Surface runoff has more effect on agricultural soils compared to those under forests due to the exposed soil surface, and the greater volume of runoff occurring, caused by more water reaching the soil surface and in a shorter period (reduced interception), and slower infiltration rates. High rates of surface runoff can also be caused by hydrophobicity of organic matter in soil following a drought or forest fires (Doerr et al., 2016). Forest fires also increase surface runoff due to reduced interception, resulting from vegetation being burnt.

**Ploughing**

Cultivation of agricultural soils removes vegetation, breaks up the structure, reduces aggregate size, and exposes the soil to rain drop impact, and wind erosion (Govers et al., 1994). The amount of soil that is able to be easily entrained and eroded is heavily influenced by the size of soil aggregates and particles at the surface, with smaller aggregate/particles requiring less energy to be moved and thus are transported with much lesser amounts of surface runoff than large soil peds. Consequently, agricultural soils that undergo cultivation are much more easily eroded, as soil structure is repeatedly broken up into much smaller aggregates, which are able to be entrained by overland flow (Hicks & Anthony, 2001; Hudson, 1993; Kammerer, 2014; Klik, 2014b; Wang et al., 2015). As well as removing the physical protection of organic matter (OM) on the soil surface, cultivation also aerates soil, increasing microbial activity and break down of organic glues binding aggregates together, and thus leaving soil more susceptible to structural degradation and erosion (Klik, 2014a; Lal, 2003; McLaren & Cameron, 1996; Stoate et al., 2001). Cultivation also leaves soil exposed to raindrop impact and sheetwash erosion, as it buries plants and organic matter that were on the soil surface that had protected it from direct exposure to raindrops, and slowed and filtered overland flow (Chaplot & Le Bissonnais, 2003; Hicks & Anthony, 2001; Van Dijk, Bruijnzeel, & Wiegman, 2003).

In addition to secondary effects of cultivation influencing the susceptibility to erosion, the act of ploughing itself transports soil downslope, creating a thinning of soils at the top of slopes, and deepening of soil at the foot of slopes (Frauenfeld & Klik, 2002; Govers et al., 1994; Lindstrom et al., 1992). Direction of ploughing (up/down slope vs contour, turning the soil upslope) has been shown to have little effect on the volume of soil transported downslope (Frauenfeld & Klik, 2002; Govers et al., 1994). However, it is important to consider that the direction of ridges created by ploughing does affect water flow downslope and therefore the potential for erosion via rill formation (Chaplot & Le Bissonnais, 2003). On the other hand, the method of cultivation has a large impact on the volume of soil transport, with mouldboard-ploughing creating approximately 2.6 times more movement than chisel ploughing, due to the inversion of the topsoil (Frauenfeld & Klik, 2002).
Compaction

Compaction of soil by heavy machinery or stock reduces macroporosity, reduces infiltration, and thereby increases erosion via sheetwash, or the formation of rills or channels (Hicks & Anthony, 2001; McDowell & Houlbrooke, 2009; Trimble & Mendel, 1995). In addition to reduced infiltration, compacted soils also have reduced water holding capacity (Houlbrooke & Laurenson, 2013), meaning that they are above field capacity after less rainfall, compared with un-compacted soils. Soils that are wet have reduced strength due to increasing pore pressure; when moderately wet they are susceptible to structural deformation in the form of compaction, while above a critical water content (plastic limit) risk of compaction is reduced and surface deformation (pugging) is increased (Houlbrooke & Laurenson, 2013; Laurenson & Houlbrooke, 2016; McDowell & Houlbrooke, 2009). Reduced shear strength due to positive pore pressure can also trigger land slippage or slides, particularly under heavy loading from traffic and machinery on roadways or farm tracks, stock, or the weight of buildings (Desai et al., 1995; Kaitna, 2014b; Kammerer, 2014; Roberds, 2005).

Irrigation

Irrigation can cause both positive and negative impacts on soil quality and erosion due to changes in soil water content. Maintaining soil moisture via irrigation in semi-arid environments aids in soil cohesion and the prevention of wind erosion (Bolte et al., 2011). However, Houlbrooke et al. (2013; 2008) and McDowell & Houlbrooke (2008, 2009) found a reduction in soil macroporosity under grazed irrigated pasture compared with grazed non-irrigated pasture, due to the reduced strength of soils with a high water content and intensification of agriculture under irrigation. This loss of structure results in reduced infiltration rates and water holding capacity (WHC) of the soil, meaning that it dries out faster (Houlbrooke & Laurenson, 2013). If the rate of water application is not subsequently adjusted to match the reduced infiltration rate, then overland flow may occur, causing sheetwash erosion (McDowell & Houlbrooke, 2008, 2009), and increasing flow into waterways, which may lead to stream bank erosion (Campo-Bescos et al., 2015; Guzman et al., 2015; Zaimes & Schultz, 2015).

Irrigation with impure water has been found to be particularly detrimental for soil physical properties, as it causes sodic conditions and thus dispersion of particles which interrupt pore flow, reducing the WHC and infiltration rate, and causing overland flow (Barradas et al., 2015; Edelstein et al., 2010; Kammerer, 2014). Furthermore, dispersed particles are small and therefore easily entrained in water flow and eroded from the site.

Drainage

Drainage of agricultural land can help to reduce soil damage by removing excess water and thus reducing the period when soil is above field capacity and at risk of structural damage by pugging or
heavy machinery, which may lead to increased sheetwash erosion. Drainage can also reduce the risk of sheetwash or rill erosion by diverting the flow of water (Hicks & Anthony, 2001). However, if soil is over-drained then this will result in the soil drying out between rainfall or irrigation events. Over-drained soil may become excessively dry, reducing cohesion, increasing hydrophobicity, and thus increasing susceptibility to erosion, as described in previous sections.

Drainage may also cause soil loss through erosion of the water channel itself. Sediment from surface wash of the surrounding landscape settles in the bottom of surface drains, which are often cleared out using diggers. Whilst this practice deepens the drains and increases drainage of water from the surrounding landscape, it clears any vegetation from the streambed and banks, exposing them to erosion (Kammerer, 2014; Klik, 2014b; Rodriguez-Blanco et al., 2013). Erosion and migration of the stream or drain banks may potentially undercut the toe of a hillslope and trigger large scale landmass movement, as some of the support for the hillslope has been removed (Kaitna, 2014b).

2.5 Soil erosion in New Zealand

Mass movement of soil in the form of landslides and earthflow is considered to be the major form of soil erosion, and this is the most-studied form of erosion in New Zealand and other hilly countries worldwide (Basher, 2008; Dymond et al., 2010; Roberds, 2005). Soil mass movement in New Zealand is largely attributed to the removal of native forests and tectonic activity, and thus there has been a relatively recent increase in the occurrence of erosion as land has been cleared for agricultural use (Basher, 2008; Dymond et al., 2010; McCaskill, 1973).

Management practices exist that are known to reduce the likelihood of erosion of agricultural land occurring, such as reverting pasture back to forestry, reducing stocking rates and diverting water flow (Basher, 2008; McCaskill, 1973). These practices, however, compromise soil conservation with agricultural productivity and therefore are generally only used in situations where it is clear that the current level of soil loss is unsustainable (Basher, 2008). A lack of knowledge exists around what level of erosion is considered to be natural and sustainable, and what level of erosion is considered to be induced to a point that it is no longer sustainable (Basher, 2008; Humphreys & Wilkinson, 2007; Larsen et al., 2014; Montgomery, 2007; Reusser et al., 2015). Furthermore, research on current erosion rates has been patchy geographically and though estimates have been made of average erosion rates nationally and regionally, little is known on hill country erosion rates in many areas (Basher, 2008; Dymond et al., 2010).

Dymond et al. (2010) produced a national soil erosion model to evaluate sedimentation produced by mass erosion under different land use scenarios, taking into account vegetation cover, annual rainfall and a coefficient determined for the terrain (Figure 2.13). Their model allows changes in sediment
discharge to be estimated, and the effect of different landuse management scenarios to be compared; including that of forestation, which will allow natural sediment production to be approximated. Most erosion models in international literature describe other forms of erosion, such as sheetwash, and any existing mass-movement erosion models are restricted to use in confined geographical areas, due to the requirement of high levels of data input. This meant that there was a requirement to produce a spatial model of soil erosion in New Zealand that is able to be used over large geographical areas. Such a map would allow region-wide planning and landuse classification by council bodies and local government (Dymond et al., 2010; Roberds, 2005), and will be of particular use in regions which are dominated by mass erosion, such as Gisborne, Taranaki and Manawatu regions. However, the model treats herbaceous vegetation and bare ground the same (10 times more erosion than under woody vegetation) due to only accounting for mass erosion processes. This approach still leaves an obvious gap in knowledge and data about the extent of diffusive and advective erosion processes in New Zealand, and the effect that different crop types have on erosion rates.

Similar factors affect soil transport via diffusive and advective erosion processes as mass movement, with cohesion, bulk density, gradient and water content being key influencers on susceptibility to soil erosion by sheetwash (Bierman & Montgomery, 2014b; Dietrich et al., 1993). Soil particle grain and ped size and organic matter content also affect soil resistance to entrainment and transport, as does the extent of vegetation cover (Basher & Ross, 2002; Hicks & Anthony, 2001). Due to the extensive cover of native forest and tussock land in New Zealand, sheetwash has not been a large contributor to soil erosion historically, though this form of erosion has become much more prevalent due to deforestation and agricultural development over the last two centuries. Cropping, and market gardening in particular, have been found to significantly increase erosion by overland flow, due to structural degradation, frequent disturbance of the soil via cultivation and long periods without plant cover (Basher & Ross, 2002; Basher et al., 1995).
Figure 2.13  Predicted mean erosion rates (tonnes km\(^{-2}\) yr\(^{-1}\)) under current land cover for the North (a) and South (b) Islands of New Zealand. Taken from Dymond et al. (2010)

2.5.1 Natural soil erosion

Susceptibility of soils in a landscape to erosion is largely determined by the geology, uplift rates and climate (Basher, 2008). New Zealand hill country has been classified under 21 different terrains, based on geology, topography, erosion processes and severity of erosion (Basher, 2008; Dymond et al., 2010). The North Island consists mostly of soft rock or crushed soft rock; mass erosion is prevalent and severe erosion areas are located on the East Cape, Taranaki, Coromandel and Northland (Basher, 2008). South Island soils have mostly developed on hard terrain and are dominated by surface erosion, with mass erosion processes much less common compared to the North Island (Basher, 2008). However, landslides have been found to be an important erosion process in high alpine areas, particularly above the tree line, and along active fault lines (Hughes et al., 2009). Gentle, loess-mantled slopes, on the other hand, are dominated by bio-turbation or tree-throw transport (Hughes et al., 2009; Roering et al., 2002); a soil transport process ignored by many erosion models.

