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Peat soil properties and seasonal surface elevation changes of drained Waikato peatlands

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Helena Georgette Layton

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Abstract

Peat surface oscillation (PSO) is the elastic seasonal change in peatland surface elevation that occurs as a response to changes in the water balance, and is an important self-regulating behaviour for sustaining hydrological functioning of intact peatlands. Drainage of peatlands leads to subsidence caused by peat consolidation, shrinkage and oxidation, which results in a non-reversible lowering of the peat surface. In the Waikato, 80% of peatlands have been drained and are now under agricultural and horticultural land uses, with subsidence rates around 20 mm y^{-1}. Ongoing monitoring of subsidence is challenged by a lack of knowledge of PSO behaviour. This study is the first of its kind to investigate PSO in drained peatlands at a regional scale.

This study investigated peat properties and hydrological and PSO regimes of the eleven study sites that comprise a Waikato regional drained peatland monitoring. These sites were under three different land uses, being dairy and dry stock farms, and blueberry orchards. Peat soil physical and chemical properties were used to determine the effect land use has on both peat soil properties and PSO. PSO was measured using the paired pressure transducer method and soil cores were taken from each site to measure bulk density, volumetric moisture content (VMC), porosity, shrinkage characteristics, carbon to nitrogen ratios (C/N), organic matter fractions (OMf), with additional grab samples taken for pH analysis.

There were general trends of decreasing pH and bulk density, and increasing porosity, C/N and OMf with increasing depth. The agricultural sites (dairy and dry stock) had greater degradation than the blueberry sites in the near surface peat but there was less of a difference in peat properties between land uses deeper in the profile. All of the study sites had higher bulk densities, and lower porosities and OMf than commonly reported in intact peatlands. These results show that land management can have a major effect on near surface peat properties and can degrade peat further than just drainage alone.

Reversible surface elevation changes were observed at all study sites, which followed a similar seasonal pattern but with different magnitudes of shrink and swell. There did not appear to be a relationship between land use or drainage history and magnitude of PSO.

Although the seasonal surface elevation changes broadly followed changes in water table depth, there did not appear to be an association between magnitude of surface elevation change and depth to the water table, in contrast to PSO studies in wetlands. The magnitude of PSO was reduced at the majority of the sites compared to previous measurements in intact peatlands, but some sites were relatively large compared to international studies of drained peatlands. There was some evidence that subsidence was occurring at all of the study sites. The results of this study have provided more detail than previously given in the literature for short-term, seasonal and annual PSO regimes.

Overall, this study found that PSO in drained peatlands is highly variable and the drivers of PSO are likely very complex. These results can be used to help further improve long-term monitoring of peat subsidence demonstrate the importance of high-resolution measurements for accurate monitoring of annual PSO cycles.

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Chapter One

Introduction

1.1 Background

Peatlands globally comprise only 2% of the Earth's land surface area and yet they store up to 20% of the world's soil carbon (Temmink *et al.*, 2022). Carbon storage in peatlands is facilitated by low rates of organic matter decomposition under high and stable water table regimes (Clymo *et al.*, 1998), which has led to peatlands becoming major carbon sinks in the global carbon cycle over millennial timescales (Gorham, 1991; Clymo *et al.*, 1998; Joosten & Clarke, 2002; Temmink *et al.*, 2022). Drainage allows for the development of peatlands for agriculture, horticulture and peat mining (Joosten & Clarke, 2002). Drainage-induced lowering of the water table results in drainage of macropores, allowing air to be introduced into the peat matrix and accelerating the rate of decomposition via microbially mediated aerobic reactions (Kellner, 2003; Dawson *et al.*, 2010; Krause *et al.*, 2021). This, in turn, leads to a permanent loss of the peat substrate and the release of CO_2 to the atmosphere; hence, drained peatlands become major carbon sources (Gorham, 1991; Qiu *et al.*, 2021). Peatland surface subsidence is also initiated by drainage due to changes in the peat physical properties and loss of organic matter by oxidation (Hooijer *et al.*, 2012; Pronger *et al.*, 2014). Changes to the physical structure of peat occur through consolidation, which occurs below the water table, and shrinkage, which occurs above the water table (Ewing & Vepraskas, 2006; Pronger *et al.*, 2014; Nusantra *et al.*, 2018).

Long-term subsidence of peat is an irreversible and ongoing process, which continues as long as the water table remains lowered (Pronger *et al.*, 2014). However, over short time scales, reversible changes in peat surface elevation have been observed and this may confound measurements of long-term irreversible rates of subsidence (Teatini *et al.*, 2004; Camporese *et al.*, 2006). Termed peat surface oscillation (PSO), it occurs over seasonal and shorter timescales (Fritz *et al.*, 2008; Howie & Hebda, 2018). PSO is an important self-regulatory process within natural peat-forming ecosystems, mitigating water table variations and promoting sustainable growth of peatland plants by reducing moisture stress in summer (Fritz *et al.*, 2008; Howie & Hebda, 2018). This process has been observed in natural peatlands, including bogs, fens, and swamps (Price *et al.*, 2005;

Fritz *et al.*, 2008; Howie & Hebda, 2018; Morton & Heinemeyer, 2019). However, far fewer studies have researched PSO and its controls within drained peatlands (Schothorst, 1977; Teatini *et al.*, 2004; Kennedy & Price, 2005; Camporese *et al.*, 2006).

In order to determine the best strategy for reducing rates of peat surface subsidence and therefore, to mitigate emissions of CO_2 and the overall permanent loss of peat, it is essential that the effects of land management practices on rates of peatland subsidence and the magnitude of PSO are understood (Howie & Hebda, 2018; Nusantra *et al.*, 2018). Furthermore, knowledge of the magnitude of PSO in drained peatlands will help inform decision-making regarding the restoration of peatlands to their natural state, as these can help determine degradation and the ability of a peatland to be restored successfully (Howie & Hebda, 2018).

1.1.1 New Zealand Peatlands

Historically, New Zealand had approximately 166,000 ha of peat wetlands, around 0.7% of the total land surface area (Davoren, 1978; Fritz *et al.*, 2008; Pronger *et al.*, 2014). Over half of this total area, approximately 94,000 ha, occurred within the present-day Waikato Region. Since the early 1900s, over 80% of Waikato peatlands have been drained, mostly for pastoral use as 60% of peat soils in the Waikato are used for dairy farming (Environment Waikato, 2006; Pronger *et al.*, 2014). This has led to large areas of land in the Waikato being subject to ongoing subsidence and organic matter oxidation, leading to further drainage upgrades and large greenhouse gas emissions (Pronger *et al.*, 2014; Campbell *et al.*, 2021). The large area of dairy farming, coupled with smaller areas of dry stock, cropping and blueberry orchards on drained peatlands in the Waikato, means there is significant incentive to continue farming on these degrading peatlands despite the obvious environmental risk.

1.1.2 Waikato Regional PSO monitoring network

A network of PSO monitoring sites was established across drained peatland areas in the Hamilton Basin, Lower Waikato and Hauraki Plains to support a long-term regional peat subsidence monitoring programme (Pronger *et al.*, 2020; Glover-Clark, 2021). The network was established to measure the magnitude of PSO and water table regimes across a range of land uses and peatlands in order to understand seasonal PSO cycles for accurate long-term monitoring of subsidence in the Waikato. A long-term goal of this programme is to inform future policy on the use of drained peatlands (Glover-Clark, 2021). The present policy goal in the Waikato Regional Council's Regional Policy Statement (Policy 14.5) is reducing subsidence rates and loss of carbon through oxidation (Waikato Regional Council, 2016).

1.2 Aims & Objectives

The aim of this research was to determine both the spatial variation and the drivers of PSO regimes[1] within Waikato drained peatlands. The determination of PSO regimes in drained peatlands is vital for future management decisions that consider both subsidence and carbon losses. Knowledge of seasonal PSO regimes will ensure accurate monitoring of long-term subsidence through detection of seasonal changes that may otherwise cause bias in subsidence measurements. This information will also expand on the current knowledge of how PSO processes differ in drained peatlands in comparison to natural peat wetlands.

To achieve this aim the objectives were to:

1. Determine the spatial variation of PSO and water table regimes across Waikato drained peatlands under different land uses
2. Measure peat soil physical and chemical properties in order to determine differences between peatlands, land uses and time since initial drainage to determine if these influence spatial variation of PSO regimes
3. Investigate drainage and land management histories to determine if these can explain spatial variation in peat soil physical and chemical properties.
4. Conduct experiments to determine differences in shrinkage characteristics of peat
5. Determine if differences in peat properties between land uses are reflected in the spatial variation of PSO regimes.

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[1] PSO regime refers to the change in surface elevation over different timescales such as seasonal or annual and is driven by external factors. This is similar to the concept of hydrological or water table regimes (Campbell & Jackson, 2004).

1.3 Thesis outline

Chapter 2 of this thesis is a literature review that outlines the current state of knowledge and research regarding peat-forming wetlands and their development, physical and chemical properties, and PSO behaviour. This chapter describes how peatland drainage transforms peat physical and chemical properties and how this leads to long-term subsidence and changes in peatland hydrological and PSO regimes. This chapter will also provide an analysis of the current gaps in knowledge regarding PSO behaviour in drained peatlands and its large spatial variation across different drained peatlands. Key studies regarding PSO behaviour in both natural and undrained peatlands will also be reviewed.

Chapter 3 introduces the field sites and their background, including drainage and land management histories. This chapter provides detailed descriptions of the methods used for hydrological and PSO measurement, and field sampling and laboratory analysis of peat samples.

Chapter 4 presents the results of the analysis of the physical and chemical characteristics of peat samples taken from field sites. These will be presented in graphs and tables with descriptions to highlight major differences between sites and land uses.

Chapter 5 presents the results of hydrological and PSO measurements at each site as well as relevant meteorological data. It will also presents seasonal statistics for hydrological and PSO regimes.

Chapter 6 will discuss the physical and chemical characteristics of the peat soils and compare them to similar studies in both New Zealand and internationally. It will evaluate whether land management and time since drainage have had a major influence on these properties. It will also discuss differences in PSO and water table regimes and compare the trends and magnitudes of PSO measured in other New Zealand and international studies. Overall, this chapter will try to explain observed differences in PSO regimes across different peatlands and land uses in the Waikato region.

Chapter 7 presents the conclusions of the overall study and provides recommendations for the implementation of the regional PSO monitoring network and improved management of pastoral and horticultural farming on drained peatlands.

Chapter Two
Literature Review

2.1 Introduction

Peat is a unique organic material that accumulates in areas of high, stable water tables (Ingram, 1983). Due to oxygen restrictions under these saturated conditions, the anaerobic environment results in reduced rates of decomposition and therefore encourages the accumulation of carbon in situ (Clymo, 1984). Globally this has led to peatlands storing vast amounts of atmospheric carbon, approximately 21% of the total soil carbon stock, despite only accounting for approximately 2.6% of the world's total land surface area (Gorham, 1991; Clymo *et al.,* 1998; Joosten & Clarke, 2002; Yu *et al.,* 2011; Xu *et al.*, 2018; Temmink *et al.*, 2022). The accumulated peats in intact peatlands have properties that are a direct result of the hydrological regime and vegetation characteristics of these peatlands (Boelter, 1968; Paivanen, 1973). Peatlands also exhibit seasonal changes in surface elevation as water inputs change; this behaviour self-regulates the hydrology of the peatland, which in turns helps to sustain peatland vegetation (Howie & Hebda, 2018; Morton & Heinemeyer, 2019). This seasonal change in surface elevation is also known as peat surface oscillation (PSO) (Fritz *et al.,* 2008). Historically, peatlands have been viewed as having no economic value in their natural state. This has led to extensive drainage across the globe, with approximately 65 million ha of the world's peatland area having been drained (Kaat & Joosten, 2009). Drainage of peatlands drastically changes the properties of the peat material. It also alters the seasonal behaviour of surface elevation changes alongside an irreversible decrease in the peat surface elevation. This irreversible decrease is called subsidence and can result in a variety of environmental issues, including an increase in carbon dioxide (CO_2) emissions to the atmosphere (Schipper & McLeod, 2002; Ewing & Vepraskas, 2006; Pronger *et al.*, 2014; Erkens *et al.*, 2016).

