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**THE EFFECTS OF IRRIGATION
ON SOIL CARBON AND NITROGEN STOCKS
OF PUMICE SOILS**

A thesis
submitted in partial fulfilment
of the requirements for the degree
of
Master of Science (Research) in Earth Sciences
at
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Abstract

The use of irrigation has become important for sustaining the production of food, fibre and biofuel. In New Zealand (NZ), irrigation of pastures is increasing in areas with seasonal water deficits, such as the Central North Island. Nationally, there was an estimated 794,443 ha of land under irrigation in 2017. A synthesis of the literature showed that soil C and N stocks response to irrigation was dependent on the initial soil organic matter content and climatic zone. However, most of the literature focused on arid/semiarid climate regimes where cereals and other crops were grown, with few studies conducted on pastoral land in temperate climates. However Mudge *et al.* (2017), measured a decrease in soil carbon (C) (6.99 t C ha^{-1}) and nitrogen (N) (0.58 t N ha^{-1}) to 0.3 m depth in irrigated grazed pastures relative to adjacent non-irrigated grazed pastures. Of their 34 paired sites across NZ, only seven were sampled from the Pumice Soil order, which was insufficient to determine whether this soil order was vulnerable to soil C and N loss.

The main objective of this thesis was to compare the total soil C and N stocks of irrigated and non-irrigated Pumice Soils. A second objective was to determine where there were any trends in changes in soil C and N in relation to irrigation duration.

Fourteen paired irrigated and adjacent non-irrigated sites were sampled in the Reporoa Basin, north of Taupo and soil C and N stocks were measured accounting for differences in soil bulk density. Most sites were sampled to 0.6 m depth, however, due to high water tables and buried soils, some sites were only sampled to 0.4 m or 0.5 m depth. One site was omitted from statistical analysis due to high residuals (F11-35) and was considered an outlier that potentially represented a poorly matched pair of sites. On average, for the remaining 13 paired sites, irrigated soils had significantly ($P < 0.05$) lower soil C stocks (5.93 t C ha^{-1}) to 0.2 m depth and lower N stocks (0.24 t N ha^{-1}) to 0.1 m depth in comparison to adjacent non-irrigated soils. When considering the full depth of the sampled soils (0-0.6 m), there were no significant changes in soil C

and N stocks ($P > 0.05$). Using this coring method, I was able to detect a change of about 6.9 % in soil C stocks and a 4.8 % in soil N stocks. This study also found no evidence of a relationship between soil response to irrigation and duration of irrigation.

With the loss of soil C and N under irrigation comes potential release of CO₂ to the atmosphere and N leaching into surrounding water bodies. Based on the findings in this thesis, there is a need for further investigation on the effects of irrigation for different Soil Orders. This research will aid farmers in understanding their land management on-farm and inform them of their potential effects on greenhouse gas emissions on a national scale.

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Chapter 1

Introduction

1.1 Background

The production of food is a fundamental requirement for human survival. The amount of land used to sustain society depends on the size and demands of the growing population (Kastner *et al.*, 2012; Krausmann *et al.*, 2013). The increased demand for food, fibre and biofuel production put pressure on the land to maintain high production per unit area (Smith *et al.*, 2016). Irrigation is one way to increase productivity per unit of land per year, by maintaining optimum soil moisture during seasonally dry periods (Kastner *et al.*, 2012; Siebert *et al.*, 2015). Sustainable use of irrigation depends on water source availability and soil services such as fertility and water storage, which is often determined by soil organic matter (SOM) content (Condrón *et al.*, 2014; Siebert *et al.*, 2015). SOM is also important for sustainable agriculture in other ways, providing a source of carbon (C) and nitrogen (N) for physiochemical and biological properties within soil, and enhancing the fertility, productivity and structure of the soil (Rasse *et al.*, 2005; Sparling *et al.*, 2006b; Barrios, 2007).

Soils are often influenced by anthropogenic processes such as land use change and different agricultural management, which can directly impact the soil ecosystem and lead to soil degradation (Batjes, 2014; Eldridge & Delgado-Baquerizo, 2017). Indirect impacts include acid rain and heavy metal atmospheric deposition caused by pollution (Smith *et al.*, 2016). Anthropogenic influences such as application of fertilisers, crop harvest and irrigation can alter soil C and N cycles, which can lead to an imbalance between photosynthetic inputs, C and N mineralisation, in some cases favouring the release of greenhouse gases (GHGs) such as carbon dioxide (CO₂) and nitrous oxide (N₂O) (Borken & Matzner, 2009; Batjes, 2014; Schipper *et al.*, 2017). Nitrogen can also be lost from the N cycle as NO₃⁻, which is highly mobile in soil water and can cause eutrophication of water bodies (Batjes, 2014; Smith *et al.*, 2016). In addition to human impacts on soil C

and N cycles, soil C and N stocks can vary naturally both temporally and spatially due to soil forming factors such as, climate, geology, dominant vegetation type, and topography (slope and erosion potential) (Batjes, 2014; Goldhaber & Banwart, 2015).

Irrigation is one form of land management used worldwide to increase crop yields for both food and animal production. In 2012, 275 million ha of arable land was irrigated, 61 % of this area was under cereal crops, 10 % vegetables and only 7 % with irrigated fodder and pastures (FAO, 2016). Pastoral land provide areas for sequestration of atmospheric CO₂ which form C sinks that retain 20 % of the global C stocks (Sparling *et al.*, 2006b; Smith *et al.*, 2016). Of the ice-free land around the globe, about 20 % of the land is covered in a variety of grasslands, including pasture, and around 70 % of this land is under agricultural use (Schipper *et al.*, 2014; Smith *et al.*, 2016).

In NZ at least 75 % of the original native forest was converted to native or exotic pasture systems following the arrival of European settlers in the 19th century (Hewitt *et al.*, 2012). Between 1840 and 2002, agricultural development had increased significantly, leading to further intensification of pastures in the 1980s to the present (MacLeod & Moller, 2006). The most recent estimate of total exotic grassland cover was around 40 % (10.7 million hectares) of New Zealand's land area in 2012 (Ministry for the Environment & Stats NZ, 2018). Therefore, the exotic grasslands are the dominant land cover in NZ. There are a range of land uses and management practises in NZ ranging from horticultural practises, dairy farming, dry-stock farms and tillage, which are likely to impact soil C and N stocks (Schipper *et al.*, 2017).

The temperate environment of NZ can lead to prolonged periods of dry spells during some parts of the year (MacLeod & Moller, 2006). Some regions require irrigation to increase productivity year round to overcome natural soil water deficits (MacLeod & Moller, 2006; Kelliher *et al.*, 2012). In the last 30 years, there has been an increased demand in the use of irrigation to increase yields, with an

estimated 794,443 ha of land under some form of irrigation in NZ, in 2017 (Dark *et al.*, 2017).

Visual changes in land use towards management using irrigation can be seen between Taupo and the Reporoa Basin, on pumice dominated soils, using Google Earth. An estimated 64,000 ha of forestry has been converted to pasture since the year 2006, based from Google Earth imagery, between Taupo and Reporoa, some of which is now irrigated. The Pumice Soil order tends to occur in sandy or pumiceous volcanic ashes that are young in age and are dominantly located around the North-East of the Central North Island. Pumice Soils are characteristic of a low clay content, low bulk density and tend to have low nutrient availability (Hewitt, 2010). The free-draining nature and low clay content of the pumiceous soils makes it more susceptible to water loss during dry seasons (Bakker *et al.*, 1996; McLaren & Cameron, 1996; Hewitt, 2010). Due to the nature of these soils, irrigation has been applied to prevent the loss of yield during dry spells. The consequence of this irrigation on soil properties is poorly understood.

In a global review of irrigation effects on soil C and N₂O emissions, Trost *et al.* (2013) observed an increase in soil C under irrigation in a variety of croplands in arid, semi-arid and humid climate regimes. Changes in soil N were investigated by comparing effects on N under different irrigation systems, and only a few studies reported a net loss of N as N₂O (Trost *et al.*, 2013). However, the overall impact on N₂O emissions was inconclusive as comparisons of N₂O emission are rare between irrigated and non-irrigated land. Due to the high proportion of irrigated area dominated by cereals and vegetables, there were few studies that have investigated the effects of irrigation on grazed pasture (Trost *et al.*, 2013; Condrón *et al.*, 2014; Mudge *et al.*, 2017). New Zealand studies investigating the effects of irrigation in pastoral systems found a net loss of soil C and N in comparison to the non-irrigated land (Kelliher *et al.*, 2012; Condrón *et al.*, 2014; Mudge *et al.*, 2017). Mudge *et al.* (2017) reported a net loss of 6.99 t C ha⁻¹ and 0.58 t N ha⁻¹ to a depth of 0.3 m, from 30 of their 34 sites from around NZ. With the loss of soil C, microbial processes may decrease due to lower energy supply from SOM, soil structure may breakdown with the decay of SOM, and

subsequently lose C and N stocks from the soil ecosystem into the atmosphere and nearby water bodies (Schipper *et al.*, 2007; Borken & Matzner, 2009; Batjes, 2014; Smith *et al.*, 2016; Mudge *et al.*, 2017).

This thesis will compare the total soil C and N stocks between irrigated and non-irrigated soils sampled from 14 paired sites around the Reporoa Basin in the Central North Island, New Zealand, to determine whether there is a measurable difference in soil C and N stocks in irrigated Pumices Soils. The data from this study will build towards further research undertaken by Manaaki Whenua - Landcare Research (LCR) on the effects of irrigation and NZ's national C balance.

1.2 Aims and objectives

The overall aim of this research is to determine whether soil C and N stocks decrease under irrigation of pastoral Pumice Soils, in the Reporoa Basin.

The following objectives were set:

1. To determine whether total soil C and N stocks are lower under irrigation in comparison to adjacent non-irrigated soil.
2. To determine any trends in the decrease in soil C and N in relation to irrigation duration.

1.3 Thesis layout

Chapter two reviews the literature on the controls of soil C and N stocks in relation to land use and management practises, specifically the application of water irrigation.

Chapter three describes the detailed methodology used for soil sampling, laboratory analysis to measure and quantify soil C and N stocks. The statistical analyses undertaken for this thesis is also described.

Chapter four presents results from the study and has been written in the form of a paper for subsequent submission to a suitable peer-reviewed journal. Methods are abbreviated but there is some repetition of material from proceeding chapters.

Chapter five contains the summary of the main conclusions of this research and recommendations for further research.

Appendices A-F, containing additional supplementary information.

Chapter 2

Literature review

2.1 Introduction

Land use change can occur in various ways, including conversion from forest to pasture, pasture to cropping and pasture to forest. With each land use change there can be large changes in soil carbon (C) and nitrogen (N) stocks depending on alterations to C and N cycling (Smith, 2008; Schipper *et al.*, 2014). Within different land uses, changes in land management practises such as the use of irrigation, can influence soil C and N stocks in various ways, including, increasing C sequestration through increased plant production or increasing loss of soil C stocks following microbial respiration, or increasing nitrate (NO_3^-) leaching and production of nitrous oxide (N_2O) (Trost *et al.*, 2013; Neilen *et al.*, 2016; Mudge *et al.*, 2017). Changes made to the storage of soil C and N within grazed ecosystems can affect the volume of greenhouse gases released into the atmosphere and nutrients leached into surrounding water bodies (Han *et al.*, 2010; Neilen *et al.*, 2016).

This literature review examines the effects of land management on soil C and N stocks in grazed pastures with specific focus on the consequences of irrigation of Pumice Soils in the Central North Island, New Zealand (NZ). Firstly, I briefly discuss NZ grazed pastures (section 2.2) with reference to land use history (section 2.2.2) and typical management practises (section 2.2.3) with a specific focus on irrigated grazed pastures in the Taupo region (section 2.2.4). Then I provide a background on soil organic matter (SOM) (section 2.3), including the different forms of soil C and N (section 2.3.1). Then I review environmental and anthropogenic controls on soil C and N stocks in section 2.3.2. Methods used to measure soil C and N are covered in section 2.3.3. Finally, irrigation is discussed in section 2.4, including the effects of increased soil moisture on C and N stocks (section 2.4.2) and previous studies on irrigation effects on these stocks (section 2.4.3).

2.2 New Zealand grazed pastures

2.2.1 Background

Land underpins much of New Zealand's economy. Exotic grasslands support primary exports and the dairy industry along with other grazing stock, covering around 10,624,386 ha of NZ (Ministry for the Environment & Stats NZ, 2018). These exotic grasslands grow on a range of soils of which there are 15 documented soil orders in NZ distributed across regions around the country (Hewitt, 2010). These soil orders vary due to different influences of the five soil forming factors; climate, parent material, time, topography, and vegetation (Goldhaber & Banwart, 2015). The soil forming factors influence the mineralogy, physical structure of the soil and the ecology within the soil biosphere (Goldhaber & Banwart, 2015). The soil orders that dominate the North Island are largely influenced by parent material, both volcanic and basement rock (East coast, Central North Island). Development of soils in the South Island have been heavily influenced by climatic gradients East-West created by the alpine fault, which causes the differentiation in vegetation East-West due to the availability of water (Hewitt, 2010).

2.2.2 History of land use conversions

New Zealand was initially covered in indigenous forests (~85 %) and grasslands pre Māori settlement. Mass deforestation was undertaken with Māori fires, to clear the land for hunting and later, pastoral grazing practices. Since the arrival of early colonisers to NZ in the early 18th century, there has been significant changes in vegetation cover and land use across the country (MacLeod & Moller, 2006). After European settlement in the 19th century, forest cover was reduced further to < 30 % as the rise of exotic grasslands for farming increased (Wilmshurst *et al.*, 2007). Some land conversions made during early settlements were inappropriate for the soil type, climatic region or ecological considerations. For example, in the 20th century "bush sickness" on Pumice Soils caused a wasting illness in ruminant animals due to a cobalt, at the time of conversion to pasture (Tonkin, 2012). Most of the converted lands were subsequently abandoned or converted into exotic forest plantations dominated by *Pinus*

radiata. Some afforestation of pastures occurred in the 1980s to support C sequestration to meet some of the requirements of the Kyoto Protocol agreement (Hewitt *et al.*, 2012).

There have been ongoing changes in the agricultural sector since the 1960s. Dairy cow numbers, stocking rates and production per hectare have increased, while land as drystock farms have decreased (MacLeod & Moller, 2006). With the increased availability of fertilisers, pasture species, imported feeds, irrigation application, and better pasture management techniques, farmers are intensifying their overall production per unit area without expanding the land needed to farm more animals (MacLeod & Moller, 2006).

2.2.3 Typical land management practises

Pastoral management is dependent on plant species, soil type, mean annual temperature, and rainfall. To correct soil deficiencies legumes, fertilisers and lime are used to optimise available soil nutrients for plant uptake (Ledgard, 2001; Lambers *et al.*, 2009). Plant species that perform best in desired environmental conditions can range from diverse swards, to perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.), and plantain/ryegrass swards (Rutledge *et al.*, 2017). Different farm management schemes for pasture production can have differing influences on plant organic matter inputs to the underlying soil (MacLeod & Moller, 2006; Schipper *et al.*, 2017). However, due to seasonal changes in rainfall and temperature, some farms need to import feed to maintain stock numbers (MacLeod & Moller, 2006).

Between 2002 and 2012, pastoral land area across NZ decreased by about 7 % due to a decline in sheep and beef farming (Ministry for the Environment & Stats NZ, 2018). With better pastoral management, farmers were able to increase their number of stock per hectare. Intensification of grazed systems has been furthered with the addition of irrigation, enabling a higher yield year round. Since 1960, irrigation has increased about 19 % per annum over that last 57 years to reach the current irrigation numbers (Dark *et al.*, 2017). By 2017,

irrigated land in NZ covered 3 % (794,443 ha) of total land area, with 64 % of irrigated land in Canterbury, 12 % in Otago, and only 3 % in the Waikato region (Dark *et al.*, 2017).

2.2.4 Land use change and grazed systems in the Taupo region

Although the focus of this thesis is the Reporoa Basin, I will broadly discuss the Taupo region as a whole to understand the history and formation of the wider area.

There are a range of land uses and vegetation cover within the Reporoa Basin; pastoral farmlands, scrubland, indigenous forest, wetlands, urban areas as well the changes from pasture to plantation forestry, plantation forest to pasture, drystock to dairy, and the introduction of irrigation (Piper, 2005; Sparling *et al.*, 2014). In the 1920-1930s, the central North Island was cleared of native forest to make way for grazed pastures. However, it was not until later on that farmers discovered their livestock were getting sick from malnutrition that was due to a cobalt deficiency (“bush sickness”) in the Pumice Soils of the region (Forbes, 1976; Vucetich & Wells, 1978). After large losses of livestock, much of the Pumice Soils were converted into plantation forestry.

In the last 20 years, areas of plantation forests in the region have been converted to dairy farms after mature trees are harvested (Sparling *et al.*, 2014). Visual changes in land use over the last 20 years towards irrigated pasture management, can be seen between Taupo and the Reporoa Basin, on pumice dominated soils, using Google Earth imagery. About 64,000 ha of forestry has been converted into pasture in between Taupo and Reporoa since the year 1999, some of which is now irrigated.

Within the Reporoa Basin, soils are dominated by material derived from the Taupo eruption $AD\ 232 \pm 5$ (1718 ± 5 cal. BP) (Hogg *et al.*, 2012), and reworked Taupo pumice sediments; these soils are broadly classified as Pumice Soils (Vucetich & Wells, 1978; Piper, 2005). Pumice Soils have a low water-holding

capacity due to the highly porous nature of the soil structure and pumice abundance in the lower depths of the soil profile (Rout, 2003; Hewitt, 2010). Most of the area is dominated by dairy farming. Due to the high porosity and the well-drained nature of these soils, irrigation has been readily adopted to maintain pasture production through summer droughts. In 2005, there were 28 farms (dairy) using irrigation with a combined area of 2,500 ha in Reporoa (Rout, 2003). Current positions of estimated irrigated areas in Reporoa are shown in Figure 2-1. Despite the increased use of irrigation in the Reporoa Basin, there has not been an investigation into the effects of irrigation on soil C and N stocks of these Pumice Soils.

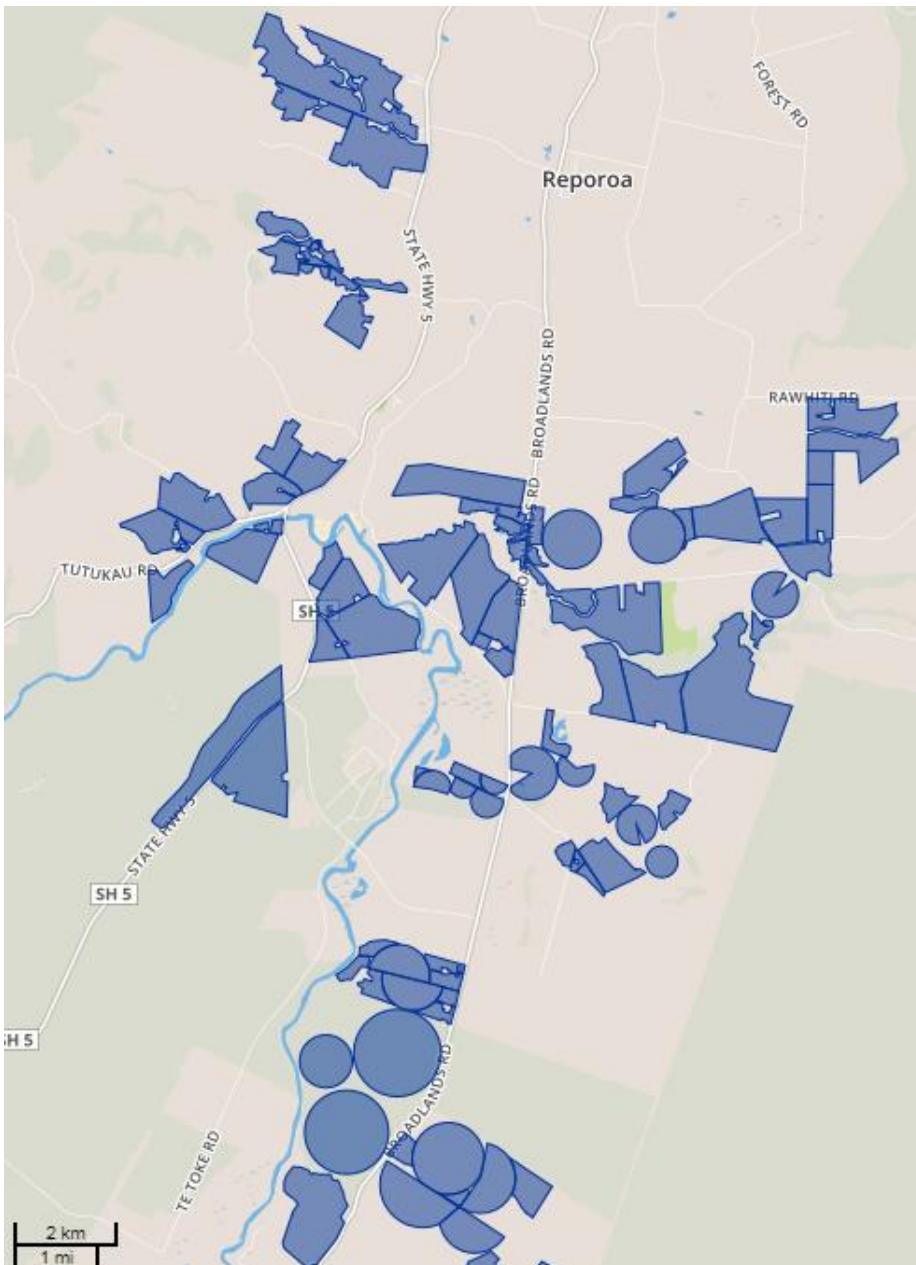


Figure 2-1: Irrigated farms in the Reporoa District. Image derived from Ministry for the Environment, using ‘irrigated land area, 2017’, layer (<https://data.mfe.govt.nz/layer/90838-irrigated-land-area-2017/>).

2.3 Soil carbon and nitrogen

2.3.1 Background on soil organic matter, carbon and nitrogen

Soil C is largest global terrestrial carbon store, derived from the sequestration of atmospheric CO₂ through photosynthetic inputs that are subsequently stored as soil organic matter (SOM) (Condon *et al.*, 2012). Soil organic matter is comprised of soil organic carbon (SOC) and various nitrogen compounds that provide a series of ecosystem services to land users and the environment (Schmidt *et al.*,

2011; Wang *et al.*, 2016). Soil organic C stocks are important for maintaining soil quality, nutrient storage, sustainable food production, and retaining water quality within a catchment (Han *et al.*, 2010). Soil organic matter is retained in soil due to the physiochemical and biological influences that protect SOM from decomposition by soil organisms (Schmidt *et al.*, 2011). Organic matter is also an important contributor to the formation of soil structure and soil aggregates (Six *et al.*, 2002; Blanco-Canqui & Lal, 2004). Soil aggregates provide physical protection for organic matter within the aggregate preventing microbial decomposition, as there is reduced oxygen within the aggregate inhibiting aerobic respiration and SOM may be held in pores too small for microbes to access (Six *et al.*, 2002).

Storage of SOC reflects the balance between photosynthetic inputs and decomposition by soil biota (Schmidt *et al.*, 2011). A wide range of environmental drivers (e.g. rainfall and temperature) alter the balance of these two processes to determine the net balance of soil C stocks. However, the C cycle is also easily disrupted by anthropogenic influences like land management, land use change and soil erosion from soil destabilisation (Janzen, 2004; Wang *et al.*, 2016). There are several different conceptual pools of stored soil C with approximate turnover rates: active pool (short term; < 10 years), intermediate pool (10-100 years) and passive pool (long term; > 100 years), that can be influenced by indirect and direct anthropogenic activities. Each pool has different availability and mechanisms for protecting SOC (von Luetzow *et al.*, 2008).

Nitrogen enters the soil profile through N fixation, animal excreta and a range of applied fertilisers. Most of N (> 95 %) stored in soil is in an organic form covalently bound to C, and mostly unavailable for plant uptake. The remaining 5 % of the total N is inorganic, in the forms of NH_4^+ , NO_3^- and nitrite (NO_2^-) (Robertson & Vitousek, 2009; Cameron *et al.*, 2013). Addition of N to a pastoral system from external inputs or through N_2 fixation by legumes is needed if agriculture is to maintain primary exports efficiently (Ledgard, 2001). The increased availability of reactive N has been needed to support the intensification of animal-based agricultural systems (de Klein & Monaghan, 2011).

Nitrogen applicators provide plants with enough N to maximise primary production, however, management of N application is needed to prevent addition of N to sensitive ecosystems (e.g. water bodies) (Robertson & Vitousek, 2009).

Excess N in the pastoral system can lead to the loss of N through leaching, volatilisation, and denitrification. The main path that N will take is dependent on pastoral composition (e.g. legumes), application process (fertiliser or animal excreta), and soil moisture content (anaerobic conditions) (Ledgard, 2001; Robertson & Vitousek, 2009). N₂O gas is produced through both denitrification and nitrification when there is too much N moving through the soil system.

2.3.2 Controls on soil C and N cycling

Environmental factors such as the soil forming factors: vegetation/biota, climate, parent material, time and topography, determine the molecular composition, SOM content, and how the soil responds to various land uses due to differing pH, nutrient availability (e.g. cation exchange capacity), soil moisture content and soil biota community (Goldhaber & Banwart, 2015; Olson & Al-Kaisi, 2015; Wang *et al.*, 2016). Due to the various soil forming factors, spatial variability of soil properties such as soil C, structure, texture and bulk density, can differ from large scale (regional) to small scale (paddock) landscapes. The main constantly observed trends for soil C and N is that they decrease with depth from the A horizon (topsoil) (Jackman, 1964; Han *et al.*, 2010; Olson & Al-Kaisi, 2015), and that had different total stocks vary with different climatic regimes (Davidson & Janssens, 2006).

Within the soil ecosystem there are three major drivers that can have both negative and positive effects on the SOM content: climate change, land use change, and change in above-ground biodiversity (Nikolaidis, 2011). Negative effects of these drivers can cause loss of soil C through erosion, soil compaction and loss of biodiversity (Nikolaidis, 2011). Anthropogenic activities are largely the cause of changes in the soil ecosystem, which influence the balances of soil C and

N cycles. Land use change can have large impacts on SOM content through erosion, tillage/cultivation, afforestation, stocking rate (e.g. compaction), and intensification of land management (Tate *et al.*, 2005; Schipper *et al.*, 2017). Changes in soil C from land use change are well documented (Tate *et al.*, 2005), C lost from soils after grasslands and forests are cultivated, are the more dramatic examples of soil C losses from land use change (Poeplau *et al.*, 2011). Accumulation of soil C takes time and stabilisation of soil C is more likely to occur under long term land uses (100 years) or in pastoral systems (Poeplau *et al.*, 2011).

The formation of soil aggregates and structure is driven by the association between different soil particles and SOM. The amount and type of clay and amount of SOM within a soil will dictate whether aggregates formed will be stable or unstable. Binding agents associated with the formation and stabilisation of soil aggregates to macro (> 250 μm) and microaggregates (< 250 μm) can be temporary, transient, or persistent (Blanco-Canqui & Lal, 2004). Residence time of SOM increases with smaller aggregate sizes as the stabilisation of SOM is largely influenced by macroaggregate turnover rates, root enmeshing, and ecosystem engineers (e.g. earthworms, ants and termites) (Six *et al.*, 2002; Rasse *et al.*, 2005; Dignac *et al.*, 2017). Tillage of soils can disturb the natural formation of soil microaggregates within macroaggregates as it removes the opportunity for temporary binding agents to form (roots, hyphae, and bacterial cells) (Blanco-Canqui & Lal, 2004). The increase in macroaggregate turnover caused by tillage, diminishes the opportunities for more microaggregates to form over time and therefore decreases SOM storage (Six *et al.*, 2002; Blanco-Canqui & Lal, 2004). The disturbance from tillage increases CO₂ production, due to the loss of micro aggregate protection of SOM and subsequent decomposition of newly exposed SOM by soil biota (Six *et al.*, 2002).

Production of CO₂ from soils is mainly derived from microbial respiration during the decomposition of SOM and root respiration (Davidson & Janssens, 2006). Soil respiration is largely controlled by soil temperature, moisture content, C substrate availability, and SOM quantity and quality (Rochette *et al.*, 1991;

Davidson & Janssens, 2006; Curtin *et al.*, 2012). Respiration increases with increasing temperature as enzymes facilitate decomposition of the wider range of organic compounds found in soil (Davidson & Janssens, 2006). Different enzymes have differing optimum conditions, which allow them to function efficiently. Intrinsic temperature sensitivity is directly dependent on the range of organic C compounds available to microbes which in turn influences the decomposition rate of each C compound (Davidson & Janssens, 2006). Apparent temperature sensitivity of enzymes is a function related to substrate limitation, when there are insufficient amounts or quality of SOM available, oxygen, and water availability (Davidson & Janssens, 2006).

Soil moisture content changes through the year with seasonal changes in climate (Gritsch *et al.*, 2015). Soil water allows transport of soluble nutrients and SOM that are used by both plants and soil biota (Borken & Matzner, 2009). Wetting of dry soils and drying of wet soils can drive microbial activity to promote CO₂ emissions (Gritsch *et al.*, 2015). When soil water is in excess, oxygen diffusion and availability is often reduced, causing microbial respiration to decrease and anaerobic pathways of decomposition become dominant along with denitrification. However, anaerobic decomposition is likely more active in peat soils rather than drier soils with intermittent wetting. Anaerobic decomposition is much slower than aerobic decomposition (Davidson & Janssens, 2006). For example, C and N mineralization in pastoral soil increased with increased soil moisture and temperature in a study by Curtin *et al.* (2012) so long as oxygen was not limiting. Above 40 % soil moisture content (matric potential of -5 kPa), can lead to a decrease in C sequestration and increase in C mineralization (Curtin *et al.*, 2012; Condon *et al.*, 2014; Gritsch *et al.*, 2015).

2.3.3 Methods used to measure soil C and N stocks

Soil C stocks are generally reported as a mass of organic C per unit of area to a depth of 0.30 m (Gifford & Roderick, 2003; Villarino *et al.*, 2014) for accounting purposes. Olson and Al-Kaisi (2015) showed that it may be necessary to sample beyond 0.30 m (tillage zone) to represent the entire rooting depth and

understand the full effect of land management practices on soil C stocks. Sampling techniques vary depending on the intended use of the results. Simple random sampling (samples from random points in the field) and stratified random sampling (samples randomly from strata in the field) are traditionally used in monitoring soil C and N. A high number of samples that encompasses the spatial variability of a site, can be derived from a systematic random sampling method. The initial location used in the systematic random sampling method is chosen at random and the rest of the points are sampled in a systematic grid (Allen *et al.*, 2010).

A stratified sampling method was used by Barnett *et al.* (2014), to test the difference in soil C and N stocks between dairy and drystock farming management practices. One pit was dug in each of the adjacent dairy and drystock paddock sites and samples were taken from each horizon to 0.6 m. Similarly Houlbrooke *et al.* (2008) used vertically inserted aluminium rings at range of depths down the soil profiles, to test the effects of irrigation on soil quality measurements between a 'dryland survey' and 'irrigated survey'. The pit method and vertical ring sampling do not encompass spatial variability of natural soil C distribution or spatial variation in soil mass/bulk density, unless multiple pits with few replicates per depth are sampled per site (Houlbrooke *et al.*, 2008; Allen *et al.*, 2010). In comparison Mudge *et al.* (2017) used a systematic random sampling approach to measure soil C and N. Mudge *et al.* (2017) used a coring method in conjunction with a random grid location with 10 systematic points within the two 10 m x 10 m grids sampled at each site. Samples were taken from every 0.1 m depth increment to include the variability in soil at depth instead of horizon.

Total C and N stocks are calculated to a given depth using soil bulk density, which is a ratio of the dry soil mass over total volume of soil, and soil C and N concentration (%) (McLaren & Cameron, 1996; Allen *et al.*, 2010). The bulk density of an individual soil can change with different land uses. Changes in bulk density can be caused by changes in surface elevation due to swelling or compaction and erosion, most commonly observed in cropping systems, grazed

pastoral lands or changes in land use (Gifford & Roderick, 2003). Not correcting for differences in soil bulk density within soil can potentially lead to an inaccurate calculation of soil C stocks (Gifford & Roderick, 2003; Wendt & Hauser, 2013).

The soil mass and bulk density vary naturally with depth and between sample sites, so in order to accurately estimate soil C stocks for comparison between sites, mass corrections need to be quantified using equivalent soil mass (EQM) (Gifford & Roderick, 2003; Wendt & Hauser, 2013), which corrects total C and N stocks collected from the same depths to a reference soil mass. This EQM technique enables adjacent pasture and cropped soil to be compared accordingly. If tilled and no-tillage soils are sampled to the same depth, this can lead to a source of error in reporting total C stocks on a fixed depth basis, unless corrections for differences in soil mass are made (Wendt & Hauser, 2013). Wendt and Hauser (2013) corrected total C stocks by applying a cubic-spline, to account for the variation in soil mass and bulk density at a given depth. Mudge *et al.* (2017) applied EQM corrections to their soil C data on irrigated grazed pastures vs non-irrigated pastures and found that both fixed depth measurements and EQM corrections gave almost identical results, the lack of difference between results in this case meant that soil bulk density and mass were similar between treatments. The need for EQM calculations is likely greatest for comparing soils where one of the soils has been physically disturbed (e.g. under sowing seed or pugging), but should be checked for compaction where there is any uncertainty of changes to soil bulk density.

2.3.4 How grazing land management practices influence soil C and N stocks

While it is recognised that soil C stocks are similar to land use change, soil C can also change between differing land management practices while under a constant land use (Hewitt *et al.*, 2012; Schipper *et al.*, 2017). Schipper *et al.* (2017) reviewed the evidence for changes in soil C with different land uses and management practices, investigating management types of grazed pastures:

stocking rate, fertiliser application, soil cultivation, and irrigation. It is often difficult to isolate the effects of management (e.g. fertilisers, irrigation or stocking rate) on soil C and N as on-farm management frequently alters one or more of these simultaneously to increase production (Schipper *et al.*, 2017).

Intensively grazed pastoral systems around NZ, such as dairy farms, tend to be on flatter landscapes, whereas drystock farms tend to be on a wider range of landscapes, from flats to hills (Schipper *et al.*, 2014). With varying topography, differing management of stocking rates, type of fertiliser, renewal of pasture, and irrigation will occur. Barnett *et al.* (2014) reported that there was a detectable loss of soil C and N between dairy and drystock adjacent paired sites, on same topography. This study was repeated by Norris (2014) using a systematic sampling technique that better accounted for spatial variation of stocks within soil. Norris (2014) reported a difference of 4.1 t C ha⁻¹ between neighbouring dairy and drystock farms. The soils sampled by Barnett *et al.* (2014) and Norris (2014), were mainly Allophanic Soils and it should be noted that Schipper *et al.* (2014) showed these soils to be more vulnerable to C losses.

Nitrogen stocks are largely influenced by stocking rate, fertiliser application, and urine patches in grazed systems (Cameron *et al.*, 2013; Neilen *et al.*, 2016). Loss of N is often as gas (N₂) and nitrous oxide (N₂O) in dairy farming systems. N₂O emissions are highest in dairy grazed pastures at 10-12 kg N₂O-N ha⁻¹ year⁻¹, due to the higher stocking rate in comparison to drystock farms (Saggar *et al.*, 2008). The concentration of N in urine patches exceeds plant requirements and is either leached from the soil as NO₃⁻ or lost as ammonium (NH₃) gas through volatilisation, with over 70 % of N gaseous losses coming from urine patches (Ledgard, 2001; Saggar *et al.*, 2008).