2.5.2 Deforestation

The removal of New Zealand’s native forests to make way for agricultural land has been relatively recent (last 160 years), and the effects of deforestation are still prevalent (Basher, 2008; McCaskill, 1973). The removal of trees has taken away the level of soil protection provided by several layers of vegetation, as well as the extensive root network adding effective cohesion to soils; these effects are explained in the sections above. Repetitive burning and heavy grazing were used to suppress regrowth of tussocks and bracken ferns in early years of pasture establishment. This burning removed organic matter on the soil surface, destroyed vegetation protecting the soil surface and
diminished the humus content of the soil, leading to accelerated wind and frost erosion (McCaskill, 1973). Removal of native vegetation and burning also lead to rill erosion and the formation of extending gullies and slips (Basher, 2008; McCaskill, 1973).

High erosion rates occur on hill country that has been cleared of forests, particularly when storms come through (Basher, 2008; Dymond, 2010; Ryan, 1991). Re-planting of erosion-prone areas using poplar and willow poles or native scrub, has been found to stabilise soil in slip-prone areas, and has been particularly effective at stabilising slopes prior to slip initiation (Basher, 2008; McCaskill, 1973). Plantation forestry has also been used to stabilise erosion-prone country, particularly in the 1980’s during an agricultural economic downturn. While commercial forestry has high erosion levels during tree harvest, erosion levels over the lifecycle of the tree is less than what occurs under pasture during the same period (Basher, 2008).

### 2.5.3 Impact of agriculture

There are many means by which agriculture influences the rate of soil erosion, including change of vegetation cover, intensification, and alteration of soil physical properties (Montgomery, 2007). In most environments worldwide, the conversion of natural land cover to agricultural systems will result in the acceleration of erosion (Montgomery, 2007; Reusser et al., 2015). In New Zealand, pastoral farming provides additional challenges in regards to managing animal production around seasonal pasture and forage crop growth. Recent decades has seen an increase in intensive farming on flat and hill country, with greater use of forage crops to feed stock when pasture growth is limited in winter months (de Wolde, 2006; Drewry & Paton, 2005).

#### Outdoors farming

In many temperate regions worldwide, such as Europe and the United Kingdom, animals are housed indoors over the winter months and fed conserved feed such as silage or grains. This allows the animals to stay warm and conserve energy when there is typically snow / cold weather outside. While New Zealand's relatively mild winters allows animals to be kept outdoors year-round, cooler temperatures over winter prohibit pasture growth, meaning that animals must be given feed in situ that has been grown over summer and autumn, or conserved as silage (de Ruiter et al., 2009; de Wolde, 2006). This has shifted the focus from growing harvestable crops such as grains in EU, UK and USA, to growing ‘standing feed' that can be fed directly to animals in New Zealand.

Traditionally in New Zealand, animals have been wintered on a pasture-based diet that was grown in autumn months, supplemented with grass silage that was harvested in spring when there is a surplus of feed. Farming intensification has created a demand for more energy-rich feed, to allow more animals to be kept on the same area through winter (de Wolde, 2006; Thorrold, 2000). A solution to
this has been to break feed animals brassica crops, such as kale or swedes, which can be grown in the paddock over summer and autumn and break fed in winter (de Ruiter et al., 2009; Drewry & Paton, 2005). A key issue that outdoor grazing in winter creates is damage to the soil by treading of cattle, commonly referred to as pugging (de Wolde, 2006; Drewry & Paton, 2005; Thorrold, 2000).

**Animal treading** causes structural deformation of soil when it is wet (Figure 2.14). As soil strength is reduced with increasing soil water content, compaction damage increases until a critical water content (at or near the plastic limit), above which surface deformation, or pugging, occurs (Laurenson & Houlbrooke, 2016). The shear stress of the weight of the animal overcomes the shear strength of the soil (which is reduced due to soil being wet), and the soil structure collapses and is destroyed, with larger effects seen from cattle than sheep due to their added weight (Houlbrooke & Laurenson, 2013; McDowell & Houlbrooke, 2008). This deformation particularly occurs in the macropores, therefore reducing pore connectivity, infiltration rates and increasing overland flow during subsequent rainfall events (Houlbrooke & Laurenson, 2013; McDowell & Houlbrooke, 2008; Trimble & Mendel, 1995). Furthermore, pugging dislodges soil particles and peds, opens the soil surface, and exposes the soil to raindrop impact. These dislodged particles are then susceptible to entrainment and erosion by overland flow (Trimble & Mendel, 1995).

![Figure 2.14 Schematic diagram of the relationship of soil consistency and water content (Adapted from Drewry et al. (2008)). The solid line shows soil volume and the dashed line shows soil bulk density. Soil water range between plastic and liquid limits (and risk of damage) is influenced by soil properties such as texture and organic matter content.](image_url)

Larger effects on structural deformation are seen on crops than on pasture, due to stock density, the removal of crop stems that slow and filter water, and aid in infiltration; and roots that support the soil (Houlbrooke & Laurenson, 2013; McDowell & Houlbrooke, 2008, 2009). Whilst pugging has the
potential to reduce infiltration rates, it also acts to reduce runoff by creating small depressions in the soil surface which store surface water and prevent overland flow from occurring (McDowell & Houlbrooke, 2009). This can cause prolonged saturated conditions, which may trigger landslides on steep hillslopes, or increase the degree of structural damage if further treading continues (Hicks & Anthony, 2001; McDowell & Houlbrooke, 2009). However, if the soil is cultivated in spring, the surface will become uniform again, and the water retention effects of pugging will be lost, while any compaction and reduced pore connectivity below cultivation depth will persist (Drewry & Paton, 2005). In addition to these effects being observed from cattle treading, they may also be caused by heavy machinery driving over the soil under damp conditions, causing compaction, reduced infiltration and increased runoff (Hicks & Anthony, 2001; Thorrold, 2000).

**Surface runoff** occurs with greater frequency and magnitude on agricultural soils, compared to native ecosystems (Reusser et al., 2015). This is due to reduced infiltration rates resulting from soil compaction and removal of vegetation cover, as discussed above (Drewry & Paton, 2005; Scholefield & Hall, 1985; Trimble & Mendel, 1995). McDowell and Houlbrooke (2008) found surface runoff volume following irrigation to be greater under cattle grazing forage crop (45 mm) compared to sheep grazing crop (25 mm), and sheep grazing pasture (13 mm). They observed a correlation between overland flow, suspended sediment production and phosphorus (P) loss, a trend also observed by Orchiston et al. (2013). McDowell and Houlbrooke (2008) reported P loss under cattle being double that of sheep on crop and seven times that of sheep on pasture. These differences were attributed to greater soil disturbance and compaction under cattle compared to sheep, and due to pasture stubble filtering sediment from overland flow. Although volume of drainage was greater than volume of overland flow, 94% of total P lost was via overland flow. Sediment and P lost via overland flow commonly ends up in surface waters, and contributes to eutrophication and sedimentation of waterways, lakes and rivers (Heathwaite et al., 2005; McDowell & Houlbrooke, 2008; Ryan, 1991). Sedimentation of waterways can lead to increased flooding risk due to reduced stream volume, whilst eutrophication alters soil chemistry and biological balance, affecting native flora and fauna habitats (Boubée et al., 1997; Ryan, 1991). In addition to these off-farm effects, the nutrients lost must be replaced through the application of fertilisers, if farm productivity is to be maintained, at an extra cost to the farmer.

**Intensification**
Agricultural intensification has led to an increase in fertiliser use, higher stocking rates, and wintering off-farm to conserve pasture for spring. Dairy cow numbers have increased from 3.84 million in 1994 to 6.70 million in 2014. In the Southland region, this intensification of land use has been even more substantial, with an increase in dairy cow numbers from 114,000 in 1994 to 700,000 in 2014 (Statistics New Zealand 2014). This recent expansion of dairying has led to more intensive farming
on flat land, and migration of other forms of agriculture to hill country, with more cropping occurring on hillslopes (de Wolde, 2006; Morris, 2013). Sheep and beef stock numbers vary seasonally, with fewer animals over winter, whilst dairy cow numbers remain more constant through different seasons (Morris, 2013), creating a larger demand for feed over winter when plant growth slows or stops. This feed gap is commonly dealt with through pasture conservation in the form of silage, and by feeding forage crops such as brassicas in the winter (de Ruiter et al., 2009; McDowell & Houlbrooke, 2009; Thorrold, 2000).

Forage crops are strip-fed, which gives the cows an allocated amount of feed per day, and increases the efficiency of the crop as less feed is wasted by trampling. With most forage crops, the entire plant is eaten (often including tubers for the likes of swedes or turnips); the soil is left exposed after the plant has been eaten. These crops are grazed at a high stocking density, meaning the exposed soil is heavily trampled during the duration the paddock is grazed, which may vary between one and three months (de Wolde, 2006; Orchiston et al., 2013).