This chapter reviews literature regarding the classification and development of peat in peat-forming ecosystems, the hydrology and carbon cycling of intact peatlands, and the resulting physical and chemical characteristics of the formed peat. The seasonal behaviour of the surface elevation and water table dynamics in hydrologically intact peatlands will then be described before examining how drainage results in subsidence of the peat. The processes behind subsidence will be reviewed alongside global and local rates of subsidence. This will then lead on to sections regarding how hydrology and carbon cycling are transformed in drained peatlands and how physical and chemical changes in the peat material reflect this. The changes in PSO behaviour in drained peatlands will then be described and lastly gaps in knowledge regarding the literature will be identified.

2.2 Classification

2.2.1 Peat and peatlands

In the literature there are different definitions of peat, for example Wetlands International define peat as organic material that has accumulated in situ, which is made up of greater than 30% organic matter as measured on a total dry mass basis (Joosten & Clarke, 2002). Other sources have suggested that peat is the incompletely decomposed remains of plant matter that is at least 50% organic matter in origin (McLay, 1986). Peatlands are areas where there is a layer of peat and it may or may not be covered by vegetation, and “mires” is the term given to an area where peat is actively being accumulated (Joosten & Clarke, 2002). A wetland is an area of high water tables, which are sustained for most of the year. The vegetation and other organisms that are present are adapted to the saturated, anoxic conditions prevalent in these areas. Wetlands may or may not result in the accumulation of peat (Joosten & Clarke, 2002; Parish *et al.*, 2008)

2.2.2 Organic soils

Soils derived from peat materials are classified as organic soils due to their high organic matter content. However, it is important to stress that not all organic soils develop from peat. The IPCC 2006 Guidelines for National Greenhouse Gas Inventories define organic soils as (Hiraishi *et al.*, 2014):

- Soils that have an organic horizon that is EITHER 10 cm thick or greater
- OR for soils with organic horizons less than 20 cm, they instead have a carbon content of greater than 12% or more mixed to 20 cm depth.
- Soils that are unsaturated for more than a few days must have an organic carbon content, as measured by the soil’s dry mass, of a minimum of 20%

- OR for soils that are subject to saturation for the whole year but contain clay, must have at least 18% organic matter as measured by the soil's dry mass
- OR for soils that are subject to being saturated and do NOT contain clay, must contain at least 12% organic carbon as measured by the soil's dry mass

In New Zealand, the Ministry for the Environment defines organic soils under the Land Use, Land Use Change and Forestry (LULUCF) section of the New Zealand Greenhouse Gas Inventory as (Ministry for the Environment, 2022):

> The organic matter in soils must be contained in soil horizons which are 30 cm or thicker, which are within 60 cm of the surface. These soils are entirely derived from peat materials or other organic parent materials, which have been accumulated under saturated conditions (wet for at least 30 consecutive days per annum or have been drained which reduces days of saturation).

The Agricultural sector of the New Zealand GHG inventory (Dresser *et al.*, 2011) includes both the above description and:

> Soils that contain a peat layer composed of 17-30% organic matter. This layer is at least 10 cm thick and wet for 30 or more days in a row or has otherwise been drained.

The two definitions used in New Zealand are summarised from (Dresser *et al.*, 2011) and in turn were derived from the New Zealand Soil Classification's definition of organic soils, which are summarised below.

In New Zealand, the New Zealand Soil Classification has a soil order that is Organic Soils (OS), of which one of the key horizons are Organic (O) horizons, which are 30 cm thick and formed entirely from peat under saturated conditions for 30 or more consecutive days. If they are not saturated for this length of time, they may have instead been drained and still classify as an O horizon. They may also be formed from other organic soil materials which are also formed under saturated conditions (Hewitt, 2009). The other two key horizons relate to leaf litter, F and H horizons, which are 40 cm or more thick. Soils in this order are also classified into four soil groups, these are, litter (OL), fibric (OF), mesic (OM) or humic (OH) (Hewitt, 2009; Hewitt *et al.,* 2021). Litter OS refers to OS that form from forest litter and this group is not relevant to the current study. Fibric OS are organic soils that have visible plant remains, mesic OS are soils where the plant matter is more decomposed, whilst humic OS have undergone strong decomposition or longer periods of decomposition leading to very little amounts of identifiable plant remains (Hewitt *et al.*, 2021).

In soil taxonomy, organic soils are termed Histosols and these are defined as soils in which at least half (≥50%) of the upper 80 cm of the soil profile is comprised of organic matter (Soil Survey Staff, 1999; Camporese *et al.,* 2006). Soil Taxonomy groups organic soils under the Histosols soil order in accordance with fibric content. Fibric Histosols are organic soils in which more than 75% of their total volume is made up of visible plant fibres, indicating very slow decomposition rates. Sapric Histosols have less than 17% of their total volume comprising visible plant fibres and Hemic Histosols have less than 75% but greater than 17% of their total soil volume comprised of visible plant fibres (Soil Survey Staff, 1999; Hiraishi *et al.,* 2014).

2.2.3 Peat formation

Peat typically develops in areas with high water inputs, which result in stable high water tables and are located in relatively flat landscapes or low-lying valleys (Ingram, 1983; Zanello *et al.*, 2011). This results in water logging in these areas, reducing the amount of oxygen and preventing aerobic decomposition from occurring (Grover & Baldock, 2013). Hence, deposition of organic matter overtakes decomposition and organic matter is accumulated in situ, this is the overarching condition required for the development of peat (Joosten & Clarke, 2002). Therefore peatlands are a function of the hydrological conditions under which they form (Parish *et al.*, 2008).

2.2.4 Peatland vegetation

Vegetation type has an important role in the formation of peat within peatlands because it is the main source of the organic matter in peatlands. Peat can develop from organic matter that is derived from a variety of different peat plant types, these include mosses, herb species or woody plant species (Davoren, 1978; Parish *et al.*, 2008). Peatlands can be classified depending on the type of plants present within the peatland. In the Northern Hemisphere, peat formation in many bogs is dominated by *Sphagnum* moss species (Kellner, 2003; Parish *et al.*, 2008). In contrast, members of the Southern Hemisphere vascular plant family Restionaceae (restiads) dominate peat formation in New Zealand, especially *Epodisma robustum* (lowlands north of 38°S) and *Empodisma minus* (alpine and lowland ecosystems south of 38° S) (Clarkson *et al.*, 2004; Wagstaff & Clarkson, 2012). *E. minus* can also be found in eastern Australia and Tasmania (Wagstaff & Clarkson, 2012). *E. robustum* is the species (alongside *Sporadanthus ferrugineus*) that is associated with formation of peats in the Torehape, Kopuatai and Moanatuatua peatlands in the Waikato and Hauraki Plains (Wagstaff & Clarkson, 2012). *Sphagnum* mosses are a minor component in New Zealand peatlands in comparison to the Northern Hemisphere (Sorrell & Gerbeaux, 2004).

2.3 Hydrology

2.3.1 The water balance of peat wetlands

The single most important factor that has control over the development of peat is the presence of water. Therefore, it is important to introduce concepts that are relevant to hydrology in peat wetlands. The water balance equation simply describes the balance between inputs, outputs and resulting water storage within an ecosystem (Ingram, 1983; Campbell & Jackson, 2004). Inputs of water in wetlands may include precipitation, surface flows (into the system from the surrounds), and groundwater flows (sometimes called lateral flows). Outputs include evaporation (transpiration, interception loss, open water surfaces, and moist soils), surface outflows and groundwater flow (Ingram, 1983; Campbell & Jackson, 2004; Siegel & Glaser, 2006). Imbalances in water inputs and outputs result in changes in store water, hence the wetland water balance equation (modified from Campbell & Jackson, 2004 and Ingram, 1983):

$$P + GI + SI - (E + ET + GO) = \Delta S \qquad (2.1)$$

Where:

P = Precipitation

GI = Groundwater inflows

SI = Surface inflows

E = Evaporation

GO = Groundwater outflows

SO = Surface outflows

ΔS = Water storage

Water table depths are often used as a proxy for changes in water storage, this is especially important when the water table is close to the surface. (Campbell & Jackson, 2004).

2.3.2 Hydrology of peat wetlands

The origin of the water being input into a peatland has a major influence on the nutrient status and therefore plant community and peat formation within peatlands. Peatlands are often classified by their water input sources and subsequent nutrient status. Water input can be classified into meteoric (or atmospheric) and telluric (or mineral) (Ingram, 1983). Meteoric inputs are in the form of precipitation (P) and this type of water input has is very low in nutrients. Wetlands that receive water solely from precipitation are therefore classed as nutrient-poor wetlands. These are called ombrotrophic (or oligotrophic) peatlands and include blanket and raised peat bogs (Campbell & Jackson, 2004; Parish *et al.*, 2008; McGlone, 2009). Telluric sources of water include groundwater inflows (GI) and surface inflows (SI), which can be high in nutrients. This is because the water from these sources has been filtered through mineral soils or rock, with surface inflows also depositing mineral sediments (Ingram, 1983). These wetlands are called minerotrophic wetlands and include fens and swamps (Parish *et al.*, 2008; McGlone, 2009). Water input and nutrient status have a large impact on the relative chemical composition and other chemical characteristics that may be found in different peats of different peatland areas (Campbell & Jackson, 2004).

Water outputs in intact peatlands largely occur due to evaporation, as well as lateral flows that occur in the surface layer of the peatland (Campbell & Jackson, 2004). Evaporation can be in the form of transpiration from plants, interception loss or evaporation directly from soil and open water surfaces. (Ingram, 1983; Campbell & Jackson, 2004).

Water storage change in intact peatlands is the main control of many of the hydrological processes occurring within a peat wetland ecosystem, as well as peatland ecology (Holden *et al.*, 2011; Grover & Baldock, 2013). Water storage in peatlands is measured using the water table, changes in water storage are reflected by fluctuations in the water table (Ingram, 1983). Peat wetlands often have high water tables and therefore much of the peat profile is saturated throughout the year. The water table is where the hydrostatic pressure is equal to the atmospheric pressure. Below the water table, water in the pores of the peat is held at pressures that are greater than atmospheric pressure, whilst above the water table they are held at pressures that are below atmospheric pressure. This means that hydrostatic pressures are positive below the water table and are negative above the water table (Kellner, 2003). The positive pore water pressures arise due to the force of gravity and negative pore water pressures due to matric suctions (Ingram, 1983). Although the development of negative pressures above the water table is associated with unsaturated pores, the peat directly above the water table can have a zone of saturated pores. This is due to capillary forces and results in a region called the capillary fringe. The capillary fringe contains pores that are saturated despite hydrostatic pressures being below atmospheric pressure. It is therefore the capillary fringe that determines the extent of saturated pores within a peat profile, not the water table (Ingram, 1983; Kellner, 2003). In undrained peat wetlands, where the water table depths are shallow, capillary rise helps to replace water that may be lost by evaporation which helps to preserve moisture in the upper layers of the profile (Campbell & Jackson, 2004).