Irrigation management in recent studies by Mudge *et al.* (2017), observed a significant difference ($P < 0.05$) in soil C and N stocks between adjacent irrigated and non-irrigated soils, where irrigated soils had less total C and N stocks by 6.99 t C ha⁻¹ and 0.58 t N ha⁻¹. Soils were sampled from all over NZ; Canterbury, Otago, Manawatū and the Bay of Plenty. Mudge *et al.* (2017) was able to confirm

the effects of irrigation on NZ soils were similar to previous research by Kelliher *et al.* (2012) and Condrón *et al.* (2014) at Winchmore, Canterbury. From these studies, it is evident that soil C can decrease in grazed pastures under irrigation. However, the temporal pattern of loss for soil C following the establishment of irrigation is not well known, nor do we understand whether these losses continue with time irrigated or come to a new equilibrium within the C cycle (Mudge *et al.*, 2017; Schipper *et al.*, 2017).

2.4 Irrigation

2.4.1 Background

Irrigation is the artificial application of water, used around the world to increase productivity of crops and pastures by reducing water limitations of primary production (Troost *et al.*, 2013; Dark *et al.*, 2017). There are a variety of irrigation techniques including sprinkler (e.g. pivot, gun and K-line pods), border dyke, flood, and drip/micro irrigation, that are used for a range of landscapes and production types (Dark *et al.*, 2017). In NZ, irrigation provides year-round water supply to areas of arable or pastoral land that would often have seasonal water deficits, that restricts stock carrying capacity and total yield (MacLeod & Moller, 2006).

Globally 20 % of cultivated agricultural land under irrigation was responsible for 40 % of the food production in 2012 (FAO, 2016). About 275 million ha of arable land was irrigated in 2012, with 61 % of the area under cereal crops, 10 % vegetables and only 7 % with irrigated fodder and pastures (FAO, 2016). In NZ there was an estimated 794,443 ha (\pm 46,000 ha) of land under irrigation in 2017 (Dark *et al.*, 2017).

2.4.2 Effects of soil moisture on soil C and N stocks

The main purpose of irrigation is to increase plant production year round by reducing water limitations to growth. This allows irrigated plants to have lower water stress during photosynthesis, as the plants can afford to transpire with the

increased soil moisture from irrigation (Tang *et al.*, 2014; Zhou *et al.*, 2016). However, additional soil moisture will also stimulate microbial activity during the otherwise dry soil conditions (Gong *et al.*, 2015). Water deficits in soil are often observed during times of drought and specific seasons when evaporation exceeds rainfall inputs. During the drying of soils, the availability of organic and inorganic soluble substrates reduces as the water films between aggregates reduces, limiting the movement of substrates to microorganisms (Borken & Matzner, 2009; Curtin *et al.*, 2012).

With changes in readily available water, soil microbial activity such as decomposition, nitrification, and denitrification, will often vary. When soil has a more negative matric potential in soil solution, water is held more tightly, with thinner water films between aggregates that are unavailable to soil microbes, causing drought stress (Borken & Matzner, 2009). Lower soil moisture may cause the microorganisms to dehydrate and decrease osmotic potential within their cell walls as the microbes equilibrate with their changing environment (Borken & Matzner, 2009). Therefore, as soils dry, soluble substrates become less available and soil microbes are unable to function fully due to the limited transport of oxygen in water films into the soil which can alternatively decrease respiration rates (Davidson *et al.*, 2000; Zhou *et al.*, 2016; Dignac *et al.*, 2017).

Lower C mineralization rates occur when soil is constantly dry or wet (saturated) (Miller *et al.*, 2005). The net losses of soil C and N are partly controlled by soil moisture as well as organic matter inputs (Curtin *et al.*, 2012). These observations would infer that greater aboveground plant organic matter inputs, from increased production during irrigation, may not be the only contributing factor driving the C and N cycling (Miller *et al.*, 2005; Borken & Matzner, 2009). Long term effects of altered precipitation and evaporation rates may either decrease or increase soil C and N mineralization and sequestration (Borken & Matzner, 2009; Trost *et al.*, 2013). If irrigation results in soil moisture contents above plant requirements, oxygen movement through the soil pores becomes limited decreasing respiration through anaerobic processes (Rochette *et al.*, 1991; McLaren & Cameron, 1996; Curtin *et al.*, 2012).

The increased application of irrigation water will increase the activity of soil microbes that were initially moisture limited (Troost *et al.*, 2013; Condrón *et al.*, 2014; Gong *et al.*, 2015). Application of irrigation in temperate pastoral environments has produced a loss of soil C and N stocks from the soil system which may be a response to increased water availability to soil biota (Kelliher *et al.*, 2012; Condrón *et al.*, 2014; Mudge *et al.*, 2017). Therefore, increasing soil microbial activity and the release of CO₂ into the atmosphere and the potential loss of soil N as a gas and/or leachate from the soil (Kochsiek *et al.*, 2009; Troost *et al.*, 2013).

2.4.3 Previous studies on irrigation effects on soil C and N

Initially it was thought that irrigation increased SOM content due to the increase of net primary production from plants (Rixon, 1966; Smith *et al.*, 2016). However, there have been observed negative and positive effects on soil C and N stocks (Troost *et al.*, 2013). When determining the consequences of irrigation on soil C and N stocks, the pre-existing SOM content needs to be taken into account, as differing climates and soil textures determine SOM stocks (Troost *et al.*, 2013; Curtin *et al.*, 2016). Therefore, different climatic regions from arid, semi-arid, humid, and temperate, all have very different stocks of SOM prior to irrigation (Troost *et al.*, 2013; Mudge *et al.*, 2017).

Troost *et al.* (2013) reviewed 14 long-term field experiments on various croplands that compared the change in soil C of an irrigated soil to a non-irrigated counterpart (Table 2-1). The majority of the field experiments were based in arid, semi-arid and humid climates. In arid and semi-arid environments SOM was generally low, and with regular irrigation increasing plant production and C inputs, soil C accumulation was noticeable in comparison to the non-irrigated counterpart. Mudge *et al.* (2017) measured a loss of total soil C and N under irrigation in the temperate climate of NZ, where seasonal irrigation is common. They estimated an average loss of 6.99 t C ha⁻¹ and 0.58 t N ha⁻¹ across 34 irrigated sites around NZ relative to their adjacent non-irrigated land (Table 2-1).

When there is more SOC present, there is a likely chance that soil C will decrease under irrigation, provided it is in a temperate-to-subtropical climate regime (Table 2-1) (Ma *et al.*, 2017; Mudge *et al.*, 2017). In arid environments, where there is a naturally low SOC, total C was likely to increase when irrigated (Trost *et al.*, 2013; Trost *et al.*, 2016). However, an increase in SOC under irrigation is not always observed, as Trost *et al.* (2014) reported no change in irrigated arid/semiarid cropped sandy soils in Germany. While these previous studies have examined the impacts of irrigation on soil C there remains few studies that have investigated the effects of irrigation in temperate pastoral systems.

In NZ's temperate environment, the consequences of irrigation on SOC stocks is not clear. Houlbrooke *et al.* (2008) investigated the effects of irrigation on soil quality measurements such as soil C and N, bulk density and macro-porosity, in the North Otago rolling downlands, of NZ. They concluded that irrigation of pastures had no detrimental effect on the measured soil parameters, which may have been due to the sampling method used but noted that their research did not cater for the influence of variation within paddock or change in soil mass with depth. Using a fixed sampling pit method both Kelliher *et al.* (2012) and Condon *et al.* (2014) found less SOC in irrigated than non-irrigated pastures, 11.2-17.3 t ha⁻¹ to 0.15 m (Table 2-1). Mudge *et al.* (2017) used a different sampling technique that allowed for the greater inclusion of spatial variability of soil and looked at a range of soil orders around the country. The methodology and high sampling numbers used enabled Mudge *et al.* (2017) to determine the decrease in soil C (6.99 t C ha⁻¹) and N (0.58 t N ha⁻¹) stocks under irrigation to 0.3 m depth ($P < 0.05$).

Table 2-1: Recent studies of changes in soil carbon and nitrogen due to the effects of irrigation land management. NR- not reported.

Reference	Climate	Crop	Soil taxonomy (USDA)	Irrigation type	Carbon	Nitrogen
Houlbrooke <i>et al.</i> (2008)	Temperate	Pasture	Aeric Fragiaquept Lamellic Haplustepts	Not specified	No measured effect (P > 0.05)	NR
Kelliher <i>et al.</i> (2012)	Temperate	Pasture	Udic Ustochrept	Border-dyke flood irrigation	9 kg C m ⁻² Loss	NR
Trost <i>et al.</i> (2013) Review of 22 different investigations	-Arid, semiarid -Humid	Pasture, corn, wheat, potato, barley, etc.	NR (texture: Sandy loam and loamy sands)	Furrow and drip	-11 % to 35 % Increase -No net effects	50 % to 140 % increase in N ₂ O
Condron <i>et al.</i> (2014)	Temperate	Pasture	Typic Dystrustept	Border-dyke flood irrigation	11.2-17.3 t ha ⁻¹ Loss (SOC)	0.2 g kg ⁻¹ loss
Trost <i>et al.</i> (2014)	Arid, semiarid	Potato, wheat, cocksfoot, rye, etc.	Abruptic Arenic	Sprinkler	No significant difference	NR
Ma <i>et al.</i> (2017)	Subtropical	Rice paddies	Gleyic-Stagnic Anthrosols	Non-flood (NFI) vs flood irrigation (FI)	0.90-18.14% Loss (FI < NFI)	NR
Mudge <i>et al.</i> (2017)	Temperate	Pasture	NR	Pivot, border-dyke/wild flood, long lateral, roto rainer	6.99 t C ha ⁻¹ Loss	0.58 t N ha ⁻¹ Loss

2.5 Research Needs

The release of greenhouse gases, such as CO₂ and N₂O, from irrigated pastoral systems is not well understood as minimal investigation has been done within temperate climates. A greater understanding of the effects of land management practices, such as water irrigation on soil C and N stocks, is required so we can begin to develop mitigation strategies that avoid losses of soil C and N from agricultural systems.

The effects of irrigation on C and N stocks of Pumice Soils is particularly unclear as Mudge *et al.* (2017) only sampled seven Pumice Soils from the Galatea Plains and did not sample the wider irrigated dairy area of the Reporoa Basin. Due to the under representation of the Pumice Soil order and range of years under irrigation, the Reporoa Basin was selected for sampling as a representative area for irrigated Pumice Soils.

Chapter 3

Methods

3.1 Introduction

The main objective of this thesis was to compare soil carbon (C) and nitrogen (N) stocks of adjacent irrigated and non-irrigated pastures that were within 100 m of each other. The overarching methodology was to:

- Identify potential paired sites in the Central North Island (section 3.2) that meet specific criteria (section 3.4.1),
- Use the sampling method developed by Norris (2014) and used by Mudge *et al.* (2017) (section 3.4) to collect soil samples for subsequent analysis of total soil C and N stocks (section 3.7.5), and
- Test whether statistical analysis of multiple paired sites (replicates) within a farm or individual pivot provide greater statistical power than analysis at the pivot or farm level (section 3.9).

This chapter describes the full methods undertaken during this research. I will begin by describing how paired sites were selected, followed by the soil sampling protocol, lab analysis of soil and roots, and statistical analysis.

3.2 Number of sampling sites required

A power analysis for a paired t Test was conducted to estimate the minimum number of sites required to find a statistically significant difference of 7 t C ha⁻¹, based on the change in soil C stocks observed by Mudge *et al.* (2017). The analysis was run with an 80 % power with a standard deviation of 8.5 t C ha⁻¹, estimated from expert opinion (Figure 3-1). This analysis identified that a minimum of 14 paired sites would be sufficient to establish a soil C response to irrigation, should the true difference be greater than 7 t C ha⁻¹. Tests were also conducted to determine the significance of differences within farm replicates compared to response between the number of farms. Testing the relationship of

multiple replicates (irrigated and non-irrigated pairs) within farm vs replicates between farms will indicate whether sampling multiple pairs within farm is the same if not better than single sites on different irrigated properties.

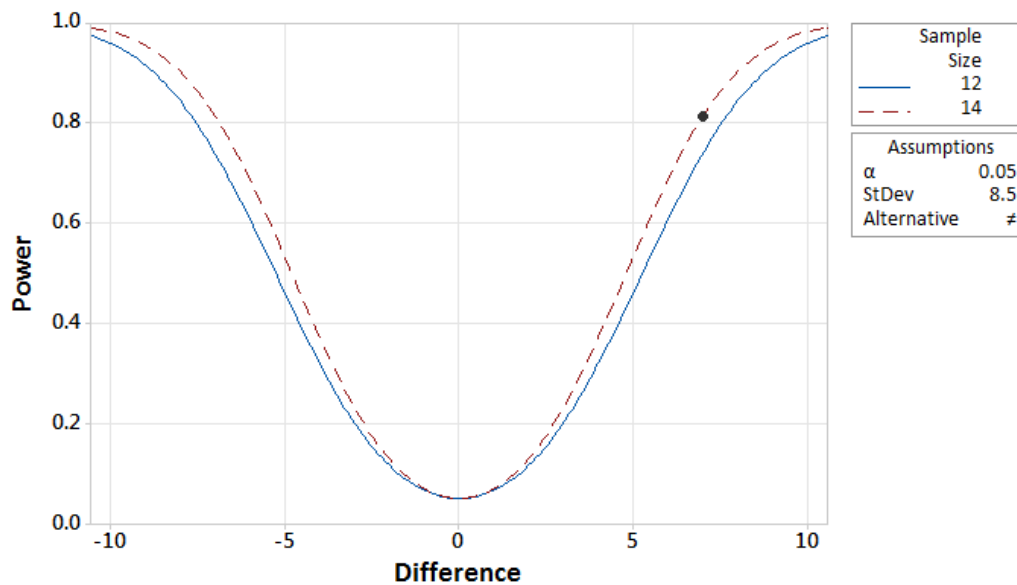


Figure 3-1: Power curve paired t Test, with 80 % (0.8) power of finding a 7 t C ha⁻¹ difference with 14 sites required for significant statistical power.

3.3 Study area

The study area for this research was the Reporoa Basin (Figure 3-2). This area was chosen because 1) irrigation is commonly used to alleviate summer soil moisture deficits, 2) it complements the previous sampling on similar Pumice Soils at Galatea in the Bay of Plenty and 3) existing connections to the community facilitated obtaining locations for potential sample sites. The general climate is temperate with mean annual temperature at 12.4°C and mean annual rainfall at 1342.8 mm, based from the nearest up-to-date climate station 1858 Taupo (2017).

The wider Taupo region is largely dominated by the Pumice Soil order from the large deposition of rhyolitic pumice eruptive materials (air-fall and pyroclastic tephra) from the Taupo volcanic eruption around 1718 ± 5 cal. BP (Vucetich & Wells, 1978; Hogg *et al.*, 2012). The soils in the Reporoa Basin were largely formed on bedded air-fall ash, pumice blocks (Upper unit), unsorted pumice blocks under lined with lapilli, ash, and rhyolite lithics (Middle unit). Collectively

the Reporoa District is covered by a non-welded Taupo ignimbrite, made up of Upper, Middle and Lower units (Froggatt, 1981; Hogg *et al.*, 2012). The lower unit does not appear within the top 60 cm of the field sites, as the eastern side of Taupo the Upper and Middle units predominate (Froggatt, 1981). The soils sampled within the Reporoa Basin are taxonomically known as Udivitrands in “Soil Taxonomy” (Lowe & Palmer, 2005; Soil Survey Staff, 2014) and as Typic Orthic Pumice Soils in the “New Zealand Soil Classification” (Hewitt, 2010).



Figure 3-2: Location of the Reporoa District, within the Waikato and Bay of Plenty region, New Zealand.

3.4 Sampling sites

Potential paired irrigated and non-irrigated sites in the Reporoa Basin were initially identified using Google Earth images along with water use resource consents obtained from LCR, coupled with my local knowledge of the area.

3.4.1 Site selection criteria

A set of site selection criteria were established based on those developed by Mudge *et al.* (2017):

- Irrigated and non-irrigated sampling areas were within 100 m of each other (Figure 3-3),
- Non-irrigated areas had never been irrigated, while irrigated areas had been irrigated for more than three years,
- Topography and soils were the same in irrigated and unirrigated areas within the pair,
- Other than irrigation, farm management had been similar on both irrigated and non-irrigated areas (e.g. uniform fertiliser application and grazing).

By following these selected criteria, it was deemed that the soils investigated had enough time to be influenced by irrigation practices in the dairy farming setting. The selection criteria of Mudge *et al.* (2017) was followed as closely as possible so sites investigated here could be compared with similar research being undertaken at the same time for other soil orders and so contribute to a nation-wide dataset. Some initially selected sites were not suitable for sampling due to inappropriate slopes within the paddock or change in fence lines, which were not noticeable from Google Earth imagery. If a site was inappropriate, the next adjacent paired site that met the criteria was selected and sampled. Farms with dairy shed effluent irrigation, as well as water irrigation, were considered acceptable so long as effluent was evenly applied to the whole paddock.

Two paired sites (F2 D2-I2 and F2 D1-I1) did not meet the original land management criteria, as the non-irrigated site was a drystock farm and the

irrigated site was on the neighbouring dairy farm. All other paired sites were sampled from dairy farms and within the same paddock.

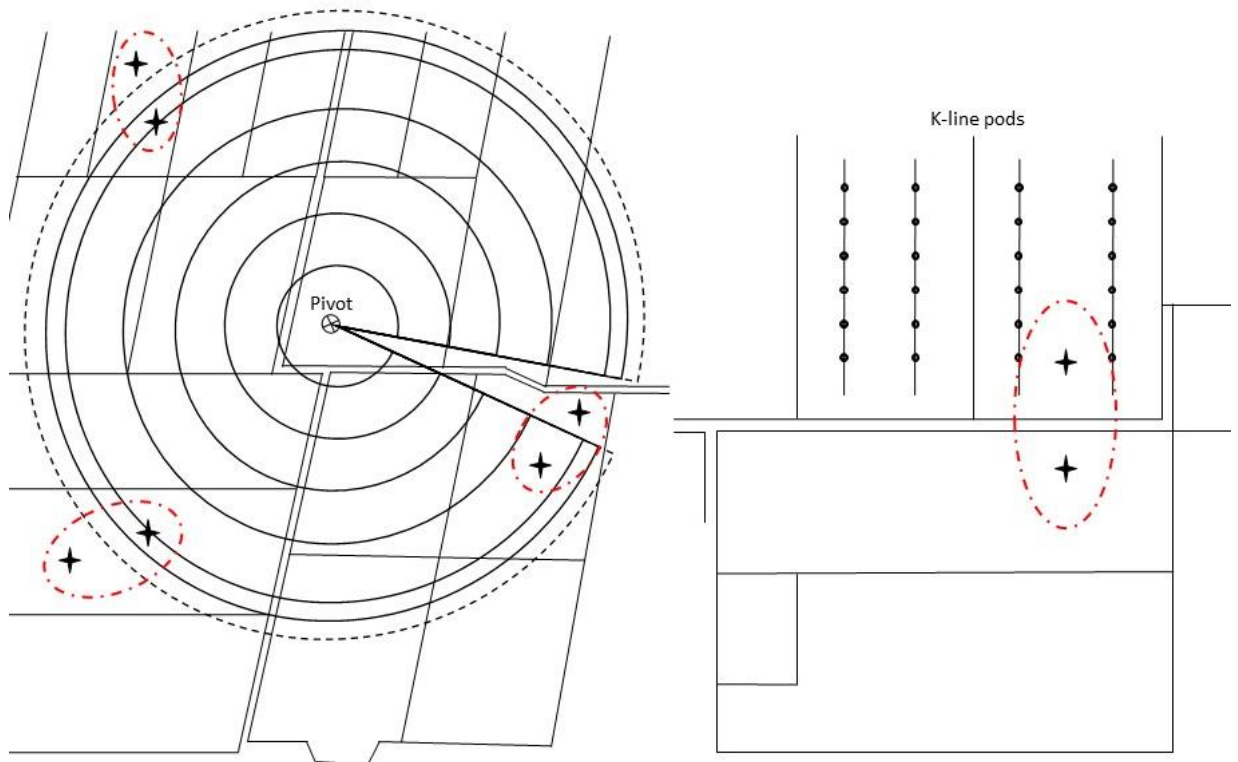


Figure 3-3: Schematic of paired sites within farm (left) and between farms (right) with sampling sites inside and outside irrigation zones. The stars represent the centre of a 20 x 20 m plot where soil samples were taken (see **Figure 3-5**). Sampled pairs are indicated by the dashed ovals within paddocks and adjacent paddocks.

3.4.2 Site selection

For all the irrigated properties identified on Google Earth, potential paired sites within a farm were numbered 1-4. From there a minimum of one sampling site was selected using a random number generator. After potential sites had been selected, landowner information was found through local knowledge of the area and using LINZ data service (Figure 3-4), and the Reporoa District phone book to obtain contact numbers for the LINZ addresses.

Landowners were contacted directly over the phone for all sites that had contacts. A brief phone interview was conducted with landowners to identify if their farms would meet the necessary requirements (described in section 3.4.1) and each site was visited and physically checked in the summer prior to sampling. This checking was to determine that the soils were similar (e.g. hand

augured to 30 cm to characterise colour, texture, horizon depths, and terrain). No detailed soil descriptions were undertaken. If a pair was not suitable because of changes in soil horizons over distance or terrain, the next closest potential site was used, where suitable. Out of the 16 initial farms identified on Google Earth imagery, only seven farmers provided consent for sampling. Some farms had several pivot irrigators, which enabled multiple paired sites within farm to be sampled. A total of 14 paired irrigated and adjacent non-irrigated sites were finally selected for sampling.

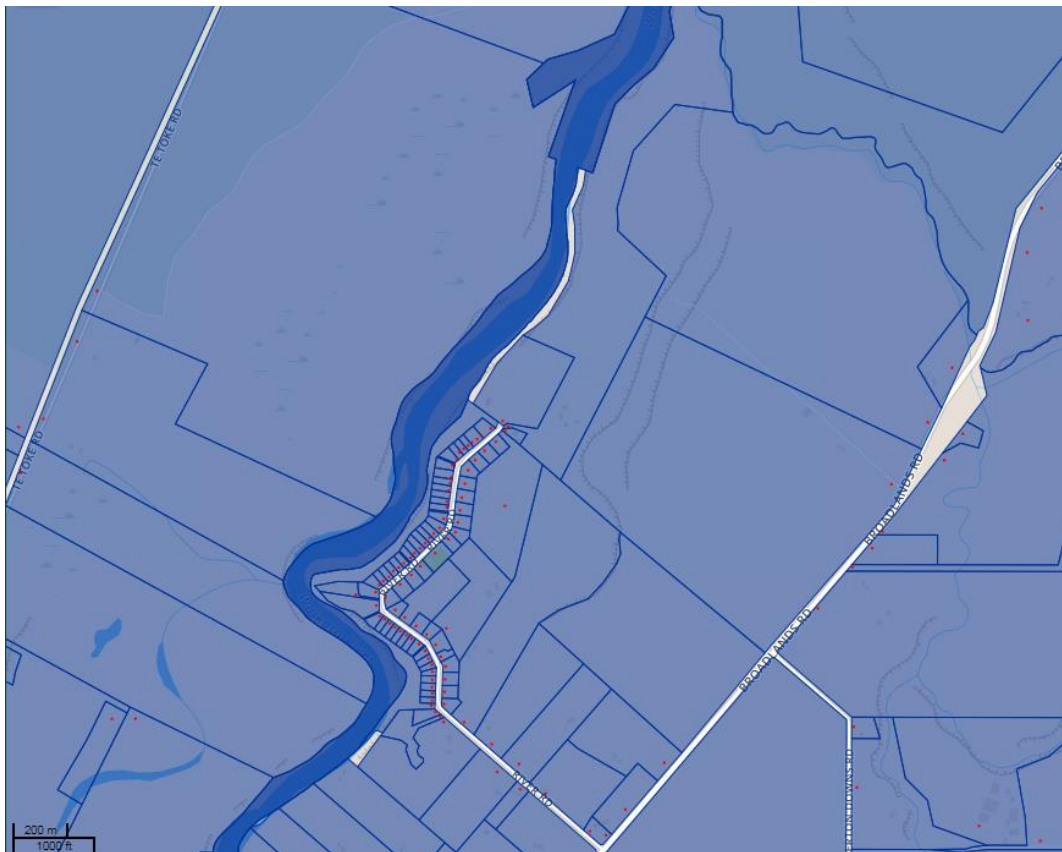


Figure 3-4: Example of LINZ data service map with layers: NZ property titles, NZ Street Address (Electoral) (Deprecated)), showing property boundaries and points with registered address. With River Road as an example (<https://data.linz.govt.nz/layers/?page=4>).

3.5 Land management questionnaire

To gain an understanding of each farm and its management, a questionnaire was developed for landowners to complete (Appendix A). Land use history was gathered from the questionnaire specifying the duration of irrigation and irrigation application rate, effluent application, stocking rate, fertiliser application, and paddock history along with other management details. The information gathered from the questionnaire was used to help interpret differences observed in soil C and N and the potential effects of irrigation. The questionnaire was adapted from one developed by Mudge *et al.* (2017). A consent form was also developed for Human ethics approval. The application number FSEN- 2017-4 was approved by the Faculty of Science and Engineering Human Research ethics sub-committee, at the University of Waikato (Appendix B).

3.6 Soil sampling

Soil sampling methods used to sample adjacent irrigated and non-irrigated pastures were based on the approach used by Mudge *et al.* (2017). For this thesis, samples were collected from the Central North Island region in the Reporoa District, with focus on Pumice Soils. Sampling took place between August and November 2017, at 14 paired sites on seven individual farms. Ten pairs were sampled in the late winter to ensure that the soil from the irrigated and non-irrigated pair was at the same if not similar field moisture content. Pairs were sampled within two days. Due to the start of milking, the remaining four paired sites were sampled in November and had noticeable differences in pasture growth, likely due to differences in field moisture content and water availability following irrigation.

Two sets of coring equipment were used to sample soil, which consisted of a motorised post driver and five sets of tubes (cores), made by Christie Engineering. There were slightly different core diameters between the two sets of equipment, with the first sampling from August 2017 used 39 mm diameter tubes and the second sampling in November had a tube diameter average of

38.99 mm. Core diameters were measured on each coring tube using electronic callipers.

Once site location was determined using the criteria in section 3.4.1 (Figure 3-3), the random location of each plot was constrained within areas if the irrigated and non-irrigated portions of the paddock which had the same landscape slope, and were greater than 2 m from fence lines and 5 m from troughs and gateways. For each treatment at each paired site, a 20 m x 20 m grid was established on the ground (Figure 3-5). The centre of the plot was estimated from GPS coordinates derived from Google Earth imaging. A total of nine cores were taken to a maximum depth of 0.6 m every 10 m on the edge of the plot and one from the centre (Figure 3-5). Some sites were only sampled to 0.4 m due to a high water table that made it difficult to remove soil from the corer without substantial disturbance from 0.4 m to 0.6 m depth. For every plot, a GPS position was taken from the first core (1) to accompany a series of photos that depicted north, east, south, and west with a landmark or long lasting land feature, enabling the same site to be found at a later date (Figure 3-6 and Appendix F).

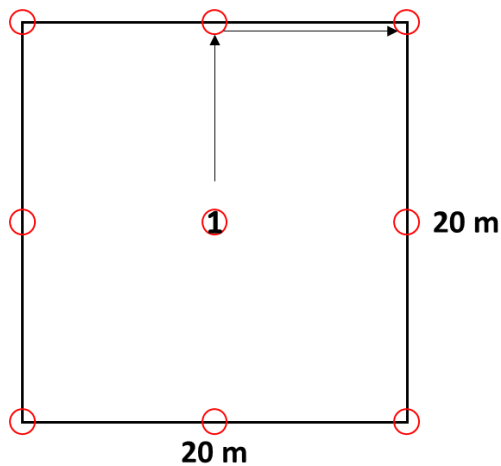


Figure 3-5: Plot sampling grid located within either irrigated or adjacent non-irrigated sites. Nine cores were sampled in total depicted by the open circles.

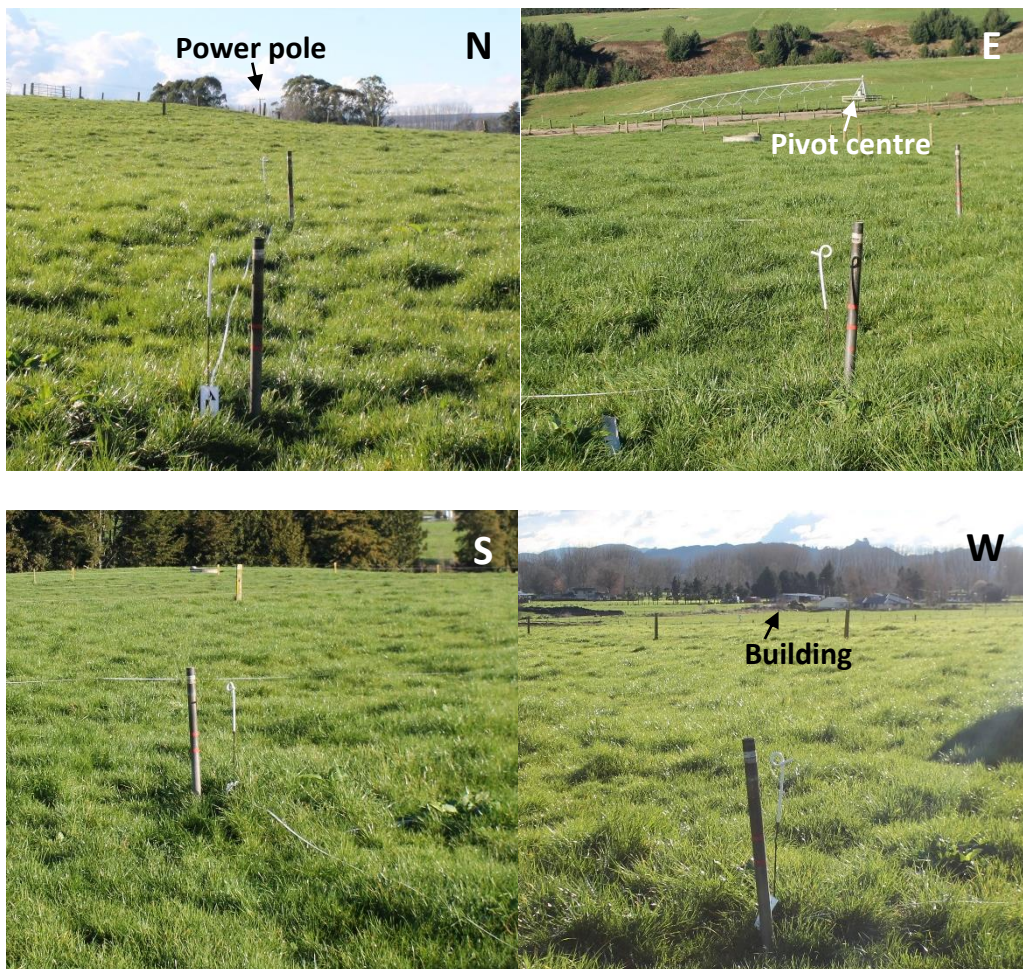


Figure 3-6: Example photographs taken for each sample site with North, East, South, West orientations from the centre core (1), with identifying long lasting land features such as a power pole. GPS coordinates were also recorded for each plot.

When sampling the nine cores within the gird, five coring cylinders were used interchangeably for each paired site. Soil cores were extracted and gently removed into half pipes (Figure 3-7). Once the nine cores had been collected, cores were placed on a cutting board and sectioned into 0.1 m increments and then bulked. A soil description was done for both the irrigated and non-irrigated pairs, describing the average depth of each horizon, colour, texture, parent material, drainage and landforms (Appendix C). If one of the soil cores appeared significantly different from the majority, either an A horizon depth, high charcoal content, or variation in overall soil horizons (Figure 3-8), it was discarded and adjacent soil resampled 0.3 m from the original hole. The samples were stored in plastic bags in a cool (4°C) room until processed and analysed.

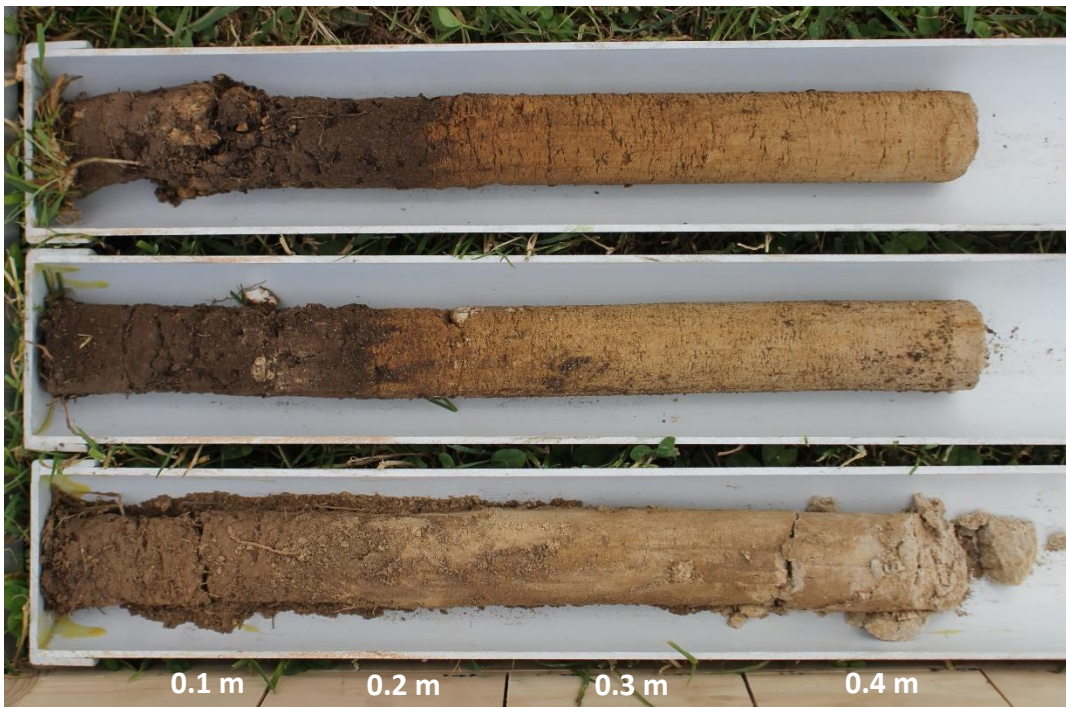


Figure 3-7: Three of nine cores laid out in half pipes for later sectioning and buking at 0.1 m increments. Image of soil from the non-irrigated paired site of F16-52.



Figure 3-8: Example of soil variation between potential non-irrigated (bottom) and irrigated (top) pairs. Distance between top and bottom cores was 40 m. This paired site was discarded due to the large visual differences in soil horizons.

3.7 Laboratory analysis

3.7.1 Sample preparation

Samples were homogenised by hand and obvious above-ground plant material removed. The whole soil sample collected from the field was weighed and then dried at 30 °C ('air' dried (AD)) in ovens, with the vent open, until the sample reached a constant weight. The oven was used to dry soil rather than air dried at room temperature, in order to process samples more rapidly and consistently. Once the samples reached a constant weight, they were passed through a 2 mm sieve and the < 2 mm fine-earth fraction and >2 mm coarse fraction weighed (Figure 3-9 A). Roots were removed by hand and weighed separately if they were over 0.01 g. Care was taken when sieving not to push through any woody material or charcoal.