Standard practice is for the cattle to have the ability to roam freely through the paddock as it is being grazed, meaning that the soil is not only trampled when the feed is being eaten, but is continued to be treaded for the duration of the rest of the paddock being grazed. It has be shown that this management strategy is the most damaging for the soil, with animal exclusion such as using a stand-off pad or a back-fence to prevent continuous trampling resulting in less soil structural damage and faster soil recovery compared to standard practice (de Ruiter et al., 2009; Drewry & Paton, 2000, 2005; Orchiston et al., 2013; Thorrold, 2000). Other management strategies such as grazing downslope instead of upslope, and the use of portable troughs to reduce the regular movement of cattle across the paddock have also been shown to reduce soil damage. Orchiston et al. (2013) showed that grazing with break fences running across slope (progressing in a downslope direction), and the avoidance of grazing critical sediment source areas where water accumulates when soil is wet, resulted in a reduction in soil erosion.

2.6 Conclusion

Soil erosion occurs in natural environments all over the world, at rates depending on the local geology, climate, vegetation cover and tectonics. Nevertheless, research has repetitively shown that erosion processes are accelerated under agricultural production, particularly as a result of conventional cultivation (Govers et al., 1996; Montgomery, 2007; Reusser et al., 2015). Quantification of soil erosion caused by agriculture is necessary to determine the economic and environmental impact that occurs from farming, both onsite and offsite. It can also be used to determine the sustainability of management practices, and the long-term impact they will have on farm production and the environment (Barry et al., 2011; Thorrold, 2000).
Land use intensification related to the expansion of dairying in New Zealand has pushed intensive forage grazing on to hillslopes (Morris, 2013). The coincidence of demand for fodder with winter, the poor ground cover provided by grazed forage crops, and the density and weight of the grazing animals has increased soil degradation and erosion (Drewry & Paton, 2005; Orchiston et al., 2013). Time of crop grazing (winter) coincides with when the soil is often saturated or at field capacity, as evapotranspiration rates are low in winter (and in some regions rainfall may be higher). As the soil is so wet, it is at higher risk of structural degradation and deformation (Orchiston et al., 2013; Thorrold, 2000). When coupled with being on a slope, soil is pushed down the slope by trampling and the force of gravity, and the downward motion of the cows' hooves as they step. This pushing of soil down slope is an induced form of creep and has not been quantified before. Existing methods for the measurement of soil creep require bulky devices that must remain in-situ and are thus unsuitable for use around stock, or measure the shape and elevation of a landscape with LiDAR or GPS surveys that are only able to detect large changes that occur over a long period. Although the effects of cattle grazing hillslopes on soil transport has been acknowledged (Trimble & Mendel, 1995), the unsuitability of current methods for measuring soil creep has resulted in a knowledge gap about rates of soil transport and the rates of erosion that result.
Chapter 3
Methodology

3.1 Experimental design

A field trial was employed to determine the effect of slope gradient and soil water content on soil transport under winter forage crop grazing by cows. Topography of the research area was characterised through the generation of a digital elevation model (DEM). Locations for ten transects were chosen to represent a sample of gradients present within the research area. At each transect, steel tracers were buried prior to cow grazing of the research area. Soil water content readings were taken prior to grazing at each transect location throughout the winter grazing period. After grazing had ceased, tracers were relocated using a metal detector. Soil transport was calculated from the change in tracer position. This same process was repeated to measure soil transport under cultivation, at the same ten transect locations. Details of each step in the experiment and characteristics of the study area are given below.

3.2 Site description

The study area was a 6 ha flat to hilly paddock (mapped as LUC 3e12 (Lynn et al., 2009)) at c. 40 meters above sea level on the Telford Farm Training Institute near Balclutha, South Otago (46° 16’ 45” S, 169° 42’ 22” E). The soil is a Mottled Fragic Pallic Soil belonging to the Timaru series (Landcare Research, 2015), formed in loess overlying Triassic sedimentary rock formed from volcaniclastic sandstone (Bishop & Turnbull, 1996). These soils are characterised by silt loam topsoil overlying dense subsurface horizons with a clay content of 20-30% (Landcare Research, 2015), which can impede drainage. Pallic soils also have relatively low structural stability, which makes them prone to pugging and structural degradation (Hewitt, 2010).

The area has a mean annual temperature of 9.8°C and mean annual rainfall of 680 mm (NIWA, 2015). The paddock was grazed over a period from June to July 2015 when mean air temperature was 5.1°C (max 17.6°C, min -5.4°C), and 144 mm of rain fell. These figures are similar to a long-term mean June-July temperature of 5.0°C and rainfall of 120 mm (NIWA, 2015). Rainfall was recorded at the site using a 0.2 mm tipping bucket rain gauge, while temperature was recorded at a NIWA station 2.5 km away (station ID: 26163). Daily climate data are included in Appendix A.

The paddock was planted in Regal® kale (Brassica oleracea spp. acephala) crop in early December 2014, after being in kale the previous season (2013/14), and in perennial ryegrass (Lolium perenne) and white clover (Trifolium repens) pasture prior to that (2013). The 2015 kale crop yielded c. 15 t
DM/ha and was grazed by a herd of 123 pregnant non-lactating dairy cows from June 16th to July 30th 2015 (45 days). Crop allocation was c. 6.1 m²/cow/day with break fences shifted twice daily (progressing in a downslope direction), and grass silage bales supplemented cow diet. The use of portable water troughs removed the need for the cows to regularly walk the length of the paddock to get water, thus reducing trampling of the soil. Cows were prevented from accessing the gateway to the paddock by the use of a back-fence and, although no other back-fences were used, cows were observed to spend the majority of their time eating and resting along the crop-face.

The area used for this research covered 3.4 ha of the 6 ha paddock, and consisted of a planar summit sloping gently to the north, with a hillslope and terrace that descended on the eastern side of the paddock (Figure 3.1). Along the eastern boundary was a pine plantation bordering an ephemeral stream. Total local relief was 17 m.

Figure 3.1 Photos of the study site taken in May, 2015: a) looking north along the western boundary, b) looking south east, c) looking south along the eastern boundary
3.3 Experimental Setup

3.3.1 Digital Elevation Model

A topographic survey was conducted by Tom Orchiston (AgResearch) in May 2015, using a Trimble R6 Real Time Kinematic (RTK) GNSS surveying system and a Trimble TSC3 controller (Figure 3.2). Individual points were captured in the New Zealand Transverse Mercator 2000 (NZTM) projection, using a RTK Rover on a backpack and the RTK system set to 'continuous topo' mode to record a point every 3 m while walking. The paddock was walked in lines of east - west orientation across the paddock, that were 5 to 15 m apart. The point cloud derived from the RTK GPS survey is shown in Appendix EE.1. High variation in distance between lines was due to steep terrain and difficulty walking through the kale crop. The RTK has a horizontal accuracy of ±8 mm and a vertical accuracy of ±15 mm when measuring a static point, but the movement of a person while walking adds an undetermined inaccuracy to the data points when the backpack is used. Data obtained from the GPS were interpolated in ArcGIS version 10.3 with a kriging routine to yield a digital elevation model (DEM) of 4 m grid size, chosen from a range of resolutions tested. The DEM was then used to determine the positioning of ten study transects within the research area. The locations of these transects were chosen to allow a representative sample of the hillslope gradients present (Figure 4.1).

Figure 3.2  Trimble R6 RTK GNSS surveying system used for capturing elevation and position points, consisting of a) the base station and b) the rover and Trimble TSC3 controller
3.3.2 Quantifying Soil Fluxes

Soil transport under cows over the duration of the experiment was estimated by measuring the movement of 18-mm diameter hardened steel balls. Twenty balls with engraved identifier numbers were placed at each of the ten study transects (200 balls in total). At each transect, eight of the 20 balls were placed at 50 mm depth below the soil surface, eight balls at 150 mm depth, and four balls at 250 mm depth. The position of each ball was measured at the soil surface, using the RTK GPS and recorded against the ball’s individual engraved number. The balls were placed in the soil in late May by augering holes of 40 mm diameter, placing the ball at the specified depths perpendicular to the surface, and back filling the hole (Figure 3.3). These balls were left in the soil over the winter grazing period and the sites were grazed as per normal.

Soil transport under cultivation was measured using the same principles as described above for soil transport under cows. Balls were placed in the soil in late-October in transects of the same layout and very close in location to the transects under cows. This allowed the same high-resolution DEMs to be used for processing cultivation data (cf. 3.3.6 Cultivation). A key difference in the cultivation experiment set up was the vertical placement of the balls beneath the soil surface, as opposed to perpendicular placement that was used for the grazed experiment. This avoided a problem of an apparent uphill displacement due to differences in how balls were placed and relocated, and the need for correction of the ball location, as described below (cf. 3.4 Data processing). Another change made was painting numbers on the balls with metal primer paint, instead of engraving them. The painted numbers were easily readable when the balls were recovered, removing the need for additional laboratory work to clean rust off the balls (cf. 3.3.4 Ball recovery).
Figure 3.3 Image sequence depicting method of ball placement: a) insertion of balls at set intervals (0.5 m) along a marker string, b) measurement of each position at the surface using RTK GPS, c) augering of 40 mm diameter holes perpendicular to the surface, d) placement of pre-marked balls along the transect, e) measurement of specified depth, f) check identification number on balls to ensure correct placement, g) placement of 18 mm ball in 40 mm diameter hole, h) backfilling of hole, i) soil surface after insertion complete
### 3.3.3 Volumetric Water Content

During the grazing period, volumetric water content (VWC) was measured at a depth of 300 mm using a Field Scout TDR100 moisture probe (Spectrum Technologies Inc.). Ten readings were taken at each transect on the day that it was grazed, and recorded on a spreadsheet. The soil was saturated (32 to 40% VWC) at all transects during the experiment. Three soil samples (200 g) were also taken at each of the ten transects to measure gravimetric water content back in the laboratory. Soil samples were stored separately in sealed, airtight bags and frozen until they were analysed at the end of winter. These samples were weighed, oven dried at 105 °C, and then re-weighed. Gravimetric water content was converted to VWC by multiplying by the ratio of the soil bulk density to the density of water (cf. 3.3.5 Bulk Density).