The relationship between changes in water storage (ΔS) and changes in water table depth (WTD) is described by the specific yield (S_y) (Ingram, 1983; Price & Schlotzhauer, 1999; Campbell & Jackson, 2004). Specific yield is defined as the amount of water that is released from storage upon the lowering of the water table by one unit of depth (Boelter, 1968; Ingram, 1983). Specific yield changes with depth and is greatest at the surface of the peat profile, due to a larger number of macropores present (Campbell & Jackson, 2004). However, Price & Schlotzhauer identified that the use of the specific yield parameter disregards the fact that water table changes in peatlands are also related to changes in peat volume. Therefore, they introduced the concept of using storativity (also called the storage coefficient, S_{tot}). Storativity is defined as a change in water storage per unit area in relation to a unit change in water table depth and is expressed as (taken from Kellner, 2003):

$$S_{\mathrm{tot}} = \Delta S/\mathrm{WTD} \qquad (2.2)$$

The total storativity of a peatland includes both specific storage (S_s), which is water storage changes in relation to changes in peat volume, and specific yield (Kellner & Halldin, 2002). This is a concept taken from water storage changes occurring in unconfined aquifers, where specific storage is often very small. However, peat is much more compressible and therefore changes in water storage can be driven by changes in peat volume. Therefore, both S_s and S_y are processes which occur when peat exhibits changes in water storage, so the storativity of peat can be expressed as (Price & Schlotzhauer, 1999; Kellner, 2003):

$$S_{\mathrm{tot}}= S_{\mathrm{sy}}+ bS_{\mathrm{s}} \qquad (2.3)$$

Where b = peat thickness

Price & Schlotzhauer (1999) concluded that both parameters would need to be considered if flotation, where water layers in the profile allow for the “lifting” of peat layers, occurred or the peat was thick enough to allow for the influence of compressibility of peat. Therefore, compressibility of the peat material is an important component in changes to water storage.

2.3.2.1 The diplotelmic model of raised bogs

Raised peat bogs have a characteristic physical morphology that influences water flows. This morphology is the development of two distinct layers that have differing hydraulic properties and hydrological functioning. The upper layer (or zone) is the acrotelm. This is the thin layer in the raised bog within which organic matter is actively being deposited (Ingram, 1982). This layer is approximately 10-50 cm thick and is where the water table fluctuates seasonally, therefore it is only periodically saturated and anaerobic (Clymo, 1984). Hence, this layer is periodically subjected to aeration, allowing aerobic decomposition to occur for some of the time. The acrotelm has high porosity, with a lower bulk density and higher proportions of macropores than the underlying catotelm. Due to these properties, hydraulic conductivity is high and therefore this is the layer where the greatest lateral flows occur within a bog (Ingram, 1982; Kellner, 2003; Campbell & Jackson, 2004).

The catotelm is the deeper layer of peat underlying the acrotelm. This layer is saturated for the entirety of the year and holds the majority of the water within a raised bog (Ingram, 1982). Despite large amounts of water within this layer, there are very few lateral flows occurring in this layer. This is attributed to the dominance of micropores and therefore a low hydraulic conductivity, which decreases with depth (Kellner, 2003; Campbell & Jackson, 2004). The peat in this layer is more decomposed than that found in the acrotelm however, a large volume of carbon is stored in this layer (Belyea & Baird, 2006). In this layer, saturation means that oxygen is consumed quicker than it can be replaced, resulting in anoxic conditions. These conditions mean that the organic matter decomposes extremely slowly in comparison to that of the acrotelm, although the rate is thought to be variable with changes in water storage (Clymo, 1984; Clymo *et al.*, 1998).

2.4 Carbon cycling within intact peatlands

Intact peatlands are significant carbon sinks within the global carbon cycle and have a positive net ecosystem carbon balance or NECB (Gorham, 1991; Chapin *et al.*, 2006; Temmink *et al.*, 2022). This is because stable high water tables lead to the dominance of anaerobic decomposition, which slows and incompletely decomposes organic matter. Slow rates of decomposition leads to the accumulation of organic matter within the peatland, burying carbon as more plant material is deposited in the acrotelm (Clymo *et* *al.*, 1998). It is through this process that peatlands globally have accumulated gigatonnes of carbon, effectively removing it from the atmosphere (Temmink *et al.*, 2022) and causing a cooling effect on the Earth's climate (Frolking *et al.,* 2006). The stability of the water table drives the accumulation of organic matter and hydrology is the main control on carbon cycling in peatlands (Blodau, 2002; Zhong *et al.*, 2020).

2.5 Characteristics of peat materials in intact peatlands

Due to the nature of the conditions and processes leading to the accumulation of peat, their resulting physical and chemical characteristics are distinctive compared to mineral soil materials. (Boelter, 1968). This section describes the major physical and chemical properties of peat.

2.5.1 Physical properties

Total porosity is the fraction of peat volume comprised of pores and includes both macropores and smaller pore sizes, as well as interconnected pore spaces (Danielson & Sutierland, 1986; McCarter *et al.,* 2020). Porosity values found in undrained peatlands are high in comparison to mineral soils, in the range of 80 to 97% of total volume (Kellner, 2003; Rezanezhad *et al.,* 2016). Peat is described as having dual porosity by having open and connected pore spaces through which water and solutes can move relatively easily. These pore spaces are described as being 'active' or 'mobile' porosity. Peat also contains closed pore spaces through which solutes and water are less likely to be able to move, although solutes can be exchanged through diffusion. These are 'inactive' or 'immobile' pores. (Rezanezhad *et al.,* 2016).

Pore size distribution is the relative proportion of different pore sizes within a representative volume of soil (Rezanezhad *et al.,* 2016). In all soils, the pore spaces can be categorised into primary and secondary pore spaces. Primary pore spaces are those that form during the formation of soil whereas secondary pore spaces form after development. This occurs either through the movement of organisms through the material or through the formation of cracks for example after drying (Liu & Lennartz, 2019). Macropores are the large pores (>50 μm) present within the peat matrix (Lennartz & Liu, 2019). In peat, macropores form as part of primary pore spaces, during the breakdown and accumulation of plant matter. This is different to mineral soils, which largely form macropores as secondary pore spaces (Lennartz & Liu, 2019). Macropores are the first to drain because of capillary forces. An inverse relationship exists between pore diameter and capillary force, the smaller the pore size the greater the amount of water it is able to retain against suction (Kellner, 2003). In peat, the proportion of macropores decrease with depth because the peat is more decomposed deeper in the profile. This decrease in macropores means there is a shift in pore size distribution and smaller pore sizes become more dominant with depth (Rezanezhad *et al.*, 2016).

Bulk density is the proportion of dry mass (solids) found within a known volume of soil (Boelter, 1968). For all soils, there is an inverse relationship between bulk density and total porosity and this also holds for peat (Liu & Lennartz, 2019). In undrained peats, bulk density is characteristically extremely low, as low as >0.01 g/cm^3 (Mustamo *et al.*, 2016; Lennartz & Liu, 2019). In New Zealand, the range of peat bulk densities from the undisturbed Kopuatai peat bog have been reported to be 0.014 – 0.052 g/cm^3 (Lambie & Ratcliffe, 2020). Mustamo *et al*. (2016) found the mean bulk density in the top 5 cm of pristine boreal peat bog in a Northern Finland was 0.045 g/cm^3. Bulk density increases with increased degree of decomposition and so bulk density increases with depth in pristine peat profiles (Paivanen, 1973; Mustamo *et al.*, 2016). The degree of decomposition of peat increases down the peat profile due to the longer time since deposition of the plant material occurred. Decomposition is difficult to measure but one way in which it can be estimated is through a qualitative field assessment called the von Post scale (Boelter, 1969). This field assessment allows for comparison of peats at different degrees of decomposition (Boelter, 1968; McLay, 1986; Verry *et al.*, 2011). As the degree of decomposition increases, organic particles are broken down and reduced in size, leading them to infill larger spaces in the peat matrix. As a result, pore spaces decrease in size and the solid material within a volume of peat increases, therefore increasing bulk density (Boelter, 1969; Paivanen, 1973). Undrained peats have relatively small proportions of solid fractions (Figure 2.1). Clymo (1983) estimated that in peat only 5-15% of the total volume would be made up of solid material, which would be organic matter and some small amount of mineral material.

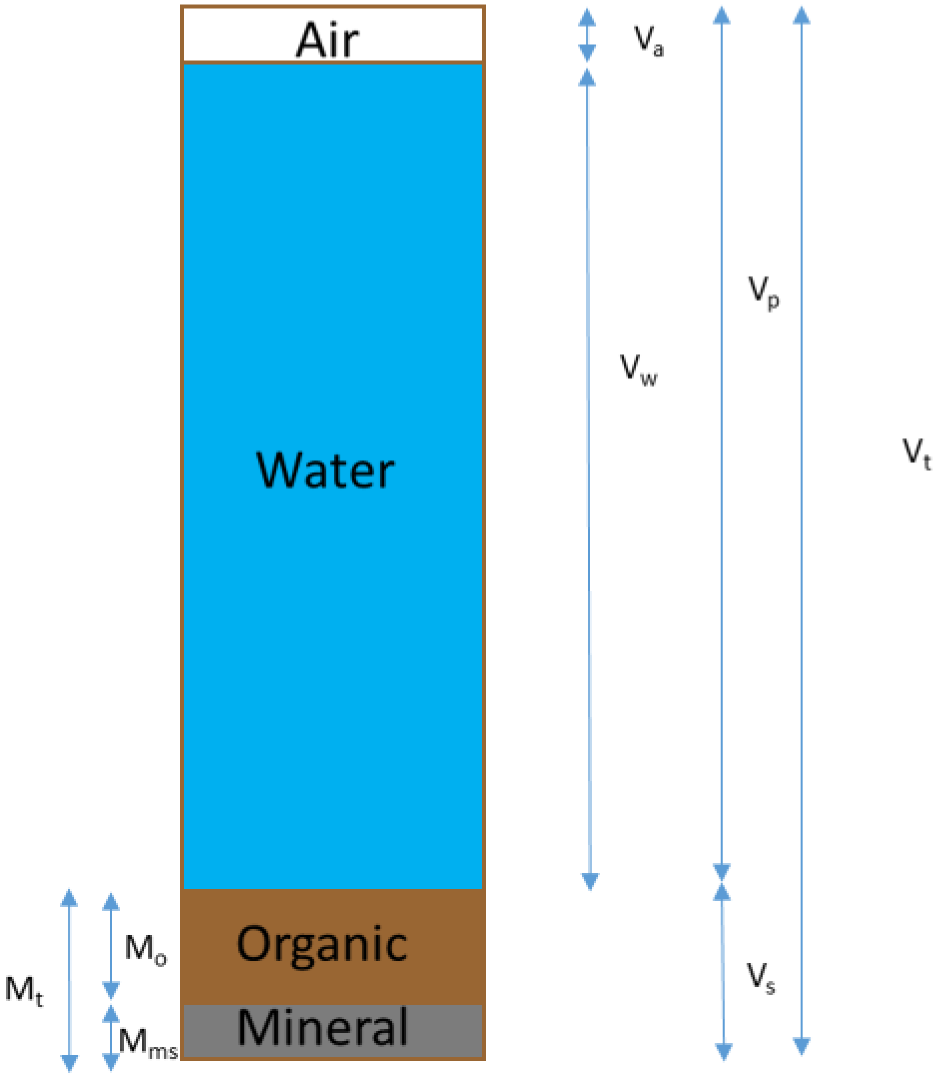

Figure 2.1 Visual description of proportions of water-filled, air-filled and solid-filled voids in a peat sample. Proportions are shown on both a volume and a mass basis. V_t = total volume of peat, V_p = Volume of pores, V_s = Volume of solids, V_a = Volume of air filled-pore spaces, V_w = Volume of water-filled pore spaces, M_t = Total "solid" mass, M_o = Mass of organic matter, M_{ms} = Mass of mineral fraction. Adapted from Figure 2 in Ewing & Vespraskas, 2006.