To determine whether root removal would substantially change total C stock measurement, the roots from a 100 g subsample of a sieved A horizon were meticulously removed using tweezers. It was found that 0.11 g of roots removed from the 100 g of AD soil, was equivalent to 0.46 % of the total C as measured on LECO for the fine-earth fraction, which could change results by 2.6 to 3 t C ha⁻¹ (working in Appendix D.1). Due to the potential influence in total C from roots, the top 0.1-0.2 m of each site was sieved twice to remove the majority of root material that may have gone through the sieve initially.

All the root and > 2 mm portions from sieving were weighed, then oven dried at 65°C, to remove any excess moisture. Subsamples of the < 2 mm sieved soil were taken to measure the moisture factor (MF) (section 3.7.3) and C and N % at each depth increment (section 3.7.2), along with a subsample of roots, to measure ¹³C isotope composition (section 3.8).



Figure 3-9: **A)** 2 mm sieve with pumice clasts >2 mm present on top of the mesh. **B)** A riffle splitter was used to subsample the sieved soil (< 2 mm) as it is able to divide dry particulate material into two half-lots rapidly.

3.7.2 Soil carbon and nitrogen

Total soil C and N % from each 0.1 m increment was measured with a combustion method using a LECO TruSpec CN Elemental Analyser at the University of Waikato. A subsample of sieved soil (approx. 4 g) was taken for C and N analysis (Figure 3-9B), which was finely ground using a ball mill, in preparation for LECO. Before grinding, any obvious roots, wood or charcoal were removed by hand for 30 seconds. Two samples of charcoal that were removed from a paired site were also ground and analysed for % C and % N.

3.7.3 Moisture factor

Two replicates of sieved AD soil (~5 g) were added to a pre-weighed aluminium tray, weighed, and then placed into an oven at 105 °C for 48 hours. After oven drying (OD), samples were placed into a desiccator then reweighed. The two replicates were measured for each increment 0.1-0.6 m, unless there was less than 350 g of total sieved soil, as a minimum of 400 g of sieved soil was needed for archiving purposes. The *MF* was determined by first calculating the soil moisture content (*MC*) using equation 3-1, then calculating *MF* using equation 3-2.

$$MC (\%) = \left(\frac{w_1 - w_2}{w_2} \right) * 100 \quad (3-1)$$

$$MF = 1 + \left(\frac{w_1 - w_2}{w_2} \right) \quad (3-2)$$

Where w_1 was the mass of the air dried soil (g) and w_2 was the mass of the oven dried soil (g). Due to the use of replicates, MF was calculated for each replicate then averaged, for each increment (Appendix E.1).

3.7.4 Fine-earth bulk density

To calculate C and N stocks at each paired site, differences in soil bulk density (BD) across pairs and depth were needed to quantify C on an area basis (Parfitt *et al.*, 2010). The volume of the soil was calculated as the volume of the core cylinder at 0.1 m increments. There were two different sets of cores used for collecting samples and so there will be two volumes used to avoid scaling errors (Core volumes (V_T) at 0.1 m were 0.00108 m³ and 0.00107 m³). The average MF of each sample was used to correct the sieved air dried soil weight to total oven dried, in order to calculate an equivalent BD (Equation 3-3).

$$BD = \left(\frac{w_{OD}}{1000000} \right) / (V_T * n) \quad (3-3)$$

Where w_{OD} was the total mass of oven dry soil, 1000000 was used to scale grams to tonnes, V_T is the total soil volume and n is the number of cores taken. BD units were expressed in $t m^{-3}$ (Appendix E).

3.7.5 Total carbon and total nitrogen

The total soil C and N stock was calculated using the fine-earth fraction (<2 mm) soil mass, which excludes pumice >2 mm, for each increment (0.1 m) (equations 3-4 and 3-5).

$$TC (t ha^{-1}) = (BD * 10^4 * 0.1 m) * \left(\frac{\% C_{OD}}{100} \right) \quad (3-4)$$

$$TN (t ha^{-1}) = (BD * 10^4 * 0.1 m) * \left(\frac{\% N_{OD}}{100} \right) \quad (3-5)$$

Where oven dried soil mass was converted to $t ha^{-1}$ at a specific depth (0.1 m) and % C_{OD} and % N_{OD} were the oven dried concentrations of C (% C) and N (% N) (Appendix E.2-3).

3.7.6 Equivalent soil mass calculations

Equivalent soil mass (EQM) corrections were applied to soil C and N stocks using a cubic spline 'simple' function, as the two treatments had varying soil masses to fixed depths. EQM was applied through a Microsoft Excel add-on (Wendt & Hauser, 2013): (<http://www.srs1software.com/SRS1CubicSplineForExcel.aspx>).

The change in soil mass could have been a factor of pumice removal, compaction or differing porosity in the soils. Soil C and N stocks were corrected to an equal soil mass (reference soil mass) for each paired site and increment, where the lightest observed soil mass was used for EQM.

3.8 Root $\delta^{13}C$

Root samples collected during soil sieving were weighed and dried at 65°C. All of the roots from the top 0.1 m of each paired site were ground in a (clean) coffee grinder for 20 seconds, or until large fibrous material was broken down. The coarse ground material was sub-sampled using a cone and quartering technique. The sub sample was finely ground using a ball mill. Carbon isotope composition ($\delta^{13}C$) was analysed at the University of Waikato Stable Isotope Unit using a Dumas elemental analyser (Europa Scientific ANCA-SL) interfaced to a mass spectrometer (Europa Scientific 20-20 Stable Isotope Analyser).

3.9 Statistical analysis

Data was analysed through the analysis of variance (ANOVA) using Genstat and Minitab software to test the significance of the observed differences in soil properties between irrigated and adjacent non-irrigated grazed pastures. Analyses were undertaken for all depths from 0-0.1 m to 0-0.6 m using EQM corrected cumulative C and N t ha⁻¹. *P* values less than 0.05 were reported as statistically significant. Analyses were carried out for soil C and N stocks, treatment, farm number vs treatment (Appendix D.2), and examine the relationship between measured cumulative soil C and N t ha⁻¹ and EQM corrected soil C stocks.

Chapter 4

Decreases in soil C and N stocks under irrigation of grazed pasture on Pumice Soils

4.1 Abstract

The use of irrigation has become important for sustaining the production of food, fibre and biofuel. In New Zealand (NZ), irrigation of pastures is increasing in areas with seasonal water deficits. Nationally, there was an estimated 794,443 ha of land under irrigation in 2017. A previous national-scale study measured a decrease in soil carbon (C) (6.99 t C ha^{-1}) and nitrogen (N) stocks (0.58 t N ha^{-1}) to 0.3 m depth from 30 of their 34 sites in irrigated grazed pastures relative to adjacent non-irrigated pastures. Of their 34 paired sites across NZ, only seven were sampled from the Pumice Soil order and within this soil order losses were not significant, possibly due to relatively low replication in the study.

To gain a more comprehensive understanding of irrigation effects on soil C and N stocks in Pumice Soils, I sampled 14 adjacent paired irrigated and non-irrigated sites in the Reporoa Basin, north of Taupo. On average, between 13 sites (excluding site F11-35), irrigated pastures had significantly ($P < 0.05$) less soil C stocks (5.93 t C ha^{-1}) to 0.2 m depth and N stocks (0.24 t N ha^{-1}) to 0.1 m depth in comparison with those of adjacent non-irrigated soils. There was no relationship between the amount of soil C lost and the length of time under irrigation. Presumably loss of soil C and N under irrigation contributed to increased emissions of CO_2 to the atmosphere and potential N leaching into surrounding water bodies. Losses of soil C and N stocks may also change other important soil properties. If the causes of these losses can be determined, it may be possible to identify irrigation approaches that minimise or halt soil C and N losses.

4.2 Introduction

Increased demand for food, fibre and biofuel production applies immense pressure on our land globally, despite an increase in efficiency of land management to work towards population demands in recent years (Krausmann *et al.*, 2013). There is only a limited amount of resources such as nutrients and water that are used daily to aid global food security, which need to be managed better if we are to maintain our current production rate (Kastner *et al.*, 2012; Smith *et al.*, 2016). The application of irrigation is one means of increasing net production per unit area of land to support food security (MacLeod & Moller, 2006; FAO, 2011). The use of irrigation maintains optimum soil moisture for the growth of plants, during seasonally dry periods and in drought prone regions (Kastner *et al.*, 2012; Siebert *et al.*, 2015). In 2012, 275 million ha of arable land was irrigated, 7 % of which was fodder and pastoral irrigated areas (FAO, 2016). There has been an increase in the demand for animal products globally between 1961 and 2007 (Kastner *et al.*, 2012). Globally, the grazed land these products come from often have lower quality soils compared to those used for crops (Kastner *et al.*, 2012). Sustainable use of irrigation on grazed pastoral systems depends on water source availability and capacity of soil to store water, which can often be influenced by initial soil organic matter (SOM) content (Condrón *et al.*, 2014; Siebert *et al.*, 2015) and other factors. SOM content is important for sustaining agriculture as SOM is critical for biological processes within the soil, enhancing fertility, productivity and also aiding the structure of soil (Rasse *et al.*, 2005; Sparling *et al.*, 2006b; Barrios, 2007).

Agricultural practices such as application of fertilisers, crop harvest and irrigation, can alter soil C and N cycles by altering photosynthetic inputs and mineralisation of soil C and N (Schipper *et al.*, 2017). Soil C and N can be lost through natural pathways as gases CO₂, N₂ and N₂O and leachate (mainly NO₃⁻ and also dissolved organic carbon) (Borken & Matzner, 2009; Batjes, 2014; Sparling *et al.*, 2016). Along with anthropogenic influences on soil, there is spatial and temporal variability in soil C and N stocks, due to soil-forming factors and temporal changes in these such as climate (Batjes, 2014). Spatial variability of soil

stocks may make it difficult to measure changes in C and N stocks under differing land managements.

Irrigation is commonly used in regions of water scarcity to increase primary production, which is thought to increase in SOM following increased above-ground plant production (Smith *et al.*, 2016). However, in a laboratory experiment by Borken and Matzner (2009), soil microbial activity increased under irrigation, because microbial CO₂ production (SOM decomposition) increased as soil was no longer in drought or water deficit. The changes in soil C and N stocks under irrigation can depend on trade-offs in plant productivity and mineralisation when moisture limitations are removed and also the climatic environment in which the system resides (Borken & Matzner, 2009; Trost *et al.*, 2013; Condon *et al.*, 2014).

In a global review of the effects of irrigation on soil C and nitrous oxide (N₂O) emissions, Trost *et al.* (2013) observed an increase in soil C under irrigation of a variety of croplands in arid and semi-arid climate regimes. The few sites in humid climates showed no net effect of irrigation on soil C and N stocks. Consequently Trost *et al.* (2013) concluded that the effect of irrigation on soil C and N may be dependent on the climatic zone and also the initial SOM content of the soil. Due to greater focus on cereals and vegetable oil production in arid and semi-arid environments, there has been a lack of research conducted on irrigated grazed pastoral systems in temperate climate regimes (Kastner *et al.*, 2012; Trost *et al.*, 2013; Mudge *et al.*, 2017). Studies investigating the effects of irrigation on temperate pastoral systems in NZ measured a net loss of soil C and N in comparison to adjacent non-irrigated pastoral soils, both in the South and North islands of NZ (Kelliher *et al.*, 2012; Condon *et al.*, 2014; Mudge *et al.*, 2017). Condon *et al.* (2014) concluded that at a 62-year field trial in Winchmore, the aboveground productivity from irrigation did not result in an increase in belowground C storage. This disconnection between above and belowground processes may have been caused by an imbalance of C inputs to outputs from the soil system that discriminated against the storage of soil C from enhanced soil respiration. Mudge *et al.* (2017) reported a net loss of 6.99 t C ha⁻¹ and 0.58 t

N ha⁻¹ to a depth of 0.3 m, from 30 of their 34 sites from around NZ. Due to wide spatial sampling and accounting for spatial variability of soil C within their sampling method, Mudge *et al.* (2017) was able to demonstrate that this loss was significant ($P < 0.05$).

In NZ, grazed pastoral systems represented about three quarters of the irrigated land in 2015, with the remaining ~25 % of irrigation being applied to vegetable, arable crops, fruit, and vineyards. Irrigated pastures were predominantly dairy based farming (~50 %) with smaller areas of sheep and beef (25 %) (IrrigationNZ, 2015). Under irrigation, farms are able to increase pastoral growth and export of animal products off farm (meat and dairy products) (IrrigationNZ, 2015). In 2017, the total irrigated area of NZ was estimated to be 794,443 ha (estimated uncertainty of $\pm 46,021$ ha) (Dark *et al.*, 2017). Regions around NZ susceptible to drought or seasonal low rainfall had the highest percentage of irrigated area: Canterbury (64 %), Otago (12 %), Marlborough (4 %), Hawke's Bay (4 %), Manawatu-Wanganui (3 %), and the Waikato (3 %) (Dark *et al.*, 2017).

In the southern Waikato and Bay of Plenty regions, soils are dominated by sandy textured free-draining soils, formed mainly from pumice, which are susceptible to drought in times of low precipitation (Rout, 2003; Hewitt, 2010). Of the 34 sites sampled nationwide by Mudge *et al.* (2017), only seven sites were located on Pumice Soils in the Galatea area in the Bay of Plenty region. There was an average difference of 4.5 t C ha⁻¹ less in irrigated than non-irrigated soils, but this loss was not statistically significant due to high variability and the low number of replicated sites. Due to the under representation of Pumice Soils in the Mudge *et al.* (2017) irrigation study, further investigation was needed, as each soil order has unique properties that could yield a difference in response to land use management (Hewitt, 2010; Schipper *et al.*, 2014).

In the Reporoa Basin, an estimated 64,000 ha of forestry has been converted to pasture since the year 2006, based on Google Earth imagery, between Taupo and Reporoa, some of which is now irrigated. Irrigation was mainly applied to dairy farms in the Reporoa Basin which enabled farms to increase dry-matter

production by 3000 to 5000 kg ha⁻¹ during the years 1998 to 2002 (Rout, 2003). The main soil order investigated in this area was the Pumice Soil order. Pumice Soils are characterised by a low clay content (~3-4 %), low bulk density (0.58 g cm⁻³) and tend to have low nutrient availability (McLaren & Cameron, 1996; Hewitt, 2010). The free-draining nature and low clay content of these pumiceous soils makes them more susceptible to water loss during dry seasons as they have estimated available water-holding capacity values of 40 and 80 mm (Bakker *et al.*, 1996; McLaren & Cameron, 1996; Rout, 2003; Hewitt, 2010). Due to the nature of these soils, irrigation has been applied to prevent the loss of yield during dry spells. The consequence of this irrigation on soil properties is poorly understood.

In this research, I investigated the effect of irrigation on soil C and N stocks in Pumice Soils from the Reporoa Basin in the central North Island, NZ. Fourteen paired irrigated and adjacent non-irrigated pasture sites were investigated; most pairs were sampled from the same paddock including an irrigated area under a centre pivot irrigator and a non-irrigated area not covered by the irrigator. This sampling approach meant that other land management practices, such as fertiliser application and stocking rate were uniform on both irrigated and non-irrigated sampling areas. However, due to difference in pasture quality and quantity under irrigation in comparison to the non-irrigated area, it is important to recognise these differences might alter where animals graze and camp. Paddock and farm specific information were obtained from landowners using a questionnaire and site information was gathered during the sampling process.

4.3 Methods

4.3.1 Site selection

The locations of the irrigated and non-irrigated adjacent pastures from 14 sites are shown in Figure 4-1. All sites used a form of sprinkler irrigation (with centre pivot most common), where time since irrigation began ranged from 3-17 years. Farms were predominantly dairy, with two non-irrigated sites on drystock farms; and all paired sites were located on Pumice Soils. Locations of farm sites are not precisely identified to maintain privacy of farm owners.

Farm sites were identified using a range of sources from Google Earth imagery, local knowledge, and water use resource consents. After site visits and talking with farm owners, paired sites that met the following criteria, developed by Mudge *et al.* (2017), were used for this research:

- Irrigated and non-irrigated sampling areas were within 100 m of each other,
- Non-irrigated areas had never been irrigated, while irrigated areas had been irrigated for more than three years,
- Topography and soils were the same in irrigated and non-irrigated areas within the pair,
- Other than irrigation, farm management had been similar on both irrigated and non-irrigated areas (e.g. uniform fertiliser application and grazing).

Sampling of paired sites took place in August and November 2017. For most sites, irrigated and non-irrigated pairs were sampled in the same paddock and the same farm. However, for two pairs, non-irrigated sites were sampled from the adjacent farm, because the entire irrigated property was irrigated. The basic farm and management information was gathered from farmers using a questionnaire derived from Mudge *et al.* (2017) (Appendix A.2), with the key information associated around irrigation duration (Table 4-1). The Reporoa Basin has an estimated mean annual temperature at 12.4°C and mean annual rainfall of 1343 mm (Station 1858 Taupo, 2017). Soils at all sites, were formed from very weakly weathered sandy, rhyolitic pumiceous tephra deposits of the Taupo

eruption of $AD\ 232 \pm 5$ (Hogg *et al.*, 2012), taxonomically known as Udivitrands in “Soil Taxonomy” (Lowe & Palmer, 2005; Soil Survey Staff, 2014) and as Typic Orthic Pumice Soils in the “New Zealand Soil Classification” (Hewitt, 2010).



Figure 4-1: General locations of 14 paired irrigated and non-irrigated sampling sites in the Reporoa Basin, NZ.

Table 4-1: Irrigation duration, maximum sampling depth, animal grazing e.g. dairy cows (DC) and drystock (DS), irrigation type, and elevation for each sampled paired site. Some irrigation information was withheld due to farmer’s request (-).

Site number	Irrigation duration (year)	Sampling depth (m)	Animal grazing	Irrigation type	Elevation (m)
F15-92B	10	0.6	DC	Pivot	315
F15a-1	10	0.6	DC	Pivot	302
F15a-7	10	0.6	DC	Pivot	307
F15a-96	10	0.6	DC	Pivot	302
F18-47	11	0.6	DC	Pivot	315
F18-X	11	0.6	DC	Pivot	313
F2-X	-	0.6	DC/DS	K-line	331
F2-XX	-	0.5	DC/DS	K-line	335
F11b-9	6	0.6	DC	Pivot	320
F11-35	6	0.6	DC	Pivot	344
F8-52	3	0.6	DC	Sprinkler Gun	435
F16-22	17	0.4	DC	Pivot	308
F16-16	17	0.4	DC	Pivot	304
F16-52	17	0.4	DC	Pivot	313

4.3.2 Soil sampling

Methods used to sample soil from irrigated and adjacent non-irrigated pastures were based on the approach of Mudge *et al.* (2017). At each paired site, one 20 m x 20 m plot was located in both the irrigated and non-irrigated pastures. The plot was orientated north from the centre of the plot, so that each plot was systematically sampled in the same orientation. Within the 20 m x 20 m plot, nine soil cores were sampled every 10 m around the edge of the plot and one in the centre.

Samples were collected using two sets of coring equipment, with an average core tube diameter of 0.039 m with a length of 0.9 m. For most sites, the corer was inserted to 0.6 m depth using a motorised post driver, unless it was impeded by stones (lithics), water table, or a buried soil horizon (Table 4-1). Each core was removed carefully from the ground and extruded into a half pipe, then placed onto a chopping block for sectioning and bulking. This process was repeated for all nine cores in both irrigated and non-irrigated plots, which were then cut into

0.1 m increments, bulked into labelled bags per depth increment, and returned to the laboratory for further processing.

4.3.3 Soil carbon and nitrogen analysis

Soil samples were air-dried in ovens at 30 °C and passed through a 2 mm sieve then weighed as fine-earth fractions. The presence of charcoal in the subsoil of Pumice Soils was common and could impact on calculations of total C and N stock contents, so extra caution was needed when sieving to remove charcoal by hand. A subsample of finely ground sieved soil (< 0.5 g) was analysed for total C and N using a LECO TruDpec CN Elemental Analyser at the University of Waikato. The total soil C and N stocks were calculated using the C and N % from LECO, corrected for oven dried soil mass to each 0.1 m depth increment. The oven dried soil mass was converted to tonnes per hectare at a specific depth (0.1 m) using the fine-earth bulk density (*BD*) (i.e. excluding pumice >2 mm) calculated from the corer area and number of cores sampled. C and N stocks were also calculated using equivalent soil mass (EQM) approach as the irrigated and non-irrigated plots had varying *BD* which may have been caused by pumice removal, compaction or differing porosity in the soil (Wendt & Hauser, 2013). Due to the differences in soil *BD* between irrigated and non-irrigated soils, EQM stocks will be reported (see chapter 3 for more details).

4.3.4 Root $\delta^{13}\text{C}$

Root samples collected during soil sieving were weighed and dried at 65°C. As root samples were being separated, there was an opportunity for an exploratory study of the consequences of irrigation on plant ^{13}C isotope composition ($\delta^{13}\text{C}$). Carbon isotope content of plant biomass can be used to make an inference on plant water use efficiency of growing pasture (Smedley *et al.*, 1991).

Root samples from paired site F15a-96 were accidentally discarded prior to ^{13}C analysis. Thirteen of the paired root samples from the top 0.1 m of each paired site were ground in a (clean) coffee grinder. The coarse ground material was sub-sampled using a cone and quartering technique, then finely ground using a ball

mill. Carbon isotope composition ($\delta^{13}\text{C}$) was analysed at the University of Waikato Stable Isotope Unit using a Dumas elemental analyser (Europa Scientific ANCA-SL) interfaced to a mass spectrometer (Europa Scientific 20-20 Stable Isotope Analyser).

4.3.5 Statistical analysis

Analysis of variance (ANOVA) using Genstat and Minitab software was used to test the significance of the observed differences in soil properties between adjacent irrigated and non-irrigated grazed pastures. Analyses were undertaken for all individual and cumulative depths from 0-0.6 m using EQM corrected cumulative C and N t ha^{-1} . *P* values less than 0.05 were reported as statistically significant. Analyses were carried out for soil C and N stocks, treatment, farm number vs treatment, and compared the relationship between measured cumulative soil C t ha^{-1} to the EQM corrected soil C stocks.

4.4 Results

4.4.1 Irrigated vs non-irrigated soil

4.4.1.1 Soil mass corrections

In most cases, cumulative C stocks were similar when calculated by fixed depths or on an EQM bases (Figure 4-2). An exception was in the top 0.1 m where variability was high. Soil mass varied within the top 0-0.2 m when comparing adjacent irrigated and non-irrigated soils with cumulative C EQM and fixed depth soil C (t ha^{-1}), (Figure 4-2). The depth 0-0.1 m regression line demonstrated that the relationship between EQM and fixed depth soil C was not as strong as the relationships for depths 0-0.2 to 0-0.6 m. Differences in soil C stocks calculated by EQM and fixed depth approaches were generally similar from depths 0-0.3 to 0-0.6 m with the majority of data points falling on the regression line. However, for consistency, all reported results of soil C and N stocks were corrected for EQM.

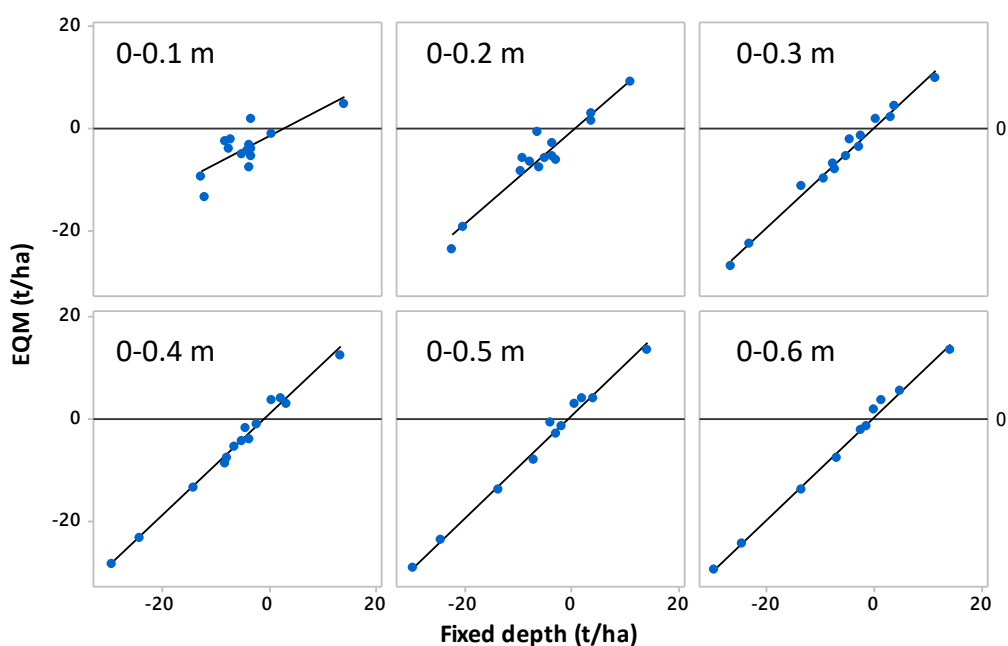


Figure 4-2: The relationship between differences between irrigated and non-irrigated soil of measured cumulative C by fixed depth (t ha^{-1}) and EQM corrected cumulative C (t ha^{-1}) from 0-0.1 to 0-0.6 m depth.

4.4.1.2 Farm number vs treatment

A nested analysis of variance was undertaken on “farm number” (e.g. F2, F8, F11, F15, F16 and F18) and “treatment” (irrigated vs non-irrigated). Six farms were sampled, some having two or three replicates within a single farm. The analysis was testing if there was any evidence that the average response to irrigation in the response variables was systematically different in some farms compared to the responses from others. The p-values for those farm treatment interactions indicate that there was no evidence of such a difference (Table 4-2). Thus, we can proceed to analyse the data with the 14 individual observations of non-irrigated and irrigated pairs.

Table 4-2: Relationship between farm number and treatment (irrigated and non-irrigated) for cumulative soil C stocks. *P* values with relation to cumulative depth.

Depth (m)	Farm number vs Treatment
0-0.1	0.29
0-0.2	0.24
0-0.3	0.45
0-0.4	0.50
0-0.5	0.48
0-0.6	0.65

4.4.1.3 Total C and N

Total soil C stocks ranged from 60 to 121 t C ha⁻¹ in the top 0.4-0.6 m of each site (Figure 4-3). Paired site F15a-1 had the highest total C within 0-0.6 m at 121 t C ha⁻¹ and F11-35 had the lowest at 60 t C ha⁻¹. Differences in average C stocks between the paired irrigated and non-irrigated soils ranged from -3.79 to +0.69 t C ha⁻¹ with irrigated soils generally having lower C stocks than non-irrigated soils (Figure 4-3). The difference in C stocks at site F11-35 (denoted by * in Figure 4-3) was detected as an outlier by the Gtest software, being a site with large residuals in comparison to other levels of difference. This paired site differed from other paired sites because the irrigated and non-irrigated sampled areas were separated by a natural drainage feature formed previously by gully erosion (Selby & Hosking, 1973).

Although there were concerns about whether the irrigated and non-irrigated sites of F11-35 were properly matched, this pair was not discarded as an outlier

from field observations. However, statistical significance of differences between total C and N was conducted with and without this paired site (Figure 4-4 and Table 4-3). With site F11-35 omitted, the overall cumulative C data has a simple normal distribution that lies within the 95 % confidence intervals (Figure 4-4 C and A).

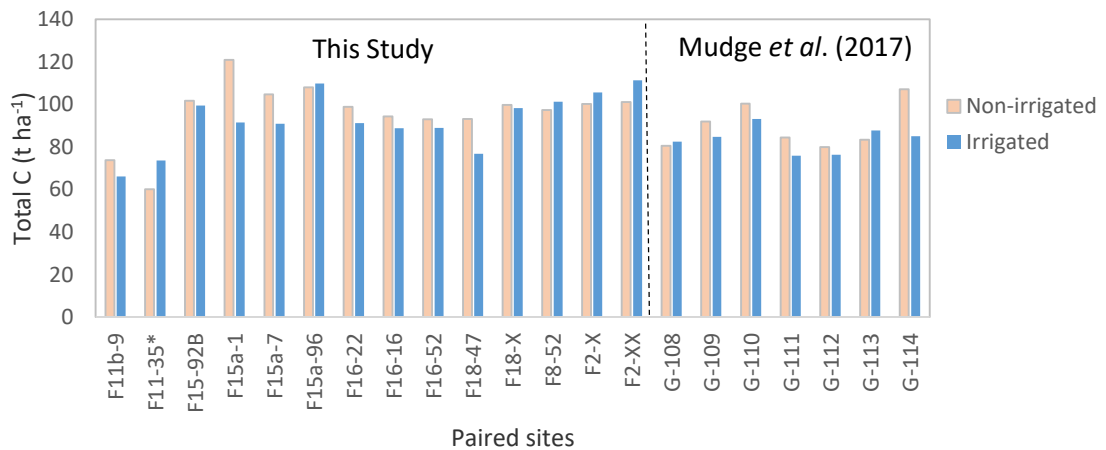


Figure 4-3: Total soil C (t ha⁻¹) stocks to maximum sampled depths of 14 paired irrigated and non-irrigated sites (0-0.6, 0-0.5, and 0-0.4 m). Seven of the Pumice Soils (G-108 to G-114) at Galatea from 0-0.5 m depth from Mudge *et al.* (2017) are presented for comparison.

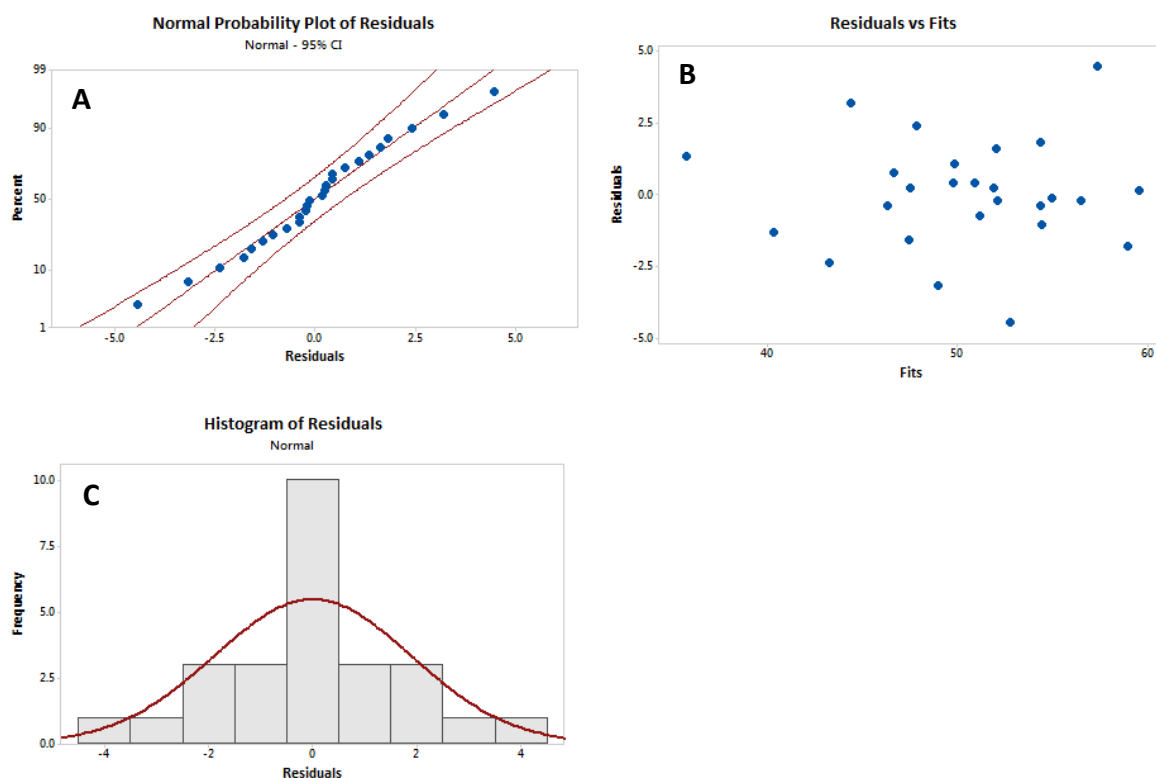


Figure 4-4: Residual plots of cumulative EQM soil C (t ha^{-1}) data, excluding site F11-35. A) Normal probability plot of residuals with 95 % confidence intervals displayed. B) Residuals versus fitted values of the data from the estimated regression line at zero. C) Histogram of residuals with a simple normal distribution curve.

Averaged soil C stocks in the top 0.2 m of non-irrigated soils across the 14 paired sites (including F11-35) was significantly less ($P \leq 0.05$) than those of the irrigated adjacent sites (Table 4-3). The mean C stock for the non-irrigated Pumice Soil was 82.7 t C ha^{-1} , and for the irrigated soil it was 77.8 t C ha^{-1} in the top 0.2 m, with a mean cumulative difference of 3.8 t C ha^{-1} for 0-0.1 m depth and an additional 1.07 t C ha^{-1} for 0.1-0.2 m depth. The maximum measured cumulative difference was at 0.2 m, with a significance of $P = 0.036$ when including F11-35 (Table 4-3). When site F11-35 was omitted from the data set, the total soil C was also significantly different between treatments to a depth of 0.2 m ($P \leq 0.05$) with a mean difference of 5.93 t C ha^{-1} (Table 4-3). The value at depth 0.3 m showed a difference of 5.58 t C ha^{-1} which was nearly (but not quite) significant to the 5 % level with $P = 0.059$.

Table 4-3: Average soil carbon stocks and the difference between adjacent irrigated and non-irrigated soils for different depths. The mean C stocks (t ha⁻¹) were adjusted for EQM. Averages are reported with (top) and without site F11-35 (bottom). Significant *P* values are shown as * *P* ≤ 0.05 and ** *P* ≤ 0.01 with the standard error of the difference (s.e.d). The number of paired sites decreased with depth.

Depth (m)	Paired sites	C t ha ⁻¹			Cum C t ha ⁻¹		Cumulative difference (t ha ⁻¹)	s.e.d
		Dry	Irrigated	Irrigation-Dry	Dry	Irrigated	Irrigation-Dry	
0.0-0.1	14	51.43	47.64	-3.79	51.43	47.64	-3.79	1.12**
0.1-0.2	14	31.23	30.15	-1.07	82.65	77.79	-4.86	1.93*
0.2-0.3	14	8.30	8.68	0.38	90.95	86.48	-4.48	2.59
0.3-0.4	14	2.82	3.31	0.50	93.77	89.79	-3.98	2.87
0.4-0.5	11	1.52	2.21	0.69	95.29	92.00	-3.29	3.8
0.5-0.6	10	0.69	-0.62	-1.32	95.98	91.37	-4.61	4.3

Depth (m)	Paired sites	C t ha ⁻¹			Cum C t ha ⁻¹		s.e.d	
		Dry	Irrigated	Irrigation-Dry	Dry	Irrigated		
0.0-0.1	13	53.26	48.79	-4.47	53.26	48.79	-4.47	1.14**
0.1-0.2	13	32.09	30.62	-1.46	85.34	79.41	-5.93	1.8*
0.2-0.3	13	8.40	8.74	0.34	93.74	88.15	-5.58	2.48
0.3-0.4	13	2.85	3.17	0.33	96.58	91.33	-5.26	2.77
0.4-0.5	10	2.35	2.63	0.28	98.93	93.95	-4.97	3.81
0.5-0.6	9	1.04	-0.62	-1.65	99.97	93.34	-6.63	4.41

Similarly, total N stocks were lower in irrigated pastures than non-irrigated (Table 4-4). Total N stocks ranged from 5.25 to 10.66 t N ha⁻¹, where paired site F15a-1 had the highest total N to 0.6 m depth and F11-35 had the lowest to 0.6 m depth (Figure 4-5). The difference of soil N stocks between irrigated and non-irrigated soils, when all sites were included, was not significant (*P* > 0.05) at 0.1 m depth, with a mean cumulative difference of 0.193 t N ha⁻¹ (Table 4-4). When F11-35 was omitted, the average difference in soil N stocks was significant to 0-0.1 m depth (0.24 t N ha⁻¹ *P* = 0.04). At 0.2 m depth the difference of 0.28 t N ha⁻¹ was nearly significant at the 5 % level at *P* = 0.053. Total N was strongly correlated with total C stocks with an R-square value of 0.94. C:N ratios ranging from 9:8 to 11:4 at 0-0.1 m depth (Figure 4-6 and Table 4-5). C:N ratios on average were lower under irrigated pasture compared to those of adjacent non-irrigated pasture (*P* = 0.003).