### 3.3.4 Ball recovery

The steel balls were recovered in September 2015 (approximately 130 days after installation), after the entire research area had been grazed and the cows were no longer in the paddock. The balls were relocated using a Garrett AT Pro metal detector (100 mm detection radius) and the exact location determined with a Bounty Hunter pin pointer metal detector. The soil above the ball was carefully excavated and when the ball was exposed, its vertical depth below the soil surface was measured, and its position was measured using the RTK GPS (Figure 3.4). Due to rusting and corrosion the ball numbers were unable to be read when they were excavated, so each ball was individually wrapped in a piece of paper with a new number, which was recorded with its location on the RTK. The metal detector failed to register balls that were buried deeper than 160 mm. For these balls, their original position was resurveyed using the RTK GPS, and then overlying soil was removed progressively until they were detected with the metal detector. As there was minimal soil movement below 160 mm, all of the deeper balls were located using this procedure. Four balls at 50 mm depth were not located.

For the second (cultivation) experiment, balls were recovered in early December after one pass with the plough. The same technique was used as described above, though without the need to record new numbers for the balls, due to the painted numbers being easily read.
Figure 3.4 Photos illustrating ball recovery method; a) location of ball with metal detector, b) precise location of ball with pin pointer, c) measurement of ball depth, d) measurement of ball position using RTK GPS
In the laboratory, numbers on the balls for the grazing experiment were revealed by submersing each ball in a beaker of water and placing it in a 'S 30 H Elmasonic' ultrasound bath for 10 to 20 minutes to remove clay and excess rust. Balls were then placed in 10% Hydrochloric acid for 5 to 10 minutes to lift embedded rust. They were then rubbed gently with a sponge, allowing the engraved number to be read and recorded against the number given to the ball when it was relocated, thereby ensuring recording of correct location.

After the balls had been located, high resolution (0.5 m to 1.3 m grid) DEMs of the ten transect locations were generated by measuring topographic points with the RTK GPS at a density of 0.25 to 1 m, depending on the terrain. These points were measured by holding the RTK rover in a static position, to enable greater accuracy and precision than can be achieved when using the rover on a backpack. Higher resolution DEMs allowed more accurate determination of the effect of gradient on soil transport, and enabled the identification of cattle tracks on steeper slopes.

3.3.5 Bulk Density

In September, intact cores were taken for soil bulk density ($\rho_b$) measurements from the flat hilltop, the steep slope, and on the terrace. At each of these locations, four cores (approximately 100 mm by 75 mm diameter) were taken; two at 50 mm depth, one at 150 mm depth, and one at 250 mm depth (measured to the centre of the core). Reduced sample intensity with increasing depth was in response to an anticipated reduction in $\rho_b$ variability.

When taken back to the lab, cores were trimmed until soil was flush with the core edge. Tins were pre-weighed for the drying process, and the contents of the cores were transferred to a tin and placed in the oven at 105°C for 48 hours. Tins were re-weighed to determine the dry weight of the soil (minus the weight of the tin). Dimensions of each core were measured to ± 0.02 mm using digital callipers, allowing its volume and thus the soil $\rho_b$ to be calculated. Soil porosity ($P$) was then calculated from $\rho_b$, assuming a particle density ($\rho_p$) of 2.65 (Equation 3.1).

\textbf{Equation 3.1:} $P = 1 - \frac{\rho_b}{\rho_p}$

3.3.6 Cultivation

The paddock was cultivated with a mouldboard plough to a depth of approximately 200 mm in early December, though the actual depth varied with the contour of the land. This was due to the trailing implement moving at depths relative to the rear of the tractor, not relative to the soil surface, and thus digging in more or less on convexities, depending on whether the tractor was travelling downslope or upslope, respectively. Soil was compacted prior to cultivation (average bulk density of 1.3 g cm$^{-3}$), as a result of treading damage during winter grazing (Figure 4.4). Additionally, the soil
was relatively dry owing to the farmer prioritising cultivation of other paddocks being sown into crop, over cultivation of paddocks being put back into pasture (such as our research area). The farmer attempted to contour-plough the paddock but due to the shape of the land relative to the fence lines, plough lines were not always parallel with the contour (Figure 3.5).

3.3.7 Soil descriptions

Descriptions of the soil profile were made at the top of the slope, on the crest of the slope, and at the foot of the slope. Pits were dug to 500 to 800 mm depth, with the depth depending on the thickness of soil overlying a dense fragipan. Morphological characteristics (texture, structure, colour, and consistence) were described using Schoeneberger et al. (1998) and Munsell Color (2000). Soils were generally dark greyish brown in the A horizon, and dark greyish brown to light olive grey in the sub soil, with fine to coarse mottles present below ~200 mm. Peds were firm to extremely hard, and brittle with silt loam texture. A dense fragipan was present at 400 to 700 mm depth, depending on pit location. Full profile descriptions are included in Appendix D.

Figure 3.5  Research area after cultivation with the mouldboard plough, looking north
### 3.4 Data processing

Geospatial data were processed in ArcGIS (version 10.3) to create DEMs and derivatives (e.g. slope and curvature), for visualisation and to create maps. Microsoft Office Excel (2007) was used to calculate ball trajectories and soil transport, and run regression analysis.

Perpendicular placement and vertical recovery of tracers created an apparent uphill displacement of even stationary balls. In the initial survey, the top of the auger hole in which the ball was placed, was recorded as the location of the ball. Because the auger hole was drilled normal to the slope this point is downhill of the ball position in the horizontal plane. The apparent displacement magnitude is given by the product of the depth of emplacement ($d$ in Figure 3.6a) and the sine of the slope angle ($\beta$) (Equation 3.2), and it is oriented 180° to the slope aspect ($\alpha$ in Figure 3.6b). The correction necessary, with respect to the E-N coordinate system, is given by Equation 3.3 and Equation 3.4.

![Figure 3.6](image)

The corrected ball location is given by adding corrections to the eastings and northings ($\Delta E$ and $\Delta N$) given by equations Equation 3.3 and Equation 3.4.

**Equation 3.2:** $a = d \times \sin \beta$

**Equation 3.3:** $\Delta E = -a \times \sin \beta$

**Equation 3.4:** $\Delta N = -a \times \cos \beta$

where $a =$ horizontal displacement (m), $d =$ depth, the initial depth (m) of the ball beneath the soil surface, $\beta =$ slope angle of the surface (degrees), $\alpha =$ aspect (degrees, relative to north), $\Delta E =$ change in easting, and $\Delta N =$ change in northing.

Once the initial position of the balls had been corrected, a displacement vector with magnitude ($D$) and orientation ($\theta$) was calculated for each ball using Equation 3.5 and 1.6, respectively.

**Equation 3.5:** $D = \sqrt{[(E_{i,c} - E_f)^2 + (N_{i,c} - N_f)^2]}$

**Equation 3.6:** $\theta = \tan^{-1}\left(\frac{(E_{i,c}-E_f)}{(N_{i,c}-N_f)}\right)$
where $E_{i,c}$ = corrected initial easting of ball, $E_f$ = easting of final ball position, $N_{i,c}$ = corrected initial northing of ball, and $N_f$ = northing of final ball position. $\theta$ was converted to angle (degrees) of movement relative to north ($\Omega$) by adding 0°, 90°, 180° or 270°, depending on the direction of movement relative to the initial ball position (Figure 3.7).

The movement of balls in the downslope direction ($V_1$) was calculated by projecting the ball displacement vector onto the gradient vector (aligned with the aspect) according to equations 1.7 and 1.8. Equation 3.7 was used if $(\alpha - \Omega) < 90^\circ$, or Equation 3.8 otherwise. $V_1$ is positive and orientated downslope if $\Omega < (\alpha \pm 90^\circ)$, and negative and oriented upslope if $\Omega > (\alpha \pm 90^\circ)$.

**Equation 3.7:** $V_1 = D \times \cos(\alpha - \Omega)$

**Equation 3.8:** $V_1 = D \times \cos((180 + \alpha) - \Omega)$

Cross-slope movement ($V_2$) was also quantified although not analysed, using Equation 3.9, where movement to the right when looking down slope is positive, and movement to the left is negative.

**Equation 3.9:** $V_2 = D \times \sin(\alpha - \Omega)$

Downslope ball displacements were averaged for balls at each of the three depths at each transect, and then volumetric soil transport was calculated assuming the motion of balls at 50 mm, 150 mm and 250 mm depths represented the depth increments 0-100 mm, 100-200 mm, and 200-300 mm, respectively. Finally, volumetric transport was summed over the three depth increments at each transect, and converted to soil transport per season, assuming that the grazing event studied is representative of standard winter grazing practice.
3.5 Modelling

3.5.1 Calibrating a soil transport law

Consistent with the initial hypothesis that soil transport under grazing and cultivation would behave diffusively, the soil flux was plotted against hillslope gradient to explore the nature of the dependency. Linear regression analysis was used to evaluate the statistical significance of a linear slope-dependent transport law and to derive the soil transport coefficient \( K \).

3.5.2 Estimation of soil erosion

Soil erosion is determined by the divergence of the soil flux (Dietrich et al., 2003). Where linear slope-dependent transport can be assumed, the transport law and the continuity equation together dictate that the erosion rate \( E \) is given by Equation 3.10.

**Equation 3.10:** \[ E = K \nabla^2 \cdot z \]

where \( K \) is the soil transport coefficient, and the second term is the topographic curvature. The latter term was calculated for the whole of the study area using the curvature function in the Spatial Analyst tools of ArcGIS (Figure 4.2). Using this curvature raster, a raster map of soil erosion was produced using Equation 3.10 in the raster calculator tool in ArcGIS.
Chapter 4

Results

4.1 Terrain characterisation

The digital elevation model (DEM) raster (Figure 4.1a) was used to generate a slope raster of 4 meter resolution, which was then used to select the location of the ten transects (Figure 4.1b), and a curvature raster (Figure 4.2) for calculation of erosion rates (cf. 3.5.2 Estimation of soil erosion). Slope varied from 0.09° to 21.1° (0.00 to 0.39 m m\(^{-1}\), respectively), with a mean slope of 7.27° (0.13 m m\(^{-1}\)). Total curvature ranged from -6.4 (concave) to 2.9 m\(^{-1}\) (convex), with a mean of -0.13 m\(^{-1}\).