Hydraulic conductivity is a measure of how easily water can move through a porous medium, such as soil or peat. Pore size and hydraulic conductivity are closely linked and small changes in peat pore size distribution can cause a significant change in hydraulic conductivity (Grover & Baldock, 2013). Water is more readily able to move through macropores than smaller pores in peat and other porous media. Hydraulic conductivity and bulk density often demonstrate a strong inverse relationship, so an increase in bulk density will lead to a decreased hydraulic conductivity (Boelter, 1969; Paivanen, 1973). In raised bogs, hydraulic conductivity has been measured to decrease by orders of magnitude with depth (Paivanen, 1973; Rezanezhad *et al.*, 2009), which is explained by compression in the catotelm coupled with an increased degree of decomposition which has led to smaller pore sizes, thus water is less able to move laterally through the peat (Ingram, 1982).

Water retention is a representation of the relationship between matric potentials and the amount of water retained in that soil (Jensen *et al.*, 2020). It is directly related to pore size distribution and can be used as a measure of the degree of decomposition of a peat (Rezanezhad *et al.*, 2016). Water retention in the upper surface layer (the acrotelm) is lower than in the deeper layer (catotelm) because of a greater dominance of macropores in the surface layer of the peat (Paivanen, 1973).

Soil moisture content (SMC) can be expressed both volumetrically and gravimetrically (Ingram, 1983). In peat, soil moisture content should be presented volumetrically, because gravimetric measurements often exceed 100% (McLay, 1986). Volumetric moisture content (VMC) is the volume of water present per unit volume of a sample of peat. Saturation occurs once all pores are filled with water and a maximum value of VMC is reached (Ingram, 1983). Soil moisture content is related to organic matter content and water table depth. VMC generally increases with proximity to the water table until saturation is reached (McLay *et al.*, 1992). Some studies have found that soil moisture content is only influenced (connected) by the water table when the water table is high enough, for example during wet periods (Price, 1997). VMC is influenced both by hydrological factors such as evaporation and precipitation, as well as soil physical properties such as pore size distribution and total porosity. Therefore, VMC is both temporally and spatially variable and can change over short time periods and over short distances (Wang *et al.*, 2021).

Peat as a porous medium has high compressibility, this is a behaviour that arises due to the structure of peat (Price *et al.*, 2005). Compressibility has been related to water storage, with large water storage capabilities meaning that the peat has large compressibility (Waddington *et al.*, 2010). However, other studies have found that the relationship between compressibility and factors such as fibre content and degree of decomposition is not as strong (Price *et al.*, 2005). This study was based on laboratory measurements, which may not fully represent processes occurring in the field.

2.5.2 Chemical properties

A high water table and waterlogging in peatlands leads to a dominance of anaerobic decomposition. This has a strong influence on the chemical composition and characteristics of the peat. The organic matter in peat is composed predominantly of carbon (C), hydrogen (H) and oxygen (O), with smaller amounts of nitrogen (N), phosphorus (P) and sulphur (S) (Leifeld *et al.*, 2020).

The pH of peat is acidic; this is due to the high proportion of organic acids such as fulvic and humic acids (Kellner, 2003). This is particularly true for bogs, which do not receive nutrient-rich water from groundwater or run-off. Further acidification of peat occurs due to plant uptake of nitrogen as NH4+, which results in the release of a proton (H+). This occurs in all peatland environments, but bogs are particularly affected due to the low buffering potential of rainwater compared to more alkaline groundwater and runoff inputs (Sorrell & Gerbeaux, 2004).

The C/N ratios in peatlands are high due to the high amount of carbon that is accumulated during peat formation (Szajdak *et al.*, 2020). They are much higher than C/N ratios in mineral soils from other terrestrial ecosystems, such as sediments. A synthesis of C/N ratios in peatlands in the Northern Hemisphere found a median C/N ratio of 55, with moss peats generally having higher ratios than other peat types (Loisel *et al.*, 2014). In New Zealand, the mean C/N ratio for bogs is 48.5, with average total carbon (TC) 97.7 cm/g^3 in comparison to total nitrogen (TN) 0.82 mg/cm^3 (Clarkson *et al.*, 2003; Sorrell & Gerbeaux, 2004). At the intact Kopuatai bog, C/N was between 42–61 depending on the hydrological zone from which the sample was taken (Lambie & Ratcliffe, 2020). C/N ratios are affected by time since deposition of the peat, with younger peats having higher C/N than much older peats (Loisel *et al.*, 2014). This is likely because older peats have been subjected to decomposition for much longer, C/N also decreases with depth due to age of the peat (Leifeld *et al.*, 2020). In general, bogs have much higher C/N ratios than other peat-forming ecosystems, this is again attributed to the lack of nutrient rich water inputs leading to low concentrations of phosphorus and nitrogen (Sorrell & Gerbeaux, 2004). Nutrient-rich peatlands have lower C/N than bogs, which are nutrient-poor. In New Zealand, the average C/N ratio for swamps was reported to be 18.0, much lower than reported for bogs, 48.5 (Clarkson *et al.*, 2003; Sorrell & Gerbeaux, 2004).

2.6 Peat Surface Oscillation in intact peatlands

Peat surface oscillation (PSO) is a phenomenon that has been observed to occur in both intact and drained peatlands (Table 2.1). It is a process where the peat surface elevation subsides and rebounds due to a variety of different processes resulting from changes to water input and outputs to the peatland ecosystem (Fritz *et al.*, 2008; Howie & Hebda, 2018). PSO is defined as the total range of reversible peatland surface changes as determined through the difference between the maximum and minimum peat surface elevation over a defined period of time (Fritz *et al.*, 2008).

Table 2.1 List of peat surface oscillation PSO studies in peatlands

Author (s)	**Title**	**Term used**	**Peatland type and location**	**Intact or drained?**	**Study type**	**Methodology**	**Time resolution**	**Length of study**	**Magnitude of PSO**
Schothorst (1977)	*Subsidence of low moor peat soils in the western Netherlands*	Reversible surface elevation change	Moor, western Netherlands	Drained	Single study site	Surface elevation manually measured against benchmark iron tubes, metal disks inserted into different layers of the peat used to determine where shrink/swell was occurring	Surface elevation measure 3 times a year	6 years	2-8 mm
Roulet, Hardill & Comer (1991)	*Continuous measurement of the depth of water table (inundation) in wetlands with fluctuating surfaces*	Peat surface elevation change	Subarctic fen, northern Québec	**Intact**	Single study site	Two sensors attached to platform at a reference level above the peat. One sensor measured water level and the other rested on peat surface, difference used to calculate depth of water table	n/a	4 months	Max change in peat surface level of 44 mm
Price & Schlotzhauer (1999)	*Importance of shrinkage and compression in determining water storage changes in peat: the case of a mine peatland*	Peat volume change	Plateau bog, Québec, Canada	Drained (cutover)	Single study site	Both water level and distance to surface manually measured in seven dip wells	Daily measurements	1 year	70-90 mm
Teatini *et al.* (2004)	*Reversible/ irreversible peat surface displacements and hydrological regimes in the Zennare Basin, Venice*	Reversible peat surface displacement	Estuarine, Venice, Italy	Drained	Single peatland	Displacement transducers attached to steel tripod (benchmark) and aluminium plate placed on peat surface to measure surface displacement	Both short (hourly) and long time period measurements	2 years	~ 10 mm in four months ~48 mm over the total study period
Kennedy & Price (2005)	*A conceptual model of volume change controls on the hydrology of cutover peats*	Volume change	Plateau bog, Québec, Canada	Drained (cutover)	Cutover vs disturbed in singular peatland	Measured surface elevation changes through displacement of aluminium rods inserted into different depths in the peat	Weekly measurements	4 months (part of a 5-year study)	Undisturbed: max of 28 mm Cutover: max of 55 mm & 28 mm (seasonal change)
Camporese *et al.* (2006)	*Hydrological modelling in swelling/shrinking peat soils*	Swell/shrink cycles	Estuarine, Venice, Italy	Drained	Single study site	Development of a hydrological model to predict irreversible/ reversible surface changes. Takes into account different soil parameters and direct measurements of elevation change via transducers attached to surface of peat	n/a	2-year experiment set up, displayed results of 3 month trial	Predicted surface elevation changes in order of magnitude 100 mm
Whittington *et al.* (2007)	*The influence of peat volume changes and vegetation on the hydrology of a kettle-*	Peat volume change	Fen, Ontario, Canada	**Intact**	3 study sites in single peatland	Altitude sensor rods in plastic tube inserted into the peat. Changes in elevation measured manually	Specific days of measuring	29 days	Each site had increase in altitude of 79

	hole wetland in Southern Ontario, Canada								mm, 63 mm and 46 mm
Fritz *et al*. (2008)	*Oscillating peat surface levels in a restiad peatland, New Zealand*	Peat Surface Oscillation (PSO)	Restiad fen, North Island, New Zealand	**Intact**	23 study sites within single peatland	Paired vibrating wire pressure transducers, one anchored to a benchmark rod embedded in mineral substrate beneath the peat, the other attached to a board fixed to the peat surface. The difference between the two measurements was used to calculate surface elevation changes. The distance from the benchmark rods to the peat surface was also measured manually along transects	Transducers measured every 15 minutes Manual measurements taken monthly	1 year	Range of 32 – 280 mm in change, average change of 149 mm
Waddington *et al*. (2010)	*Differential peat deformation, compressibility, and water storage between peatland microforms*	Peat deformation	Open fen, Québec, Canada	**Intact**	Single study site	Elevation changes manually measured via rods inserted to different depths in the peat. Water table measured using counterbalanced pulley on potentiometer connected to a data logger	Manual measurements taken twice a week Water table depth measured continuously	~ 3 months (during the growing season)	20-90 mm of seasonal change
Reeve *et al*. (2013)	*Seasonal changes in peatland surface elevation recorded at GPS stations in the Red Lake Peatlands, northern Minnesota, USA*	Seasonal peat deformation	Fen and bog, northern Minnesota, United States of America	**Intact**	Multiple sites within single peatland	GPS network measured only large changes in surface elevation of peat	GPS sampled every 30s, data download daily	1 year	Range of 38 – 253 mm
Howie & Hebda (2018)	*Bog surface oscillation (mire breathing): A useful measure in raised bog restoration*	Bog Surface Oscillation (BSO)	Raised bog, British Columbia, Canada	**Intact**, drained & restored	Drained vs intact/ restored sites in single peatland	Manually measured the height of PVC piezometers and wells from the peat surface	Monthly measurements	4-12 years	Range of 20 – 340 mm, average 108 mm
Morton & Heinemeyer (2019)	*Bog breathing: The extent of peat shrinkage and expansion on the blanket bogs in relation to water table, heather management and dominant vegetation and its implications for*	Bog breathing	Blanket bog, United Kingdom	Partially drained	Study sites with different vegetation within a single peatland	Peat surface manually measured as distance between top of steel pole inserted into peat and disc fixed to peat surface. Water table depth also measured manually.	Distance between disc and pole measured when installed and then another seven times	2 years	Range of 2-31 mm, average of 13 mm