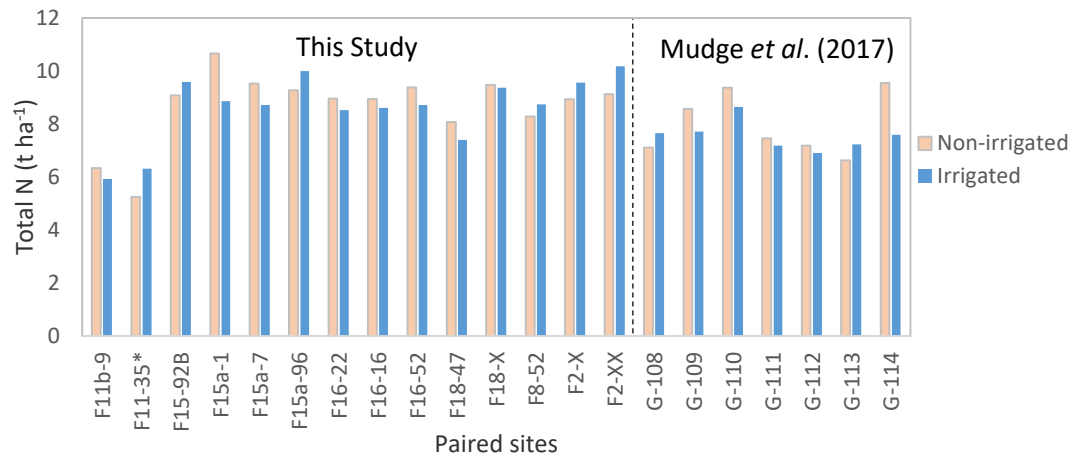


Figure 4-5: Total N (t ha^{-1}) stocks to maximum sampled depth of 14 paired irrigated and non-irrigated site. Seven Pumice Soils (G-108 to G-114) at Galatea from 0-0.5 m from Mudge *et al.* (2017) are presented for comparison.

Table 4-4: Average soil nitrogen stocks and the difference between adjacent irrigated and non-irrigated soils for different depths. The mean N stocks (t ha^{-1}) were adjusted for EQM. Averages are reported with (top) and without site F11-35 (bottom). Significant P values are shown as * $P \leq 0.05$ with the standard error of the difference (s.e.d). The number of paired sites decreased with depth.

		N t ha^{-1}			Cum N t ha^{-1}		$\text{Cumulative difference (t ha}^{-1}\text{)}$	
Depth (m)	Paired sites	Dry	Irrigated	Irrigation-Dry	Dry	Irrigated	Irrigation-Dry	s.e.d
0.0-0.1	14	4.79	4.60	-0.19	4.79	4.60	-0.193	0.09
0.1-0.2	14	2.71	2.70	-0.01	7.50	7.30	-0.202	0.13
0.2-0.3	14	0.70	0.76	0.06	8.20	8.06	-0.146	0.19
0.3-0.4	14	0.25	0.29	0.04	8.46	8.35	-0.110	0.21
0.4-0.5	11	-0.01	0.16	0.17	8.45	8.51	0.058	0.29
0.5-0.6	10	0.04	-0.06	-0.10	8.49	8.45	-0.042	0.33
Omitted F11-35		N t ha^{-1}			Cum N t ha^{-1}			
Depth (m)	Paired sites	Dry	Irrigated	Irrigation-Dry	Dry	Irrigated	Irrigation-Dry	s.e.d
0.0-0.1	13	4.97	4.73	-0.24	4.97	4.73	-0.240	0.10*
0.1-0.2	13	2.78	2.75	-0.04	7.76	7.48	-0.278	0.12
0.2-0.3	13	0.71	0.77	0.06	8.47	8.25	-0.222	0.18
0.3-0.4	13	0.26	0.28	0.02	8.73	8.53	-0.198	0.20
0.4-0.5	10	0.06	0.21	0.16	8.78	8.74	-0.042	0.30
0.5-0.6	9	0.07	-0.06	-0.12	8.85	8.68	-0.165	0.35

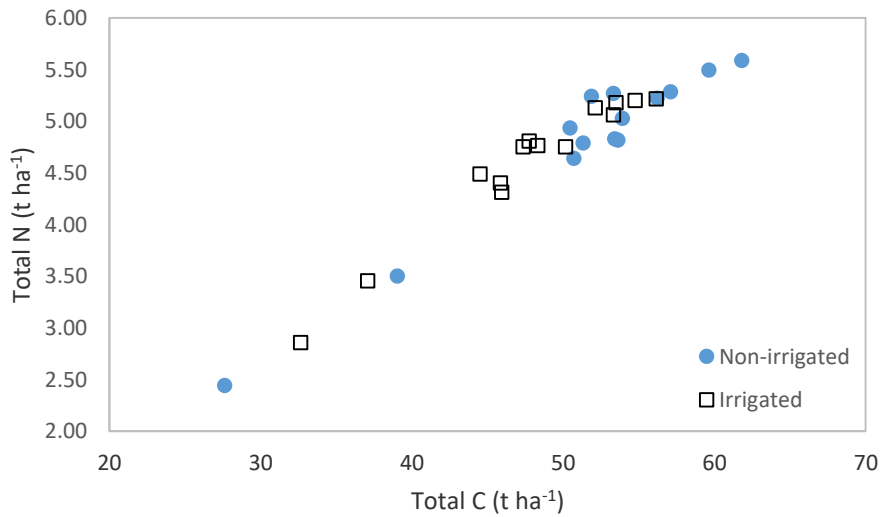


Figure 4-6: Relationship between total C and N stocks of irrigated and non-irrigated sites for cumulative C and N to maximum sampled depths of each paired site. Data points have a linear regression of $y = 0.095x + 0.03$ ($R^2 = 0.94$).

Table 4-5: Soil C:N ratios of 0-0.1 m depth for each paired irrigated and adjacent non-irrigated site, and the total averages. A t-Test: Paired Two Sample for Means was carried out, *P*-value of 0.003.

Site	Non-irrigated	Irrigated
F11-35	11.31	11.43
F11b-9	11.17	10.72
F15-92B	10.74	10.55
F15a-1	11.06	10.14
F15a-7	10.76	10.16
F15a-96	11.13	10.43
F16-16	10.22	9.96
F16-22	10.85	10.53
F16-52	9.89	9.93
F18-47	11.05	9.92
F18-X	10.15	10.05
F2-X	10.71	10.66
F2-XX	10.92	10.33
F8-52	10.81	10.78
Average	10.77	10.40

4.4.2 Differences in C stocks vs irrigation duration

Of the 12 paired sites where irrigation duration information was available, there is no evidence of a duration effect on differences in soil C stocks (Figure 4-7).

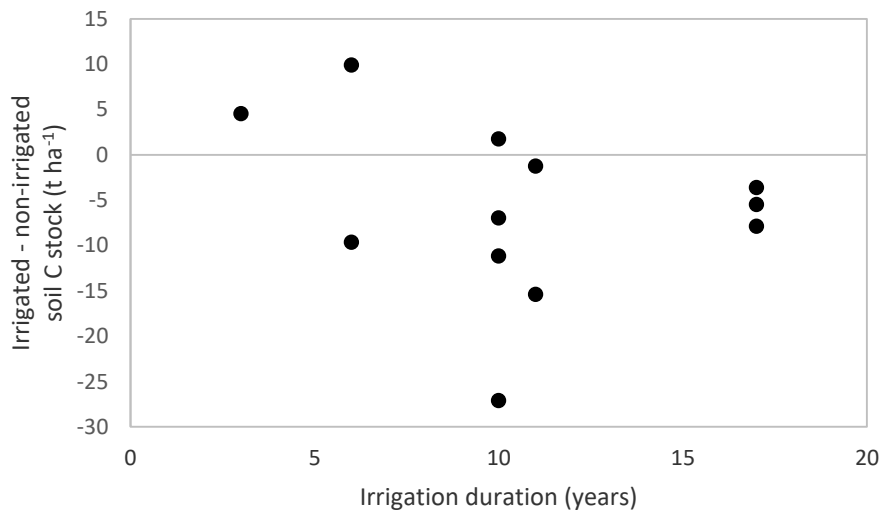


Figure 4-7: Difference in mean C stocks (irrigated – non-irrigated (Dry)), for 0-0.3 m depth of 12 paired sites plotted against irrigation duration (years).

4.4.3 Root $\delta^{13}\text{C}$

The C isotope composition of bulk root mass was more negative at the irrigated sites compared to the composition of non-irrigated pairs ($P = 0.028$) (Figure 4-8). This meant that the irrigated pasture was discriminating more against the heavier isotope (^{13}C). On average, roots from irrigated pasture had a value of -30.04 ‰ and from non-irrigated pasture -29.66 ‰. Assuming that plants on irrigated and non-irrigated pastures were subject to the same atmospheric vapour pressure deficit, significant differences between irrigated and non-irrigated root $\delta^{13}\text{C}$ suggested that the irrigated pastures had lower water use efficiency (WUE).

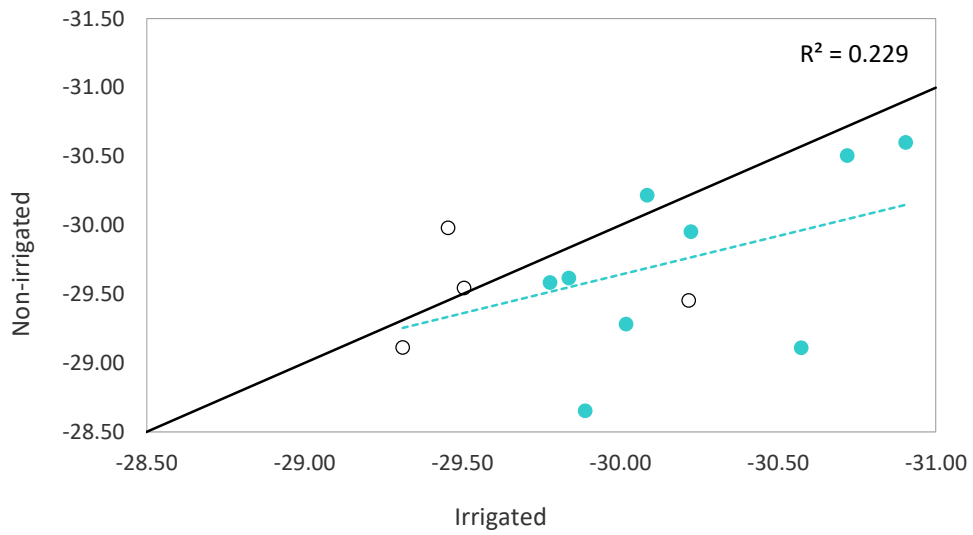


Figure 4-8: Root $\delta^{13}\text{C}$ (‰) from 0-0.1 m depth of 13 adjacent irrigated and non-irrigated paired sites (site F15a-96 missing). Regression of $y = 0.56x - 12.79$ where $R^2 = 0.23$. Black 1:1 line. Closed markers were sampled in August and open markers sampled in November.

4.5 Discussion

4.5.1 Soil C and N stocks of irrigated and non-irrigated pastures

The use of irrigation to increase yields has been demonstrated to have an influence on soil C and N stocks (Trost *et al.*, 2013; Mudge *et al.*, 2017). However, the net effect of irrigation can be negative or positive depending on the initial soil C stocks and climate (Trost *et al.*, 2013). On average, across 14 paired irrigated and non-irrigated adjacent sites sampled from Pumice Soils (Vitrandis), irrigated grazed pastures had significantly less total soil C stocks to 0.2 m depth ($P < 0.05$) (Table 4-3) with no significant loss of total soil N stocks (Table 4-4), in comparison to the stocks of adjacent non-irrigated soil. The response of soil C and N stocks to irrigation was observed throughout the soil profile. Although the cumulative differences in C stocks increased with depth, it was not possible to demonstrate significant differences between treatments from 0.3 m to 0.6 m depth, because of insufficient sample/site replication (Table 4-3 and Table 4-4).

The soil mass of irrigated and non-irrigated paired sites varied between irrigated and non-irrigated soil samples for 0-0.1 and 0-0.2 m depth (Figure 4-2) due to variations in soil *BD* near the soil surfaces. These differences were taken into account when calculating C stocks to ensure valid comparisons of total C and N stocks between treatments (Wendt & Hauser, 2013; Olson & Al-Kaisi, 2015). There was no significant difference between cumulative EQM-adjusted C stocks and fixed depth cumulative C stocks from 0.3 to 0.6 m depth. However, due to the variation in the difference between cumulative EQM C and fixed depth cumulative C stocks at 0-0.1 and 0-0.2 m, EQM C stocks were used instead of summation using fixed depth increments to prevent over or under estimation of soil stock observations from the effects of irrigation on total soil C and N stocks (Wendt & Hauser, 2013).

In NZ, Mudge *et al.* (2017) measured decreases of stocks of 6.99 t C ha⁻¹ and 0.58 t N ha⁻¹ from 30 of their 34 paired irrigated and non-irrigated sites. Of these 34 sites, seven were sampled from Pumice Soils in Galatea in the Bay of Plenty. Data from these Pumice Soil sites are used here for comparison.

4.5.2 Differences in C stocks between irrigated and non-irrigated sites

Originally 14 paired sites were sampled and differences between soil C stocks of irrigated and non-irrigated sites were similar (Table 4-3). However, the analysis of variance (ANOVA) and residuals strongly suggested site F11-35 was an outlier. For the purpose of this thesis discussion this site was not included. Results from site F11-35 may have not been representative of the effects of irrigation on soil C because the pair was separated by an old drainage channel, formed from gully erosion, which was characteristic of the landscape throughout the property.

On average for the 13 paired sites, irrigated soils had 5.93 t ha⁻¹ less soil C than adjacent non-irrigated soils for the 0-0.2 m depth (Table 4-3). This observed response to irrigation was similar to the C stock losses reported by Mudge *et al.* (2017) (6.99 t C ha⁻¹ for 0-0.3 m). However, for 0-0.1 m depth, the difference between irrigated and non-irrigated soil was significant, 4.47 t C ha⁻¹ ($P < 0.01$), whereas Mudge *et al.* (2017) did not find a significant loss with 1.44 t C ha⁻¹ ($P = 0.052$). For the top 0.2 m depth, Mudge *et al.* (2017) measured a greater loss of 3.33 t C ha⁻¹ ($P < 0.001$). The difference of soil C stocks between paired sites was most likely due to irrigation, because Schipper *et al.* (2014) noted the Pumice Soil order had not lost soil C under grazing management through time. So assuming there is no change in C soil stocks in the non-irrigated pasture, the difference in soil C was due to a loss of soil C following irrigation rather than gains of soil C in the non-irrigated sites.

For the 0.3-0.5 m depth, the difference between the treatments on average increased 0.32 t C ha⁻¹ ($P > 0.05$), showing a small increase in C stocks with irrigation (Table 4-3). While not significant, this slight increase of C stocks at depth might suggest some movement of soil C or dissolved organic C (DOC) down the profile that accumulated at 0.3-0.5 m. Additional application of water to the upper 0.1 m of a soil profile, on top of rainfall, can lead to leaching of DOC (Ghani *et al.*, 2010; Sparling *et al.*, 2016). A NZ study showed that Gley Soils (Aquept) had greater leaching of DOC than Allophanic Soils (Udand) (Schipper *et al.*, 2007;

Ghani *et al.*, 2010). Ghani *et al.* (2010) acknowledged that the soil mineralogy, SOM content and other soil properties can lead to differences in DOC leaching rates. The Allophanic Soil was more rapidly draining, minimising the time for diffusion of DOC from the soil aggregates into soil solution, causing the Allophanic Soil to have lower leached DOC.

With the low leaching rate of DOC from an Allophanic Soil, a free draining Pumice Soil would be thought to show similar DOC losses. However, in an earlier study by Sparling *et al.* (2006a) using lysimeters, Pumice Soils irrigated with waste water had higher losses of DOC than Allophanic Soils (Pumice 546 kg ha⁻¹ and Allophane 173.7 kg ha⁻¹). In comparison to the non-irrigated Pumice Soil lysimeter (86.1 kg ha⁻¹), the irrigated lysimeter had lost a further 459.9 kg C ha⁻¹, showing irrigation may also reduce C stocks through the leaching of DOC. It would seem unlikely that leaching of DOC would be the main contributor of losses of C stocks from the soil.

Often soil C stocks are not reported below 0.3 m depth due to high costs of sample collection and analysis (Olson & Al-Kaisi, 2015). However, reporting C stocks beyond the tillage zone (0-0.3 m) to 0.6 m can provide a fuller picture of where soil C and other nutrients may go or how deep a land management practice can have an effect on the soil profile. Olson and Al-Kaisi (2015), suggested sampling the rooting zone or to 1-2 m depth, but this sampling depth was not feasible with the manual coring approach used in this thesis. The range of sampling depths used allowed me to conclude whether differences in soil C stocks were significant or not when including or excluding depth information from the overall data set. Sampling to 0.6 m depth allowed the net effect of irrigation on soil C to be tested and demonstrated a total loss of 6.63 t C ha⁻¹ from 0-0.6 m ($P > 0.05$) (Table 4-3). The cumulative difference was not significant for the 0-0.6 m depth, but the lack of significance was likely due to a low number of samples at depth as some paired sites were only able to be sampled to 0.4 or 0.5 m (Table 4-1). If losses are mainly constrained to the upper horizons of the soil, sampling deeper appears to add increasing variability but not increasing

losses, which then compromises the ability to measure statistically significant differences.

4.5.2.1 Implications of soil C losses

Pastoral land uses are a large store of C providing there is minimal disturbance to soil properties (Lal, 2004). If soil C is lost from pastures due to irrigation land management, it is clear that the way irrigation is used needs reanalysed, as stored soil C is likely being lost to the atmosphere. Loss of C could potentially have negative influences on water infiltration, retention, plant growth, soil structure/aggregation, and nutrient availability within soils (Six *et al.*, 2002; Powlson *et al.*, 2015). The main loss of soil C under irrigation might be attributed to enhanced soil respiration when soil moisture limitations are removed during dry periods (Mudge *et al.*, 2017). Increased soil moisture can enhance soil biological activity and decomposition in soils (Borken & Matzner, 2009; Curtin *et al.*, 2012). Increased activity and decomposition leads to increased soil/microbial respiration of CO₂ gas, removing soil C from the system. This means that the increases in aboveground inputs of organic matter following irrigation are insufficient to balance the increased losses from microbial respiration.

4.5.3 Differences in N stocks between irrigated and non-irrigated sites

The C:N ratio of both irrigated and non-irrigated soils ranged from 9.8 to 11.4 for 0-0.1 m depth (Table 4-5). The ratio was often higher in non-irrigated than irrigated soil ($P < 0.01$). Due to the strong correlation between soil C and N ($R^2 = 0.94$), when soil C was lost, soil N was also lost (Figure 4-6) (Schipper *et al.*, 2014). Therefore, N stocks would generally show the same response to irrigation as soil C stocks. However, non-irrigated soils only had 0.24 t N ha⁻¹ ($P < 0.05$ excluding site F11-35) more than adjacent irrigated soils in the top 0.1 m of the soil profile (Table 4-4). As with C stocks, N lost from Pumice Soils was greater than the reported average losses presented in Mudge *et al.* (2017) for the same depth (0.06 t N ha⁻¹ $P \geq 0.05$). However, in this study, I was unable to detect any significant differences in the change of soil N between the two treatments below the top 0.1 m.

Soil N is stored mainly as organic N (95 %) and can be lost from soil through leaching, gaseous pathways, plant up-take, and removed by animal consumption/product (McLaren & Cameron, 1996; Robertson & Vitousek, 2009). Assuming an average irrigation length of 10.6 years and a constant rate of N loss, this results in an estimated loss of 22.5 kg N ha⁻¹ yr⁻¹ from the topsoil of irrigated Pumice Soils. The average application of N fertiliser between sampled farms was 181 kg ha⁻¹ yr⁻¹ and a loss of 22.5 kg N ha⁻¹ yr⁻¹ equates to 12.4 % of the applied N lost each year from the topsoil. This 22.5 kg N ha⁻¹ yr⁻¹ loss is not dependent on applied N, but this 12.4 % loss from irrigated soil is high relative to N inputs. The period over which N was lost is not known and could have been 22.5 kg ha⁻¹ yr⁻¹ or there may have been a larger initial loss at the onset of irrigation that subsequently reached a new equilibrium with time (Mudge *et al.*, 2017). The pathways by which soil N was lost from the soil is also uncertain.

4.5.3.1 Implications of soil N losses

Loss of N stocks from the soil represents a reduction in soil fertility that in the absence of inputs could result in a loss of plant production and could have a negative effect on the surrounding environment (independent of inputs) (Cameron *et al.*, 2013). If an initial flush of soil N was lost after irrigation application, rapid changes of soil N stocks would occur mainly through leaching and plant up-take. Rapid losses through leaching would have major effects on surrounding water bodies within the catchment potentially causing eutrophication of water bodies (Cameron *et al.*, 2013). In the investigated site area (Figure 4-1), smaller catchments all contribute towards the Waikato River, north of Lake Taupo. Leaching of soil N could have serious implications on nearby water bodies and groundwater due to the high permeability of the Taupo pumice material in the underlying the soil (Piper, 2005).

Water quality of the Waikato River is important as it contributes to town water supplies, irrigation schemes around the Waikato region, recreational activities for sport and leisure, and hydropower schemes. Water quality decreases after

the Ohaaki Bridge monitoring site in Reporoa and continues to decline further as the river moves downstream towards Hamilton (Vant, 2013). Since 1993, nitrate concentrations (mg N m^{-3}) in the Waikato River have increased by 2.8 % each year. The main increase in nitrate content occurred during the monitoring time of 2003-2012 (Vant, 2013). Enrichment of the Waikato River through nitrate leaching could cause an increase in aquatic weed growth and the potential for algal blooms in the hydro lakes along the river. However, the contribution of N losses from irrigated pastures of the Reporoa Basin is not known.

4.5.4 Irrigation duration

Mudge *et al.* (2017) was unable to find evidence of a relationship between changes in soil C stocks and duration of irrigation. The current study was also unable to find evidence of any effect of irrigation duration on soil C stocks. However, this lack of evidence could have been due to low replication with only five farms providing data on irrigation duration (Table 4-1 and Figure 4-7). When combining data with the Pumice Soil data collected from the Galatea Plains (Mudge *et al.*, 2017), the relationship between differences in soil C stocks and irrigation duration still did not show any obvious trends with soil C and time (Figure 4-9).

The lack of evidence of a loss of soil C and N stocks with time suggests that the loss is rapid when the sites are first irrigated. Mudge *et al.* (2017) suggested that initial loss of C stocks may have occurred within the first 10 years of irrigation as soil C stocks change over a period of time, not instantaneously (Poeplau *et al.*, 2011). After the initial loss the irrigated soil may have come to a new equilibrium, which can be supported in new steady states being reached when changing from one land use to another (Poeplau *et al.*, 2011). Similarly, in a decadal study by Schipper *et al.* (2013) at Winchmore, two irrigation treatments were applied to soils to maintain a 10 % and 20 % soil moisture content and compared to non-irrigated pasture. Soil C stocks were measured from 0-75 mm depth. The 20 % treatment had overall lower C stocks than 10 % irrigated and the non-irrigated soil. Over time, the total C stocks for each treatment increased

(Figure 3a in Schipper *et al.* (2013)). The research from Schipper *et al.* (2013) suggested that irrigated soil C stocks were less under irrigation, but may increase through time at 0-75 mm depth after the initial first sampling in 1960. Schipper *et al.* (2013) pointed out that C stock increases were likely due to the soil recovering after border-dyke formation when topsoil had been removed.

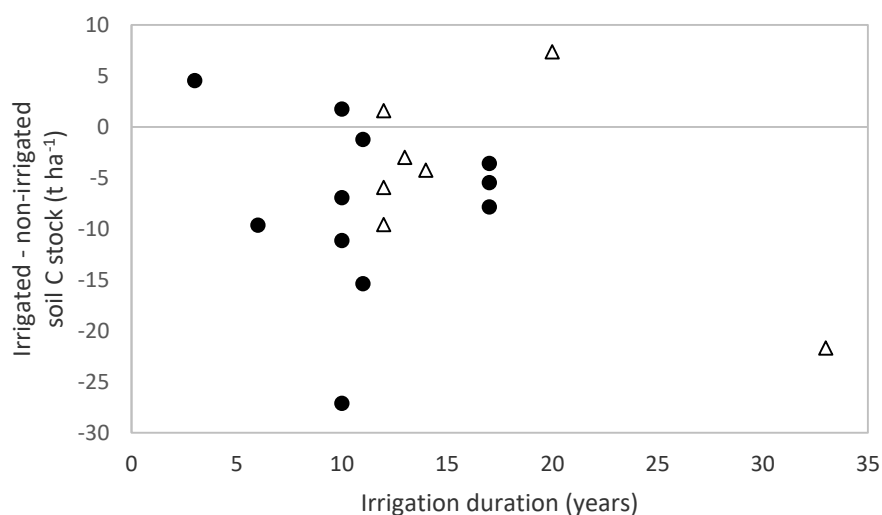


Figure 4-9: Change in C stock as a function of time since irrigation commenced for Reporoa (circle) and Galatea (triangle) paired sites (0-0.3 m depth) (F11-35 omitted).

4.5.5 Water use efficiency of irrigated and non-irrigated pastures

During sampling for soil C and N there was an opportunity collect root biomass and measure C isotope composition ($\delta^{13}\text{C}$) of pasture roots from the adjacent irrigated and non-irrigated sites to look at potential differences in WUE. In C3 plants, leaf $\delta^{13}\text{C}$ can be used to measure WUE and assuming all plants are subject to the same atmospheric vapour pressure deficits (VPD) (Smedley *et al.*, 1991); the theory underpinning this relationship is described in Farquhar *et al.* (1989). Results showed $\delta^{13}\text{C}$ was more negative (higher ^{13}C discrimination) in the roots of irrigated pastures (Figure 4-8) suggesting that WUE was lower in comparison to that of adjacent non-irrigated pastures. However, no data was collected for VPD, which may have been higher for the non-irrigated sites and therefore I am unable to conclude with complete certainty that WUE was higher for non-irrigated pasture.

This comparison of $\delta^{13}\text{C}$ between paired irrigated and non-irrigated sites was only done as an initial investigation of potential differences in pasture WUE between adjacent pairs and was not a key focus of this thesis. Typically $\delta^{13}\text{C}$ plant leaves are used to measure WUE, whereas sampling the plant root biomass is novel and has potential to be used to integrate over annual time periods. However, there are a range of uncertainties associated with using root biomass opposed to leaves, including the time period roots integrate WUE over and also potential differences in plant species composition between irrigated and non-irrigated pairs (Farquhar *et al.*, 1989; Mefti *et al.*, 2008). Therefore, despite the preliminary work suggesting a significant difference in WUE between adjacent irrigated and non-irrigated pastures, further research is needed to grasp a better understanding of the relationship between root $\delta^{13}\text{C}$ and plant WUE under irrigation.

4.6 Conclusions

This thesis provides supporting evidence that irrigation had a significant effect on soil C and N stocks in Pumice Soils. Irrigation reduced soil C stocks by 5.93 t ha^{-1} ($P < 0.05$) at 0-0.2 m depth and N stocks by 0.24 t ha^{-1} ($P < 0.05$) at 0-0.1 m depth. Combined with Pumice Soil data from Mudge *et al.* (2017) at Galatea, there was no evidence of a relationship with losses of soil C stocks and irrigation duration. However, the overall result of irrigation duration effects on soil C may be misrepresented or hindered depending on the depth at which stock differences are reported.

The measured decreases in soil C following irrigation agreed with findings from a number of previous studies including those of Kelliher *et al.* (2012), Condon *et al.* (2014) and Mudge *et al.* (2017). Consequently, irrigation practises may need to be monitored more carefully to understand the size of these changes and whether alternative irrigation scheduling might avoid or minimise losses. Given the changing climate over the last 50 years, there is going to be an increased demand for the use of irrigation in the future of pastoral systems, to maintain or increase aboveground yield and animal products from the land. With the increased use of irrigation, there may be a net increase in losses of soil C stocks as CO_2 into the atmosphere. With the loss of C stocks comes the concomitant losses of soil N stocks that may contribute to enhanced nitrate leaching.

Based on the findings in this thesis, there is a need for further investigation of the effects of irrigation for different soil orders around NZ. This research will aid farmers to have a better understanding of their land management on-farm and inform them of their potential effects on greenhouse gas emissions on a national scale. Now is the time to encourage and find ways to prevent loss of soil C stocks or increase soil C sequestration.

Chapter 5

Summary and Conclusions

5.1 Introduction

Globally, soil C is important for life as it contributes to soil structure, fertility, water retention, and thus food, biofuel, and fibre production (Krausmann *et al.*, 2013; Smith *et al.*, 2016). More C is stored in soil than in the atmosphere and decreases in soil C storage can result in the release of C into the atmosphere as greenhouse gas CO₂ (Condon *et al.*, 2012). Conversely, increasing soil C can remove CO₂ from the atmosphere.

A study by Mudge *et al.* (2017) demonstrated a significant difference of soil C and N stocks in irrigated pastures in comparison to adjacent non-irrigated pastures around NZ. There was a net loss of 6.99 t C ha⁻¹ and 0.58 t N ha⁻¹ from irrigated soils to 0.3 m depth. However, when separated into regions, differences in soil C were only significant in the Canterbury region, as there was an insufficient number of sites from other regions.

In the study of Mudge *et al.* (2017), only seven Pumice Soils were sampled and a loss of 4.5 t C ha⁻¹ was measured in Galatea, Bay of Plenty ($P > 0.05$). This was not significant in part due to high variability and the low number of replicate sites. Irrigation of grazed pastures has increased on Pumice Soils in the Central North Island over the last 20 years as the region is prone to droughts during times of low precipitation and the low water-holding capacity of the Pumice Soils (Rout, 2003; Hewitt, 2010). Due to the under-representation of Pumice Soils in the Mudge *et al.* (2017) study, further investigation was needed to test whether Pumice Soils did lose C under irrigation, as each soil order has unique properties that could yield a different response to irrigation.

International literature suggested that the impact of irrigation on soil C and N was dependent on the initial SOM content and climate of where the soil is formed (Trost *et al.*, 2013). However, the majority of this literature was based on

measurements made in arid and semi-arid regions for arable cropped soils, which made it difficult to interpret the potential effects on temperate pastoral environments, such as in the Galatea Plains/Reporoa Basin.

The main aim of this thesis was to determine whether there were significant differences in soil C and N between irrigated and non-irrigated grazed pastures on Pumice Soils in the Reporoa Basin. To achieve this aim, 14 paired adjacent irrigated and non-irrigated sites were sampled using the coring method adapted from Mudge *et al.* (2017) and soil C and N stocks were calculated using equivalent soil mass (EQM) corrections.

The following sections will summarise the key findings of this research presented in chapter 4, section 4.4. Recommendations for future research are provided in section 5.4.

5.2 Differences in soil C and N stocks between irrigated and non-irrigated pasture

In total, six separate farms were sampled and in some cases two to three replicates/paddocks were sampled within farm, which meant a nested analysis of variance for “farm number” (e.g. F2, F8, F11, F15, F16, and F18) and “treatment” (irrigated vs non-irrigated) was used. The analysis by farm showed no significant difference in cumulative C stocks between treatments for all sampled depths ($P > 0.05$). The variability of soil types within a farm was so great that multiple replicates sampled from one property were able to be analysed as individual sites. When analysis of variance was conducted at the individual paddock “paired site” level (13 pairs), significant ($P < 0.05$) differences for both soil C and N stocks between treatments were able to be determined.

For the 0-0.2 m depth, there was an average of 5.93 t C ha⁻¹ less soil C in irrigated soils compared to adjacent non-irrigated soil ($P < 0.05$). This finding was in agreement with the average difference measured by Mudge *et al.* (2017) for a range of soils around NZ (6.99 t C ha⁻¹). The lower total C stocks in irrigated soils

has previously been attributed to increased soil microbial respiration due to an increase in soil moisture availability, releasing CO₂ into the atmosphere (Borken & Matzner, 2009; Mudge *et al.*, 2017). However, soil C stocks could also have decreased/lost due to leaching of dissolved organic C (Sparling *et al.*, 2006a). Few studies have shown changes in soil C stocks under irrigated pastures, in temperate climates (Kelliher *et al.*, 2012; Condrón *et al.*, 2014; Mudge *et al.*, 2017). With development of soil sampling techniques, we are now able to have a higher sampling number per site, to better account for soil variability.

Losses of soil N stocks were only significant for the 0-0.1 m depth, with a difference of 0.24 t N ha⁻¹ between adjacent irrigated and non-irrigated soils. This decrease was less than that measured by Mudge *et al.* (2017) who reported differences of 0.58 t N ha⁻¹ to 0.3 m depth. On an annual basis, averaged across 10.6 years, which was the average time the sampled soils were irrigated in this thesis, 22.5 kg ha⁻¹ of soil N was lost each year. However, this calculation of annual loss was dependent on whether irrigation effects occur consistently through time or effects were most pronounced at the beginning of irrigation. If there was rapid loss of soil N stocks in the early stages of irrigation, it was possible that much of this N was leached from the soil or lost through denitrification. However, due to the low abundance of clay minerals in Pumice Soils, denitrification would be lower than N leaching (Cameron *et al.*, 2013). The rapid loss of N through leaching could potentially have adverse effects on water bodies within the surrounding catchment (Cameron *et al.*, 2013).

For the whole soil profile (0-0.6 m), the total difference in soil C was 6.63 t C ha⁻¹, however, this difference was not statistically significant ($P = 0.2$). For soil N, the total difference between irrigated and non-irrigated soils (0-0.6 m depth) was 0.17 t N ha⁻¹ ($P = 0.66$). To be more certain of differences for different depths, the number of paired sites would have needed to be greater.

5.3 Differences in C stocks vs irrigation duration

The second objective of this thesis was to determine any trends in the decrease in soil C and N in relation to irrigation duration.

There was no evidence of an effect of irrigation duration differences in soil C stocks for these Pumice Soils (Figure 4-7). Including the data from the Galatea Pumice Soils from Mudge *et al.* (2017), there was still no evidence for increasing losses of soil C with irrigation duration. Mudge *et al.* (2017) also concluded that there was insufficient evidence to determine whether irrigation effects on soil C and N occurred through time. Consequently, it is hypothesised that the main effect of irrigation on soil organic matter occurred in the early stages after the start of irrigation. This may also mean that after initial losses of soil C stocks, a new steady state equilibrium may be reached (Poeplau *et al.*, 2011; Mudge *et al.*, 2017). To determine whether the loss of soil C and N stocks occur with the initiation of irrigation, further research is required on properties that have been irrigated for shorter time periods e.g. 1-5 years.