![Figure 4.1 Rasters displaying a) DEM and b) terrain and locations of the ten transects, with slope in degrees and gradient (m m\(^{-1}\)) in parentheses, produced in ArcGIS with a grid size of 4 m. White dots are transect locations, which are labelled with transect IDs.](image)

DEM datasets of 2 m, 3 m, 4 m, 5 m, 6 m, and 8 m resolution were generated, and slope, curvature and erosion rasters were produced from each of these. A grid size of 4 m resolution was chosen to present data, as this was the finest resolution that did not display linear artefacts created from capturing data points for the DEM by walking in parallel lines across the paddock. The resulting erosion raster from each of these six resolutions are presented in Appendix E.2. The effect of each resolution on the frequency distribution of erosion rates is presented in Appendix E.3.
Figure 4.2 Raster displaying total curvature (plan + profile), produced in ArcGIS. White dots are transect locations, which are labelled with transect IDs.

A high resolution DEM (0.5 to 1.3 m) was produced at each of the ten transects (Appendix E.4); resolution depended on the local terrain, with steeper sites having denser point clouds. These high resolution DEMs were used to determine the aspect for each transect location, and the slope for each individual ball trajectory. Slope of the detailed DEMs ranged from a minimum of 0.09 degrees at transect A9 to maximum of 34.8 at transect E1. This compares to a range of 0.09 to 21.1 for the lower resolution initial DEM, with the increase in recorded steepness being at least partially attributed to the high resolution DEMs capturing stock tracks that did not exist prior to the grazing period, which would have increased slope on a micro-scale, as mini-terraces were formed (Figure 4.3).

Figure 4.3 Slope rasters for transects E1 (a), F2 (b) and J10 (c), illustrating track formation and the resulting effect on ball transport under cattle grazing. Rasters are all of 25 cm resolution.
4.2 Soil characteristics

4.2.1 Soil morphology
Depth of topsoil varied with position in the landscape, with topsoil being shallowest on the crest (160 mm), followed by top flat (220 mm), then the foot of the slope (290 mm). Depth to fragipan was shallowest on the crest, then foot slope, then top flat (420 mm, 600 mm and 680 mm, respectively). Bulk density was also found to vary with location, with the most porous soil being located on the slope (1.03 g cm$^{-3}$ at 50 mm depth, 1.27 g cm$^{-3}$ at 300 mm depth), and becoming more compacted on the top flat (1.16 g cm$^{-3}$, 1.29 g cm$^{-3}$), then the terrace (1.28 g cm$^{-3}$, 1.34 g cm$^{-3}$).

4.2.2 Soil water content
Soil was at or near saturation throughout the trial period, with mean volumetric water content (VWC) at each transect ranging from 32 to 40%, as measured using TDR, or 48 to 73%, as determined in the laboratory. The large difference between VWC values measured with the TDR probe and those determined in the laboratory (Appendix A) is likely due to the TDR integrating VWC to 300 mm depth, while the soil samples were taken from the soil surface and likely included overlying surface water. These VWC compare to mean porosity of 56% to 100 mm depth, or 51% to 300 mm depth. No relationship was found between VWC and soil transport, and the data collected were not used further, other than confirming that soils remained near saturation throughout the grazing trial period.

4.3 Soil transport under cattle grazing

4.3.1 Depth profiles of tracer movement
It was evident from visual observations in the field that treading damage, such as pugging, occurred in the top 200 to 300 mm of the soil profile. Figure 4.4 illustrates pugging damage to the research area after grazing had ceased, and a lack of soil shear strength, as evident by the soils failure to support a person’s body weight.

![Figure 4.4  Evidence of pugging damage after grazing has ceased. Photos taken September 2015.](image)
Despite the visual evidence of deeper pugging damage, ball displacements showed downslope movement was significant (p=0.01) only in the top 100 mm of soil (Figure 4.5). The depth-profile of ball displacement approximated a negative exponential function, although other forms occurred (Figure 4.5). Small differences in ball positions at 250 mm depth were generally within the uncertainty of the RTK GPS (±8 mm), and within the precision of measurements possible with an 18 mm ball in a 40 mm-diameter auger hole.

![Figure 4.5](image)

Five individual balls were removed from the data, where balls appeared to have moved excessively and independently from the soil and where there was an obvious explanation for this movement, in addition to four balls not found (Table 4.1). A bale-ring feeder had been situated very close to transect B, which may have resulted in some balls getting stuck in the hooves of cows, or in the tread of a vehicle tyre. A back fence excluding stock from the gateway to the paddock intersected transect C and two balls had been moved along this fence line, presumably by cattle walking up and down it.
Table 4.1  List of balls missing or excluded from data as outliers. Downslope displacement of balls removed compared to the average for that transect (Transect avg) and the anticipated reason for movement are given. Negative values indicate movement upslope, while positive values represent downslope movement. All missing and excluded balls had been positioned at 50 mm depth

<table>
<thead>
<tr>
<th>Transect</th>
<th>Ball ID</th>
<th>Displacement</th>
<th>Transect avg</th>
<th>Reason for exclusion</th>
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<td>Missing</td>
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</tr>
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4.3.2  Soil-transport model

The downslope soil flux under winter grazing increased with increasing slope gradient (Figure 4.6). A significant (p<0.001) positive linear relationship was found between soil transport and slope gradients up to 0.25 m m\(^{-1}\) (c. 14°). The slope of the regression equation, which equates to the transport coefficient, \(K\), (or topographic diffusivity) in a linear slope-dependent transport equation (Equation 1.1) was 0.12 ± 0.02 m\(^2\) y\(^{-1}\).

Soil transport on gradients greater than 0.25 was non-systematic, with rapid transport measured at transect F2 (gradient 0.394), due to a cattle track crossing through the middle of it. In contrast, the soil fluxes at transects J10 (0.34 m m\(^{-1}\)) and E1 (0.48 m m\(^{-1}\)) were similar to those at transects with gradient of < 0.25 m m\(^{-1}\). At both of these transects cattle tracks were evident but did not intersect the transect (Figure 4.3).

Based on the relationship between soil flux and gradient, a linear slope-dependent transport model was adopted (Equation 1.1), but its application was limited to slopes of gradient < 0.25 m m\(^{-1}\). It was not deemed appropriate to adopt a more complicated and theoretically unjustified transport law to
fit the data at gradients >0.25 m m⁻¹. The implications of the limited applicability of the soil transport model are discussed more fully in the discussion.

**Figure 4.6** Soil transport flux ($q_s$) under grazing at different slope gradients ($S$). A linear regression line is shown for gradients of <0.25, where the relationship was determined to be $q_s = 0.1175 + 0.0001 \times (R^2=0.91, \ p<0.001)$.

### 4.3.3 Soil erosion model

Soil flux ($q_s$) downslope results in erosion (net loss) of soil of convex areas, and accumulation (net gain) of sediment in concave areas, as explained by Equation 1.2 and illustrated by Figure 4.7. Erosion rates were estimated by extrapolating the soil transport model calibrated at our transect locations over the research area. Erosion was calculated by multiplying the transport coefficient, $K$, by total curvature (which was determined using the initial DEM captured in May), using Equation 3.10 in ArcGIS, to produce an erosion raster (Figure 4.8b). A dataset of erosion over the entire research area was exported from ArcGIS (Figure 4.9), allowing average values to be calculated in Microsoft Excel.

Over the winter grazing period, soil flux within our research area caused erosion of up to 3.4 mm soil depth on shoulders of slopes and terraces, and gains of up to 7.6 mm at the foot of the slopes and in a basin (Figure 4.8b). Convexities of up to 8.5 m⁻¹ were situated along the shoulder of the slope running approximately through the middle of the site, along a terrace above the south-east corner, and along a lineation running from west to east (Figure 4.8a). These two ridges form a basin in the centre-west of the research area, which consists of an approximately -6.5 m⁻¹ concavity. A comparison of Figure 4.8a and Figure 4.8b show these convex areas are where high erosion occurred. Soil erosion had a negative skew around a median of 0.10 mm (Figure 4.9), though mean erosion was calculated to be -0.15 mm (accumulation). These data show that a greater area of the hillslope was
eroding (54%), though some areas were accumulating high volumes of sediment. Of the eroding area, 32% (18% of total area) was eroding at greater than 0.8 mm per winter grazing season.

Figure 4.7 Depiction of erosion at convex areas (left) and deposition in concave areas (right). The black line represents the initial soil surface, while the red line represents the surface resulting after soil transport.

Figure 4.8 Maps of the research area showing a) curvature (m⁻¹) of the research area, and b) soil erosion (E) (m/season). Both maps have a grid size of 4 meters.
Figure 4.9  Histogram of erosion in the research area, showing distribution with a negative skew around a median of 0.1 mm erosion. Negative numbers indicate deposition of soil.

4.4  Soil transport resulting from Cultivation

4.4.1  Depth profiles of tracer movement

Downslope soil transport under cultivation was found to have a significant relationship with depth (p<0.01), with shallower balls moving further than deeper balls; similar to transport under grazing (Figure 4.10). Depth profiles took on negative exponential, linear and humped forms. Movement of balls at 50 mm depth was consistently high (0.3 to 0.7 m), while there was greater variation in the transport at 150 mm and 250 mm depths.
Despite a relationship existing between soil transport and depth, there was no significant (p>0.05) linear relationship between soil flux and hillslope gradient due to cultivation (Figure 4.11). Distance of soil transport was highly variable, and average downslope transport of soil appeared to be affected by a factor of greater importance than slope gradient. The relationship appears to be in the form of a trough, with minimum transport at a gradient of c. 0.16 (slope 9.03°), though this relationship was not explored as it has no theoretical foundation.