	carbon stock assessments								
Glover-Clark & Campbell (2021)	*Peatland surface oscillation at two dairy farms on Moanatuatua drained peatland*	Peatland Surface Oscillation (PSO)	Former raised bog, New Zealand	Drained	2 study sites in single peatland	Similar to Fritz et al (2008). Two water levels transducers, one attached to a benchmark and the other attached to a horizontal steel rode fixed in the surface peat soil.	Half-hourly measurements	1 year, 5 months	Max surface elevation change of 122.6 mm and 84.2 mm at each site
Evans *et al*. (2021)	*A novel low-cost high resolution camera system for measuring peat subsidence and water table dynamics*	Short-term and seasonal peat surface elevation changes	Peat swamp, Central Kalimantan	Drained	8 study sites in single peatland with different land uses	Time-lapse camera, used metal strip and pole for reference Water table measured via dip wells and flotation device	Initially images taken at 3-hourly measurements and then daily	2 years	80 mm shrinkage and 30 mm rebound, with net annual subsidence of 50 mm
Bradley *et al*. (2022)	*Identification of typical ecohydrological behaviours using InSAR allows landscape-scale mapping of peatland condition*	Peatland surface motion	Blanket bog, northern Scotland	**Intact** & drained	Multiple intact and drained study sites that are within single peatland	Satellite InSAR technology measured gross changes in peat surface elevation	Images gathered every 6-12 days depending on satellite	18 months	Maximum amplitude of 9 mm
Imran *et al*. (2022)	*Long term dynamics of surface fluctuation in a peat swamp forest in Sarawak, Malaysia*	Peat surface deformation	Tropical peat swamp, Malaysia	**Intact** forest (National Park)	Multiple study sites within single peatland	ABS pipe inserted into substratum underlying the peat, initial surface measured with line on pipe, this was reference point for changes in surface elevation	Monthly measurements	~ 9 years	4.0 mm – 4.4 mm y^{-1}

In intact peatlands PSO is a response to changes to water storage (and therefore water table depth), which occurs seasonally (Fritz *et al.*, 2008). During the dry season, a negative water balance leads to lowering of the water table and an increase in effective stress on the peat resulting in consolidation in the zone below the water table and a resulting drop in peat surface elevation (Price, 2003; Kennedy & Price, 2005; Fritz *et al.*, 2008; Howie & Hebda, 2018). There may also be physical shrinkage that occurs above the water table as pores that were once filled with water collapse. Price (2003) found that the greatest amount of volume change (approximately 5-15% of total volume in their study), occurred in the surface layer. They attributed this to the development of greater negative pressures in this layer compared to deeper in the peat. During the wet season, the water table rises, refilling drained pore spaces with water. An overall increase in soil moisture increases pore water pressure, restoring buoyancy and causing a reduction in effective stress (Price, 2003; Kennedy & Price, 2005). As a response to increased water inputs, the peat material "swells" and therefore the surface rises. This process can also occur on much shorter timescales, e.g., in response to rain events (Fritz *et al.*, 2008; Howie & Hebda, 2018). The main controls on this behaviour in functioning peat wetlands are changes in water table depth and the corresponding changes in water content in the peat (Camporese *et al.*, 2006). This seasonal oscillation is thought to be an important protective behaviour for sustaining peatland ecology. The decrease in surface elevation of the peat allows for peatland plants to be brought closer to the water table as well as protecting against further losses of water by lateral flows (Howie & Hebda, 2018). The movement of the peat surface also helps protect the peatland against extreme fluctuations in water table depths, preventing air from entering the peat structure and degrading the peat (Holden *et al.*, 2011).

A study of the importance of PSO behaviour in natural peatlands was carried out by Fritz *et al*. (2008), who developed a novel high-frequency measurement technique and proposed new terminology. The important terms are absolute water level (AWL), relative water level (RWL) and surface elevation (SE). AWL is the water table depth as measured with respect to a benchmark, in Fritz *et al*. (2008) this was a metal rod inserted through the peatland and anchored within the underlying mineral substratum. RWL is the water table depth in relation to the peat surface and is a measure of the thickness of the unsaturated zone (Schlotzhauer & Price, 1999; Fritz *et al.*, 2008). SE is surface elevation and is calculated as $SE = AWL - RWL$ (where RWL is defined as negative when the water table is beneath the peat surface) (Fritz *et al.*, 2008).

Fritz *et al.* (2008) found that the slope of the relationship between AWL and SE could determine the driving mechanism for PSO. Figure 2.2 shows an example of their findings. A 1:1 linear relationship suggests flotation at the upper end of the SE versus AWL distribution as being the main driver of PSO in very wet conditions (Figure 2.2). Flotation occurs when there are layers of water within the peat profile meaning the overlying buoyant peat can be 'lifted' as water inputs increase (Fritz *et al.*, 2008). They also found that, when the slope of the AWL versus SE relationship plots with a lower slope, the physical processes of consolidation and shrinkage are likely the dominant forces driving the PSO behaviour.

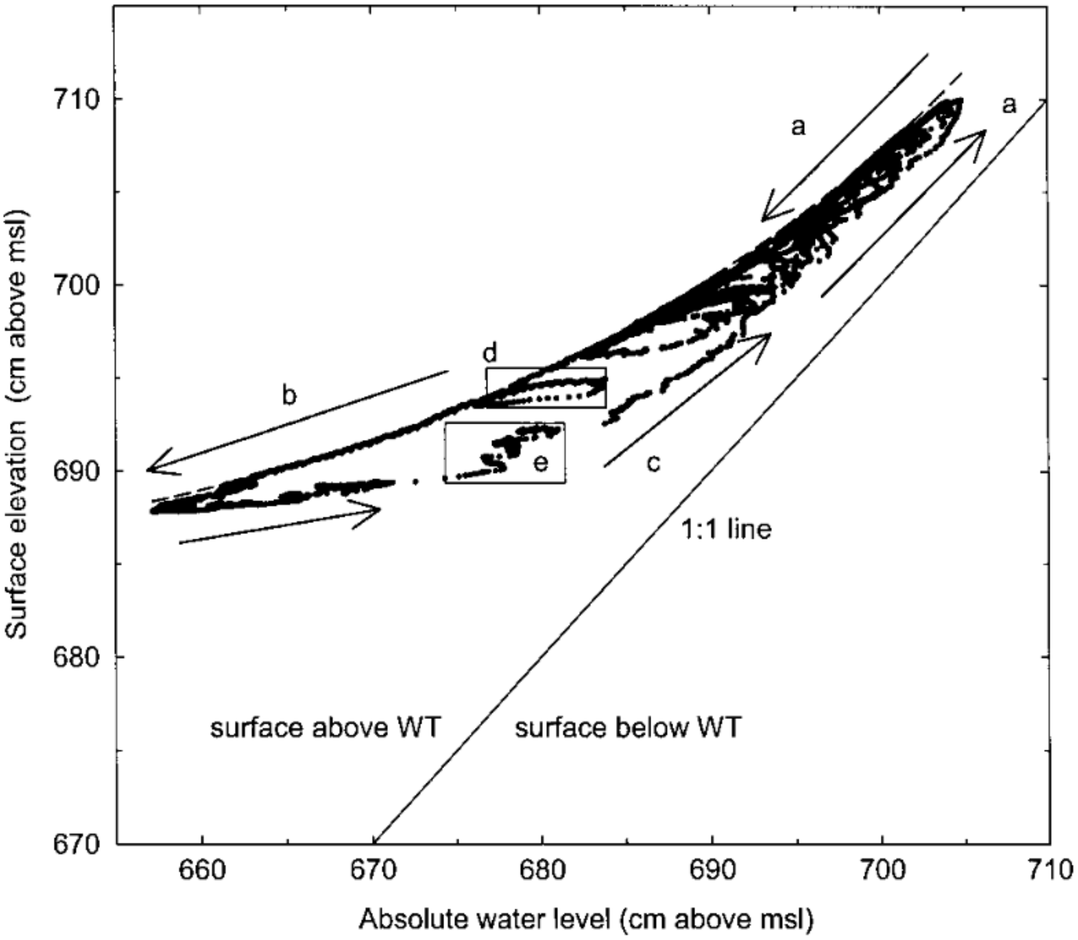

Figure 2.2 Peat surface oscillation vs absolute water level over an annual period from 15-minute measurements for a New Zealand fen peatland, the upper curved data bounds delineate the 'drying curve' while the lower bounds were formed during wetting, Considerable hysteretic behaviour caused "loops" between these curves (Source, Fritz *et al.* (2008)

Fritz *et al*. (2008) observed hysteresis in the peat surface rebound following rain events and the rewetting season. This was observed as both AWL and SE rose in response to increased water inputs from a rainfall event. However, once rainfall stopped and AWL began to recede, the surface continued to rise. This hysteretic behaviour can be seen in Figure 2.2 as loops (labelled ‘d’). Fritz *et al*. (2008) found hysteretic behaviour to be more pronounced in the dry seasons than in the wet season. Hysteresis was observed after single rain events as well as seasonally and daily. Fritz *et al*. (2008) suggested that hysteresis came about because of changes to AWL and the effects this causes (changes to peat volume), operating on different time scales. This means that although AWL changes occur rather quickly, changes to effective stress are much slower. Therefore, surface elevation changes appear to be delayed compared to rapid changes in AWL. Horizontal strains may have also contributed to hysteresis due to the variability of PSO magnitudes spatially.

Hysteresis has also been observed by other studies on PSO behaviour in undrained peatlands (Kennedy & Price, 2005; Waddington *et al.*, 2010; Howie & Hebda, 2018). Howie & Hebda (2018) suggested that hysteresis is part of the self-regulating mechanisms of peatlands, whereby water retention at the surface remains high to combat stress during the dry season. They also suggested that it may be due to hydrophobicity of the peat once dried, resulting in lag in surface response due to difficulty in peat absorbing water once rewetting begins (Howie & Hebda, 2018).

2.7 Drainage and subsidence

2.7.1 Processes

Peatland subsidence describes the irreversible lowering of the peat surface elevation that resulting from peatland drainage. Subsidence is separate from the reversible changes in surface elevation comprising PSO. Therefore, in drained peatlands PSO superimposes over subsidence, which can make the determination of subsidence rates difficult unless year-round measurements of the surface oscillation cycles are undertaken (Camporese *et al.*, 2006).

Drainage of peatlands have occurred worldwide including in New Zealand, where it has occurred at large scales for the development of land for agriculture and horticulture (Schipper & McLeod, 2002; Pronger *et al.*, 2014; Campbell *et al.*, 2021). Drainage results in the artificial lowering of the water table and as a result, water-filled pore spaces are emptied. Two physical mechanisms drive subsidence in peatlands, consolidation and shrinkage (Price *et al.*, 2003; Ewing & Vepraskas, 2006).