5.4 Future research

Losses of soil C and N from irrigated Pumice Soils were significant to 0.2 m and 0.1 m depth respectively. However, there was a non-significant decrease in soil C from irrigated soil to 0.6 m depth ($P > 0.05$). It is hypothesised that this difference in soil C between adjacent irrigated and non-irrigated grazed pastures was mainly driven by increased microbial respiration due to elevated soil moisture content used to maintain pasture production during seasons with low precipitation (Borken & Matzner, 2009; Kelliher *et al.*, 2012). However, loss of soil C from leaching of dissolved organic C (DOC) also needs to be considered. A lysimeter experiment, with irrigation of waste water, showed an increase in leaching of DOC through intact soil cores (0.5 m diameter by 0.7 m depth) (Sparling *et al.*, 2006a). Losses of DOC may need to be considered as a secondary pathway of C loss to soil respiration of CO₂. The in-field ceramic suction cup sampler method used by Sparling *et al.* (2016) could be developed further to measure leached DOC on a larger scale with their recommended changes to the

sampling technique of increasing sampling intensity and shorted time frequency of sampling soil solution. However, installation of ceramic cups could be time constraining as well as expensive and there is no estimated total average for DOC leaching for specific soils. Knowledge of average DOC leaching rates is a global issue which makes it hard to determine amounts of leached DOC under land management types and climates (Sparling *et al.*, 2016).

As Schipper *et al.* (2014) demonstrated different soil orders displayed different responses to grazed land management through time. Allophanic and Gley Soils had a loss of soil C over time, while other soil orders did not change. The different soil properties of each soil order would have influenced soil C dynamics, making some soil orders more susceptible to loss of C than others. This research gives insight into the effects of irrigation on the Pumice Soil order. If I was able to measure a difference of 5.93 t C ha⁻¹ (6.9 %) and 0.24 t N ha⁻¹ (4.8 %) in Pumice Soils then other soil orders might also have losses soil C and N stocks, but broader soil order effects are currently unknown due to limited replication within different soil orders (Mudge *et al.*, 2017).

If we are able to determine the a significant difference in the response of soil C and N stocks to irrigation for different soil orders, it would be interesting to determine whether the response to irrigation was also evident following irrigation of other land uses, such as arable production. But first, we need to understand the mechanisms that cause the changes in soil C and N stocks between adjacent irrigated and non-irrigated grazed pastures. Determining the reasons for net changes in soil C and N stocks from irrigated land could be important for identifying management practices that focus on the retention of soil organic matter or developing mechanisms that could increase soil C retention.

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Appendix A

Preliminary documents

A.1 Participant information sheet and consent form

Participant information sheet



Project Title

Effects of Irrigation on Soil Carbon and Nitrogen in Pumice Soils

Purpose

This research is conducted as partial requirement for MSc (Research) in Earth Science. This project requires the researcher to choose a topic and conduct research on the topic through using surveys or interviews to gain knowledge of farm management, along with collected soil samples from various sites.

What is this research project about?

The aims of this research project are to determine whether adjacent irrigated and non-irrigated pastures, on Pumice Soils, have a net loss of soil carbon and nitrogen stocks, as previously demonstrated from other regions around New Zealand by Mudge et al. (2017). A supplementary aim is to determine trends in the loss of soil carbon and nitrogen in relation to time under irrigation, using multiple replicates within farms. Additional data from Pumice Soils will add to our current knowledge of the effects of irrigation on soil nutrients and soil organic matter. The data collected may encourage a change the way we irrigate our pastures to prevent losses of valuable soil carbon and nitrogen stocks.

What will you have to do and how long will it take?

In most cases, the researcher will want you to complete a farmer questionnaire. This should take about 15 minutes. The researcher may ask for relevant documents or sources accessible for this research, such as farm maps or map of irrigator path. You will be asked to give consent prior to filling out the farmer questionnaire.

What will happen to the information collected?

The information collected on farm management and analysed soil samples, will be used by the researcher to write a research report for the credit of a specific paper (MSc (Research) thesis). It is possible that published articles, presentations/conferences and posters, may be the outcome of the research. Only the researcher, supervisor and Landcare Research will be privy to the notes, documents and the paper written. Afterwards, notes, documents will be destroyed and recordings erased five years after publication. The researcher will keep questionnaires, relevant documents and a copy of the paper but will treat them with the strictest confidentiality. No participants will be named or self-identified in the publications and every effort will be made to disguise their identity.

Declaration to participants

If you take part in the study, you have the right to:

- Ask any further questions about the study that occurs to you during your participation;
- Be given access to a summary of findings from the study when it is concluded;
- Refuse to answer any particular question, and to withdraw from the study before...XX.XX.17..../once analysis has commenced on the data; and
- Withdraw from the study at any time

Who's responsible?

If you have any questions or concerns about the project, either now or in the future, please feel free to contact either:

Researcher:

Jamie Millar Phone: 022 361 7258

email: jamie.millar@hotmail.co.nz

Supervisor:

Louis Schipper Phone: 07 838 4468

email: schipper@waikato.ac.nz

Consent form for participants



Effects of Irrigation on Soil Carbon and Nitrogen in Pumice Soils

Consent Form for Participants

I have read the **Participant Information Sheet** for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that

Tick either option a) or option b)

- a) I am free to withdraw from the study before...XX.XX.17...., or to decline to answer any particular questions in the study. I understand I can withdraw any information I have provided up until the researcher has commenced analysis on my data; or
- b) I am free to withdraw from the study at any time, or to decline to answer any particular questions in the study. I understand I can withdraw any information I have provided up until the research being sent for publication

I agree to provide information to the researchers under the conditions of confidentiality set out on the **Participant Information Sheet**.

I agree to participate in this study under the conditions set out in the **Participant Information Sheet**.

Signed: _____

Name: _____

Date: _____

Additional Consent as Required

I agree / do not agree to my images (of paired sites) being used

Signed: _____

Name: _____

Date: _____

Researcher's Name and contact information: Jamie Millar:
Phone: 022 361 7258
Email: jamie.millar@hotmail.co.nz

Supervisor's Name and contact information: Louis Schipper:
Phone: +64 7 838 4468
Email: schipper@waikato.ac.nz

A.2 Farmer questionnaire

Information about paddock where soils will be sampled

Site ID _____

Farmer/contact name	
Contact phone number	
Address	
Email	
<u>Key information to determine if site is suitable</u>	
How long has 'contact' known the property?	
How many years has paddock been a <u>dairy farm</u>? <ul style="list-style-type: none"> • What was it prior if converted in last ~25 years 	
How many years has paddock been irrigated? <ul style="list-style-type: none"> • Has it been '<u>continuous</u>' (i.e. no years when irrigator broken for full season)? • Has the dryland area ever been irrigated? 	
25 year paddock history, major changes? <ul style="list-style-type: none"> • Contouring • Changes in fence positions • Long periods of <u>cropping</u> (i.e. not single fodder crop in relation to re-grassing). 	
Except for irrigation, is the paddock treated uniformly? <ul style="list-style-type: none"> • Fertiliser? • Grazing (i.e. don't stand off cows on dry end) • Crops/cultivation/egressing. Has whole paddock been done at once? 	
Any dairy effluent applied? <ul style="list-style-type: none"> • Does it go through pivot? • Any other fertiliser through pivot? 	
If so how much and how often?	
<u>Additional information to aid with data interpretation etc.</u>	
Total farm area (ha)	
Effective (milking) area (ha)	
Irrigated area (ha)	

Herd size, peak milking number, breed	
Replacements on/off farm	
Other drystock	
kg MS/season	
Typical irrigation rate (mm/hr or day) <ul style="list-style-type: none"> Note if pivot or k line 	
Typical <u>annual</u> irrigation (mm/y or days/y)	
How much N fertiliser is typically applied? <ul style="list-style-type: none"> What type When? Are the rates the same on the paddock's irrigated and non-irrigated areas? 	
What other fertiliser/lime is typically applied? <ul style="list-style-type: none"> What type When? How much? Are the rates the same on the paddock's irrigated and non-irrigated areas? 	
Any organic fertiliser applied (e.g. whey, chicken manure)? <ul style="list-style-type: none"> If so, what type, when and how much? 	
Any dairy effluent applied? <ul style="list-style-type: none"> If so how much and how often? 	
Is paddock usually grazed during winter?	
Is paddock strip grazed?	
If supplements fed, what type? <ul style="list-style-type: none"> How much? 	
How long has pdk been in pasture? <ul style="list-style-type: none"> i.e. when converted from forest? 	
How long have pastures been grazed by cows/cattle?	
Other grazers?	
How old is the present pasture?	

<p>Sward species last sown</p> <ul style="list-style-type: none"> • Method of sowing (i.e. direct drill, or after crop) 	
<p>Do cows typically congregate/rest more on the irrigated or dry area of the paddock, or vice versa? (not including 'grazing' time).</p>	
<p>Farm location</p>	

A.3 Paired site information sheets

Dryland area									
Paired site #		GE Id #		Date		Paddock Id			
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)									
Notes									

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East		North		Photos		
Series		NZSC				
Horizon						
FH						
Depth (cm)						
Colour						
Texture group						
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF						
Stones %						
Smop fine/coarse						
Drainage		Permeability		Depth class		
DSLO (cm)		Rooting depth		Root barrier		
Profile material class		Rock class		Rock - fines		
PM origin		Geology		Slope		
Landform	Ridge Shoulder	Backslope Spur	Hollow Foothlope	Terrace Channel	Valley Plateau	
Notes						

Irrigated area									
Paired site #		GE Id #		Date		Paddock Id			
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)									
Notes									

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East		North		Photos		
Series		NZSC				
Horizon						
FH						
Depth (cm)						
Colour						
Texture group						
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF						
Stones %						
Smop fine/coarse						
Drainage		Permeability		Depth class		
DSLO (cm)		Rooting depth		Root barrier		
Profile material class		Rock class		Rock - fines		
PM origin		Geology		Slope		
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes						

Appendix B

Human Ethics

Dr Karsten Zegwaard

Chair, Human Ethics
Faculty of Science & Engineering
Te Pūtaiao me te Mātauranga Pūkaha
The University of Waikato
Private Bag 3105
Hamilton, New Zealand

Telephone 64-7-838 4892
Email k.zegwaard@waikato.ac.nz



**THE UNIVERSITY OF
WAIKATO**
Te Whare Hōwhiri o Waikato

To: Jamie Millar
Date: 11-7-2017
From: Dr Karsten Zegwaard
Subject: Ethical approval for research
Application # FSEN-2017-4

Dear Jamie

The Faculty of Science and Engineering Human Research ethics sub-committee has considered your proposal "*Effects of Irrigation on Soil Carbon and Nitrogen in Pumice Soils*".

The proposal, as attached, is approved. If you wish to vary the terms of the approved application in any way, please contact me to request an amendment.

We wish you all the best with your research!

Signed



The University of Waikato

Application for Ethics Approval

Faculty of Science and Engineering Human Research Ethics Sub-committee (Social Sciences)

Application Instructions

This form should be used by FSEN students or staff to request approval to collect any data from human subjects in their research. Complete this form by deleting any instructions under each heading and inserting your information. Note you should read the Human Research Ethics Regulations prior to completing the application (see <http://calendar.waikato.ac.nz/assessment/ethicalConduct.html>). Ensure that your research supervisor has read through your application and approved its submission to the ethics committee before submitting it.

When complete, submit one unsigned **electronic** copy of the application to the Chair of the Committee, Dr Karsten Zegwaard (k.zegwaard@waikato.ac.nz). Please note that all documents should be in one Microsoft Word file, including any appendices.

You will receive feedback on your application within three weeks of submitting it. You will then be advised of any changes that may be required, and these should be addressed. Once amendments have been made, submit an electronic copy to Dr Karsten Zegwaard. You will then be advised if your application is approved. Once your application is approved, and signed by you, the chair and (if applicable) your supervisor, you may commence collecting data.

Any questions regarding whether an application is required for a study or on how to complete the application can be emailed to Dr Karsten Zegwaard (k.zegwaard@waikato.ac.nz).

The University of Waikato

Application for Ethics Approval

Faculty of Science and Engineering Human Research Ethics Sub-committee

1 Title of Project

Effects of Irrigation on Soil Carbon and Nitrogen in Pumice Soils

2 Researcher(s) and Contact Details

a Name of applicant (and student ID number is applicable)

Jamie Millar
1208171

b FSEN School/Centre/Unit

Earth Sciences

c Contact Address

264 Clyde Street, Hamilton East

d Phone number

0223617258

e Relevant paper applicant is enrolled in (if applicable)

ERTH595-17C (HAM)

f Other personnel

Supervisor: Louis Schipper

Research supervisor: Paul Mudge, Landcare Research

3. Research Design Proposal

a. Research Objectives

The aims of this research project are to determine whether adjacent irrigated and non-irrigated pastures, on Pumice Soils, have a net loss of soil carbon and nitrogen stocks, as previously demonstrated from other regions around New Zealand by Mudge *et al.* (2017). A supplementary aim is to determine trends in the loss of soil carbon and nitrogen in relation to time under irrigation, using multiple replicates within farms.

Additional data from Pumice Soils will add to our current knowledge of the effects of irrigation on soil nutrients and soil organic matter. The data collected may encourage a change the way we irrigate our pastures to prevent losses of valuable soil carbon and nitrogen stocks.

b. Research Methodology

Farm sites were selected using Google Earth imaging to find farms with irrigation. Potential landowners were identified from finding the address of the farm and then finding a landline number associated to the address. Landowners from properties of interest will be contacted by phone or onsite, to introduce them to the research and ask permission to work on their land. Notification of confidentiality and option of withdrawal of collected data, from participant and farm, will also be stated. Site specific information will be collected from the landowners during a site visit using a questionnaire (Appendix A). Once consent is given to gain access the property, along with a completed questionnaire, soil sampling can begin. The questionnaire will ask about the type of irrigation, duration, and other management practises that took place since irrigation started, to obtain the maximum amount of information needed to form a detailed data set on selected paired sites. The questionnaire also requires landowners/participants to fill out personal contact details, so they can be contacted by myself during the research.

Farmers will be provided with a brief overview of the project purpose and objectives (Appendix: A), along with a verbal discussion on the methods of soil sampling will be conducted.

c. Significance of Research Project

Additional data from Pumice Soils will add to our current knowledge of the effects of irrigation on soil nutrients and soil organic matter. The data collected may encourage a change in the way we irrigate our pastures to prevent losses of valuable soil carbon and nitrogen stocks.

Timetable of Events

Date Gain ethics approval
10.07.17

Date Gather research data
10.07.17

Date Analyse data
31.12.17

4 Research Procedures

a Procedure for recruitment of participants

Participants will be recruited over the phone or during physical introduction.

- Once a form of contact is established to the correct landowner, they will be contacted over the phone. I introduce myself as a MSc student from the University of Waikato and ask if I may talk to the person who is in charge of managing the farm.
- Once talking to the participant of interest, I indicate my reason for calling, establish what my research is about and if they would be interested in taking part in the research.
- When interest is indicated over the phone, confidentiality of collected information and data is established along with the knowledge that the participant may withdraw the collected information/data up to a given time.
- When the participant is on board, a physical introduction will be arranged along with a site investigation time.

Maximum of 20 participants will be recruited.

b Procedures in which research participants will be involved

Participants are required to fill out the provided questionnaire and indicate hazards on the property during time of sampling (Appendix: A). This task may take up to 15 mins. Participants are only required to fill out contact details and the key information section of the questionnaire, it is up to the participant if they want to provide further information of their farm management.

Once the desired paired sites are known to the participant, he or she will be required to show me to the sites or point me in the right direction, so I do not drive through areas that may harm me or disturb stock. Time taken to show me around the property depends on the size of the farm and distance between different

paired sites. Investigation of multiple paired sites may take up to 4 hours (four paired sites) max to a minimum of an hour (1-2 paired sites). Knowledge of farm hazards are to keep myself safe during sampling time, as each farm will be different.

After site investigation, a later date will be set to collect soil samples from the property. At the time of sample collection, participants will be contacted over the phone to ask when would be a suitable time to enter the property. They will then again be notified once I have left the property either over the phone or in person. From the time of collection onwards, participants will be notified of the analysed results from their farm through email, or of preference of communication.

After analysis of soil samples and knowledge of results, participants will be encouraged to keep in contact until the written thesis is complete. Participants will be invited to meet up and discuss the meaning of their personal farm results and/or the overall effects measured in the Reporoa District. If all participants are interested, a presentation on the overall results of the research can be arranged to be made to the participants as a group.

c Procedures for handling information and materials produced in the course of the research

People that have access to participant questionnaires, that is not myself, consist of Louis Schipper (Supervisor) and Paul Mudge (Landcare Research). All hard copy data collected, questionnaires, is kept separate from University of Waikato and Landcare Research access, they have to ask me to see the hard copies, if required. A locked space is to be organised. All electronic data that is summarised from questionnaires is kept on password protected devices. Any other electronic files created from information provided on the questionnaires will be non-self-identifying as each farm and participant will be coded along with no specific information based on production of milk solids (MS) and farm size.

All data and information collected from participants will be kept for a duration of five years after publication.

5 Ethical Concerns

a Access to participants

There is no pre-existing relationships between any of my participants and me. They may only know of me from high school association with their children or with my younger siblings. I will gain access to potential participants by back tracing addresses to landlines using the Reporoa District telephone directory. Then follow through with section 4.a.

b Informed consent

Appendix B-C will be used to when gaining informed consent from the participant. Appendix B will introduce the participant to the details behind the purpose of the research. Appendix C provides the participant with information on what the research is about, what is required of them as a participant and inform them on how the data collected, from the farm, may be utilised.

c Confidentiality

Following section 4.c and Appendix B, information collected from participants via the farmer questionnaire (Appendix: A), will not be used in a manner that enables participants and their properties to be identified in any publication. The location of the properties will be generalised, so no one can pin-point the location of sampled sites and the home of the participant. This will be done by providing a coding system for farm identification only known to me, and the use of generalised GSP coordinates. Any data that is published will not identify participants nor will it be self-identifying.

d Potential harm to participants

This research could cause stress to participants as some information that can be provided to me from the questionnaire, could reveal light on poor farm management practises, water allocation rescores consents and potential yearly earnings of the participants. This information is not directly asked in the questionnaire, however it could be calculated. Knowledge of such personal information is not my purpose for the questionnaire. If participants are uncomfortable with these

specific areas of the questionnaire, they are not obliged to fill them out.

For any reason stress is still felt by the participant, either at the time of acquiring informed consent or later on the research, they are notified that they are able to withdrawal information collected from the questionnaire and any unanalysed data from the property (Appendix: B-C).

e Participants right to decline

If participants decline to being involved in the research over the phone, any information on them will be removed and erased from the research. If informed consent is given and the participant has decided to withdraw during the research, they will have indicated previously in Appendix B-C as to which form of withdrawal they are comfortable with.

f Arrangements for participants to receive information

Participants will be notified of the results of their soil samples either through email, or their preferred form of contact. Once the overall research analysis is complete farmers will be given a summary of the results either in person or potentially in a presentation setting with all participants (section 4.b).

g Use of information

Any data collected and analysed from participants and the soil samples from their property, may be made publically available through publication of thesis, conference presentations, journal articles, and posters.

h Conflicts of interest

There may be a conflict of interest, if the participant is lead to believe that I think the use of irrigation is negative in terms of overall impact on environment. This will be resolved by specifying that I believe irrigation is necessary to gain maximum primary production on farm to increase annual farm production rates. Also that irrigation is not one of the most environmentally impacting farm management practise.

i Cultural sensitivity

There will be no cultural conflict as I was bought up in the community that they live in. The participant families may know each other and my family due to the school communities of Broadlands Primary School, Reporoa Primary School, and

Reporoa College.

j Compensation for participation

No compensation will be provided to participants, as it is at their own intention to join the research, there is no incentive provided. Participants may be sent a letter of thanks in the mail, to know that their participation in the research was much appreciated.

k Procedure for resolution of disputes

If any issues are raised by the participant they are welcome to contact me in the first instance. If the participant and I are unable to resolve the issue over the phone or in person, they will be advised to contact my supervisor at their discretion. Such contacts will be provided to the participant in Appendix B.

6 Ethical Statement

The project will follow the University of Waikato Human Research Ethics Regulations 2008 and the ethical guidelines of the NZARE and include the following. Informed consent of participants will be obtained, without coercion. Exploitation (or perception of exploitation) of researcher-participant relationship will be prevented. Privacy and confidentiality will be respected. The participant will own the raw material collected, and their requests regarding the material will be honored. Participation in the research will not impact academically on the participants.

7 **Legal Issues**

a Copyright

Copyright will not be an issue here. Intellectual property of the participants is provided from completed questionnaires. This intellectual property will be safe guarded, acknowledgement of participants will be made in a way that is non-self-identifying, as per the signed informed consent. Once soil samples are collected and analysed, the data produced from this analysis will belong to the University of Waikato

b Ownership of materials produced

Ownership is explained in Appendix B-C that the participant reads before giving informed consent.

c Any other legal issues relevant to the research

No further legal issues can be seen past what is presented above

8 **Place in which the research will be conducted**

Data will be gathered from participants in the comfort of their homes.

9 **Has this application in whole or part previously been declined or approved by another ethics committee?**

No, this is the first time submitting for approval.

10 **For research to be undertaken at other facilities under the control of another ethics committee, has an application also been made to that committee?**

N/A

11 **Further conditions**

State here: In the event of this application being approved, the undersigned agrees to request approval from the FSEN Human Research Ethics sub-committee for any change subsequently proposed.

12 **Applicant Request for Approval of Ethics Application**

This should be signed by the applicant and their research supervisor only after receiving feedback from the committee after the first electronic submission, as per instructions on the front of this document.

As the applicant:

For the study described, I agree to follow the conditions as specified in this application

Signed

J. Muller

Date

10/7/17

(if applicable)

As the applicant's research supervisor:

I am aware of this study and the conditions under which it is proposed to be undertaken

Signed

L. A. Schipper

Date

11/7/17

The ethics application is approved

Signed on behalf of the Committee


(Chairperson of the Committee or their nominee)

Date

11-7-17

Appendix: A

Farmer questionnaire (P. Mudge personal communications, November 17th 2016)

Farmer/contact name	
Contact phone number	
Address	
Email	
<u>Key information to determine if site is suitable</u>	
How long has 'contact' known the property?	
How many years has paddock been a <u>dairy farm</u>? <ul style="list-style-type: none"> • What was it prior if converted in last ~25 years 	
How many years has paddock been irrigated? <ul style="list-style-type: none"> • Has it been '<u>continuous</u>' (i.e. no years when irrigator broken for full season)? • Has the dryland area ever been irrigated? 	
25 year paddock history, major changes? <ul style="list-style-type: none"> • Contouring • Changes in fence positions • Long periods of <u>cropping</u> (i.e. not single fodder crop in relation to re-grassing). 	
Except for irrigation, is the paddock treated uniformly? <ul style="list-style-type: none"> • Fertiliser? • Grazing (i.e. don't stand off cows on dry end) • Crops/cultivation/regrassing. Has whole paddock been done at once? 	
Any dairy effluent applied? <ul style="list-style-type: none"> • Does it go through pivot? • Any other fertiliser through pivot? If so how much and how often?	
<u>Additional information to aid with data interpretation etc.</u>	
Total farm area (ha)	
Effective (milking) area (ha)	
Irrigated area (ha)	
Herd size, peak milking number, breed	

Replacements on/off farm	
Other drystock	
kg MS/season	
Typical irrigation rate (mm/hr or day) <ul style="list-style-type: none"> Note if pivot or k line 	
Typical <u>annual</u> irrigation (mm/y or days/y)	
How much N fertiliser is typically applied? <ul style="list-style-type: none"> What type When? Are the rates the same on the paddock's irrigated and non-irrigated areas? 	
What other fertiliser/lime is typically applied? <ul style="list-style-type: none"> What type When? How much? Are the rates the same on the paddock's irrigated and non-irrigated areas? 	
Any organic fertiliser applied (e.g. whey, chicken manure)? <ul style="list-style-type: none"> If so, what type, when and how much? 	
Any dairy effluent applied? <ul style="list-style-type: none"> If so how much and how often? 	
Is paddock usually grazed during winter?	
Is paddock strip grazed?	
If supplements fed, what type? <ul style="list-style-type: none"> How much? 	
How long has pdk been in pasture? <ul style="list-style-type: none"> i.e. when converted from forest? 	
How long have pastures been grazed by cows/cattle?	
Other grazers?	
How old is the present pasture?	
Sward species last sown <ul style="list-style-type: none"> Method of sowing (i.e. direct drill, or after crop) 	
Do cows typically congregate/rest more on the irrigated or dry area of the paddock, or vice versa? (not including 'grazing' time).	
Farm location	

Appendix: B

EFFECTS OF IRRIGATION ON SOIL CARBON AND NITROGEN STOCKS IN PUMICE SOILS

In New Zealand, irrigation of pastured land is increasing in areas with seasonal water deficits, such as Canterbury and the Central North Island. A recent study by Mudge *et al.* (2017), measured a decrease in soil carbon (C) (6.99 t C ha^{-1}) and nitrogen (N) (0.58 t N ha^{-1}) to 0.3 m depth in irrigated grazed pastures in comparison with an adjacent non-irrigated pasture. These losses may be due to increased soil organic matter decomposition relative to photosynthetic inputs. Losses of soil C can adversely affect soil quality, fertility and increase atmospheric CO₂ inputs. Furthermore, losses of soil N may increase N₂O atmospheric emissions and nitrate leaching into water bodies. It was unclear whether the losses measured by Mudge *et al.* (2017) were dependent on Soil Order and/or length of time pasture had been irrigated. Only seven paired sites were sampled by Mudge *et al.* (2017) on Pumice Soils in Galatea, despite the increasing use of irrigation on dairy farms in the Central North Island, Reporoa.

Additional data from Pumice Soils will add to our current knowledge of the effects of irrigation on soil nutrients and soil organic matter. The data collected may encourage a change in the way we irrigate our pastures to prevent losses of valuable soil C and N stocks. Maintaining soil organic matter could also benefit primary production and provide nutrient management within south-eastern catchment of the Waikato River.

Objectives

The aims of this research project are to determine whether adjacent irrigated and non-irrigated pastures, on Pumice Soils, have a net loss of soil C and N stocks, as previously demonstrated from other regions around New Zealand by Mudge *et al.* (2017). A supplementary aim is to determine trends in the loss of soil C and N in relation to time under irrigation, using multiple replicates within farms.

Appendix: C

Participant information sheet



Project Title

Effects of Irrigation on Soil Carbon and Nitrogen in Pumice Soils

Purpose

This research is conducted as partial requirement for MSc (Research) in Earth Science. This project requires the researcher to choose a topic and conduct research on the topic through using surveys or interviews to gain knowledge of farm management, along with collected soil samples from various sites.

What is this research project about?

The aims of this research project are to determine whether adjacent irrigated and non-irrigated pastures, on Pumice Soils, have a net loss of soil carbon and nitrogen stocks, as previously demonstrated from other regions around New Zealand by Mudge et al. (2017). A supplementary aim is to determine trends in the loss of soil carbon and nitrogen in relation to time under irrigation, using multiple replicates within farms. Additional data from Pumice Soils will add to our current knowledge of the effects of irrigation on soil nutrients and soil organic matter. The data collected may encourage a change the way we irrigate our pastures to prevent losses of valuable soil carbon and nitrogen stocks.

What will you have to do and how long will it take?

In most cases, the researcher will want you to complete a farmer questionnaire. This should take no longer than 15 minutes. The researcher may ask for relevant documents or sources accessible for this research, such as farm maps or map of irrigator path. You will be asked to give consent prior to filling out the farmer questionnaire.

What will happen to the information collected?

The information collected on farm management and analysed soil samples, will be used by the researcher to write a research report for the credit of a specific paper (MSc (Research) thesis). It is possible that published articles, presentations/conferences and posters, may be the outcome of the research. Only the researcher, supervisor and Landcare Research will be privy to the notes, documents and the paper written. Afterwards, notes, documents will be destroyed and recordings erased five years after publication. The researcher will keep questionnaires, relevant documents and a copy of the paper but will treat them with the strictest confidentiality. No participants will be named or self-identified in the publications and every effort will be made to disguise their identity.

Declaration to participants

If you take part in the study, you have the right to:

- Ask any further questions about the study that occurs to you during your participation;
- Be given access to a summary of findings from the study when it is concluded; and

(Tick one or the other)

EITHER,

- Refuse to answer any particular question, and to withdraw from the study before...31.10.17..../analysis has commenced on the data;

OR,

- Refuse to answer any particular question, and to withdraw from the study at any time

Who's responsible?

If you have any questions or concerns about the project, either now or in the future, please feel free to contact either:

Researcher:

Jamie Millar Phone: 022 361 7258 email:

jamie.millar@hotmail.co.nz

Supervisor:

Louis Schipper Phone: 07 838 4468 email: schipper@waikato.ac.nz

Consent form for participants



Effects of Irrigation on Soil Carbon and Nitrogen in Pumice Soils

Consent Form for Participants

I have read the **Participant Information Sheet** for this study and have had the details of the study explained to me. My questions about the study have been answered to my satisfaction, and I understand that I may ask further questions at any time.

I also understand that

Tick either option a) or option b)

- b) I am free to withdraw from the study before...31.10.17...., or to decline to answer any particular questions in the study. I understand I can withdraw any information I have provided up until the researcher has commenced analysis on my data; or
- b) I am free to withdraw from the study at any time, or to decline to answer any particular questions in the study. I understand I can withdraw any information I have provided up until the research being sent for publication

I agree to provide information to the researchers under the conditions of confidentiality set out on the **Participant Information Sheet**.

I agree to participate in this study under the conditions set out in the **Participant Information Sheet**.

Signed: _____

Name: _____

Date: _____

Additional Consent as Required

I agree / do not agree to my images (of paired sites) being used

Signed: _____

Name: _____

Date: _____

Researcher's Name and contact information: Jamie Millar:
Phone: 022 361 7258
Email: jamie.millar@hotmail.co.nz

Supervisor's Name and contact information: Louis Schipper:
Phone: +64 7 838 4468
Email: schipper@waikato.ac.nz

Appendix C

Field Data

C.1 Paired sites information

Dryland area									
Paired site #	F15-92B	GE Id #		Date	10.07.17	Paddock Id	92B		
Farm name	Twin Creeks								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	23	17	20	20	20	17	15	18	20
Notes	Large P clasts 35 cm down	P 30 cm down	Fine sands	Course sand 20-40 cm	P 20-40 Sand 45-60		Fine sand	Fine sand	Fine sand

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°32'***.**	Photos	IMG 0192-0196 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	Bw2			
FH						
Depth (cm)	20	35	60			
Colour	10YR 2/3	10YR 6/4	10YR 7/3			
Texture group	Sand/silt	Sand/gravel	Silt-gravel			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	0-1	2	3	3-2		
Stones %	0	<1	<2			
Smop fine/coarse						
Drainage	Well drained	Permeability	high	Depth class		
DSLO (cm)		Rooting depth	25 cm	Root barrier	-	
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	Rhyolite	
PM origin	Taupo	Geology	Low rolling slope	Slope	<5°	
Landform	Ridge	Backslope	Hollow	Terrace	Valley	

	Shoulder	Spur	Footslope	Channel	Plateau	
Notes	-some cores had sand with presence of charcoal - Pumice clasts vary in size between 30 -2 mm					

Irrigated area									
Paired site #	F15-92B	GE Id #		Date	10.07.17	Paddock Id	92B		
Farm name	Twin Rivers								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	18	20	20	18	18	25	20	20	20
Notes	Stones 5 mm size ~20 %	Large P clasts in A and 50 cm	Course sand with P and lithics	Course sand, P <5 mm size	Gravel sands 55-60 cm	Stained Bw or deep topsoil	Raw P 50-60 cm	Raw P 50-60 cm	High lithic, 50 % at 52-60 cm

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'**.**. **	North	38°32'**.**. **	Photos	IMG 0207-0211 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	Bw2	C (raw)		
FH						
Depth (cm)	20	35	50-60	60		
Colour	10YR 2/2	10YR 5/6	10YR 6/4	-		
Texture group	Sand	Sand	Course/fine sand	Gravel		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	0	2	2	3-2		
Stones %		~1		~20		
Smap fine/coarse						
Drainage	Well drained	Permeability	high	Depth class		
DSLO (cm)		Rooting depth	25-30 cm	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	Rhyolite	
PM origin	Taupo	Geology	Low rolling slope	Slope	< 5°	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	

Notes	-No charcoal visible like F15 D2
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Dryland area										
Paired site #	F15a-1	GE Id #		Date	11.07.17	Paddock Id	1			
Farm name	Twin Rivers									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9	
(cm)		15	16	22	22	20	20	20	20	
Notes	N/A	Mottles <10 %	30-60 cm course sand	35-60 cm course sand	35-60 cm course sand	48-60 cm sand	48-60 cm sand	56-60 cm sand	56-60 cm sand	

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°31'***.**	Photos	IMG 0233-0236 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	Bw2	C (raw)		
FH						
Depth (cm)	20	35	50	60		
Colour	10YR 2/2	10YR 6/4	10YR 7/3			
Texture group	Silt	Silt	Clay/silt	Sand		
Mottles ab/sz/dist/colour			<10 %	<10 %		
pH CSIRO						
NaF	2	3	0-2			
Stones %						
Smop fine/coarse						
Drainage	Moderate	Permeability	intermediate	Depth class		
DSLO (cm)		Rooting depth	40 cm	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<5°	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	-Core 1 not take, unable to remove from core tube as lower horizons were very wet, cemented to the inside of the tube due to the motion from the post driver -More clover present than F15a I3 -Cores 3-7 hard to remove from tubes					

Irrigated area									
Paired site #	F15a-1	GE Id #		Date	11.07.17	Paddock Id	1		
Farm name	Twin Creeks								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	17	17	17	14	17	22	18	20
Notes		Fine sand at 56 cm	Fine sand at 56 cm	Some A in Bw from core	Sandy 50 cm	-	Coarse gravely pumice Bw	-	Darker Bw than other cores

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°31'***.**	Photos	IMG 0220-0224 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	Bw2/Raw			
FH						
Depth (cm)	20	30	60			
Colour	10YR2/3	10YR7/4	10YR8/3			
Texture group	Silt	Sand/gravel	Fine-coarse sand			
Mottles ab/sz/dist/colour	-	-	-			
pH CSIRO						
NaF	1	3	1-2			
Stones %	-	<1	<1			
Smap fine/coarse						
Drainage	Good	Permeability	High	Depth class		
DSLO (cm)		Rooting depth	30 cm	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	Pasture mainly ryegrass					

Dryland area									
Paired site #	F15a-7	GE id #		Date	11.07.17	Paddock id	7		
Farm name	Twin Creeks								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	19	20	20	16	18	20	16	20
Notes	30-40 cm raw pumice	30-40 pumice	30 cm pumice (Shoulder)	25-35 pumice	20-38 pumice	26-40 pumice	30-40 pumice	30-45 pumice	28-45 pumice

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'**. **	North	38°31'**. **	Photos	IMG 0261-0264 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	Pumice	B2		
FH						
Depth (cm)	20	30	40	60		
Colour	10YR2/2	10YR7/6		10YR7/2		
Texture group	Silt/sandy	Sandy	Gravel +	Sand		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1	2-3	2	0-1		
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	High	Depth class		
DSLO (cm)		Rooting depth	40 cm	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	10 - <5	
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	<u>Terrace</u> Channel	Valley Plateau	
Notes	B2 appeared to be a non-welded ignimbrite					