In convex areas of the paddock, pale subsoil was seen at the surface (Figure 3.5), indicating that either these areas were cultivated deeper, and/or the sum of erosion over years under agricultural production has significantly thinned the soil on the shoulders of the slopes. Accordingly, and due to the lack of relationship between soil transport and gradient, the correlation between soil transport.
and total curvature values (numerical representation of profile and plan curvature, positive values = convex, negative values = concave) extracted from Arc GIS, was explored (Figure 4.12). No significant linear relationship exists.

**Figure 4.12** Average downslope soil transport vs average total curvature. Legend is transect IDs

### 4.5 Soil transport under the combined forage crop system

Despite the lack of relationship found between gradient and soil transport under cultivation, mean downslope displacement across all sites was much greater than that under grazing cows (0.082 vs 0.021 m$^3$ m$^{-1}$ per season, respectively). When these values are compared, it is clear that soil transport under forage cropping systems is much greater than from under cow hooves alone (Figure 4.13).

**Figure 4.13** Mean downslope soil transport flux at each transect, for cow grazing (Cow) and cultivation (Cult). Note: Gradient was calculated as an average for the path of ball transport; due to balls moving further under cultivation, their representative values vary from those for transport under cows
Chapter 5
Discussion

5.1 Soil and local conditions

5.1.1 Soil water content

Soil remained near saturation throughout the grazing period; it is likely that the soil was consistently above the plastic limit, and this is the expected reason that no relationship was found between water content and soil transport. Marlow and Pogacnik (1985) reported that the greatest amount of stream bank erosion via cattle trampling occurs at >10% VWC, far below the water content measured in this study. Houlbrooke et al. (2009) concluded that a lack of difference between spring grazing management practices on soil compaction (though all grazed treatments had significantly less porosity than a ‘never grazed’ treatment) was likely due to soil compaction occurring at lower water contents (near or below plastic limit) than at which pugging effects are visible (Figure 2.14).

The high soil water content over the period of the trial is a result of rainfall exceeding combined evapotranspiration and plant uptake. These conditions are typical of the winter period in South Otago and Southland. Mean temperature throughout the grazing period was also representative of typical conditions. Low temperatures lead to low plant growth and thus little transpiration occurs and high soil water conditions result (McDowell & Houlbrooke, 2009).

5.1.2 Management practices

Grazing management practices undertaken for the trial were typical of common practice and recommended best-management practices for the area. The paddock was grazed with break fences running parallel to the contour, progressing in a downslope direction. Orchiston et al. (2013) determined that this practice resulted in significantly reduced erosion via overland flow (11% of erosion caused by grazing across slope), under similar soil and weather conditions to this trial. Management practices employed in this trial were typical for the region; hence, it is considered that the erosion rates measured are representative of those expected to what occur under winter-grazing practice on similar soil types. Additionally, as the landscape and soils of our research area are commonly found throughout South Otago (Bruce, 1973a; McIntosh et al., 1997), our results are considered representative of this region.
5.2 Soil transport - soil depth relationship

Depth of placement was found to have a significant (p=0.01) effect on displacement of balls. At transects of all gradients, shallow balls moved further downhill than deeper balls (Figure 4.5 and 4.10). This is likely to reflect less overlying / surrounding soil to resist shear stress and therefore deformation under the pressure of a cow hoof; the soil at the surface is able to move upwards and outwards when treded, commonly called pugging (Houlbrooke et al., 2009). When the effect of treading is applied on a slope, soil deformation will occur preferentially in a downslope direction, resulting in net downslope soil displacement (Trimble & Mendel, 1995). Adding to the passive gravitational movement of pugged soil, is the active transport of soil downslope in reaction to cows climbing uphill or braking as they descend. The motion of the balls indicates most of the transport is restricted to the upper 100 mm of soil.

Soil compaction is likely to have also contributed to downslope movement of soil. Drewry et al. (2004) documented compaction of soil under a spring pasture grazing, showing that shallower soil (0-50 mm) suffered greater compaction than deeper soil (50-100 mm). On a hillslope, the downward (vertical) motion of the soil and compression of pores that contributes to compaction and an increase in bulk density, also represents transport of soil in a downslope direction, dependent on the hillslope gradient (Trimble & Mendel, 1995). However, Drewry and Paton (2005) found that soil compaction was greater at 50 -100 mm than 0 -50 mm, at 1.5 to 4 months following winter grazing. This is consistent with the results of this study, showing soil at 0 -100 mm to be less dense than soil at greater depths, at 48 days post-grazing. This less dense surface soil is due to the ameliorating effects of freeze-thaw from snow and heavy frosts, the soil drying out, and the activity of soil organisms in spring (Dexter, 1991; Drewry & Paton, 2000), as well as the weight of overlying topsoil compacting the subsoil (Trimble & Mendel, 1995). Based on the findings discussed above, if compaction was the major contributor to downslope soil motion then one would expect a displacement depth-profile with a peak in the subsoil, not at the surface as was documented here.

An additional factor influencing reduced soil displacement with depth is the soil type: silt overlying clay. The overlying silt material is easily deformed when wet, destroying the structure and resulting in soil transport downslope, whilst the dense clay layer is more stable, and thus little movement occurs. This underlying clay layer also acts as a barrier to water drainage, further increasing the high water content in surface soils, and susceptibility of the overlying soil to reduced stability associated with high water content conditions (Hewitt, 2010; Trimble & Mendel, 1995). These factors resulted in greater transport of shallower balls under the grazing experiment (Figure 4.5), as deeper balls were located in denser soil below the Ah horizon (Appendix A). This transport-depth relationship follows the velocity profile typical of creep erosion, reported by Dietrich et al. (2003).
The cultivation experiment displayed a greater displacement of soil and to a greater depth than the grazing experiment (Figure 4.10). This reflects the higher ground pressure of the plough (deeper penetration) and the higher energy input (more work done) by the cultivation, which was sufficient to at least partially overcome shear strength differences in the soil. Although the plough depth was set to 200 mm below the soil surface, movement of balls placed at 250 mm depth occurred at four transect locations (Figure 4.10). This was due to the plough being set at a depth relative to the tractor, not to the soil surface itself; resulting in irregular ploughing depth as the implement was towed over uneven terrain. Frauenfeld and Klik (2002) also reported irregular cultivation depth using mouldboard plough and chisel implements under a highly regulated trial in Austria.

5.3 Soil-flux-gradient relationship

5.3.1 Transport under grazing

Changes in soil transport on slopes of gradient greater than 0.25 was non-systematic, due to a change in animal behaviour in this area. On steeper slopes, cows tended to walk in tracks across the slope, creating spatially variable soil transport (Figures 4.3 & 5.1). The magnitude of transport measured on the steeper slopes was related to whether or not a stock track intersected the transect. Rapid transport was measured at transect F2 (gradient 0.394) due to a track crossing through the middle of it. A comparatively small amount of transport was measured at transects at J10 and E1 (gradients 0.342 and 0.484, respectively), which coincidentally ended up positioned between tracks (Figures 4.3 & 4.6).

Initial observation of the data suggested that a non-linear transport relationship may exist, with the relationship appearing linear at low gradients, then becoming logarithmic-like on steeper slopes (Figure 4.6). This contrasts to a relationship derived from mechanistic considerations by Roering et al. (1999), in which soil transport increases in a near linear fashion at low gradients but increases non-linearly as gradients approach a critical value. In their analysis, soil transport arises from power applied isotopically to a hillslope in the form of soil disturbance, with downslope transport resulting from asymmetrical forces resisting transport in downslope versus upslope direction.

The power applied to disturbing soil under cow grazing on hillslopes is highly anisotropic – nearly all power being applied in a downslope direction regardless of whether cows are ascending or descending. However, this anisotropy is unlikely to explain the different functional relationships between soil transport and gradient under cow grazing versus Roering et al’s model; they argue insensitivity of their model to the assumption of isotropic power distribution. Instead, the levelling-off of the relationship under grazing likely stems from a change in behaviour of cattle on steeper
slopes. It appears that in order to minimise their own energy output, cows restrict their movements to discrete tracks, which consolidate and become more effectual pathways.

Stock track formation is common place throughout New Zealand, and in areas where animals are farmed outdoors worldwide (Rosser, 2006; Trimble & Mendel, 1995). Some previous studies have found cattle tracks and pugging to be the result of both compaction of the soil and displacement via plastic flow around the hoof (Scholefield & Hall, 1986; Trimble & Mendel, 1995). In addition to the potential for plastic flow along the edges of stock tracks, soil may be removed on animal hooves under wet soil conditions and surface flow erosion is thought to contribute to the formation and deepening of stock tracks on slopes (Rosser, 2006; Trimble & Mendel, 1995). Stock preferentially walk along tracks because soils are compacted, and thus less energy is required to walk upon it than soft ground. Consequently, less energy is required to traverse the same distance across the slope than to walk up it, and thus less energy is exerted into transporting soil downslope (Trimble & Mendel, 1995). As less energy is spent transporting soil, the cow uses less energy overall.

Such a minimisation of energy expenditure, and hence application of power to the slope, is a reasonable strategy given the animals’ aim of maximising energy intake while minimising expenditure. The result appears to be no, or only slowly increasing soil transport above a gradient of about 0.25. The true form of the relationship above this gradient will, however, require more experimentation to overcome the sampling problems posed by the spatial variability of transport. Despite not having a full mathematical characterisation of the transport equation, the linear relationship defined for gradients less than 0.25 (Figure 4.6) applies to more than 94% of the research area and hence is an adequate description for the purposes of estimating soil erosion (see below).

![Figure 5.1](image1.jpg)  ![Figure 5.1](image2.jpg)

**Figure 5.1** Stock tracks formed a) across the steeper slopes, and b) positioned above transect E1

### 5.3.2 Transport under cultivation

No obvious relationship was found between soil transport under cultivation and slope gradient, with downslope soil transport appearing to have been influenced by a factor more important than gradient (Figure 4.11). This contradicts findings of previous studies, which proved clear relationships
between transport and gradient, both via contour ploughing and ploughing up- and down-slope (Frauenfeld et al., 2001; Govers et al., 1994). These studies were both conducted under highly controlled conditions, where tractor direction and speed were regulated and thus soil was always turned the same way. A gradient dependency in our study may have been obscured by changes in the direction of tractor movement and thus direction of soil transport while ploughing. Although the contour ploughing technique was attempted, tractor movement was relative to the fence lines and was not always directly parallel with contour, due to the differing aspects of slopes in the paddock (Figure 3.5 & Figure 4.1). Though tractor movements were more controlled than in this experiment, Frauenfeld and Klik (2002) also found poor correlation between slope gradient and soil transport under tillage for 92 experiments they analysed. They speculated that the high level of variation was caused by differences in soil water content and tractor speed.