Consolidation is comprised of primary consolidation and secondary compression, both occur below the water table as the result of a loss of pore-water pressure, leading to increased effective stress on the peat structure (Price *et al.*, 2003; Kennedy & Price, 2005). Primary consolidation, sometimes called normal compression, results from a decrease in pore-water volume, which is equal to the decreased peat volume (McLay *et al.*, 1992; Price & Schlotzhauer, 1999; Terzaghi, 1943 *in* Kennedy & Price, 2005). Primary consolidation occurs rapidly after drainage as the water table depth increases (Nusantra *et al.*, 2018). Secondary compression is the settling of the saturated peat under increased load until the peat becomes stable, it occurs at a slower rate than primary consolidation. (Kennedy & Price, 2005; Nusantra *et al.*, 2018). Consolidation can be partially reversible if pore-water pressure is restored and there is a decrease in effective stress on the peat structure. This is dependent on a strain limit, if the strain that has occurred is greater than the pre-consolidation pore-water pressure the pore-water pressure cannot be restored by increasing water supply to the system (Terzaghi, 1943 *in* Kennedy & Price, 2005; Price et *al.*, 2003).

Shrinkage is the collapse of drained macropores due to the development of negative pressures, and this occurs above the water table (Kennedy & Price, 2005). Both consolidation and shrinkage result in increased bulk density, decreased porosity and a shift in pore size distribution (Price *et al.*, 2003; Kennedy & Price, 2005). Compaction is another process which causes a loss of peat volume above the water table (Hooijer *et al.*, 2012; Nusantra *et al.*, 2018). It is the result of the physical application of pressure to unsaturated peat material with heavy vehicles, such as tractors, and high stocking rates (Pronger *et al.*, 2014). Shrinkage and compaction are often unable to be distinguished from each other (Hooijer *et al.*, 2012; Nusantra *et al.*, 2018). Price & Schlotzhauer (1999) determined that consolidation occurring below the water table is likely to be a great contributor to total subsidence than shrinkage above the water table.

The physical processes contributing to subsidence caused by drainage are accompanied by a permanent loss of peat mass due to the mineralisation of the organic matter via oxidation. This process results in a decrease in the organic matter fraction, with a consequent increase in the mineral fraction of the peat (Grønlund *et al.*, 2008; Kluge *et al.*, 2008; Leifeld *et al.*, 2011). Through oxidation, there is an increase in bulk density and further peat subsidence (Schipper & McLeod, 2002; Gebhardt *et al.*, 2010; Zanello *et al.*, 2011; Pronger *et al.*, 2014). Mineralisation occurs when atmospheric oxygen (O_2) enters pore spaces in the peat that had been previously saturated, allowing oxygen to react with carbon held in peat organic matter, leading to a net release of CO_2 to the atmosphere, a process that is mediated by microorganisms present in the peat (Säurich *et al.*, 2019; Krause *et al.*, 2021). Oxidation is a much slower component of subsidence that is ongoing and continues after initial shrinkage and consolidation have occurred. It will continue until all of the peat organic material has been lost (Pronger *et al.*, 2014).

Subsidence is often classified into stages representing the dominant subsidence processes, described by Ewing & Vepraskas (2006) as primary and secondary subsidence. Primary subsidence is the initial rapid subsidence that is dominated by consolidation due to the increase in effective stress on the peat matrix. Secondary subsidence was described as being initially dominated by rapid shrinkage from the collapse of macropores, but this was then taken over by slow, ongoing oxidation of organic matter in the peat material (Ewing & Vepraskas, 2006). Pronger *et al.*, (2014) estimated that oxidation comprised 38% of subsidence in the first 80 years after drainage in Waikato peatlands. During ongoing subsidence, after 80 years since drainage, this increased to 48%. Another Waikato study found that loss of organic matter from peat was responsible for 37% of the total subsidence and compaction was responsible for 63% for a time period of 40 years (Schipper & McLeod, 2002). In Norway, it was estimated that whilst shrinkage and compaction were dominant (accounted for 38% and 62% of total subsidence respectively) in the first 25 years following drainage, oxidation accounted for 49% of the total subsidence over the entire drainage period (53 years) (Grønlund *et al.*, 2008). Both

Grønlund *et al.* (2008) and Pronger *et al.* (2014) considered the first 25 years after drainage to be the time when physical processes were dominant over oxidation.

2.7.2 Rates of subsidence

Subsidence rates differ widely depending on a variety of factors such as peat type, peat depth, drainage history and land management history (Pronger *et al.*, 2014). Rates of subsidence may also be affected by the underlying substratum, however, there is evidence that this is only true if the peat is shallow (Dawson *et al.*, 2010).

On a global scale, peatlands have historically been viewed as having very little economic value unless they were drained. Hence, many peatlands in places such as the Netherlands, Germany, northern European countries, Ireland and the UK have been drained for the past thousand years (Erkens *et al.*, 2016). This has led to a massive loss of functioning peatland areas for example, in Sweden, only 25% of the country's total wetlands have been left in their pristine state (Löforth, 2001, *in* Kellner, 2003). A strong relationship between the rate of subsidence and time since drainage has been established (Ewing & Vepraskas, 2006; Pronger *et al.*, 2014). For example, Dawson *et al.* (2010) found that the rate of subsidence over a 13-year period for a drained agricultural peatland in the United Kingdom was 1.48 cm/yr. In Switzerland; a drained temperate fen had an average subsidence rate of 1.26 cm/yr. This study found that 23-64% of this subsidence could be attributed to oxidation which translated to a release of 2.5-5.5 t C ha y^{-1} (Leifeld *et al.*, 2011).

In the Waikato Region of the North Island of New Zealand, some drained peatland subsidence rates have been determined. The Waikato Region has had approximately 80% of its total peatland area drained for development, mainly for dairy farming and horticulture, such as blueberry orchards and maize cropping (Environment Waikato, 2006; Glover-Clark, 2020; Pronger *et al.*, 2020; Glover-Clark, 2021). In comparison to drainage in the Northern Hemisphere, New Zealand peatlands have been drained for a much shorter time, with the earliest drainage occurring in the late 1800s to early 1900s (Pronger *et al.*, 2014). A study by Schipper & McLeod (2002) compared the depth and carbon content of peat located above the Taupo tephra layer (200 years AD) in both an undrained area and drained area of the Moanatuatua peat bog. In the 40 years after initial drainage, the peat at the drained site had subsided by 137 cm; this translated to an average of 3.4 cm of subsidence per year. The rate of carbon loss was estimated to be 3.7 t C ha y^{-1} (Schipper & McLeod, 2002).

Pronger *et al.,* (2014) also undertook a study to determine rates of initial peat subsidence during the 1920s- 2000s (historic) and ongoing subsidence from the 2000s to the 2010s (contemporary) in the Waikato and Hauraki Plains regions. Rates of both historic and contemporary subsidence were determined by comparing surveys that were undertaken in the 1920s, early 2000s and a survey they undertook themselves in the early 2010s. These rates were then compared to rates of similar time periods globally through a meta-study of previous literature. Historic subsidence was determined to occur at a rate of 2.6 cm y^{-1} and contemporary at a rate of 1.9 cm y^{-1} (Pronger *et al.*, 2014). They found these rates to be consistent with rates around the world, despite differences in peatland characteristics. Contemporary subsidence is dominated by oxidation, leading to a complete loss of peat within the next century (Pronger *et al.*, 2014).

2.7.3 Hydrology of drained peatlands

Drainage of peatlands has a major impact on their hydrology. Drainage results in an increase of the depth to the water table, which in turn has a major implication for all aspects of the hydrological function of peatlands (Holden *et al.*, 2004). The construction of drainage ditches in peatlands can significantly increase the spatial variation of water table dynamics across a peatland area (Holden *et al.*, 2006). Drained peatlands typically have large seasonal fluctuations in water table depth and are more responsive to rainfall events when compared to intact peatlands (Holden *et al.*, 2011). Rapid rises in water tables after rainfall are caused by decreases in specific yields after drainage (Mustamo *et al.*, 2016). Decreased specific yields are the result of increased bulk density as there is a strong relationship between these two properties (Liu *et al.*, 2020). A relationship between water storage and drainage has also been established (Price & Schlotzhauer, 1999). This relationship is also dependent on land use type for example, one study found that peatlands drained for agriculture have much more rapid and ongoing losses of water storage compared to drained peatlands under forestry (Liu *et al.*, 2020). A loss of peat thickness can also be attributed to a loss in water storage (Price & Schlotzhauer, 1999;

Liu *et al.*, 2020). Liu *et al.,* (2020) determined that a loss of peat thickness contributed to >80% of the loss in water storage capacity, while Price & Schlotzhauer (1999) found that it was attributable to at least 50% of the water storage changes. Menberu *et al.,* (2021) found that, in drained peatlands with high bulk densities (> 0.3 g cm^{-3}) overland flows are increased, leading to a reduction of water storage capacity. After drainage the distinctive layering of the acrotelm and catotelm found in functioning peatlands is lost leading to lower hydraulic conductivity and specific yield values (Mustamo *et al.*, 2016). Price & Schlothauer (1999) suggested that for peat that has a high bulk density or is well oxidised, changes in water storage are driven primarily by gravitational forces. Therefore, changes in specific yield alone would be sufficient in estimating water storage changes, as compressibility is decreased due to increased bulk density. This relationship is expressed in the storativity equation as described by Price & Schlotzhauer (1999), shown in equation 2.3 of this chapter. Some previous studies have suggested that the capillary rise in peat may be increased after drainage due to a shift to greater proportions of small pores. This is because smaller pores are able to hold more water against suction and so there is also an increase in water retention in drained peatlands (Kellner, 2003; Price *et al.*, 2003).

2.7.4 Carbon cycling in drained peatlands

Drainage changes how carbon is cycled in peatlands and this is largely due to an accelerated rate of organic matter decomposition. Drainage of peatlands artificially lowers the water table, introducing atmospheric oxygen, resulting in aerobic conditions, and increasing rates of microbially mediated aerobic decomposition,

The net amount of carbon being released from a peatland overtakes the rate at which carbon is accumulated into the peatland, because aerobic decomposition occurs at a rate that is around 50 times faster than the rate at which anaerobic deposition occurs (Clymo, 1983). This transforms peatlands from significant carbon sinks to sources (Blodau, 2002; Couwenberg, 2011; Joosten *et al.*, 2012; Zhong *et al.*, 2020; Qiu *et al.*, 2021; Temmink *et al.*, 2022). A drained peatland may also lose carbon through loss of dissolved inorganic carbon (DIC), dissolved organic carbon (DOC) and particulate organic carbon (POC). Drained peatlands may have a higher risk of erosion, especially if the area is converted to pasture for grazing or is cleared for cropping. Therefore, there is an increased risk of a loss of carbon through POC as the peat is eroded and exported away from the peatland (Evans & Warburton, 2010).

2.8 Characteristics of developed peat in drained peatlands

Subsidence causes changes in the physical and chemical properties of peat as physical and chemical processes occur after drainage.

2.8.1 Physical properties

The physical properties of peat in drained peatlands are markedly different to the properties described for undrained peatlands. In drained peatlands, porosity is often substantially reduced. This is because of shrinkage and consolidation resulting from the drainage of macropores and increased effective stress on the peat matrix (Price & Schlotzhauer, 1999). However, the formation of cracks due to drying may lessen this reduction in total porosity, especially near the surface (Lennartz & Liu, 2019). Mustamo *et al.,* (2016) found that cultivated peatlands had porosities on average of 71% in the top layer, and this increased with depth. This is a lower porosity than what is typically found in pristine peat which is usually 80% or greater (Kellner, 2003).