Irrigated area									
Paired site #	F15a-7	GE Id #		Date	11.07.17	Paddock Id	7		
Farm name	Twin Creeks								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	12	12	15	20	15	17	20	18
Notes	High pumice in Bw	20-40 cm pumice	12-40 pumice	20-40 pumice	20-40 pumice	25-35 pumice	18-35 pumice	30-36 pumice	25-40 pumice

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°31'***.**	Photos	IMG 0246-0250 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	Pumice	B2		
FH						
Depth (cm)	15	25	35	60		
Colour	10YR2/2	10YR6/6		10YR7/2		
Texture group	Sandy	Sandy	Gravel	Sand		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1	2	3	3-0		
Stones %						
Smap fine/coarse						
Drainage	Good	Permeability	High	Depth class		
DSLO (cm)		Rooting depth	30 cm	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<8	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes						

Dryland area									
Paired site #	F15a-96	GE Id #		Date	12.07.17	Paddock Id	96		
Farm name	Twin Creeks								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	19	20	20	21	20	30	15	19	16
Notes	19-40 cm fine sand	20-30	20-40	20-35	20-35	No fine sand	30-46 fine sand	19-20	16-30

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'**.**. **	North	38°31'**.**. **	Photos	IMG 0275-0281 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	B2	Raw		
FH						
Depth (cm)	20	30	50	60		
Colour	10YR2/2	10YR5/6	10YR6/4	-		
Texture group	Sandy	Fine sand	Fine sand	Sand		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1	2	2-1	2		
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	high	Depth class		
DSLO (cm)		Rooting depth	30+ cm	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	< 5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	Core 6, may have been infilled pivot irrigator track, as paddock had been recently re-grass. Pasture 60 % ryegrass and 40 % clover					

Irrigated area									
Paired site #	F15a-96	GE Id #		Date	12.07.17	Paddock Id	96		
Farm name	Twin Creeks								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	19	15	15	20	35	14	15	19	22
Notes	15-30 large pumice	15-30 large pumice	20-30	20-30	Silty sand Bw	14-30 large pumice 20-25 Charcoal	20-30 +charcoal at 30 cm	19-25 large pumice 46-55 sand	22-30 large pumice

WP # (plot centre)	Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°31'***.**	Photos	
Series	NZSC			IMG 0289-0296 (Appendix F)	
Horizon	A	Bw	B2	Pumice	
FH					
Depth (cm)	20	30	50		
Colour	10YR2/2	10YR5/6	10YR7/3		
Texture group	Silt	Sandy loam	Fine snd	Sand/gravel	
Mottles ab/sz/dist/colour					
pH CSIRO					
NaF	1	2	1-2		
Stones %					
Smop fine/coarse					
Drainage	Good	Permeability	High	Depth class	
DSLO (cm)		Rooting depth	40 cm	Root barrier	
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	
PM origin	Taupo	Geology		Slope	<5
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau
Notes	Less clover present than Dry				

Dryland area									
Paired site #	F11-35	GE Id #		Date	28.11.17	Paddock Id	35		
Farm name	Tahi								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	17	20	20	17	20	22	16	22	20
Notes	Bw 17-30	Bw 20-32	Bw 20-30	No visible Bw	No visible Bw	Bw light in colour 22-30	Bw light in colour 16-30	Bw 22-30	Bw 20-35 Charcoal at 20-30

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°19'**.**. **	North	38°35'**.**. **	Photos	IMG 0538-0542 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	B			
FH						
Depth (cm)	20	35	60			
Colour	10YR4/4	10YR6/6	10YR7/3			
Texture group	Silty sand	Loamy sand	Loamy sand			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1	3	2-3			
Stones %		<1	<5			
Smop fine/coarse						
Drainage	good	Permeability	Moderate - high	Depth class		
DSLO (cm)		Rooting depth	40+	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Undulating</u>
Notes	Pasture dry, no resent rainfall. Fe ³⁺ present around pumice clasts at depth					

Irrigated area									
Paired site #	F11-35	GE Id #		Date	28.11.17	Paddock Id	35		
Farm name	Tahi								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	18	20	25	10	10	11	10	20	18
Notes	Pumice clasts BW 18-35 cm Stones: rhyolite 40-60	Mixed A/B horizon Bw to 60	Bw 25-40 cm	Bw 10-25 Stones present	Bw 10-20	Bw 11-40	Bw 10-40	Bw 20-35	Bw 18-30

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°19'***.**	North	38°35'***.**	Photos	IMG 0525-0529 (Appendix F)	
Series		NZSC				
Horizon	A	BW	B			
FH						
Depth (cm)	15	30	60			
Colour	10YR3/4	10YR6/6	10YR7/3			
Texture group	Sandy loam	Sandy loam	Sandy loam			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1	3	3			
Stones %	<1	<3	<5			
Smop fine/coarse						
Drainage	good	Permeability	Mod-high	Depth class		
DSLO (cm)		Rooting depth	40+	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Undulating</u>
Notes	Fe ³⁺ present at 40-60 cm around pumice clasts Very coarse textured soil					

Dryland area									
Paired site #	F11b-9	GE id #		Date	28.11.17	Paddock Id	9		
Farm name	Tahi								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	12	12	15	15	17	15	20	23	23
Notes	No Bw Large loose pumice at 12-60	Same as 1	Bw 15-25 Large loose pumice 25-60	Bw 15-25 Large loose P 25-60	Bw 17-22 Large loose P 22-60	No Bw Large loose P 15-60	Bw 20-35 Not much loose Pumice	Bw 23-30 Loose P 30-60	Bw 23-30 Loose P 30-60

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°19'**.**. **	North	38°34'**.**. **	Photos	IMG 0550-0554 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	B			
FH						
Depth (cm)	18	30	60			
Colour	10YR2/2	10YR6/4	10YR7/2			
Texture group	Loamy sand	Loamy sand	Loamy sand			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	4			
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	Mod-high	Depth class		
DSLO (cm)		Rooting depth	40	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley <u>Plateau</u>	<u>Undulating</u>
Notes	Soil was dry, colour was not done on moist soil					

Irrigated area									
Paired site #	F11b-9	GE Id #		Date	28.11.17	Paddock Id	9		
Farm name	Tahi								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	14	14	17	20	20	17	12	20	18
Notes	Bw 14-30 Charcoal 30-40	Bw 14-30	Bw 17-30 Charcoal 40-50	Bw 20-30	Bw 20-30	Bw 17-30	Bw 12-22	No Bw	Bw 18-30

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°19'***.**	North	38°34'***.**	Photos	IMG 0562-0566 (Appendix F)	
Series		NZSC				
Horizon	A	Bw	B			
FH						
Depth (cm)	17	30	60			
Colour	10YR3/3	10YR6/6	10YR7/3			
Texture group	silty	Loamy sand	Loamy sand			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	3			
Stones %						
Smap fine/coarse						
Drainage	Good	Permeability	Mod-high	Depth class		
DSLO (cm)		Rooting depth	40	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley <u>Plateau</u>	<u>Undulating</u>
Notes	Fe ³⁺ around pumice in lower horizons 7.5YR5/6					

Dryland area									
Paired site #	F8-52	GE Id #		Date	27.11.17	Paddock Id	52		
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	12	15	20	10	15	20	10	12
Notes	Bw 20-30 Sand 30-60	Bw 12-20 Sand 35-55	Bw 15-30 Sand/Pumice 50-60	No Bw S/P 30-60	Bw 10-15 Pumice 30-60	Bw 15-23	Dark Bw 20-40 Pumice 40-60	Bw 10-15 Sand 15-40	Bw 12-20 Sand 30-40

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°24'***.**	North	38°28'***.**	Photos	IMG 0512-0517 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B	Sand/Pumice		
FH						
Depth (cm)	15	20	40	60		
Colour	10YR2/3	10YR4/6	10YR7/3	N/A		
Texture group	Silty loam	Sandy loam	Sandy loam	Sand/gravel		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2	3	3	2		
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	Mod-high	Depth class		
DSLO (cm)		Rooting depth	30-40	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	>5	
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	Higher sand content than Irrigated Paddock was sprayed from new crop					

Irrigated area									
Paired site #	F8-52	GE Id #		Date	27.11.17	Paddock Id	52		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	15	20	15	15	8	10	20	5	20
Notes	Bw 15-30 Loose pumice 45-60	Loose P 32-55		Bw 15-20 Loose P 45-60	Bw 8-40	Bw 10-30 Loose P 30-60	Bw 20-30 Loose P 35-60	Bw 5-35 Loose P 35-60	Loose P 23-50

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting <u>Cores</u>	
East	176°24'***.**	North	38°28'***.**	Photos	IMG 0497-0502 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B	Pumice		
FH						
Depth (cm)	12	30	40	30-60		
Colour	10YR3/3	10YR5/8	10YR6/4			
Texture group	Loamy sand	Loamy sand	silty loam	Gravel		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2	3	3	2		
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	Mod-high	Depth class		
DSLO (cm)		Rooting depth	30-40	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin	Taupo	Geology		Slope	5	
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	Paddock was sprayed from new crop					

Dryland area									
Paired site #	F16-52	GE Id #		Date	29.11.17	Paddock Id		52	
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	13	13	13	12	15	15	15	15	17
Notes	Bw to 25 cm	Bw-30	Bw-25	Bw-22	Bw-23	Bw-25	Bw-25	Bw-25	Bw-30

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°20'**.**. **	North	38°29'**.**. **	Photos	IMG 0584-0588 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B			
FH						
Depth (cm)	14	23	40			
Colour	10YR3/3	10YR5/6	10YR7/3			
Texture group	Silt	Silt	Fine sand/silt			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	2			
Stones %						
Smop fine/coarse						
Drainage	Moderate to poor	Permeability	Good	Depth class		
DSLO (cm)		Rooting depth	40	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin		Geology		Slope	<3	
Landform	Ridge Shoulder	Backslope Spur	Hollow Foolslope	Terrace Channel	Valley Plateau	
Notes	High water table. Cores sampled to maximum depth of 40 cm. No obvious changes in pasture between irrigated and dry pasture.					

Irrigated area									
Paired site #	F16-52	GE Id #		Date	29.11.17	Paddock Id	52		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	13	17	17	12	13	20	15	16	15
Notes	Bw to 20	No Bw	Bw-25	Bw-25	Bw-20	Bw-40	Bw-35 Mixing of A and B from worms	Bw-25	Bw-30

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting <u>Cores</u>	
East	176°20'***.**	North	38°29'***.**	Photos	IMG 0573-0576 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B			
FH						
Depth (cm)	15	25	40			
Colour	10YR2/3	10YR5/6	10YR7/3			
Texture group	silt	silt	Fine sand/silt			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	2			
Stones %						
Smap fine/coarse						
Drainage	Mod-poor	Permeability	Good	Depth class		
DSLO (cm)		Rooting depth		Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin		Geology		Slope	<3	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	<u>Terrace</u> Channel	Valley Plateau	
Notes	High water table. Cores sampled to maximum depth of 40 cm, Fe ³⁺ present in B horizon around roots					

Dryland area									
Paired site #	F16-22	GE Id #		Date	25.07.17	Paddock Id	22		
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	16	12	18	15	13	16	16	15	16
Notes	Pumice at 30 cm and 38	P 30 and 40	P 25 and 35-40	P 15-22 Sand at 30	P 26 Sand 33-40	P 26-30 Sandy pumice 35-40	P 25-28 Sand 35-40	P 30 Sandy pumice 32-40	Pumice in A horizon

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°20'**. **	North	38°29'**. **	Photos	IMG 0407-0413 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B			
FH						
Depth (cm)	15	30	40			
Colour	10YR2/2	10YR5/6	10YR6/4			
Texture group	Silt	Silt	Silt			
Mottles ab/sz/dist/colour			<10 % ab			
pH CSIRO						
NaF	2-3	2	2-1			
Stones %						
Smop fine/coarse						
Drainage	Moderate	Permeability	Moderate	Depth class		
DSLO (cm)		Rooting depth	40	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin		Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Undulating</u>
Notes	No surface pugging like the irrigated area of the paddock, no standing water					

Irrigated area									
Paired site #	F16-22	GE Id #		Date	25.07.17	Paddock Id	22		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	18	18	13	15	15	16	16	14	11
Notes	Large pumice 30-40 cm	LP with charcoal @35	LP 30-40	LP 35-40	LP 30-40	LP 35-40	LP 35-40	LP 35-40	LP 25-40

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°20'***.**	North	38°29'***.**	Photos	IMG 0395-0398 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	Pumice			
FH						
Depth (cm)	16	30+	30-40			
Colour	10YR2/3	10YR6/4				
Texture group	Silt	Silt				
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2	3-2	2-1			
Stones %						
Smop fine/coarse						
Drainage	Mod-poor	Permeability	moderate	Depth class		
DSLO (cm)		Rooting depth	35	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin		Geology		Slope	<8	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Undulating</u>
Notes	Water table was visible for most cores at 40 cm depth. Charcoal was photographed then removed from soil core. The land surface was gently rolling towards surrounding terraces.					

Dryland area									
Paired site #	F16-16	GE Id #		Date	24.07.17	Paddock Id	16		
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	20	20	15	15	15	17	17	22
Notes	Sampled to 40 cm					to 40 cm	to 40 cm	to 40 cm	to 40 cm

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°20'***.**	North	38°29'***.**	Photos	IMG 0381-0385 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw				
FH						
Depth (cm)	18	30+				
Colour	10YR2/3	10YR5/6				
Texture group	Silt	Silt				
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3-1				
Stones %						
Smop fine/coarse						
Drainage	Moderate	Permeability	Mod-good	Depth class		
DSLO (cm)		Rooting depth	40+	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin		Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	Undulating
Notes	Water table was visible for most cores at 40 cm depth, Fe ³⁺ present in B horizon around roots. Bioturbation between A and B horizon with little to no pumice present.					

Irrigated area									
Paired site #	F16-16	GE Id #		Date	24.07.17	Paddock Id	16		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	23	19	20	8	20	19	19	15	18
Notes	Sampled to 40 cm								

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°20'***.**	North	38°29'***.**	Photos	IMG 0370-0373 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw				
FH						
Depth (cm)	19	30+				
Colour	10YR2/3	10YR5/6				
Texture group	Silt	Silt				
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF						
Stones %						
Smap fine/coarse						
Drainage	moderate	Permeability	Mod/good	Depth class		
DSLO (cm)		Rooting depth	40+	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines		
PM origin		Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	Undulating
Notes	Water table was visible for most cores at 40 cm depth, Fe ³⁺ present in B horizon around roots.					

Dryland area									
Paired site #	F18-47	GE Id #		Date	18.07.17	Paddock Id	47		
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	16	15	16	21	20	25	15	17	20
Notes		Coarse sand 15-20	Coarse sand 18-25	Pumice 21-25	Pumice 20-25	Pumice 25-55	Coarse sand 15-30 Pumice 40-55	Coarse sand 32-40 Pumice 45-52	Coarse sand 30-37 Pumice 45-52

WP # (plot centre)	Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'**.**. **	North	38°29'**. **. **	IMG 0354-0358 (Appendix F)	
Series		NZSC	Pumice		
Horizon	A	Bw	B		
FH					
Depth (cm)	20	30	60		
Colour	10YR2/3	10YR5/6	10YR6/3		
Texture group	Silt	Gravel sized pumice	Silty sand/pumice		
Mottles ab/sz/dist/colour					
pH CSIRO					
NaF	1-3	3	2-3		
Stones %					
Smop fine/coarse					
Drainage	Good	Permeability	High	Depth class	
DSLO (cm)		Rooting depth	40+	Root barrier	
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	
PM origin		Geology		Slope	< 5
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau
Notes					

Irrigated area									
Paired site #	F18-47	GE Id #		Date	18.07.17	Paddock Id	47		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	15	30*	13	20	20	17	19	19	19
Notes	Pumice 15-25 Gravel size	Dark at 25-30	Coarse pumice sand 22-30	Most of core P and light B	Pumice 21-27 gravel size	Pumice 17-45 gravel size	Pumice 19-45 gravel size	Coarse sand/gravel size pumice	Coarse sand/gravel size pumice

WP # (plot centre)	Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'**.**. **	North	38°29'**.**. **	IMG 0337-0344 (Appendix F)	
Series		NZSC	Pumice		
Horizon	A	Bw	B		
FH					
Depth (cm)	19	30	60		
Colour	10YR2/3	10YR7/6	10YR7/3		
Texture group	Silty sand	Sandy/gravel	Fine sand		
Mottles ab/sz/dist/colour					
pH CSIRO					
NaF	1-3	3	2		
Stones %					
Smap fine/coarse					
Drainage	Good	Permeability	High	Depth class	
DSLO (cm)		Rooting depth	30	Root barrier	
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	
PM origin		Geology		Slope	<5
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau
Notes	Core 2 excluded from sampling as it was too different (see photo 0339), was sampled twice and was unable to match the majority of cores. May have been an infilled old fire pit. 8 cores instead of 9.				

Dryland area									
Paired site #	F18-X	GE Id #		Date	18.07.17	Paddock Id	?		
Farm name									
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	30	22	17	20	15	15	10	20	17
Notes	Pumice sand size 30-36	Pumice sand size 22-26	Pumice sand size 17-22	Pumice sand size 20-22 No Bw	Pumice sand size 15-22 Alluvial sands	Pumice sand size 15-22 Alluvial sands	Pumice sand size 10-15 Large P 20-30	20-45 large sorted pumice	Pumice sand size 17-25 Large P 40-45

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°29'***.**	Photos	IMG 0304--0309 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B	Sand		
FH						
Depth (cm)	16	22	50	60		
Colour	10YR2/3	10YR6/6	10YR6/3			
Texture group	Silty sand	Gravel	Fine sand	Sand		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1-2	3	2-3	3		
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	high	Depth class		
DSLO (cm)		Rooting depth	30-40	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin		Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	Charcoal throughout profile < 5 mm in size. Paddock appears torn up in places (wild pigs maybe).					

Irrigated area									
Paired site #	F18-X	GE Id #		Date	18.07.17	Paddock Id	?		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	20	20	17	22	27	17	21	20
Notes	Sorted pumice 20-38 Alluvial sand 48	unsorted pumice 28-45 Alluvial sand 50-58	Sorted pumice 20-25 Alluvial sand 35-40	Pumice 17-25 Lithics ~20 % 30-55	Pumice 22-30	Pumice 27-35	Large pumice 20-25 Alluvial sand 50-60	Large pumice 30-35 Smaller gravel size P 40-60	Large pumice 20-25 Smaller gravel size P 35-41

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°21'***.**	North	38°29'***.**	Photos	IMG 0320-0326 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B	Sand		
FH						
Depth (cm)	20	30	50+	50-60		
Colour	10YR3/2	10YR4/6	10YR6/4			
Texture group	silt	Coarse sand/gravel	Coarse/fine sand	sand		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	1-2	3	3	3		
Stones %						
Smap fine/coarse						
Drainage	Good	Permeability	High	Depth class		
DSLO (cm)		Rooting depth	40	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin		Geology		Slope	<5	
Landform	Ridge Shoulder	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	
Notes	Charcoal throughout profile < 5 mm in size, not as much as seen in Dry. Land surface was more disturbed than Dry area (wild pigs?) Alluvial sands had quartz present, with 200 m distance from stream, as possible source.					

Dryland area									
Paired site #	F2-X	GE Id #		Date	01.08.17	Paddock Id	?		
Farm name	Drystock farm								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	22	20	21	18	22	23	20	21
Notes	Coarse sands/pumice 30-60 Quartz and charcoal present	Coarse sands/pumice 30-40 Pumice (10 mm) 40-60	Coarse sand 35-60, no pumice	Coarse sands/pumice 23-60	Coarse sands/pumice 35-60	Coarse sands/pumice 25-40 non-welded ignimbrite 40-60	Coarse sands/pumice 45-60 less quartz	Coarse sands/pumice 45-60 less quartz	Coarse sand: alluvial 30-55 non-welded ignimbrite 55-60

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°18'**.**. **	North	38°26'**. **. **	Photos	IMG 0421-0429 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B			
FH						
Depth (cm)	20	32	30-40	60		
Colour	10YR2/3	10YR4/6	10YR6/4			
Texture group	Sandy loam	sand	sand			
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	3	2		
Stones %			<5			
Smop fine/coarse						
Drainage	Good	Permeability	high	Depth class		
DSLO (cm)		Rooting depth	50+	Root barrier		
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	lithics	
PM origin		Geology		Slope	<10	
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Easy-mod rolling</u>
Notes	Charcoal present in sands					

Irrigated area									
Paired site #	F2-X	GE Id #		Date	01.08.17	Paddock Id	?		
Farm name	Irrigated dairy farm								
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	20	20	17	20	20	18	18	15	
Notes	Coarse sand 40-48 Dark staining + charcoal 48-55	Bw 20-60 sand	Sand 25-60	Sand 30-47 Coarse sand 47-50 Pumice 50-60	Pumice 27-60	Dark soil/ash 50-60	Coarse sand 40-50 Pumice + sand 50-60	Bw with P 15-33 Loose P 48-60	Loose P 33-60

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°18'***.**	North	38°26'***.**	Photos	IMG 0437-0445 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	Bw	B			
FH						
Depth (cm)	19	25	30-35	60		
Colour	10YR2/3	10YR5/6	10YR6/4			
Texture group	Sany loam	Fine sand	Fine sand	Sand/gravel		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	3	2		
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	high	Depth class		
DSLO (cm)		Rooting depth	30	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines	lithics	
PM origin		Geology		Slope	<8	
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Easy rolling</u>
Notes	All cores were different, most similar to 30-40 cm depth. However, recommend discarding 50-60 cm. Refer to photos 0437-0444.					

Dryland area									
Paired site #	F2-XX	GE Id #		Date	02.08.17	Paddock Id	?		
Farm name	Dry Stock farm								
A horizon depth	Core 1	Core 2	Core 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	21	17	19	20	25	19	21	23	21
Notes	Fine to coarse sand	Fine-coarse sand 50-60 + pumice	Burnt area 50-60	Fine-coarse sand 30-60 + pumice	Charcoal 50, removed	Loose P 30-60	Sand ~40-60	Sand + P 46-60	Loose P 40-60

WP # (plot centre)	Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°18'**.**. **	North	38°26'**.**. **	IMG 0475-0476	
Series		NZSC	Pumice	IMG 0484-0488	
Horizon	A	Bw	B		
FH					
Depth (cm)	20	30	40+		
Colour	10YR2/1	10YR5/6	10YR6/3		
Texture group	Sandy loam	sand	sand		
Mottles ab/sz/dist/colour					
pH CSIRO					
NaF	2-3	3	2		
Stones %					
Smop fine/coarse					
Drainage	Good	Permeability	High	Depth class	
DSLO (cm)		Rooting depth	50	Root barrier	
Profile material class		Rock class	Rhyolite/Pumice	Rock - fines	
PM origin		Geology		Slope	<5
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau
Notes	Same weather conditions as the 1 st but rained overnight. Fertiliser was applied during sampling Had to sample two 10x10 plots as the 20x20 was too close to the fence of the irrigated adjacent paddock and shoulder of the slope.				

Irrigated area									
Paired site #	F2-XX	GE Id #		Date	01.08.17	Paddock Id	?		
Farm name									
A horizon depth	Core 1 Pit 1	Core 2 Pit 2	Core 3 Pit 3	Core 4	Core 5	Core 6	Core 7	Core 8	Core 9
(cm)	21	21	21	17	18	22	20	20	20
Notes	Dark B 21-34 loose P 34-45 Buried A 45-60	Dark B 21-34 Fine sand 30-45 Buried A 45-60	Dark B 21-32 Loose P 32-50 Buried A 50-60	Fine sand 17-33 Loose P 33-46 Tephra 46-48 Buried A 48-60	Fine sand 18-37 Buried A 37-60?	Dark staining 22-46 Loose P 46-60	Dark B 20-25 Fine sand 25-40 Loose P 40-56 Tephra 56-60	Fine + coarse sand 20-35 Loose P 35-60	Fine sand 20-37 Loose P 37-60

WP # (plot centre)		Observer		Obsvn. type	Pit Auger Cutting Cores	
East	176°18'***.**	North	38°26'***.**	Photos	IMG 0455-0467 (Appendix F)	
Series		NZSC	Pumice			
Horizon	A	B	Bw	B	Pumice	
FH						
Depth (cm)	20	25-30	20-30	10 cm thick below 20	50	
Colour	10YR7/1	7.5YR3/2	10YR5/8	10YR6/4		
Texture group	Silty loam	Sandy loam	sand	sand		
Mottles ab/sz/dist/colour						
pH CSIRO						
NaF	2-3	3	3	3	2	
Stones %						
Smop fine/coarse						
Drainage	Good	Permeability	High	Depth class		
DSLO (cm)		Rooting depth	40	Root barrier		
Profile material class		Rock class	Rhyolite/ Pumice	Rock - fines		
PM origin		Geology		Slope	<8	
Landform	Ridge <u>Shoulder</u>	Backslope Spur	Hollow Footslope	Terrace Channel	Valley Plateau	<u>Easy rolling</u>
Notes	Core 6 removed due to dark staining of overall core, see photos 0462-0464. Buried A horizon, suggest removing soil from 50-60 cm					

Appendix D

Calculations

D.1 Root carbon %

100 g subsample of soil from a 0-0.10 m sample was taken to measure the root mass in 100 g of soil, to test whether removing roots from <2 mm sieved soil would impact the overall total C measurements.

- 100 g_{soil} had 0.11 g_{roots}
- Roots are about 50 % C
- Total soil C in Pumice Soils 12 % (Jackman, 1960)
 - Estimating 12 g C in 100 g of Pumice soil
- Root C accounts for 0.46 % of total C in 100 g_{soil} (equation D-2)
- $Total\ C\ t\ ha^{-1} = BD * 100 * 100 * 0.1\ m * \left(\frac{0.4583}{100}\right)$
- Estimated root C using a bulk density (BD) of 0.57 and 0.66 g cm⁻³ (McLaren & Cameron, 1996)
 - 2.6 t C ha⁻¹ (equation D-3)
 - 3.03 t C ha⁻¹ (equation D-4)
- Due to previous observed changes in total soil C from irrigated and non-irrigated pastures measured at 7.99 t C ha⁻¹ (Mudge *et al.*, 2017), an additional 2.6 to 3 t C ha⁻¹ from root C could make a big difference in total C measurements within 0-0.10 m depth.

$$0.11\ g\ roots * \frac{0.5}{1\ g\ roots} = 0.055\ g\ carbon\ in\ 100\ g\ soil \quad (D-1)$$

$$\frac{0.055\ g\ root\ C}{12\ g\ soil\ C} * 100 = 0.4583\ \% C \quad (D-2)$$

$$0.57\ g\ cm^{-3} * 100 * 100 * 0.1\ m * \left(\frac{0.4583}{100}\right) = 2.612\ t\ C\ ha^{-1} \quad (D-3)$$

$$0.66\ g\ cm^{-3} * 100 * 100 * 0.1\ m * \left(\frac{0.4583}{100}\right) = 3.025\ t\ C\ ha^{-1} \quad (D-4)$$

D.2 Statistical analysis of variance for C and N

Analysis of variance **DEPTH = 0 - 10 cm**

=====

Variate: Cum_C_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	1179.250	235.850	9.35	
Farm_num.Paired_site_num stratum	8	201.893	25.237	2.85	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	100.455	100.455	11.36	0.010
Farm_num.Treatment	5	66.225	13.245	1.50	0.291
Residual	8	70.754	8.844		
Total	27	1618.578			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 49.5

Treatment	Dry	Irr
	51.4	47.6
Farm_num Treatment	Dry	Irr
F11	48.8	50.3
rep.	2	2
F15	53.2	45.9
rep.	4	4
F16	51.5	47.5
rep.	3	3
F18	52.4	46.7
rep.	2	2
F2	50.2	48.9
rep.	2	2
F8	50.0	49.0
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	Treatment
rep.	14	unequal	
d.f.	8	8	
s.e.d.		4.21	min.rep
	1.12	3.32	max-min
		2.10	max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	12.89225	2.57845	11.61	
Farm_num.Paired_site_num stratum	8	1.77713	0.22214	3.74	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.26009	0.26009	4.38	0.070
Farm_num.Treatment	5	0.31117	0.06223	1.05	0.452
Residual	8	0.47490	0.05936		
Total	27	15.71554			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 4.70

Treatment	Dry	Irr
	4.79	4.60
Farm_num Treatment	Dry	Irr
F11	4.60	4.79
rep.	2	2
F15	4.90	4.50
rep.	4	4
F16	4.85	4.55
rep.	3	3
F18	4.83	4.56
rep.	2	2
F2	4.68	4.71
rep.	2	2
F8	4.73	4.66
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	14	unequal
d.f.	8	8
s.e.d.		0.345 min.rep
	0.092	0.272 max-min
		0.172 max.rep

Analysis of variance

=====

Variate: Cum_C_t_ha_EQM **without F11-35**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	430.922	86.184	4.34	
Farm_num.Paired_site_num stratum	7	139.030	19.861	2.37	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	129.572	129.572	15.47	0.006
Farm_num.Treatment	5	36.708	7.342	0.88	0.542
Residual	7	58.623	8.375		
Total	25	794.855			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 51.0

Treatment	Dry	Irr
	53.3	48.8
Farm_num Treatment	Dry	Irr
F11	52.0	50.0
rep.	1	1
F15	54.7	47.4
rep.	4	4
F16	53.0	49.0
rep.	3	3
F18	53.9	48.2
rep.	2	2
F2	51.7	50.4
rep.	2	2
F8	51.5	50.5
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	13	unequal
d.f.	7	7
s.e.d.		4.09 min.rep
	1.14	3.24 max-min
		2.05 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	4.55913	0.91183	5.86	
Farm_num.Paired_site_num stratum	7	1.08996	0.15571	2.58	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.37278	0.37278	6.18	0.042
Farm_num.Treatment	5	0.16520	0.03304	0.55	0.737
Residual	7	0.42221	0.06032		
Total	25	6.60929			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 4.85

Treatment	Dry	Irr
	4.97	4.73
Farm_num Treatment	Dry	Irr
F11	4.88	4.83
rep.	1	1
F15	5.05	4.65
rep.	4	4
F16	5.01	4.70
rep.	3	3
F18	4.99	4.72
rep.	2	2
F2	4.84	4.87
rep.	2	2
F8	4.89	4.82
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	13	unequal
d.f.	7	7
s.e.d.		0.347 min.rep
	0.096	0.275 max-min
		0.174 max.rep

Analysis of variance

=====

Variate: Cum_C_t_ha_EQM **DEPTH = 0 - 20 cm**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	3148.11	629.62	16.20	
Farm_num.Paired_site_num stratum	8	310.97	38.87	1.49	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	165.30	165.30	6.35	0.036
Farm_num.Treatment	5	219.27	43.85	1.68	0.244
Residual	8	208.29	26.04		
Total	27	4051.94			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 80.2

Treatment	Dry	Irr
	82.7	77.8
Farm_num Treatment	Dry	Irr
F11	79.6	80.9
rep.	2	2
F15	85.7	74.8
rep.	4	4
F16	83.4	77.1
rep.	3	3
F18	84.5	76.0
rep.	2	2
F2	78.8	81.7
rep.	2	2
F8	78.6	81.8
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment	
rep.	14	unequal	
d.f.	8	8	
s.e.d.		7.22	min.rep
	1.93	5.70	max-min
		3.61	max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	31.6890	6.3378	15.38	
Farm_num.Paired_site_num stratum	8	3.2963	0.4120	3.36	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.2864	0.2864	2.34	0.165
Farm_num.Treatment	5	1.1307	0.2261	1.85	0.210
Residual	8	0.9799	0.1225		
Total	27	37.3823			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 7.40

Treatment	Dry	Irr
	7.50	7.30
Farm_num Treatment	Dry	Irr
F11	7.29	7.50
rep.	2	2
F15	7.66	7.14
rep.	4	4
F16	7.67	7.13
rep.	3	3
F18	7.59	7.20
rep.	2	2
F2	7.16	7.64
rep.	2	2
F8	7.27	7.53
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	Treatment
rep.	14	unequal	
d.f.	8	8	
s.e.d.		0.495	min.rep
	0.132	0.391	max-min
		0.247	max.rep

Analysis of variance

=====

Variate: Cum_C_t_ha_EQM **without F11-35**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	1492.17	298.43	7.62	
Farm_num.Paired_site_num stratum	7	274.28	39.18	1.85	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	228.44	228.44	10.80	0.013
Farm_num.Treatment	5	175.57	35.11	1.66	0.261
Residual	7	148.03	21.15		
Total	25	2318.49			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 82.4

Treatment	Dry	Irr
	85.3	79.4
Farm_num Treatment	Dry	Irr
F11	85.6	79.1
rep.	1	1
F15	87.8	76.9
rep.	4	4
F16	85.5	79.2
rep.	3	3
F18	86.6	78.1
rep.	2	2
F2	80.9	83.8
rep.	2	2
F8	80.8	84.0
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	13	unequal
d.f.	7	7
s.e.d.		6.50 min.rep
	1.80	5.14 max-min
		3.25 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	14.46432	2.89286	7.21	
Farm_num.Paired_site_num stratum	7	2.80942	0.40135	4.32	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.50279	0.50279	5.41	0.053
Farm_num.Treatment	5	0.93679	0.18736	2.02	0.193
Residual	7	0.65009	0.09287		
Total	25	19.36340			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 7.62

Treatment	Dry	Irr
	7.76	7.48
Farm_num Treatment	Dry	Irr
F11	7.80	7.44
rep.	1	1
F15	7.88	7.36
rep.	4	4
F16	7.89	7.35
rep.	3	3
F18	7.81	7.42
rep.	2	2
F2	7.38	7.86
rep.	2	2
F8	7.49	7.75
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	13	unequal
d.f.	7	7
s.e.d.		0.431 min.rep
	0.120	0.341 max-min
		0.215 max.rep

Analysis of variance

=====

Variate: Cum_C_t_ha_EQM **DEPTH = 0 -30 cm**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	3540.27	708.05	15.58	
Farm_num.Paired_site_num stratum	8	363.46	45.43	0.97	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	140.32	140.32	3.00	0.122
Farm_num.Treatment	5	244.81	48.96	1.05	0.454
Residual	8	374.73	46.84		
Total	27	4663.59			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 88.7

Treatment	Dry	Irr
	91.0	86.5
Farm_num Treatment	Dry	Irr
F11	88.6	88.8
rep.	2	2
F15	94.1	83.3
rep.	4	4
F16	91.5	85.9
rep.	3	3
F18	92.9	84.6
rep.	2	2
F2	86.4	91.1
rep.	2	2
F8	86.4	91.0
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	14	unequal
d.f.	8	8
s.e.d.		9.68 min.rep
	2.59	7.65 max-min
		4.84 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	34.5982	6.9196	14.32	
Farm_num.Paired_site_num stratum	8	3.8664	0.4833	2.00	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.1498	0.1498	0.62	0.454
Farm_num.Treatment	5	1.3244	0.2649	1.10	0.431
Residual	8	1.9338	0.2417		
Total	27	41.8726			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.13

Treatment	Dry	Irr
	8.20	8.06
Farm_num Treatment	Dry	Irr
F11	8.04	8.22
rep.	2	2
F15	8.37	7.89
rep.	4	4
F16	8.36	7.90
rep.	3	3
F18	8.32	7.94
rep.	2	2
F2	7.81	8.45
rep.	2	2
F8	7.92	8.34
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	Treatment
rep.	14	unequal	
d.f.	8	8	
s.e.d.		0.695	min.rep
	0.186	0.550	max-min
		0.348	max.rep