Direction of tractor movement on some of the flatter transects (A9 and B8; gradients 0.02 and 0.06, respectively) occurred in a downslope direction, resulting in high soil transport, whilst the tractor crossed diagonal to the contour at several other transects. This resulted in inconsistency in the direction that soil and balls were turned by the plough. Transect C5 (gradient 0.16) appears to have been partially in the 'headlands' where the tractor turns at the end of the paddock, as suggested by its location and the high variability in direction and magnitude of transport observed. While the irregularity in transport has resulted in no systematic relationship with slope, it has given a realistic representation of what occurs in the 'real world' of farming and the amount of variability in soil transport that occurs when farmers actually cultivate their paddocks.

If data from the four flattest transects (A, B, G & H) are removed, then a significant linear relationship exists (p<0.02) for the remaining six transects. The movement of the tractor in a downhill direction can explain the high transport measured at transects A and B, however, no explanation could be found for the high transport at transects G and H (gradients 0.10 and 0.05, respectively) that would justify their removal from the dataset. Although no linear relationship was found between gradient and soil transport for all ten transects, soil on steeper slopes had greater transport than soil on lesser slopes (Figure 4.11). Over an extended period of time, and after repeated cultivation events, cumulative transport is expected to be greater for steeper slopes and a relationship between soil transport and gradient may become evident if tracers were left in the soil long enough.

The relationship between soil transport and curvature of slope was also explored, but no correlation was found (Figure 4.12). Due to the plough moving at depths relative to the tractor, it was thought that curvature may cause variation in cultivation depth as the tractor passed over uneven terrain. Whilst there was no significant relationship with curvature, the four transects that displayed highest total transport also displayed more transport of balls at 250 mm depth (Figure 4.10 & Figure 4.12).
This suggests some systematic relationship between observed cultivation depth and soil transport flux, though the cause of this variation in depth remains unknown. It is possible that the land surface curvature over the length corresponding to the wheelbase of the tractor and plough did play a part, rather than the curvature at the transect location itself, as the topography that the tractor itself spans would determine the depth of the trailing plough. However, we have no way of exploring this hypothesis without knowing the precise direction the tractor was travelling at each transect.

Although further cultivation processes were done in the field (e.g. discs, Cambridge roller) that would induce further soil transport, mouldboard ploughing is understood to cause the greatest proportion of transport (Frauenfeld et al., 2001; Lindstrom et al., 1992). Furthermore, additional cultivation would reduce aggregate size and increase the chance of balls moving independently from the soil. Consequently, balls were recovered after ploughing only had been completed, and prior to other forms of cultivation. It is therefore possible that total soil transport resulting from the cultivation process is greater than what our results show. Frauenfeld et al. (2001) and Govers et al. (1994) also recovered tracers after the initial ploughing phase and thus our methodology is comparable to other research in this field.

5.3.3 Forage crop system

To consider the impact of forage cropping systems as a whole, it is important to look at the combined effect of transport under cows and cultivation. Although there was no relationship found between gradient and soil transport under cultivation, Figure 4.13 illustrates that cultivation induces much more transport than cows, with mean transport across all gradients of 0.082 vs 0.021 m$^3$ m$^{-1}$, respectively.

Forage crop grazing usually encompasses two cultivations: the first is undertaken when the seedbed is prepared for sowing of the crops and the second when paddocks are re-established into pasture. This adds another episode of soil transport to the total effect of forage cropping above what we measured. The effects of cultivation have been well documented in the literature and demonstrated in this study; though we cannot be sure whether the rate of soil transport pre-grazing would be comparable to that following grazing, due to the difference in soil conditions.

5.4 Soil erosion

As no relationship existed between soil transport under cultivation and gradient, the corresponding erosion that occurred under the forage crop system was not calculable; erosion values presented are for transport under cows only. Although these erosion figures are used to represent soil erosion under the forage cropping system, in reality, it is expected the intensity of erosion to be higher than this, due to additional transport caused by cultivation.
Slope-dependent soil transport results in a divergence of flux (erosion) in convex areas and convergence of flux (accumulation) in concave areas, due to the conservation of mass law (Smith & Bretherton, 1972). As soil erosion rates from this research were simulated based on linear slope-dependent transport on gradients up to 0.25 m m\(^{-1}\), the distribution of erosion within the research area was dependent on slope curvature (Figure 4.8). Consequently, the soil erosion rates reported here are dependent upon the resolution of the DEM (cf. Appendix E.2). The 4 m resolution DEM selected produced erosion rates of up to 3.4 mm and deposition rates of up to 7.6 mm per event. A higher resolution DEM resulted in a greater range of erosion and deposition rates (up to 14 mm erosion and 19 mm deposition for a 2 m DEM), though these high rates correspond to areas of strong curvature along the linear artefacts produced when capturing the DEM points, as discussed in 4.1 Terrain characterisation. Accordingly, they are likely to be spurious. A lower resolution DEM produced a slightly smaller range of erosion rates (2 mm erosion, 6 mm deposition for 8 m resolution), though we expect this is due to the DEM not capturing some of the real variability in the terrain.

5.5 Context

Estimated soil erosion rates indicate that cows grazing forage crops in winter induce soil erosion that exceeds natural soil erosion or soil production rates. Roering et al. (2002) reported erosion rates due to diffusive soil transport process of up to 0.02 mm/yr in a tectonically active area of North Canterbury. Given that our research area is not tectonically active, we would expect natural soil erosion rates to be lower than this, indicating that our median erosion rate of 0.1 mm far exceeds soil transport under natural conditions. Because soil erosion resulting from linear slope-dependent soil transport is directly proportional to curvature, soil erosion rates will vary from site to site according to topography. The soil transport coefficient, K, normalises for differences in topography and can be used as a direct means of comparison of erosion potential, independent of topography. Roering et al. (2002) presented a mean k-value of 0.012 m\(^2\) yr\(^{-1}\) which, when compared to our K-value of 0.12 m\(^2\) yr\(^{-1}\), indicates that soil transport under forage crop grazing is at least ten-fold greater than natural transport rates for the area. Accordingly, erosion rate will be an order of magnitude higher for slopes of the same curvature.

A comparison of our erosion rates with the range of empirically determined soil production rates of 0.03 -0.08 mm yr\(^{-1}\) (Montgomery, 2007) shows that under winter forage crop grazing, soil is being eroded faster than what it can be replaced. Of our research area, 51% was eroding at >0.08 mm yr\(^{-1}\) and 18% was eroding at >0.8 mm yr\(^{-1}\), ten times greater than typical soil production. However, these expected soil production rates are for the conversion of bedrock to soil. The Pallic soils of our research area have been formed in loessial deposits from several glacial periods, the most recent
being the last ice advances of the Otira glacial stage 22,000-14,000 years BP (Bruce, 1973b; Suggate, 1990). Eden and Hammond (2003) report mean annual loess accumulation rates of 0.07-0.15 mm yr\(^{-1}\) since the last glacial maximum. However, this accumulation all occurred during the Otira glacial period, and the region has experienced no deposition in the post glacial period (Bruce, 1973b), and no soil production occurs from bedrock due to the depth of loessial deposits protecting the underlying rock from the physical and chemical weathering processes that produce soil. Thus, any soil lost through erosion is not being replaced. The effect of this lost soil is therefore cumulative and the net result will impact future generations using the land.

The effects of natural and anthropogenic erosion processes is already evident in the landscape, with thinning of topsoil on the slope crest (cf. 4.2.1 Soil morphology) and subsoil being visible on the shoulders of slopes post-cultivation (Figure 3.5). Basher and Ross (2002) and Basher et al. (1995) also reported large fragments of subsoil visible in the topsoil after ploughing. Basher and Ross (2002) measured long-term soil redistribution and erosion rates under intensive market gardening of three fields in Pukekohe. Mean erosion rates of 0.7 mm, 1.1 mm and 3.0 mm yr\(^{-1}\) were found for the three fields, with a range of 9.2 mm erosion to 10.0 mm accumulation per year. Tillage accounted for 10-20% of this erosion, with the remainder being attributed to erosion via overland flow resulting from poor soil cover for a large portion of the year. Meanwhile, Basher et al. (1995) found a cropping system in the South Canterbury downlands to cause significant soil redistribution within the field, but no net erosion. A comparative study under pasture at a nearby site showed significantly less soil redistribution than under cropping, and a net sediment accumulation resulted, likely transported by wind from nearby intensively cultivated fields; both wind and water erosion were thought to be involved with soil redistribution throughout both fields. Orchiston et al. (2013) looked at the effect of forage crop grazing management on erosion via overland flow. Their trial showed a mean erosion rate over the catchment of 0.013 mm per winter when grazing downslope and avoiding gullies, compared to 0.114 mm when grazing upslope and in critical source areas. As the work by Orchiston et al. (2013) was under the same soil and management conditions as this research, a similar overland flow erosion rate can be expected, which would be in addition to the erosion rates that we present for erosion under grazing.

A key difference between these forms of erosion and how they are measured is that Orchiston et al. (2013) measured the sediment leaving the primary area of concern in overland flow (i.e. the paddock), but did not identify soil that had been redistributed within the paddock. This trial, on the other hand, measured soil transport and estimated soil erosion from land surface morphometry within the paddock. The approach used by Orchiston et al. (2013) only allows the calculation of an average erosion rate, to be applied across the paddock in a 'blanket-approach', and does not identify the actual source of the sediment or where the effects of the erosion will be seen. In contrast, the
approach taken in this study does not directly measure sediment leaving the catchment, and therefore, it is not known if erosion or accumulation occurs at the rates that we specify, though areas within the paddock that are eroding are indicated. Govers et al. (1996) combined measurement and modelling of soil transport, and found that while modelled erosion rates were similar to those measured, sediment accumulation was less than predicted. They hypothesised that the sediment deposited in concave areas via diffusive transport was removed by overland flow erosion due to the concentration of water in these areas.