The processes driving subsidence in drained peatlands ultimately results in an increase in bulk density. This is firstly by the consolidation of peat, as buoyancy is lost and then the shrinkage of peat that occurs when macropores collapse (Price & Schlotzhauer, 1999; Price *et al.*, 2003; Rezanezhad *et al.*, 2016). Bulk densities of drained peatlands across the globe are in the ranges from 0.17 g cm^{-3} up to 0.50 g/cm^3 and possibly higher (Schwärzel *et al.*, 2002; Dawson *et al.*, 2010; Kechavarzi *et al.*, 2010; Mustamo *et al.*, 2016). In New Zealand, McLay *et al.,* (1992) reported bulk density of 0.31 ±0.01 g cm^{-3} in the top layer of a drained agricultural peat profile. There is a strong relationship between bulk density and other soil properties such as total porosity and macroporosity. These relationships can be used to estimate changes to other related properties such as hydraulic conductivity. Therefore, bulk density can be used to estimate how other properties may change as a result of drainage (Menberu *et al.*, 2021). In drained peat, there is also an overall shift in pore size distribution to a larger proportion of small pore spaces (Figure 2.3) (Price, 2003; Kennedy & Price, 2005; Kechavarzi *et al.*, 2010; Rezanezhad *et al.*, 2016).

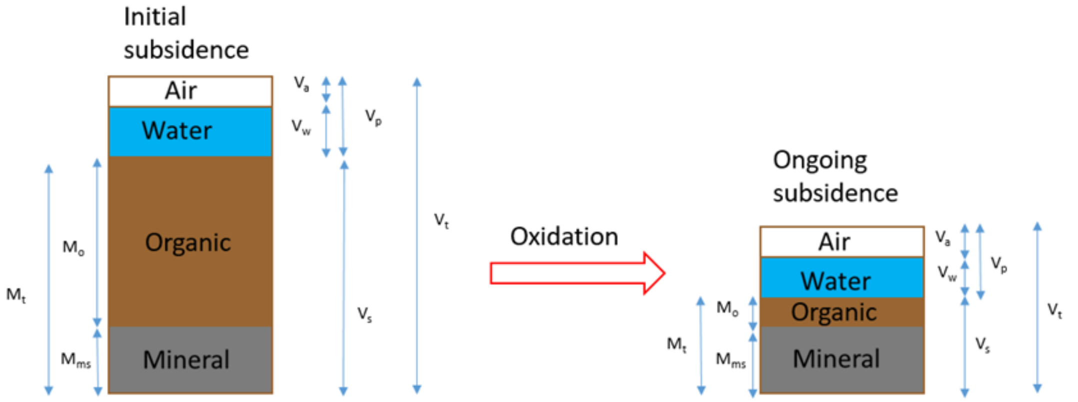

Figure 2.3 Schematic showing how ratios of water, air and solids change after initial subsidence and how oxidation affects these ratios with ongoing subsidence (adapted from Ewing & Vespraskas, 2006).

Drained peats have lower hydraulic conductivities than those found at undrained peatlands, indicating that lateral flows are much less once peatlands are drained (Menberu *et al.*, 2021). This decreased hydraulic conductivity is a direct result of a decreased proportion of macropores. Mustamo *et al.*, (2016) demonstrated that, upon draining, peatlands lose their distinct two-layered morphology. This was observed as a decreased specific yield coupled with a decreased hydraulic conductivity in the surface layer (Mustamo *et al.*, 2016). This specific study contradicted the findings of Menberu *et al.* (2016) by stating that the properties of highly degraded peats were not reliable predictors for changes in hydraulic conductivity.

There is also an increase in water retention in drained peat due to a greater proportion of smaller pores and increased bulk density due to drainage (Boelter, 1968; Price, 2003). Although water retention is high, much of it is held at very high suctions and therefore the water is unavailable for plant use (McLay *et al.*, 1992). McLay *et al.* (1992) attributed this unavailability of water for plants to the sorption of water to organic matter. However, the shift in pore size distribution due to the collapse of macropores is the dominating factor that drives an increase in water retention (Whittington *et al.*, 2007). Higher water retention is also associated with a decrease in S_y and less water can be readily drained by suction (Price *et al.*, 2003). VMC is decreased at drained peatlands that have been intensively drained, even when the peat is at saturation. At increased suctions, however, VMC has been observed to increase and this is often reflected by a sensitive response of water table depth to rainfall events, which also relates to lowered specific yields (Paivanen, 1973; Mustamo *et al.*, 2016). This is largely related to the shift in pore size distribution that occurs due to subsidence processes related to drainage (Mustamo *et al.*, 2016). Soil moisture content at the surface layers of drained peatlands may be significantly reduced as water table levels deepen. This occurs because the rate at which water is lost through evaporation is faster than the rate at which water content can be replaced through capillary rise (Price, 2003; Nugraha *et al.*, 2017).

Peat often becomes hydrophobic upon drying, making it difficult to rewet (Holden *et al.*, 2004; Holden *et al.*, 2006). This has been attributed to the presence of hydrocarbon chains, nonpolar fragments and amino acids, all of which have hydrophobic components within their molecular structures (Szajdak *et al.*, 2020).

The compressible nature of peat may be reduced in drained peatlands. Previous studies have found that the compressibility of peat decreases with increasing bulk density associated with decreased peat volume that occurs after drainage (Price *et al.*, 2005; Whittington & Price, 2006; Gebhardt *et al.*, 2010).

2.8.2 Chemical properties

Drainage of peatlands affects the chemical properties of peat because of an increased aerobic decomposition and loss of carbon. Therefore, the organic matter content of drained peatlands is reduced as oxidation continues (Liu *et al.*, 2019). A loss of carbon can be estimated through measurements of ash contents of peat. This concept is derived from the process of oxidation, which consumes organic carbon and leaves behind only the already existing mineral matter (Grønlund *et al.*, 2008; Leifeld *et al.*, 2011; Krüger *et al.*, 2015).

The pH of drained peatlands is largely attributed to land use. Drained peat under agriculture often has lime added to increase pH towards more favourable conditions for pasture, whilst fertiliser inputs may also increase pH (Hikmatullah & Sukarman, 2014). Drying may also increase the pH of peat and it has been suggested that when measuring peat pH, a field moist sample must be analysed to avoid inaccuracy of pH measurements (McLay, 1986). However, pH appears to still decrease down the profile as greater amounts of organic matter are found (McLay, 1986; Szajdak *et al.*, 2020).

C/N decreases after drainage due to the introduction of atmospheric O_2 to the peat structure. This results in increased aerobic decomposition which leads to carbon being mineralised and the ratio of carbon to nitrogen decreases (Bader *et al.*, 2018). Aerobic decomposition in drained peatlands favours carbon over nitrogen; therefore, enrichment of nitrogen also contributes to lower C/N (Säurich *et al.*, 2019; Ratcliffe *et al.*, 2020; Szajdak *et al.*, 2020). Decreasing C/N is related to increased bulk density, which is due to increased aerobic decomposition leading to increased bulk density (Liu & Lennartz, 2019). Decreased C/N, particularly in drained peatlands for agriculture, are also attributed to increased N inputs through the use of N-based fertilisers (Krüger *et al.*, 2015; Leifeld *et al.*, 2020).

2.9 Peat surface oscillation in drained peatlands

PSO has been observed in drained peatlands (Table 2.1), but is distinctly different to PSO observed in intact peatlands. It is thought that the compressibility (or elasticity) of peat is a major factor in determining the potential magnitude of PSO in a peatland (Price & Schlotzhauer, 1999; Kennedy & Price, 2005; Howie & Hebda, 2018). Price & Schlotzhauer (1999) suggested that if peat has low compressibility due to severe degradation, gravity induced drainage dominates changes in water storage and in response, surface elevation changes. In drained peatlands, the dominating processes driving PSO behaviour are most likely very different to those dominating undrained peatlands. For example, flotation will not occur in drained peatlands, due to lowering of the water table and the reduction of water content in the peat matrix as well as the effect of increased bulk density (Price & Schlotzhauer, 1999; Fritz *et al.*, 2008). The saturated zone in intact peatlands is also much deeper than it is in drained peats and so a larger part of the peatlands is subject to fluctuating water table levels. Also, some parts of the undrained peatlands, near the surface, may never reach saturation (Holden *et al.*, 2011). Another factor that is thought to determine the magnitude of PSO in peatlands is water table depth, with shallower water tables contributing to greater ranges of PSO (Fritz *et al.*, 2008; Howie & Hebda, 2018). Greater water table depths can increase subsidence seen during the summer dry periods, which may not be completely reversible leading to further degradation of the peat (Price *et al.*, 2003).

A change in pore size distribution, such as that caused by drainage, may result in a decrease in the total amount of annual shrink and swell. Furthermore, this may continue to decline as seasonal shrinkage associated with PSO occurs annually (Kennedy & Price, 2005; Gebhardt *et al.*, 2010). Glover-Clark (2020) noted that a drained site with the higher bulk density had a smaller magnitude of PSO than the adjacent site. This further suggests that the effect that drainage has on compressibility influences PSO behaviour.

When Glover-Clark & Campbell (2021) plotted SE against RWL (Figure 2.4) after measuring PSO in a drained peatland used for dairy farming, the relationship and patterns observed were far more complex compared to those reported by Fritz *et al.*, (2008) (Figure 2.2). However, hysteresis is still evident in drained peatlands during changes in surface elevation. The red diamonds on Figure 2.2 are used to show the same RWL but a different SE to highlight the irreversible component of subsidence (distance between the red diamonds) occurring as part of the normal seasonal PSO (Glover-Clark & Campbell, 2021). This shows the difficulty in separating subsidence from annual PSO.

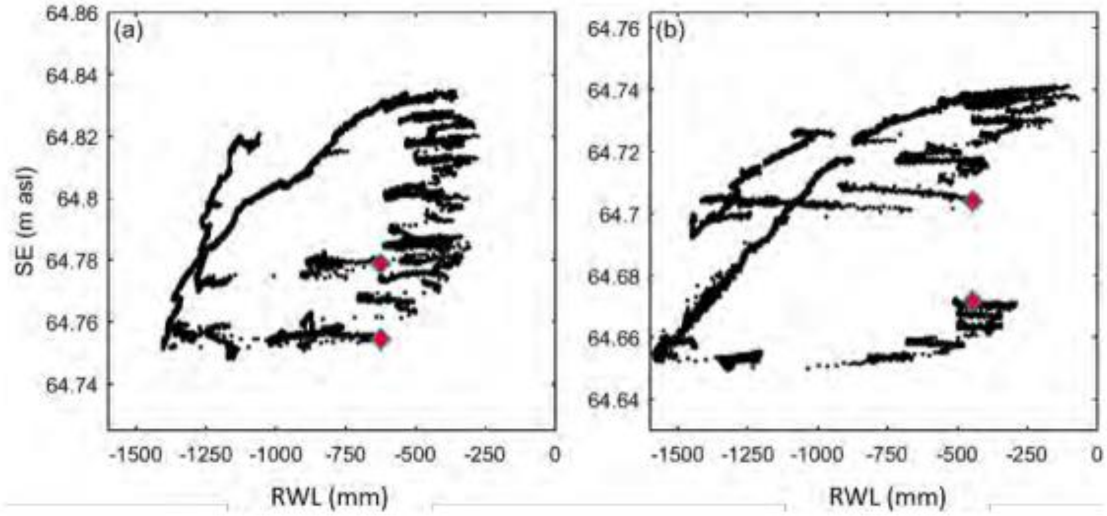

Figure 2.4 RW: vs SE plots for 1 March 2019- 1 August 2020 for two adjacent sites in the Moanatuatua peatland. (Glover-Clark & Campbell, 2021)

Hysteresis has been observed to occur in drained peatlands, Schwärzel *et al.,* (2002) suggested that hysteresis could be attributed to alterations of pore structure caused by shrinkage, hydrophobicity of the dried peat, or the inclusion of air as water-filled pores empty. Howie & Hebda (2018) reported that the more strongly drained plant communities in their study displayed the least amount of hysteresis, indicating a loss in water storage capacities of the peat at these sites.