Analysis of variance

=====

Variate: Cum_C_t_ha_EQM **without F11-35**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	1765.30	353.06	7.58	
Farm_num.Paired_site_num stratum	7	326.25	46.61	1.17	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	202.72	202.72	5.08	0.059
Farm_num.Treatment	5	228.79	45.76	1.15	0.418
Residual	7	279.17	39.88		
Total	25	2802.24			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 90.9

Treatment	Dry	Irr
	93.7	88.2
Farm_num Treatment	Dry	Irr
F11	95.8	86.1
rep.	1	1
F15	96.4	85.5
rep.	4	4
F16	93.8	88.1
rep.	3	3
F18	95.1	86.8
rep.	2	2
F2	88.6	93.3
rep.	2	2
F8	88.7	93.2
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	13	unequal
d.f.	7	7
s.e.d.		8.93 min.rep
	2.48	7.06 max-min
		4.47 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	16.1310	3.2262	6.61	
Farm_num.Paired_site_num stratum	7	3.4141	0.4877	2.27	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.3199	0.3199	1.49	0.262
Farm_num.Treatment	5	1.2329	0.2466	1.15	0.419
Residual	7	1.5056	0.2151		
Total	25	22.6035			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.36

Treatment	Dry	Irr
	8.47	8.25
Farm_num Treatment	Dry	Irr
F11	8.59	8.12
rep.	1	1
F15	8.60	8.11
rep.	4	4
F16	8.59	8.13
rep.	3	3
F18	8.55	8.17
rep.	2	2
F2	8.04	8.68
rep.	2	2
F8	8.15	8.57
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	
rep.	13	Treatment	
d.f.	7	unequal	
s.e.d.		7	
	0.182	0.656	min.rep
		0.519	max-min
		0.328	max.rep

Analysis of variance
 =====

Variate: Cum_C_t_ha_EQM **DEPTH = 0 - 40 cm**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	3637.51	727.50	16.17	
Farm_num.Paired_site_num stratum	8	359.97	45.00	0.78	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	110.98	110.98	1.92	0.203
Farm_num.Treatment	5	274.15	54.83	0.95	0.500
Residual	8	462.61	57.83		
Total	27	4845.22			

Tables of means
 =====

Variate: Cum_C_t_ha_EQM

Grand mean 91.8

Treatment	Dry	Irr
	93.8	89.8
Farm_num Treatment	Dry	Irr
F11	90.8	92.8
rep.	2	2
F15	97.0	86.5
rep.	4	4
F16	94.6	88.9
rep.	3	3
F18	96.0	87.6
rep.	2	2
F2	88.8	94.7
rep.	2	2
F8	89.7	93.9
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	
rep.	14	Treatment	
d.f.	8	unequal	
s.e.d.		10.75	min.rep
	2.87	8.50	max-min
		5.38	max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation F pr.	d.f.	s.s.	m.s.	v.r.
Farm_num stratum	5	35.6544	7.1309	14.68
Farm_num.Paired_site_num stratum	8	3.8847	0.4856	1.60
Farm_num.Paired_site_num.Treatment stratum				
Treatment	1	0.0848	0.0848	0.28 0.612
Farm_num.Treatment	5	1.4622	0.2924	0.96 0.493
Residual	8	2.4316	0.3040	
Total	27	43.5178		

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.40

Treatment	Dry	Irr
	8.46	8.35
Farm_num Treatment	Dry	Irr
F11	8.25	8.55
rep.	2	2
F15	8.62	8.18
rep.	4	4
F16	8.64	8.16
rep.	3	3
F18	8.59	8.21
rep.	2	2
F2	8.05	8.75
rep.	2	2
F8	8.19	8.61
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	14	unequal
d.f.	8	8
s.e.d.		0.780 min.rep
	0.208	0.616 max-min
		0.390 max.rep

Analysis of variance
 =====

Variate: Cum_C_t_ha_EQM **without F11-35**

Source of variation	d.f.	s.s.	m.s.	v.r.	F	pr.
Farm_num stratum	5	1937.11	387.42	7.98		
Farm_num.Paired_site_num stratum	7	339.78	48.54	0.97		
Farm_num.Paired_site_num.Treatment stratum						
Treatment	1	179.64	179.64	3.59	0.100	
Farm_num.Treatment	5	238.82	47.76	0.96	0.502	
Residual	7	349.96	49.99			
Total	25	3045.30				

Tables of means
 =====

Variate: Cum_C_t_ha_EQM

Grand mean 94.0

Treatment	Dry	Irr
	96.6	91.3
Farm_num Treatment	Dry	Irr
F11	98.3	89.6
rep.	1	1
F15	99.2	88.7
rep.	4	4
F16	96.8	91.1
rep.	3	3
F18	98.1	89.8
rep.	2	2
F2	91.0	96.9
rep.	2	2
F8	91.8	96.1
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	
rep.	13	Treatment	
d.f.	7	unequal	
s.e.d.		10.00	min.rep
	2.77	7.91	max-min
		5.00	max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	5	17.5623	3.5125	6.79	
Farm_num.Paired_site_num stratum	7	3.6197	0.5171	1.91	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.2552	0.2552	0.94	0.364
Farm_num.Treatment	5	1.2964	0.2593	0.96	0.500
Residual	7	1.8914	0.2702		
Total	25	24.6250			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.63

Treatment	Dry	Irr
	8.73	8.53
Farm_num Treatment	Dry	Irr
F11	8.84	8.41
rep.	1	1
F15	8.85	8.41
rep.	4	4
F16	8.87	8.39
rep.	3	3
F18	8.82	8.44
rep.	2	2
F2	8.28	8.98
rep.	2	2
F8	8.42	8.84
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	
rep.	13	Treatment	
d.f.	7	unequal	
s.e.d.		7	
	0.204	0.735	min.rep
		0.581	max-min
		0.368	max.rep

Analysis of variance
 =====

Variate: Cum_C_t_ha_EQM **DEPTH = 0 - 50 cm**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	3785.08	946.27	15.23	
Farm_num.Paired_site_num stratum	6	372.90	62.15	0.78	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	59.44	59.44	0.75	0.420
Farm_num.Treatment	4	314.35	78.59	0.99	0.480
Residual	6	477.03	79.51		
Total	21	5008.80			

Tables of means
 =====

Variate: Cum_C_t_ha_EQM

Grand mean 93.6

Treatment	Dry	Irr
	95.3	92.0
Farm_num Treatment	Dry	Irr
F11	92.2	95.1
rep.	2	2
F15	99.0	88.3
rep.	4	4
F18	97.9	89.3
rep.	2	2
F2	90.1	97.2
rep.	2	2
F8	91.6	95.7
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	11	unequal
d.f.	6	6
s.e.d.		12.61 min.rep
	3.80	9.97 max-min
		6.30 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F	pr.
Farm_num stratum	4	36.3666	9.0917	14.86		
Farm_num.Paired_site_num stratum	6	3.6701	0.6117	1.32		
Farm_num.Paired_site_num.Treatment stratum						
Treatment	1	0.0185	0.0185	0.04	0.848	
Farm_num.Treatment	4	1.1542	0.2885	0.62	0.664	
Residual	6	2.7850	0.4642			
Total	21	43.9944				

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.48

Treatment	Dry	Irr
	8.45	8.51
Farm_num Treatment	Dry	Irr
F11	8.32	8.64
rep.	2	2
F15	8.65	8.32
rep.	4	4
F18	8.66	8.30
rep.	2	2
F2	8.09	8.87
rep.	2	2
F8	8.25	8.71
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num	
rep.	11	unequal	
d.f.	6	6	
s.e.d.		0.964	min.rep
	0.291	0.762	max-min
		0.482	max.rep

Analysis of variance
 =====

Variate: Cum_C_t_ha_EQM **without F11-35**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	2073.77	518.44	7.19	
Farm_num.Paired_site_num stratum	5	360.50	72.10	0.99	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	123.73	123.73	1.71	0.248
Farm_num.Treatment	4	272.42	68.10	0.94	0.510
Residual	5	362.45	72.49		
Total	19	3192.86			

Tables of means
 =====

Variate: Cum_C_t_ha_EQM

Grand mean 96.4

Treatment	Dry	Irr
	98.9	94.0
Farm_num Treatment	Dry	Irr
F11	100.4	92.5
rep.	1	1
F15	101.8	91.1
rep.	4	4
F18	100.7	92.1
rep.	2	2
F2	92.9	100.0
rep.	2	2
F8	94.4	98.5
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	10	unequal
d.f.	5	5
s.e.d.		12.04 min.rep
	3.81	9.52 max-min
		6.02 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	19.2714	4.8179	6.84	
Farm_num.Paired_site_num stratum	5	3.5198	0.7040	1.57	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.0085	0.0085	0.02	0.896
Farm_num.Treatment	4	1.1549	0.2887	0.64	0.655
Residual	5	2.2425	0.4485		
Total	19	26.1973			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.76

Treatment	Dry	Irr
	8.78	8.74
Farm_num Treatment	Dry	Irr
F11	8.97	8.55
rep.	1	1
F15	8.93	8.60
rep.	4	4
F18	8.94	8.58
rep.	2	2
F2	8.37	9.15
rep.	2	2
F8	8.53	8.99
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num
rep.	10	Treatment
d.f.	5	unequal
s.e.d.		5
	0.300	0.947 min.rep
		0.749 max-min
		0.474 max.rep

Analysis of variance

=====

Variate: Cum_C_t_ha_EQM **DEPTH = 0 - 60 cm**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	3552.39	888.10	12.22	
Farm_num.Paired_site_num stratum	5	363.46	72.69	0.79	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	106.07	106.07	1.15	0.333
Farm_num.Treatment	4	243.03	60.76	0.66	0.648
Residual	5	462.64	92.53		
Total	19	4727.59			

Tables of means

=====

Variate: Cum_C_t_ha_EQM

Grand mean 93.7

Treatment	Dry	Irr
	96.0	91.4
Farm_num Treatment	Dry	Irr
F11	92.2	95.2
rep.	2	2
F15	99.1	88.2
rep.	4	4
F18	98.1	89.2
rep.	2	2
F2	90.9	96.4
rep.	1	1
F8	91.7	95.6
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	10	unequal
d.f.	5	5
s.e.d.	4.30	13.60 min.rep
		10.75 max-min
		6.80 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	34.4307	8.6077	12.48	
Farm_num.Paired_site_num stratum	5	3.4494	0.6899	1.26	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.0090	0.0090	0.02	0.903
Farm_num.Treatment	4	0.7900	0.1975	0.36	0.827
Residual	5	2.7290	0.5458		
Total	19	41.4080			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.47

Treatment	Dry	Irr
	8.49	8.45
Farm_num Treatment	Dry	Irr
F11	8.30	8.63
rep.	2	2
F15	8.64	8.30
rep.	4	4
F18	8.66	8.27
rep.	2	2
F2	8.15	8.78
rep.	1	1
F8	8.24	8.70
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num
rep.	10	Treatment
d.f.	5	unequal
s.e.d.		5
	0.330	1.045 min.rep
		0.826 max-min
		0.522 max.rep

Analysis of variance
 =====

Variate: Cum_C_t_ha_EQM **without F11-35**

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	1968.94	492.23	5.56	
Farm_num.Paired_site_num stratum	4	354.16	88.54	1.01	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	197.58	197.58	2.25	0.208
Farm_num.Treatment	4	171.49	42.87	0.49	0.747
Residual	4	350.48	87.62		
Total	17	3042.65			

Tables of means
 =====

Variate: Cum_C_t_ha_EQM

Grand mean 96.7

Treatment	Dry	Irr
	100.0	93.3
Farm_num Treatment	Dry	Irr
F11	100.5	92.9
rep.	1	1
F15	102.1	91.2
rep.	4	4
F18	101.1	92.2
rep.	2	2
F2	93.9	99.4
rep.	1	1
F8	94.7	98.6
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	9	unequal
d.f.	4	4
s.e.d.		13.24 min.rep
	4.41	10.47 max-min
		6.62 max.rep

Analysis of variance

=====

Variate: Cum_N_t_ha_EQM

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Farm_num stratum	4	18.5411	4.6353	5.57	
Farm_num.Paired_site_num stratum	4	3.3313	0.8328	1.53	
Farm_num.Paired_site_num.Treatment stratum					
Treatment	1	0.1229	0.1229	0.23	0.660
Farm_num.Treatment	4	0.6555	0.1639	0.30	0.865
Residual	4	2.1836	0.5459		
Total	17	24.8344			

Tables of means

=====

Variate: Cum_N_t_ha_EQM

Grand mean 8.76

Treatment	Dry	Irr
	8.85	8.68
Farm_num Treatment	Dry	Irr
F11	8.97	8.56
rep.	1	1
F15	8.94	8.59
rep.	4	4
F18	8.96	8.57
rep.	2	2
F2	8.45	9.08
rep.	1	1
F8	8.53	9.00
rep.	1	1

Standard errors of differences of means

Table	Treatment	Farm_num Treatment
rep.	9	unequal
d.f.	4	4
s.e.d.		1.045 min.rep
	0.348	0.826 max-min
		0.522 max.rep

Appendix E

Raw data

E.1 Moisture factor calculations

Table E-1: Moisture factor (MF) calculations from moisture content (MC %). Average MF (ave. MF) were used for further total C and N calculations (**Table E-2** and **Table E-3**).

Site	Depth	Non-irrigated (g)					Irrigated (g)							
		Air Dry	Oven Dry	Container	MC	MF	ave. MF	Air Dry	Oven Dry	Container	MC	MF	ave. MF	
F15	92B	0.0-0.1	5.07	4.784	0.89	5.98	1.06		5.04	4.779	0.88	5.46	1.05	
			5.07	4.794	0.89	5.76	1.06	1.06	4.96	4.697	0.9	5.60	1.06	1.06
	0.1-0.2	5.02	4.826	0.88	4.02	1.04		5.08	4.877	0.89	4.16	1.04		
		4.98	4.771	0.89	4.38	1.04	1.04	5.04	4.845	0.9	4.02	1.04	1.04	
	0.2-0.3	5.05	4.978	0.89	1.45	1.01		5	4.922	0.88	1.58	1.02		
		5.04	4.968	0.89	1.45	1.01	1.01	5.02	4.927	0.89	1.89	1.02	1.02	
	0.3-0.4	5.06	4.996	0.88	1.28	1.01		5.04	4.993	0.9	0.94	1.01		
		5.04	4.999	0.89	0.82	1.01	1.01	5.01	4.953	0.89	1.15	1.01	1.01	
	0.4-0.5	5.08	5.053	0.89	0.53	1.01		4.99	4.912	0.88	1.59	1.02		
		5.01	4.962	0.89	0.97	1.01	1.01	5.02	4.964	0.89	1.13	1.01	1.01	
0.5-0.6	5.02	4.998	0.89	0.44	1.00		5.02	4.96	0.9	1.21	1.01			
	5.03	5.015	0.88	0.30	1.00	1.00	5	4.936	0.89	1.30	1.01	1.01		
F15a	1	0.0-0.1	5.07	4.778	0.89	6.11	1.06		4.98	4.671	0.88	6.62	1.07	
			5.02	4.723	0.89	6.29	1.06	1.06	5.01	4.766	0.88	5.12	1.05	1.06
	0.1-0.2	5.03	4.812	0.89	4.53	1.05		5.01	4.784	0.89	4.72	1.05		

			5.03	4.792	0.89	4.97	1.05	1.05	5.01	4.804	0.89	4.29	1.04	1.05
	0.2-0.3		4.98	4.865	0.89	2.36	1.02		5.06	4.936	0.89	2.51	1.03	
		5	4.888	0.89	2.29	1.02	1.02	4.98	4.855	0.9	2.57	1.03	1.03	
	0.3-0.4		4.98	4.865	0.89	2.36	1.02		4.99	4.911	0.88	1.61	1.02	
		5.04	4.941	0.89	2.00	1.02	1.02	5.08	4.99	0.89	1.80	1.02	1.02	
	0.4-0.5		5.06	4.965	0.89	1.91	1.02		5.01	4.946	0.89	1.29	1.01	
		5.03	4.941	0.89	1.80	1.02	1.02	5.04	4.955	0.89	1.72	1.02	1.02	
	0.5-0.6		5.06	5.002	0.89	1.16	1.01		5.06	5.023	0.88	0.74	1.01	
		5.05	5.002	0.89	0.96	1.01	1.01	5.02	4.969	0.88	1.03	1.01	1.01	
			Non-irrigated				Irrigated							
Site	Depth		Air Dry	Oven Dry	Cont.	MC	MF	ave. MF	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF
F15a 7	0.0-0.1		5.07	4.778	0.88	6.11	1.06		5.03	4.745	0.88	6.01	1.06	
			4.98	4.695	0.89	6.07	1.06	1.06	5.03	4.75	0.88	5.89	1.06	1.06
	0.1-0.2		5.05	4.812	0.9	4.95	1.05		5.01	4.779	0.88	4.83	1.05	
			5.03	4.789	0.89	5.03	1.05	1.05	5.07	4.84	0.87	4.75	1.05	1.05
	0.2-0.3		5.02	4.854	0.87	3.42	1.03		4.99	4.844	0.88	3.01	1.03	
			5.05	4.888	0.87	3.31	1.03	1.03	-					1.03
	0.3-0.4		5.08	5.004	0.88	1.52	1.02		5.08	5.008	0.88	1.44	1.01	
		-						1.02	-					1.01
	0.4-0.5		5.09	5.042	0.88	0.95	1.01		5.09	5.049	0.88	0.81	1.01	
			5.03	5	0.87	0.60	1.01	1.01	5.07	5.029	0.89	0.82	1.01	1.01
	0.5-0.6		4.98	4.949	0.88	0.63	1.01		5.01	4.975	0.87	0.70	1.01	
			5.01	4.97	0.89	0.80	1.01	1.01	5.02	4.986	0.87	0.68	1.01	1.01
			<hr/>											
	96	0.0-0.1	5.04	4.728	0.88	6.60	1.07		5.01	4.96	0.89	1.01	1.01	
			4.98	4.685	0.88	6.30	1.06	1.06	5.06	4.942	0.89	2.39	1.02	1.02
		0.1-0.2	5.03	4.778	0.88	5.27	1.05		5.04	4.951	0.89	1.80	1.02	
			4.99	4.75	0.89	5.05	1.05	1.05	5	4.987	0.89	0.26	1.00	1.01
		0.2-0.3	5.03	4.934	0.88	1.95	1.02		5	4.934	0.9	1.34	1.01	

		0.3-0.4	5.01	4.906	0.89	2.12	1.02	1.02	5	4.919	0.89	1.65	1.02	1.01
			5	4.942	0.89	1.17	1.01		5.02	4.806	0.9	4.45	1.04	
		0.4-0.5	5.02	4.951	0.88	1.39	1.01	1.01	5.01	4.782	0.89	4.77	1.05	1.05
			5.02	4.978	0.88	0.84	1.01		4.99	4.779	0.88	4.42	1.04	
		0.5-0.6	5.03	4.983	0.89	0.94	1.01	1.01	5.04	4.713	0.9	6.94	1.07	1.06
			5	4.964	0.88	0.73	1.01		5.02	4.673	0.89	7.43	1.07	
			4.99	4.95	0.89	0.81	1.01	1.01	5	4.746	0.89	5.35	1.05	1.06
			Non-irrigated					Irrigated						
Site		Depth	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF
F16	22	0.0-0.1	4.99	4.696	0.89	6.26	1.06		5.06	4.736	0.9	6.84	1.07	
			5.06	4.757	0.89	6.37	1.06	1.06	5.03	4.717	0.89	6.64	1.07	1.07
		0.1-0.2	5.07	4.842	0.9	4.71	1.05		5.04	4.839	0.87	4.15	1.04	
			5.06	4.847	0.89	4.39	1.04	1.05	5.06	4.853	0.89	4.27	1.04	1.04
		0.2-0.3	5.01	4.87	0.9	2.87	1.03		5.01	4.899	0.87	2.27	1.02	
			5.01	4.884	0.89	2.58	1.03	1.03	5.01	4.882	0.87	2.62	1.03	1.02
		0.3-0.4	5.04	4.989	0.88	1.02	1.01		5.04	4.918	0.89	2.48	1.02	
			5.07	5.011	0.87	1.18	1.01	1.01	5.01	4.915	0.88	1.93	1.02	1.02
	16	0.0-0.1	5	4.728	0.87	5.75	1.06		5.02	4.745	0.88	5.80	1.06	
			5.02	4.751	0.86	5.66	1.06	1.06	5.02	4.734	0.88	6.04	1.06	1.06
		0.1-0.2	5.07	4.834	0.89	4.88	1.05		5.03	4.805	0.86	4.68	1.05	
			5	4.753	0.88	5.20	1.05	1.05	5.03	4.775	0.89	5.34	1.05	1.05
		0.2-0.3	5.04	4.954	0.87	1.74	1.02		5.05	4.896	0.88	3.15	1.03	
			5.01	4.896	0.88	2.33	1.02	1.02	5.02	4.867	0.87	3.14	1.03	1.03
		0.3-0.4	5	4.878	0.89	2.50	1.03		5.05	4.939	0.89	2.25	1.02	
			5.01	4.882	0.87	2.62	1.03	1.03	5.04	4.913	0.88	2.58	1.03	1.02
F18	47	0.0-0.1	5.04	4.746	0.88	6.19	1.06		5.06	4.79	0.89	5.64	1.06	
			5.02	4.717	0.88	6.42	1.06	1.06	5	4.767	0.88	4.89	1.05	1.05
		0.1-0.2	5.07	4.858	0.87	4.36	1.04		5.06	4.875	0.88	3.79	1.04	

			5	4.786	0.86	4.47	1.04	1.04	5	4.827	0.88	3.58	1.04	1.04
	0.2-0.3		5.05	4.96	0.88	1.81	1.02		5.01	4.938	0.89	1.46	1.01	
			5.02	4.939	0.88	1.64	1.02	1.02	5.01	4.94	0.87	1.42	1.01	1.01
	0.3-0.4		5	4.957	0.89	0.87	1.01		5.01	4.994	0.88	0.32	1.00	
			5	4.924	0.89	1.54	1.02	1.01	5.01	4.971	0.87	0.78	1.01	1.01
	0.4-0.5		5.01	4.947	0.88	1.27	1.01		5.06	5.027	0.88	0.66	1.01	
			5	4.966	0.89	0.68	1.01	1.01	5.02	4.989	0.87	0.62	1.01	1.01
	0.5-0.6		5.04	5.002	0.87	0.76	1.01		5	4.958	0.88	0.85	1.01	
			5.05	5.019	0.87	0.62	1.01	1.01	5.03	4.993	0.87	0.74	1.01	1.01
			Non-irrigated				Irrigated							
Site	Depth		Air Dry	Oven Dry	Cont.	MC	MF	ave. MF	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF
	X	0.0-0.1	5.01	4.708	0.89	6.41	1.06		5.05	4.738	0.88	6.59	1.07	
			5.02	4.633	0.98	8.35	1.08	1.07	5.05	4.713	0.88	7.15	1.07	1.07
		0.1-0.2	4.98	4.756	0.89	4.71	1.05		5.02	4.775	0.89	5.13	1.05	
			5.02	4.789	0.89	4.82	1.05	1.05	5.04	4.764	0.9	5.79	1.06	1.05
		0.2-0.3	5	4.905	0.89	1.94	1.02		5.02	4.854	0.88	3.42	1.03	
			5.02	4.91	0.87	2.24	1.02	1.02	5.03	4.862	0.87	3.46	1.03	1.03
		0.3-0.4	5.01	4.97	0.88	0.80	1.01		5.06	5.001	0.86	1.18	1.01	
			4.99	4.932	0.88	1.18	1.01	1.01	5.01	4.953	0.86	1.15	1.01	1.01
		0.4-0.5	5	4.967	0.88	0.66	1.01		5.04	4.994	0.85	0.92	1.01	
			5.03	4.982	0.88	0.96	1.01	1.01	4.99	4.954	0.86	0.73	1.01	1.01
		0.5-0.6	5	4.974	0.89	0.52	1.01		5.04	5.018	0.87	0.44	1.00	
			5.02	4.992	0.88	0.56	1.01	1.01	5.07	5.033	0.88	0.74	1.01	1.01
F2	XX	0.0-0.1	5.06	4.815	0.9	5.09	1.05		5.02	4.784	0.88	4.93	1.05	
			5.06	4.829	0.89	4.78	1.05	1.05	5.01	4.762	0.88	5.21	1.05	1.05
		0.1-0.2	5	4.808	0.87	3.99	1.04		5.02	4.889	0.87	2.68	1.03	
			5.03	4.855	0.87	3.60	1.04	1.04	5.06	4.909	0.87	3.08	1.03	1.03
		0.2-0.3	5.01	4.91	0.88	2.04	1.02		5	4.906	0.88	1.92	1.02	

			5.04	4.953	0.88	1.76	1.02	1.02	5.04	4.954	0.88	1.74	1.02	1.02
		0.3-0.4	5.02	4.97	0.87	1.01	1.01		5.05	5.024	0.87	0.52	1.01	
			5.05	5.01	0.87	0.80	1.01	1.01	5.05	5.005	0.88	0.90	1.01	1.01
		0.4-0.5	5.03	4.978	0.88	1.04	1.01		5.07	5.026	0.87	0.88	1.01	
			5.05	5.021	0.87	0.58	1.01	1.01	5.01	4.957	0.88	1.07	1.01	1.01
		0.5-0.6	5.2	5.004	0.86	3.92	1.04		N/A					
			5.01	5.009	0.86	0.02	1.00	1.02						
		Non-irrigated					Irrigated							
Site		Depth	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF
	X	0.0-0.1	5.01	4.771	0.88	5.01	1.05		5.05	4.807	0.91	5.06	1.05	
			5	4.784	0.86	4.52	1.05	1.05	5	4.788	0.89	4.43	1.04	1.05
		0.1-0.2	5.01	4.85	0.87	3.30	1.03		5.08	4.895	0.88	3.78	1.04	
			5.05	4.885	0.88	3.38	1.03	1.03	5.04	4.857	0.87	3.77	1.04	1.04
		0.2-0.3	5.03	4.936	0.87	1.90	1.02		5.06	4.965	0.88	1.91	1.02	
			5.04	4.96	0.87	1.61	1.02	1.02	5.01	4.937	0.88	1.48	1.01	1.02
		0.3-0.4	5.01	4.964	0.9	0.93	1.01		5.06	4.998	0.87	1.24	1.01	
			5.04	4.981	0.89	1.18	1.01	1.01	5.05	4.991	0.88	1.18	1.01	1.01
		0.4-0.5	5.04	4.984	0.87	1.12	1.01		5	4.966	0.87	0.68	1.01	
			5.02	5.003	0.88	0.34	1.00	1.01	5.02	4.982	0.86	0.76	1.01	1.01
		0.5-0.6	5.06	5.044	0.88	0.32	1.00		5	4.915	0.87	1.73	1.02	
			5.02	5.004	0.87	0.32	1.00	1.00	5.01	4.952	0.87	1.17	1.01	1.01
F8	52	0.0-0.1	5.02	4.782	0.86	4.98	1.05		5.05	4.813	0.87	4.92	1.05	
			5.01	4.765	0.88	5.14	1.05	1.05	5.01	4.771	0.87	5.01	1.05	1.05
		0.1-0.2	5.01	4.856	0.87	3.17	1.03		5.05	4.898	0.89	3.10	1.03	
			5	4.838	0.88	3.35	1.03	1.03	5	4.85	0.88	3.09	1.03	1.03
		0.2-0.3	5.05	4.951	0.88	2.00	1.02		5.03	4.92	0.88	2.24	1.02	
			5.03	4.944	0.86	1.74	1.02	1.02	5.03	4.913	0.88	2.38	1.02	1.02
		0.3-0.4	5.01	4.942	0.9	1.38	1.01		5	4.927	0.89	1.48	1.01	

			5.02	4.96	0.9	1.21	1.01	1.01	5.02	4.949	0.88	1.43	1.01	1.01
		0.4-0.5	5.03	5.002	0.87	0.56	1.01		5	4.934	0.89	1.34	1.01	
			5	4.98	0.88	0.40	1.00	1.00	-					1.01
		0.5-0.6	5.01	4.996	0.87	0.28	1.00		5.01	4.951	0.9	1.19	1.01	
			5.04	5.027	0.87	0.26	1.00	1.00	-					1.01
Site	Depth	Non-irrigated					Irrigated					ave. MF		
		Air Dry	Oven Dry	Cont.	MC	MF	Air Dry	Oven Dry	Cont.	MC	MF			
F11	35	0.0-0.1	5.02	4.726	0.88	6.22	1.06		5.03	4.789	0.89	5.03	1.05	
			5	4.681	0.92	6.81	1.07	1.07	5.04	4.773	0.89	5.59	1.06	1.05
	0.1-0.2	5.05	4.871	0.88	3.67	1.04		5.03	4.857	0.88	3.56	1.04		
		5.06	4.893	0.87	3.41	1.03	1.04	5.05	4.899	0.87	3.08	1.03	1.03	
	0.2-0.3	5.01	4.908	0.89	2.08	1.02		5.04	4.963	0.88	1.55	1.02		
		5.02	4.955	0.88	1.31	1.01	1.02	5	4.883	0.94	2.40	1.02	1.02	
	0.3-0.4	5.04	4.978	0.88	1.25	1.01		5.06	5.013	0.88	0.94	1.01		
		5.01	4.967	0.87	0.87	1.01	1.01	5.01	4.93	0.89	1.62	1.02	1.01	
	0.4-0.5	5.05	4.99	0.89	1.20	1.01		5.04	4.984	0.89	1.12	1.01		
		5	4.939	0.9	1.24	1.01	1.01	5	4.962	0.88	0.77	1.01	1.01	
0.5-0.6	5.02	4.946	0.9	1.50	1.01		5	4.962	0.89	0.77	1.01			
	5.02	4.96	0.89	1.21	1.01	1.01	5.06	4.994	0.91	1.32	1.01	1.01		
F11b	9	0.0-0.1	5.05	4.798	0.9	5.25	1.05		3.28	3.09	0.92	6.15	1.06	
			5.03	4.777	0.89	5.30	1.05	1.05	5	4.738	0.9	5.53	1.06	1.06
	0.1-0.2	5.07	4.914	0.89	3.17	1.03		5.02	4.832	0.89	3.89	1.04		
		5.06	4.911	0.88	3.03	1.03	1.03	5.04	4.848	0.87	3.96	1.04	1.04	
	0.2-0.3	5.07	4.958	0.89	2.26	1.02		5.01	4.935	0.88	1.52	1.02		
		5.06	4.933	0.9	2.57	1.03	1.02	5	4.914	0.88	1.75	1.02	1.02	
	0.3-0.4	5.05	4.969	0.9	1.63	1.02		5.03	4.927	0.92	2.09	1.02		
		5.01	4.887	0.89	2.52	1.03	1.02	5.01	4.913	0.89	1.97	1.02	1.02	
	0.4-0.5	5.06	5.012	0.88	0.96	1.01		5.05	5.001	0.87	0.98	1.01		

			5	4.941	0.9	1.19	1.01	1.01	5	4.94	0.88	1.21	1.01	1.01
	0.5-0.6		5.04	5	0.86	0.80	1.01		5.01	4.501	0.88	11.31	1.11	
			5.02	4.954	0.88	1.33	1.01	1.01	5	4.946	0.88	1.09	1.01	1.06
Site	Depth	Non-irrigated					Irrigated							
		Air Dry	Oven Dry	Cont.	MC	MF	ave. MF	Air Dry	Oven Dry	Cont.	MC	MF	ave. MF	
F16	52	0.0-0.1	5.01	4.728	0.88	5.96	1.06		5.02	4.755	0.88	5.57	1.06	
			5.02	4.732	0.88	6.09	1.06	1.06	5.04	4.764	0.89	5.79	1.06	1.06
	0.1-0.2	5.05	4.824	0.88	4.68	1.05		5	4.792	0.89	4.34	1.04		
		5.03	4.785	0.88	5.12	1.05	1.05	5.01	4.807	0.88	4.22	1.04	1.04	
	0.2-0.3	5	4.869	0.87	2.69	1.03		5.02	4.894	0.89	2.57	1.03		
		5.02	4.882	0.89	2.83	1.03	1.03	5	4.898	0.88	2.08	1.02	1.02	
	0.3-0.4	5	4.881	0.89	2.44	1.02		5.01	4.894	0.89	2.37	1.02		
5.01		4.895	0.89	2.35	1.02	1.02	5.06	4.951	0.89	2.20	1.02	1.02		

E.2 Data from soil lab analysis

Table E-2: Oven dry (OD) percent C and N, total > 2 mm pumice and roots weight (g), total OD soil mass (g), Fine earth bulk density (BD). Missing data denoted by *.