The identification of eroding areas in a catchment is important, as they will have less topsoil in place and therefore a loss in production is imminent. Direct loss of soil reduces nutrients available for plant growth, as they are adhered to the soil particles that are eroded, whilst soil thinning decreases rooting depth for plants and reduces the amount of water able to be held in the soil; all three effects have the potential to lead to a loss in crop or pasture production (Dominati et al., 2010). In addition to these on-farm effects, soil dislodged beneath cow hooves or cultivation is more easily transported and eroded by overland flow (Govers et al., 1996; McDowell & Houlbrooke, 2008; Trimble & Mendel, 1995). This leads to off farm effects, such as increased flooding risks, eutrophication, and damage to in-stream habitats and recreational services downstream (Barry et al., 2011; Dominati et al., 2010).
Chapter 6
Conclusions

- Soil transport is greater at shallower depths, under both grazing and cultivation.
- Transport distance and soil flux is greater under cultivation than under cow grazing.
- Soil transport rates under cow grazing increase linearly with slope gradient, up to 0.25 m.m^{-1}, and hence soil transport under cow grazing behaves diffusively, lowering (eroding) convexities and infilling concavities.
- Stock track formation causes variable and undetermined transport rates on gradients >0.25 m m^{-1}.
- Winter forage crop grazing results in unsustainable erosion rates:
  - >50% of the area eroded at rates at greater than soil production rates;
  - >18% of area eroded at rates at ten-fold higher than soil production rates.
- The total effect of winter forage cropping on erosion is likely to be greater than values presented in this paper, due to the additional effects of cultivation and overland flow erosion.

6.1 Limitations

A limitation of this study is that it remains to be proven that ball transport is representative of soil transport. Interpretation of the data has been conducted under the assumption that the steel ball bearings moved with the soil mass, not independently of it. The rejection of outliers where differences were obvious (such as excessive transport alongside a back fence, where a ball may have been caught in the hoof of a cow) should have improved representativeness.

Additionally, the correction process for the location of ball placement, to remove apparent uphill movement balls caused by differences in ball placement and ball recovery methods, introduces a potential source of error. While the implementation of this calculation largely improved readings for the positioning of balls, it relies on the assumption that holes were augured exactly perpendicular to the slope. Small amounts of 'movement' still present for some deeper balls are likely due to human error in drilling 'perpendicular' to the slope.
Erosion rates presented in this study have been determined from the relationship between soil transport flux and slope gradient. Uncertainties in this relationship \((K = 0.12 \pm 0.02 \text{ m}^2\text{y}^{-1})\) have been propagated through into the calculation of soil erosion rates. While the uncertainty of the relationship between soil transport and gradient is presented, an uncertainty analysis on erosion rates themselves has not been conducted and therefore the values presented are an estimate.

### 6.2 Future research

In view of the results from this study, it is clear that further research is required to fully explore the relationship between soil transport under forage crop grazing and slope gradient. More data is required on gradients \(> 0.25 \text{ m.m}^{-1}\), to understand the behaviour of the relationship on these steeper areas, and to determine whether a linear or non-linear relationship exists. It is suggested that the placement of balls in an 'X' rather than a line will increase the likelihood of cows walking over transects on these steeper gradients.

The repetition of this study in different regions will allow the effects of different climates and soil types to be explored. Coefficient values for different soil types could then be determined, and the effects of forage cropping on soil transport in different areas may be determined. These data would then allow the identification of more susceptible soil types, and recommended best practice could be to avoid winter forage cropping on the vulnerable areas.

In addition to the identification of at-risk areas to be avoided, there is potential value for research into the reduction or mitigation of erosion via other means. Some farm management factors have been previously identified to reduce soil damage by compaction or overland flow, such as reduced stocking intensity, use of back fences, on/off grazing and grazing in a progressive downslope direction. The effects of these factors on direct soil transport under grazing could be determined through additional research. Soil transport may also be reduced through different crop establishment techniques, such as alternate strips of forage crop and pasture running parallel to the contour. It is hypothesised that this will help stabilise soil on slopes and thus reduce soil transport (in addition to filtering sediment from overland flow). It is also hypothesised that direct drilling of crop into pasture will reduce transport as it will leave the soil intact, which in addition to the presence of pasture roots, will add strength to the soil and enable it to resist deformation and erosion under grazing. The implementation of direct drilling will also remove an episode of soil transport by cultivation, reducing the sum of soil transport under the forage cropping system.

The results of this study, along with review of the literature, have identified a need for further research on soil transport under cultivation. Detailed studies are required to examine the effect of gradient on soil transport. This will allow the relationship between gradient and transport to be
described, if one exists, enabling the modelling of the effects of cultivation over large areas. Repeated cultivation experiments are also necessary to determine the long term effects of cultivation, particularly over variable terrain, such as was present with this study.
References


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# Appendix A

## Climate data

Table A.1 Climate data collected from Cliflo station 26163, for the period of 1 June to 30 June 2015. Station 26163 is situated 2.5 km north of the field site, which was located in paddock N19 at Telford farm. A tipping rain gauge was installed in N19, the data from which are included in column 'Rain N19'. Tmax = daily maximum temperature, Tmin = daily minimum temperature, Tgmin = daily minimum temperature at grass-level, and Sun = daily number of sunshine hours.

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<th>Date</th>
<th>Rain (mm)</th>
<th>Rain N19 (mm)</th>
<th>Tmax (°C)</th>
<th>Tmin (°C)</th>
<th>Tgmin (°C)</th>
<th>Sun (Hrs)</th>
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Table A. 2  Climate data collected from Cliflo station 26163, for the period of 1 July to 31 July 2015. Station 26163 is situated 2.5 km north of the field site, which was located in paddock N19 at Telford farm. A tipping rain gauge was installed in N19, the data from which are included in column 'Rain N19'. Tmax = daily maximum temperature, Tmin = daily minimum temperature, Tgmin = daily minimum temperature at grass-level, and Sun = daily number of sunshine hours

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<th>Tmin (°C)</th>
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Appendix B

Soil water content

Table B. 1  Volumetric water content (VWC) readings taken using a Field Scout TDR100. Ten readings were taken at each transect on the date-of or -prior to being grazed, and the average for each transect (Avg) is given.

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Table B.2  Soil water contents, as determined in the laboratory from samples taken in the field at the time of grazing, expressed as gravimetric (GWC) and volumetric (VWC). GWC was calculated from the proportion of the water in the soil (Water wt) to the weight of dry soil (Soil dry wt). Water wt was calculated from the difference between initial weight (Wet wt) of the sample and its final weight (Dry wt) after drying in the ovens. Soil weight was calculated by subtracting the tin weight (Tin wt) from the wet and dry weights. GWC was multiplied by the bulk density (BD) to give VWC. BD values are taken from three representative locations (Loc), from within the research area (Figure C.1). GWC and VWC are also expressed as averages (Avg) for each transect. Note: BD values are averages for the 50 mm depth cores only, as this is where the soil samples for moisture content were taken from.

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Appendix C

Bulk Density

Figure C. 1  Map depicting the location where cores were taken for bulk density determination. St = Steep, Fl = Flat, Ter = Terrace.
Table C.1  Measurements and calculations to determine bulk density (BD), at three locations within the research area. Four cores were taken at each location; two at 50 mm depth (5A and 5B), one at 150 mm depth (15), and one at 250 mm depth (25). Depth measurements were to the center of the cores. Core diameter (Diam.) and height were used to calculate core volumes (Volume). Soil dry weight (Soil DW) was calculated from total dry weight (DW) and tin weight (tin wt). Soil bulk density (BD) was determined from Volume and Soil DW. Average BD (Avg) is given for the two 50 mm cores (Top) and all four cores (All) at each location. Soil cores were taken in the field post-grazing but pre-cultivation, on September 15th, 2015.

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Appendix D

Soil descriptions

Figure D. 1 Map showing the location of the three soil pits, where TF = Top Flat, Cr = Crest and Con = Concave. Descriptions of these pits are included below.
D.1 Soil pits

Figure D. 2 Pit faces used for soil descriptions at a) Top Flat, b) Crest and c) Concave locations
## D.2 Soil descriptions

### Table D.1 Soil description at Top Flat location

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### Notes

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Table D. 3 Soil description at Concave location

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Notes: mole plough hole @ ~48cm. Vertical veins of reduced soil. Hor. 6 was harder digging, but easier to rupture peds than Hor. 5. Mottles in Hor 6 were many in small areas but few over whole horizon.
Appendix E

ArcGIS output

E.1 Point cloud

Figure E. 1 Elevation points captured over the research area using the RTK GPS on a backpack. This point cloud was used to create the digital elevation model and subsequent data layers, such as slope, curvature and erosion.
E.2 Erosion maps

Figure E. 2 Soil erosion output rasters at a) 2 m resolution, b) 3 m resolution, c) 4 m resolution, d) 5 m resolution, e) 6 m resolution, f) 8 m resolution
E.3  Distribution of erosion

Figure E. 3  Histograms of erosion output at a) 2 m, b) 3 m and c) 4 m raster resolutions
Figure E.4  Histograms of erosion output at a) 5 m, b) 6 m and c) 8 m raster resolutions
E.4 High resolution DEMs

Figure E. 5 High resolution DEMs generated at each of the ten transects, with transect ID and mean elevation determined from the low resolution DEM in the top left corner of each plot. Direction of aspect is indicated by an arrow. Ball displacement at 50 mm depth under cattle grazing is indicated with dark (initial position) and light (final position) blue dots.

Available at: http://www.grassland.org.nz/publications/nzgrassland_publication_2783.pdf