Sample number	Paired site number	Oven dry			Total > 2mm		< 2 mm				
		N % OD	C % OD	C:N ratio	>2 mm (g) (Air dried)	>2 mm (g) OD	Total OD soil (g)	BD (t/m ³)	Total soil (ha)	Cumulative Total soil (ha)	Reference Soil mass (t/ha)
F15D2 0.1	F15-92B	1.02	10.96	10.74	69.05	67.71	563	0.52	523	523	485
F15D2 0.2	F15-92B	0.48	5.53	11.56	129.64	127.72	621	0.58	578	1101	988
F15D2 0.3	F15-92B	0.08	1.05	12.43	131.70	131.39	700	0.65	651	1752	1516
F15D2 0.4	F15-92B	0.03	0.41	12.41	162.91	161.37	658	0.61	612	2364	2223
F15D2 0.5	F15-92B	0.02	0.28	12.70	161.52	160.38	677	0.63	630	2994	2913
F15D2 0.6	F15-92B	0.01	0.25	16.64	179.60	178.55	727	0.68	677	3671	3510
F15I2 0.1	F15-92B	0.98	10.35	10.55	73.52	82.40	521	0.48	485	485	485
F15I2 0.2	F15-92B	0.51	5.95	11.74	175.97	173.39	542	0.50	504	988	988
F15I2 0.3	F15-92B	0.13	1.56	11.70	198.03	196.74	568	0.53	528	1516	1516
F15I2 0.4	F15-92B	0.08	0.78	9.89	166.34	164.84	760	0.71	707	2223	2223
F15I2 0.5	F15-92B	0.12	0.49	4.07	160.29	159.06	741	0.69	689	2913	2913
F15I2 0.6	F15-92B	0.03	0.36	12.11	215.49	214.47	642	0.60	597	3510	3510
F15aD3 0.1	F15a-1	0.91	10.03	11.06	11.71	9.42	589	0.62	616	616	616
F15aD3 0.2	F15a-1	0.50	6.01	12.07	5.78	5.68	694	0.73	727	1343	1343
F15aD3 0.3	F15a-1	0.11	1.28	11.28	1.69	1.70	717	0.75	751	2093	2093
F15aD3 0.4	F15a-1	0.05	0.53	10.39	26.14	25.99	716	0.75	749	2842	2655
F15aD3 0.5	F15a-1	0.03	0.24	8.83	38.96	38.77	664	0.69	695	3537	3188
F15aD3 0.6	F15a-1	0.01	0.11	9.68	102.69	102.20	811	0.85	848	4385	3765
F15aI3 0.1	F15a-1	0.77	7.80	10.14	10.76	10.37	687	0.64	639	639	616

F15aI3 0.2	F15a-1	0.40	4.36	10.81	14.69	14.38	823	0.77	765	1404	1343
F15aI3 0.3	F15a-1	0.07	0.67	9.83	46.09	45.64	778	0.72	724	2128	2093
F15aI3 0.4	F15a-1	0.04	0.35	9.91	143.20	141.82	567	0.53	528	2655	2655
F15aI3 0.5	F15a-1	0.02	0.19	8.73	202.99	200.78	573	0.53	533	3188	3188
F15aI3 0.6	F15a-1	0.01	0.11	9.77	146.68	145.66	620	0.58	576	3765	3765
F15aD1 0.1	F15a-7	0.95	10.19	10.76	21.53	17.00	593	0.55	552	552	552
F15aD1 0.2	F15a-7	0.52	5.84	11.32	45.80	45.07	686	0.64	638	1189	1150
F15aD1 0.3	F15a-7	0.18	1.99	11.37	172.47	170.47	440	0.41	409	1599	1420
F15aD1 0.4	F15a-7	0.06	0.69	11.10	282.63	280.00	267	0.25	248	1847	1717
F15aD1 0.5	F15a-7	0.02	0.16	9.98	168.31	166.94	570	0.53	530	2377	2335
F15aD1 0.6	F15a-7	0.01	0.08	10.23	136.53	135.55	741	0.69	689	3066	3015
F15aI1 0.1	F15a-7	0.93	9.41	10.16	25.74	25.25	606	0.56	564	564	552
F15aI1 0.2	F15a-7	0.49	5.24	10.75	78.97	77.96	630	0.59	586	1150	1150
F15aI1 0.3	F15a-7	0.14	1.56	10.97	289.34	286.42	290	0.27	269	1420	1420
F15aI1 0.4	F15a-7	0.04	0.43	11.20	298.17	296.06	320	0.30	297	1717	1717
F15aI1 0.5	F15a-7	0.01	0.17	14.01	171.60	170.30	664	0.62	618	2335	2335
F15aI1 0.6	F15a-7	0.01	0.09	9.85	136.02	134.20	731	0.68	680	3015	3015
F15aD4 0.1	F15a-96	1.03	11.42	11.13	109.97	*	505	0.47	469	469	469
F15aD4 0.2	F15a-96	0.54	6.66	12.28	123.34	*	593	0.55	552	1021	1021
F15aD4 0.3	F15a-96	0.13	1.61	12.10	106.01	*	654	0.61	608	1629	1416
F15aD4 0.4	F15a-96	0.05	0.66	12.33	67.35	*	755	0.70	702	2331	1844
F15aD4 0.5	F15a-96	0.03	0.40	11.87	88.55	*	836	0.78	777	3109	2464
F15aD4 0.6	F15a-96	0.02	0.26	10.96	152.35	*	926	0.86	862	3970	3137
F15aI4 0.1	F15a-96	0.93	9.66	10.43	66.62	*	557	0.52	518	518	469
F15aI4 0.2	F15a-96	0.60	6.63	11.11	111.88	*	602	0.56	560	1078	1021
F15aI4 0.3	F15a-96	0.32	3.90	12.15	238.80	*	363	0.34	338	1416	1416

F15aI4 0.4	F15a-96	0.10	1.19	12.03	182.22	*	460	0.43	428	1844	1844
F15aI4 0.5	F15a-96	0.04	0.47	12.63	111.07	*	666	0.62	620	2464	2464
F15aI4 0.6	F15a-96	0.02	0.22	12.84	140.58	*	724	0.67	673	3137	3137
F18D1 0.1	F18-47	0.98	10.81	11.05	63.28	61.62	531	0.49	494	494	494
F18D1 0.2	F18-47	0.46	5.59	12.12	113.24	111.54	540	0.50	502	996	996
F18D1 0.3	F18-47	0.11	1.40	12.65	173.65	172.03	499	0.46	464	1460	1460
F18D1 0.4	F18-47	0.04	0.45	12.82	107.12	106.40	580	0.54	539	1999	1999
F18D1 0.5	F18-47	0.02	0.28	12.28	141.84	140.88	590	0.55	549	2548	2548
F18D1 0.6	F18-47	0.02	0.22	12.16	163.95	162.89	613	0.57	570	3118	3118
F18I1 0.1	F18-47	0.90	8.92	9.92	57.89	56.63	493	0.52	515	515	494
F18I1 0.2	F18-47	0.36	4.02	11.20	97.68	96.11	546	0.57	571	1087	996
F18I1 0.3	F18-47	0.08	0.92	11.05	149.32	147.90	394	0.41	413	1499	1460
F18I1 0.4	F18-47	0.03	0.37	10.97	88.45	87.76	520	0.54	545	2044	1999
F18I1 0.5	F18-47	0.02	0.23	10.33	123.15	122.43	509	0.53	533	2577	2548
F18I1 0.6	F18-47	0.01	0.14	11.15	95.26	94.76	661	0.69	692	3268	3118
F18D3 0.1	F18-X	1.00	10.14	10.15	49.67	49.01	623	0.58	580	580	515
F18D3 0.2	F18-X	0.50	5.58	11.10	147.12	145.49	528	0.49	492	1072	1043
F18D3 0.3	F18-X	0.15	1.60	10.47	159.66	158.31	522	0.49	486	1557	1407
F18D3 0.4	F18-X	0.04	0.54	13.25	107.19	106.54	601	0.56	559	2117	1859
F18D3 0.5	F18-X	0.03	0.32	10.67	154.10	153.35	587	0.55	547	2663	2436
F18D3 0.6	F18-X	0.01	0.14	14.00	113.92	113.34	901	0.84	839	3502	3290
F18I3 0.1	F18-X	0.98	9.89	10.05	54.37	53.43	553	0.51	515	515	515
F18I3 0.2	F18-X	0.56	6.01	10.75	144.68	142.67	568	0.53	529	1043	1043
F18I3 0.3	F18-X	0.21	2.44	11.80	234.99	232.60	391	0.36	363	1407	1407
F18I3 0.4	F18-X	0.06	0.74	12.17	237.43	235.91	486	0.45	452	1859	1859
F18I3 0.5	F18-X	0.04	0.36	9.00	173.28	172.24	620	0.58	577	2436	2436

F18I3 0.6	F18-X	0.01	0.16	16.00	178.74	177.94	917	0.85	854	3290	3290
F2D2 0.1	F2-X	0.72	7.67	10.71	36.37	35.86	719	0.67	669	669	669
F2D2 0.2	F2-X	0.38	4.38	11.64	62.43	61.74	771	0.72	717	1386	1386
F2D2 0.3	F2-X	0.13	1.45	11.47	124.35	123.35	770	0.72	716	2102	2102
F2D2 0.4	F2-X	0.04	0.42	11.79	146.77	146.00	785	0.73	730	2833	2833
F2D2 0.5	F2-X	0.02	0.32	13.57	160.27	159.66	754	0.70	701	3534	3515
F2D2 0.6	F2-X	0.03	0.41	16.22	174.80	174.16	684	0.64	636	4171	3973
F2I2 0.1	F2-X	0.64	6.85	10.66	28.98	28.67	753	0.70	701	701	669
F2I2 0.2	F2-X	0.46	5.12	11.05	38.31	37.89	807	0.75	751	1452	1386
F2I2 0.3	F2-X	0.11	1.28	11.19	67.53	66.92	792	0.74	737	2189	2102
F2I2 0.4	F2-X	0.05	0.53	11.58	120.84	120.20	729	0.68	678	2867	2833
F2I2 0.5	F2-X	0.03	0.44	13.59	174.00	173.41	696	0.65	648	3515	3515
F2I2 0.6	F2-X	0.04	0.72	16.25	185.04	184.29	492	0.46	458	3973	3973
F11bD2 0.1	F11b-9	0.68	7.63	11.17	117.17	114.03	622	0.58	579	579	492
F11bD2 0.2	F11b-9	0.28	3.32	12.00	185.63	183.14	608	0.57	566	1145	1075
F11bD2 0.3	F11b-9	0.12	1.63	13.87	292.32	288.65	505	0.47	470	1615	1615
F11bD2 0.4	F11b-9	0.03	0.38	12.16	268.55	265.78	484	0.45	450	2065	2065
F11bD2 0.5	F11b-9	0.01	0.16	11.71	265.75	263.14	497	0.46	463	2528	2528
F11bD2 0.6	F11b-9	0.01	0.13	12.69	302.34	299.52	575	0.53	535	3062	3062
F11bI2 0.1	F11b-9	0.70	7.53	10.72	107.97	105.46	529	0.49	492	492	492
F11bI2 0.2	F11b-9	0.27	3.07	11.28	176.56	174.10	626	0.58	583	1075	1075
F11bI2 0.3	F11b-9	0.10	1.10	10.80	233.67	231.01	604	0.56	562	1637	1615
F11bI2 0.4	F11b-9	0.03	0.55	16.43	238.05	225.29	611	0.57	568	2206	2065
F11bI2 0.5	F11b-9	0.01	0.26	17.89	218.09	216.21	621	0.58	578	2784	2528
F11bI2 0.6	F11b-9	0.01	0.10	11.32	265.09	263.09	783	0.73	729	3512	3062
F11D2 0.1	F11-35	0.61	6.85	11.31	152.85	147.21	434	0.40	404	404	404

F11D2 0.2	F11-35	0.27	3.17	11.82	181.02	178.93	680	0.63	633	1036	1036
F11D2 0.3	F11-35	0.09	1.03	11.62	218.05	216.13	739	0.69	688	1724	1724
F11D2 0.4	F11-35	0.03	0.36	11.38	214.28	212.74	733	0.68	682	2406	2406
F11D2 0.5	F11-35	0.03	0.23	8.62	248.58	246.96	774	0.72	720	3126	3126
F11D2 0.6	F11-35	0.01	0.16	13.24	252.66	251.35	831	0.77	773	3899	3899
F11I2 0.1	F11-35	0.66	7.55	11.43	147.15	144.05	596	0.55	555	555	404
F11I2 0.2	F11-35	0.23	2.71	11.81	193.08	194.56	659	0.61	613	1168	1036
F11I2 0.3	F11-35	0.09	1.05	12.00	208.15	206.46	771	0.72	717	1885	1724
F11I2 0.4	F11-35	0.05	0.66	12.60	225.32	223.84	778	0.72	724	2610	2406
F11I2 0.5	F11-35	0.02	0.27	12.51	255.42	282.36	836	0.78	778	3388	3126
F11I2 0.6	F11-35	0.01	0.15	11.16	283.87	253.96	861	0.80	802	4190	3899
F8D 0.1	F8-52	0.89	9.59	10.81	41.79	40.87	640	0.60	596	596	596
F8D 0.2	F8-52	0.25	3.44	13.84	71.05	70.15	737	0.69	686	1282	1282
F8D 0.3	F8-52	0.11	1.45	13.15	64.72	64.13	819	0.76	762	2044	1953
F8D 0.4	F8-52	0.05	0.64	12.57	143.20	142.34	834	0.78	776	2820	2437
F8D 0.5	F8-52	0.02	0.24	13.12	291.61	290.62	882	0.82	821	3641	2773
F8D 0.6	F8-52	0.02	0.21	13.12	266.85	265.94	766	0.71	713	4354	3038
F8I 0.1	F8-52	0.87	9.34	10.78	33.22	32.40	663	0.62	617	617	596
F8I 0.2	F8-52	0.28	3.91	13.85	51.80	51.10	726	0.68	676	1294	1282
F8I 0.3	F8-52	0.14	1.70	12.32	106.23	105.41	709	0.66	659	1953	1953
F8I 0.4	F8-52	0.07	0.80	11.21	233.86	232.83	520	0.48	484	2437	2437
F8I 0.5	F8-52	0.05	0.44	9.04	304.51	303.57	361	0.34	336	2773	2773
F8I 0.6	F8-52	0.02	0.24	10.78	293.01	281.66	285	0.27	266	3038	3038
F2D1 0.1	F2-XX	0.69	7.53	10.92	44.72	44.03	725	0.67	674	674	673
F2D1 0.2	F2-XX	0.39	4.48	11.43	51.74	51.40	837	0.78	779	1454	1419
F2D1 0.3	F2-XX	0.13	1.44	11.46	71.71	71.31	793	0.74	738	2192	2146

F2D1 0.4	F2-XX	0.06	0.52	9.24	97.59	165.40	758	0.71	706	2898	2713
F2D1 0.5	F2-XX	0.03	0.45	14.19	176.65	176.44	748	0.70	696	3594	3158
F2I1 0.1	F2-XX	0.77	7.95	10.33	26.92	26.52	642	0.67	673	673	673
F2I1 0.2	F2-XX	0.41	4.75	11.47	37.17	36.79	713	0.75	747	1419	1419
F2I1 0.3	F2-XX	0.17	1.94	11.72	46.47	46.02	694	0.73	727	2146	2146
F2I1 0.4	F2-XX	0.07	0.83	11.79	166.65	165.33	541	0.57	566	2713	2713
F2I1 0.5	F2-XX	0.07	0.81	12.45	233.25	232.00	426	0.45	446	3158	3158
F16D1 0.1	F16-22	0.85	9.18	10.85	6.46	5.51	699	0.65	650	650	650
F16D1 0.2	F16-22	0.38	4.26	11.36	16.57	16.34	777	0.72	723	1373	1373
F16D1 0.3	F16-22	0.08	0.95	11.38	90.34	89.10	729	0.68	678	2051	2051
F16D1 0.4	F16-22	0.03	0.33	11.27	110.47	109.26	679	0.63	631	2683	2683
F16I1 0.1	F16-22	0.80	8.42	10.53	4.11	3.92	700	0.65	651	651	650
F16I1 0.2	F16-22	0.33	3.61	10.97	1.05	1.03	875	0.81	814	1465	1373
F16I1 0.3	F16-22	0.06	0.72	11.33	56.83	56.12	776	0.72	722	2187	2051
F16I1 0.4	F16-22	0.03	0.36	11.08	201.64	199.29	535	0.50	498	2685	2683
F16D6 0.1	F16-16	0.69	7.06	10.22	0.92	0.93	774	0.72	720	720	714
F16D6 0.2	F16-16	0.42	4.56	10.96	0.19	0.17	851	0.79	792	1511	1511
F16D6 0.3	F16-16	0.06	0.74	11.38	0.00	0.00	899	0.84	836	2347	2337
F16D6 0.4	F16-16	0.03	0.25	9.27	0.55	0.54	920	0.86	856	3202	2985
F16I6 0.1	F16-16	0.67	6.63	9.96	1.78	1.64	768	0.71	714	714	714
F16I6 0.2	F16-16	0.38	4.19	10.92	0.53	0.62	880	0.82	819	1533	1511
F16I6 0.3	F16-16	0.07	0.73	10.56	0.10	0.09	863	0.80	803	2337	2337
F16I6 0.4	F16-16	0.02	0.21	9.16	0.20	0.21	698	0.65	649	2985	2985
F16D7 0.1	F16-52	0.78	7.76	9.89	7.48	6.85	718	0.67	668	668	668
F16D7 0.2	F16-52	0.44	4.33	9.83	3.76	3.67	749	0.70	697	1366	1366
F16D7 0.3	F16-52	0.09	0.96	10.33	0.85	0.77	821	0.76	764	2130	2130

F16D7 0.4	F16-52	0.04	0.41	10.00	0.30	0.28	941	0.88	876	3006	3006
F16I7 0.1	F16-52	0.72	7.13	9.93	6.22	5.99	724	0.67	674	674	668
F16I7 0.2	F16-52	0.38	3.94	10.50	1.81	1.78	830	0.77	773	1447	1366
F16I7 0.3	F16-52	0.09	0.96	10.44	0.20	0.24	859	0.80	799	2246	2130
F16I7 0.4	F16-52	0.03	0.37	12.00	0.76	0.79	920	0.86	856	3102	3006

E.3 Total carbon and nitrogen stocks

Table E-3: Total soil C and N stocks for fixed depth and Equivalent soil mass (EQM), with number of cores and sample volume.

Sample number	Paired site number	N (t/ha)	Cumulative N (t/ha)	Cumulative N (t/ha) EQM	C (t/ha)	Cumulative C (t/ha)	Cumulative C (t/ha) EQM	Number of cores	Sample Volume (m ³)
F15D2 0.1	F15-92B	5.35	5.35	5.03	57.4	57.4	53.9	9	0.001075
F15D2 0.2	F15-92B	2.77	8.11	7.81	32.0	89.4	85.7	9	0.001075
F15D2 0.3	F15-92B	0.55	8.66	8.59	6.8	96.2	95.3	9	0.001075
F15D2 0.4	F15-92B	0.20	8.86	8.82	2.5	98.7	98.1	9	0.001075
F15D2 0.5	F15-92B	0.14	9.00	8.99	1.8	100.5	100.3	9	0.001075
F15D2 0.6	F15-92B	0.10	9.10	9.08	1.7	102.1	101.7	9	0.001075
F15I2 0.1	F15-92B	4.75	4.75	4.75	50.2	50.2	50.2	9	0.001075
F15I2 0.2	F15-92B	2.55	7.31	7.31	30.0	80.1	80.1	9	0.001075
F15I2 0.3	F15-92B	0.71	8.01	8.01	8.2	88.4	88.4	9	0.001075
F15I2 0.4	F15-92B	0.56	8.57	8.57	5.5	93.9	93.9	9	0.001075
F15I2 0.5	F15-92B	0.84	9.41	9.41	3.4	97.3	97.3	9	0.001075
F15I2 0.6	F15-92B	0.18	9.59	9.59	2.2	99.5	99.5	9	0.001075
F15aD3 0.1	F15a-1	5.59	5.59	5.59	61.8	61.8	61.8	8	0.000956
F15aD3 0.2	F15a-1	3.62	9.21	9.21	43.7	105.4	105.4	8	0.000956
F15aD3 0.3	F15a-1	0.85	10.06	10.06	9.6	115.1	115.1	8	0.000956
F15aD3 0.4	F15a-1	0.38	10.44	10.36	4.0	119.0	118.1	8	0.000956
F15aD3 0.5	F15a-1	0.19	10.63	10.56	1.6	120.7	120.1	8	0.000956
F15aD3 0.6	F15a-1	0.10	10.72	10.66	0.9	121.6	121.0	8	0.000956
F15aI3 0.1	F15a-1	4.91	4.91	4.77	49.8	49.8	48.3	9	0.001075
F15aI3 0.2	F15a-1	3.08	8.00	7.87	33.3	83.1	81.8	9	0.001075

F15aI3 0.3	F15a-1	0.50	8.49	8.48	4.9	88.0	88.0	9	0.001075
F15aI3 0.4	F15a-1	0.19	8.68	8.68	1.9	89.9	89.9	9	0.001075
F15aI3 0.5	F15a-1	0.12	8.80	8.80	1.0	90.9	90.9	9	0.001075
F15aI3 0.6	F15a-1	0.06	8.86	8.86	0.6	91.5	91.5	9	0.001075
Sample number	Paired site number	N (t/ha)	Cumulative N (t/ha)	Cumulative N (t/ha) EQM	C (t/ha)	Cumulative C (t/ha)	Cumulative C (t/ha) EQM	Number of cores	Sample Volume (m ³)
F15aD1 0.1	F15a-7	5.22	5.22	5.22	56.2	56.2	56.2	9	0.001075
F15aD1 0.2	F15a-7	3.29	8.52	8.40	37.3	93.5	92.1	9	0.001075
F15aD1 0.3	F15a-7	0.72	9.23	9.01	8.1	101.6	99.2	9	0.001075
F15aD1 0.4	F15a-7	0.15	9.39	9.32	1.7	103.3	102.6	9	0.001075
F15aD1 0.5	F15a-7	0.08	9.47	9.47	0.8	104.2	104.1	9	0.001075
F15aD1 0.6	F15a-7	0.06	9.53	9.52	0.6	104.7	104.7	9	0.001075
F15aI1 0.1	F15a-7	5.22	5.22	5.13	53.1	53.1	52.1	9	0.001075
F15aI1 0.2	F15a-7	2.86	8.09	8.09	30.7	83.8	83.8	9	0.001075
F15aI1 0.3	F15a-7	0.38	8.47	8.47	4.2	88.0	88.0	9	0.001075
F15aI1 0.4	F15a-7	0.11	8.58	8.58	1.3	89.3	89.3	9	0.001075
F15aI1 0.5	F15a-7	0.07	8.66	8.66	1.0	90.4	90.4	9	0.001075
F15aI1 0.6	F15a-7	0.06	8.72	8.72	0.6	90.9	90.9	9	0.001075
F15aD4 0.1	F15a-96	4.82	4.82	4.82	53.6	53.6	53.6	9	0.001075
F15aD4 0.2	F15a-96	2.99	7.81	7.81	36.7	90.3	90.3	9	0.001075
F15aD4 0.3	F15a-96	0.81	8.62	8.48	9.8	100.1	98.6	9	0.001075
F15aD4 0.4	F15a-96	0.37	8.99	8.74	4.6	104.8	101.6	9	0.001075
F15aD4 0.5	F15a-96	0.26	9.26	9.05	3.1	107.9	105.5	9	0.001075
F15aD4 0.6	F15a-96	0.21	9.47	9.27	2.3	110.2	108.0	9	0.001075
F15aI4 0.1	F15a-96	4.80	4.80	4.40	50.1	50.1	45.8	9	0.001075
F15aI4 0.2	F15a-96	3.34	8.14	7.89	37.1	87.2	84.2	9	0.001075

F15aI4 0.3	F15a-96	1.08	9.23	9.23	13.2	100.4	100.4	9	0.001075
F15aI4 0.4	F15a-96	0.42	9.65	9.65	5.1	105.5	105.5	9	0.001075
F15aI4 0.5	F15a-96	0.23	9.88	9.88	2.9	108.4	108.4	9	0.001075
F15aI4 0.6	F15a-96	0.12	10.00	10.00	1.5	109.9	109.9	9	0.001075
Sample number	Paired site number	N (t/ha)	Cumulative N (t/ha)	Cumulative N (t/ha) EQM	C (t/ha)	Cumulative C (t/ha)	Cumulative C (t/ha) EQM	Number of cores	Sample Volume (m ³)
F18D1 0.1	F18-47	4.83	4.83	4.83	53.4	53.4	53.4	9	0.001075
F18D1 0.2	F18-47	2.31	7.14	7.14	28.0	81.5	81.5	9	0.001075
F18D1 0.3	F18-47	0.51	7.66	7.66	6.5	87.9	87.9	9	0.001075
F18D1 0.4	F18-47	0.19	7.85	7.85	2.4	90.4	90.4	9	0.001075
F18D1 0.5	F18-47	0.13	7.97	7.97	1.5	91.9	91.9	9	0.001075
F18D1 0.6	F18-47	0.10	8.08	8.08	1.3	93.2	93.2	9	0.001075
F18I1 0.1	F18-47	4.63	4.63	4.49	46.0	46.0	44.5	8	0.000956
F18I1 0.2	F18-47	2.05	6.68	6.53	23.0	69.0	67.1	8	0.000956
F18I1 0.3	F18-47	0.34	7.03	7.01	3.8	72.7	72.6	8	0.000956
F18I1 0.4	F18-47	0.18	7.21	7.20	2.0	74.7	74.6	8	0.000956
F18I1 0.5	F18-47	0.12	7.33	7.32	1.2	76.0	75.9	8	0.000956
F18I1 0.6	F18-47	0.09	7.41	7.40	1.0	76.9	76.7	8	0.000956
F18D3 0.1	F18-X	5.80	5.80	5.27	58.8	58.8	53.3	9	0.001074
F18D3 0.2	F18-X	2.47	8.27	8.18	27.5	86.3	85.3	9	0.001074
F18D3 0.3	F18-X	0.74	9.01	8.88	7.8	94.1	92.8	9	0.001074
F18D3 0.4	F18-X	0.23	9.24	9.16	3.0	97.1	95.9	9	0.001074
F18D3 0.5	F18-X	0.17	9.40	9.34	1.8	98.8	98.2	9	0.001074
F18D3 0.6	F18-X	0.08	9.49	9.48	1.2	100.0	99.8	9	0.001074
F18I3 0.1	F18-X	5.06	5.06	5.06	50.9	50.9	50.9	9	0.001074
F18I3 0.2	F18-X	2.95	8.02	8.02	31.8	82.7	82.7	9	0.001074

F18I3 0.3	F18-X	0.75	8.77	8.77	8.9	91.5	91.5	9	0.001074
F18I3 0.4	F18-X	0.27	9.04	9.04	3.3	94.9	94.9	9	0.001074
F18I3 0.5	F18-X	0.23	9.28	9.28	2.1	97.0	97.0	9	0.001074
F18I3 0.6	F18-X	0.09	9.36	9.36	1.4	98.3	98.3	9	0.001074
Sample number	Paired site number	N (t/ha)	Cumulative N (t/ha)	Cumulative N (t/ha) EQM	C (t/ha)	Cumulative C (t/ha)	Cumulative C (t/ha) EQM	Number of cores	Sample Volume (m ³)
F2D2 0.1	F2-X	4.79	4.79	4.79	51.3	51.3	51.3	9	0.001074
F2D2 0.2	F2-X	2.70	7.49	7.49	31.4	82.7	82.7	9	0.001074
F2D2 0.3	F2-X	0.90	8.40	8.40	10.4	93.1	93.1	9	0.001074
F2D2 0.4	F2-X	0.26	8.66	8.66	3.1	96.2	96.2	9	0.001074
F2D2 0.5	F2-X	0.16	8.82	8.82	2.2	98.4	98.4	9	0.001074
F2D2 0.6	F2-X	0.16	8.98	8.93	2.6	101.0	100.2	9	0.001074
F2I2 0.1	F2-X	4.50	4.50	4.31	48.0	48.0	45.9	9	0.001074
F2I2 0.2	F2-X	3.48	7.98	7.79	38.4	86.4	84.3	9	0.001074
F2I2 0.3	F2-X	0.84	8.83	8.79	9.4	95.9	95.5	9	0.001074
F2I2 0.4	F2-X	0.31	9.14	9.13	3.6	99.5	99.4	9	0.001074
F2I2 0.5	F2-X	0.21	9.35	9.35	2.9	102.4	102.4	9	0.001074
F2I2 0.6	F2-X	0.20	9.56	9.56	3.3	105.7	105.7	9	0.001074
F11bD2 0.1	F11b-9	3.96	3.96	3.50	44.2	44.2	39.0	9	0.001074
F11bD2 0.2	F11b-9	1.57	5.52	5.41	18.8	63.0	61.5	9	0.001074
F11bD2 0.3	F11b-9	0.55	6.07	6.07	7.7	70.6	70.6	9	0.001074
F11bD2 0.4	F11b-9	0.14	6.21	6.21	1.7	72.3	72.3	9	0.001074
F11bD2 0.5	F11b-9	0.06	6.28	6.28	0.8	73.1	73.1	9	0.001074
F11bD2 0.6	F11b-9	0.05	6.33	6.33	0.7	73.8	73.8	9	0.001074
F11bI2 0.1	F11b-9	3.46	3.46	3.46	37.1	37.1	37.1	9	0.001074
F11bI2 0.2	F11b-9	1.59	5.05	5.05	17.9	55.0	55.0	9	0.001074

F11bI2 0.3	F11b-9	0.57	5.62	5.60	6.2	61.2	61.0	9	0.001074
F11bI2 0.4	F11b-9	0.19	5.81	5.78	3.1	64.3	63.7	9	0.001074
F11bI2 0.5	F11b-9	0.08	5.89	5.86	1.5	65.8	65.3	9	0.001074
F11bI2 0.6	F11b-9	0.07	5.96	5.92	0.8	66.5	66.2	9	0.001074
Sample number	Paired site number	N (t/ha)	Cumulative N (t/ha)	Cumulative N (t/ha) EQM	C (t/ha)	Cumulative C (t/ha)	Cumulative C (t/ha) EQM	Number of cores	Sample Volume (m ³)
F11D2 0.1	F11-35	2.44	2.44	2.44	27.6	27.6	27.6	9	0.001074
F11D2 0.2	F11-35	1.70	4.14	4.14	20.0	47.7	47.7	9	0.001074
F11D2 0.3	F11-35	0.61	4.75	4.75	7.1	54.7	54.7	9	0.001074
F11D2 0.4	F11-35	0.22	4.96	4.96	2.5	57.2	57.2	9	0.001074
F11D2 0.5	F11-35	0.19	5.16	5.16	1.6	58.9	58.9	9	0.001074
F11D2 0.6	F11-35	0.09	5.25	5.25	1.3	60.1	60.1	9	0.001074
F11I2 0.1	F11-35	3.67	3.67	2.86	41.9	41.9	32.6	9	0.001074
F11I2 0.2	F11-35	1.41	5.07	4.92	16.6	58.6	56.7	9	0.001074
F11I2 0.3	F11-35	0.63	5.70	5.58	7.5	66.1	64.7	9	0.001074
F11I2 0.4	F11-35	0.38	6.08	6.00	4.8	70.9	69.8	9	0.001074
F11I2 0.5	F11-35	0.16	6.25	6.21	2.1	72.9	72.4	9	0.001074
F11I2 0.6	F11-35	0.11	6.35	6.31	1.2	74.1	73.7	9	0.001074
F8D 0.1	F8-52	5.28	5.28	5.28	57.1	57.1	57.1	9	0.001074
F8D 0.2	F8-52	1.70	6.99	6.99	23.6	80.7	80.7	9	0.001074
F8D 0.3	F8-52	0.84	7.83	7.74	11.1	91.8	90.8	9	0.001074
F8D 0.4	F8-52	0.39	8.23	8.09	5.0	96.7	95.0	9	0.001074
F8D 0.5	F8-52	0.15	8.37	8.21	2.0	98.7	96.6	9	0.001074
F8D 0.6	F8-52	0.11	8.49	8.28	1.5	100.2	97.4	9	0.001074
F8I 0.1	F8-52	5.35	5.35	5.22	57.7	57.7	56.1	9	0.001074
F8I 0.2	F8-52	1.91	7.26	7.24	26.4	84.1	83.8	9	0.001074

F8I 0.3	F8-52	0.91	8.17	8.17	11.2	95.3	95.3	9	0.001074
F8I 0.4	F8-52	0.35	8.51	8.51	3.9	99.2	99.2	9	0.001074
F8I 0.5	F8-52	0.16	8.68	8.68	1.5	100.7	100.7	9	0.001074
F8I 0.6	F8-52	0.06	8.74	8.74	0.6	101.3	101.3	9	0.001074
Sample number	Paired site number	N (t/ha)	Cumulative N (t/ha)	Cumulative N (t/ha) EQM	C (t/ha)	Cumulative C (t/ha)	Cumulative C (t/ha) EQM	Number of cores	Sample Volume (m ³)
F2D1 0.1	F2-XX	4.65	4.65	4.64	50.8	50.8	50.7	9	0.001074
F2D1 0.2	F2-XX	3.05	7.70	7.62	34.9	85.7	84.8	9	0.001074
F2D1 0.3	F2-XX	0.93	8.63	8.60	10.7	96.3	96.0	9	0.001074
F2D1 0.4	F2-XX	0.40	9.03	8.95	3.7	100.0	99.2	9	0.001074
F2D1 0.5	F2-XX	0.22	9.25	9.13	3.2	103.2	101.2	9	0.001074
F2I1 0.1	F2-XX	5.18	5.18	5.18	53.5	53.5	53.5	8	0.000955
F2I1 0.2	F2-XX	3.09	8.27	8.27	35.5	89.0	89.0	8	0.000955
F2I1 0.3	F2-XX	1.21	9.48	9.48	14.1	103.1	103.1	8	0.000955
F2I1 0.4	F2-XX	0.40	9.88	9.88	4.7	107.8	107.8	8	0.000955
F2I1 0.5	F2-XX	0.29	10.17	10.17	3.6	111.4	111.4	8	0.000955
F16D1 0.1	F16-22	5.50	5.50	5.50	59.6	59.6	59.6	9	0.001075
F16D1 0.2	F16-22	2.71	8.21	8.21	30.8	90.4	90.4	9	0.001075
F16D1 0.3	F16-22	0.56	8.77	8.77	6.4	96.9	96.9	9	0.001075
F16D1 0.4	F16-22	0.18	8.96	8.96	2.1	98.9	98.9	9	0.001075
F16I1 0.1	F16-22	5.21	5.21	5.20	54.8	54.8	54.8	9	0.001075
F16I1 0.2	F16-22	2.68	7.89	7.76	29.4	84.2	82.7	9	0.001075
F16I1 0.3	F16-22	0.46	8.35	8.31	5.2	89.5	89.0	9	0.001075
F16I1 0.4	F16-22	0.16	8.52	8.51	1.8	91.3	91.3	9	0.001075
F16D6 0.1	F16-16	4.97	4.97	4.93	50.8	50.8	50.4	9	0.001075
F16D6 0.2	F16-16	3.29	8.26	8.26	36.1	86.8	86.8	9	0.001075

F16D6 0.3	F16-16	0.54	8.80	8.80	6.1	93.0	93.0	9	0.001075
F16D6 0.4	F16-16	0.23	9.02	8.95	2.1	95.1	94.3	9	0.001075
F16I6 0.1	F16-16	4.75	4.75	4.75	47.3	47.3	47.3	9	0.001075
F16I6 0.2	F16-16	3.14	7.90	7.85	34.3	81.6	81.1	9	0.001075
F16I6 0.3	F16-16	0.56	8.45	8.45	5.9	87.5	87.5	9	0.001075
F16I6 0.4	F16-16	0.15	8.60	8.60	1.4	88.9	88.9	9	0.001075
F16D7 0.1	F16-52	5.24	5.24	5.24	51.9	51.9	51.9	9	0.001074
F16D7 0.2	F16-52	3.07	8.32	8.32	30.2	82.1	82.1	9	0.001074
F16D7 0.3	F16-52	0.71	9.02	9.02	7.3	89.4	89.4	9	0.001074
F16D7 0.4	F16-52	0.36	9.38	9.38	3.6	93.0	93.0	9	0.001074
F16I7 0.1	F16-52	4.84	4.84	4.81	48.1	48.1	47.7	9	0.001074
F16I7 0.2	F16-52	2.90	7.74	7.57	30.5	78.5	76.7	9	0.001074
F16I7 0.3	F16-52	0.74	8.48	8.44	7.7	86.2	85.8	9	0.001074
F16I7 0.4	F16-52	0.26	8.74	8.72	3.2	89.4	89.0	9	0.001074

E.4 Root $\delta^{13}\text{C}$ data

Table E-4: Root $\delta^{13}\text{C}$ data LECO from 0-0.1 m depth for non-irrigated and irrigated pasture.

Paired site number	Non-irrigated	Irrigated
F15a-96	(was discarded)	
F15-92B	-30.22	-30.09
F15a-7	-29.95	-30.22
F15a-1	-29.11	-30.57
F16-22	-29.62	-29.84
F16-16	-28.65	-29.89
F18-X	-29.58	-29.78
F2-XX	-30.51	-30.72
F2-X	-30.60	-30.90
F8-52	-29.45	-30.22
F11-35	-29.54	-29.51
F11b-9	-29.11	-29.31
F16-52	-29.98	-29.45
F18-47	-29.28	-30.02

Table E-5: Paired t-Test of two sample for means.

	<i>Non-irrigated</i>	<i>Irrigated</i>
Mean	-29.6625	-30.0397
Variance	0.327371	0.237711
Observations	13	13
Pearson Correlation	0.47856	
Hypothesized Mean Difference	0	
df	12	
t Stat	2.490799	
P(T<=t) one-tail	0.014195	
t Critical one-tail	1.782288	
P(T<=t) two-tail	0.02839	
t Critical two-tail	2.178813	

Appendix F

Paired site photos

This appendix is attached as a CD-ROM which includes the following:

- Photographs of the 14 paired sites
- Orientation of the centre of the plots, with images of north, east, south, and west.
- Cores, pasture vegetation and anything interesting that was visible at the time of sampling.