The most important defining factor that distinguishes PSO from subsidence is that PSO is a reversible process, which occurs in both intact and drained peatlands (Fritz *et al.*, 2008). Subsidence is the irreversible loss of peat volume that occurs as a direct result of drainage and is not a natural process in intact peatlands. It also leads to the complete loss of peat via oxidation making subsidence a significant environmental, economic and social issue (Hooijer *et al.*, 2012; Aich *et al.*, 2013; Campbell *et al.,* 2021).

2.10 Summary of literature and gaps in knowledge

The extent of studies regarding PSO behaviour in peatlands is relatively small compared to the literature on subsidence following drainage of peatlands. Studies investigating differences in PSO behaviour across different drained peatlands and different land uses is even smaller. Generally, studies investigating PSO behaviour in drained peatlands are limited to one peatland (Glover-Clark & Campbell, 2021), or those that cover a wider spatial extent do not provide high resolution measurements (Reeve *et al.*, 2013; Bradley *et al.*, 2022) (Table 2.1). Far fewer studies have investigated how differences in land management may be related to differences in PSO (Evans *et al.*, 2021). Peat properties are affected by drainage and appear to drive the compressibility of peat and therefore the magnitude of PSO (Price & Schlotzhauer, 1999; Price *et al.*, 2005; Gebhardt *et al.*, 2010; Waddington *et al.*, 2010). Hence, it is important to investigate how different land uses may affect PSO across many different peatlands. In New Zealand, there have been no studies investigating how PSO may differ across both different land uses and different peatlands, and no study has tried to link these differences to peat soil physical and chemical properties. There are four main gaps in knowledge regarding PSO in drained peatlands:

- A general lack of high temporal resolution measurements of PSO
- How PSO differs spatially, especially at a regional scale
- Influence of different land uses on PSO in drained peatlands
- Influence of peat soil properties on PSO in drained peatlands

Chapter Three

Study sites and methods

3.1 Introduction

This chapter provides an overview of the study sites and their drainage histories, as well as the original peatland area. The methodology for field sampling, PSO and hydrology monitoring and data downloads, laboratory analyses and post-processing of data is also described in this chapter.

3.2 Overview of Study Sites

The regional PSO monitoring network consisted of 11 sites at the time of this study (Table **3.1**). The PSO sites were located in the Rukuhia, Moanatuatua, Komakarau, Torehape and Motukaraka peatlands in the Waikato region, Te-Ika-a-Māui, Aotearoa, New Zealand (Figure 3.1). All the study sites were on peatlands that were initially drained during the 20th Century. The PSO sites were installed on dairy farms, blueberry orchards and dry stock farms (Glover-Clark, 2021). The sites were chosen to represent a variety of agricultural land uses on drained peatlands in the Waikato region, and they represent the range of peatland types and locations. All four of the blueberry sites were paired with adjacent dairy sites. At Rukuhia a dry stock farm was also included in the vicinity of the dairy and blueberry paired sites (Figure 3.1). Replicated pairs of dairy farms and blueberry orchards allowed direct comparisons of surface elevation change and water level between different land uses. However, at the Kom_DS (Komakarau) dry stock site and the Motukaraka (Mot_Dairy) dairy farm site did not have a contrasting land use set up at the time of this study. Table 3.1 outlines each site and basic background information. The exact locations of the PSO sites are not listed for landowner privacy reasons.

Table 3.1 Overview of field sites, former peatlands and other relevant background information (Credit: Glover-Clark, 2021)

Site Code	**Land use**	**Former Peatland**	**Peatland type**	**Peat depth (m)**	**Drainage History (years)**
Moa_Dairy	Dairy farm	Moanatuatua	Oligotrophic*	7.0	~48
Moa2_Dairy	Dairy farm	Moanatuatua	Oligotrophic*	4.4	~69
Moa_BB	Blueberry orchard	Moanatuatua	Oligotrophic*	6.5	~43
Moa2_BB	Organic blueberry orchard	Moanatuatua	Oligotrophic*	4.7	~31
Ruk_Dairy	Dairy farm	Rukuhia	Oligotrophic*	9.5	~60
Ruk_DS	Dry-stock farm	Rukuhia	Oligotrophic*	~10.1	~60
Ruk_BB	Blueberry orchard	Rukuhia	Oligotrophic*	10.0	~53
Tor_Dairy	Dairy farm	Torehape	Oligotrophic+	6.0	~53
Tor_BB	Blueberry orchard	Torehape	Oligotrophic+	5.5	~56
Kom_DS	Dry-stock farm with maize cropping	Komakorau	Oligotrophic*	3.8	~53
Mot_Dairy	Organic dairy farm	Motukaraka swamp	Minerotrophic#	~5.35	~56

* Source: Davoren, 1978

+ Source: Moore & Clarkson, 2007

Source: Tilsley & Findley, 1981

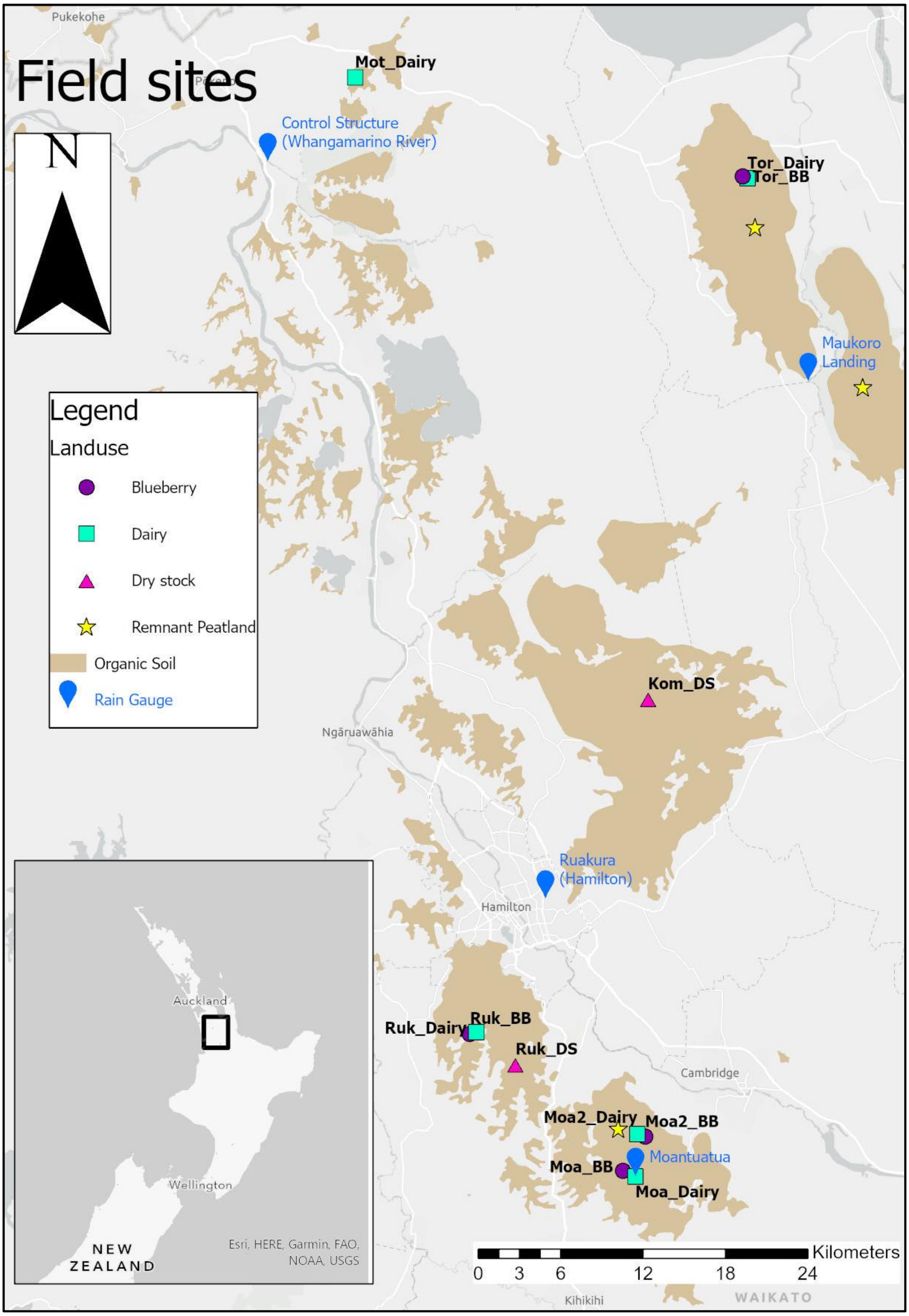

Figure 3.1 Waikato peatland map with the study sites, peatlands and location of rain gauges. Organic soil overlay from Manaaki Whenua Landcare Research, Smap online (2022) .

3.3 Time since drainage

3.3.1 Moanatuatua

The Moanatuatua peatland is located 15.5 km to the southeast of Hamilton in the Waikato Region and spans an area of 8470 ha (84.7 km^2) (Davoren, 1978). This peatland was a raised bog with the dominating vegetation being *Sporadanthus traversii* and *Empodisma minus* (Campbell, 1964; Shearer, 1997). This vegetation is the reason it is referred to as a restiad peat bog, as these plants belong to the Restionacae family. Peat accumulation has been estimated to have began in around 13, 000 BP and occurred at a rate of 1 mm y^{-1} (on average) (Hogg *et al.*, 1987; Shearer, 1997). Initial drainage attempts within the Moanatuatua peatland took place from the late 1800s (Auckland Star, 1916 *in* Pronger et al., 2014). However, intense drainage for the development of the area came into full swing from the 1930s to the 1950s (Glover-Clark, 2020; Wallace, 1978 *in* Pronger et al., 2014). In order to confirm drainage dates for each PSO site in the Moanatuatua peatland and other peatlands, historic aerial photographs were analysed, using the online resource Retrolens (LINZ, n.d.). The GPS coordinates of the sites were input to Retrolens to locate aerial photographs. The exact location of each site in the aerial photographs was estimated by comparing roads and landmarks nearby. These were then used to determine drainage by assessing the vegetation cover and comparing aerial photographs from different years (Figure3.2) These photographs confirmed that Moa2_Dairy was the first site to be drained, around 1953. Moa2_BB was the last to be drained, as it was purchased in 1991 and developed for Monavale Blueberries (Monavale Blueberries, 2021).

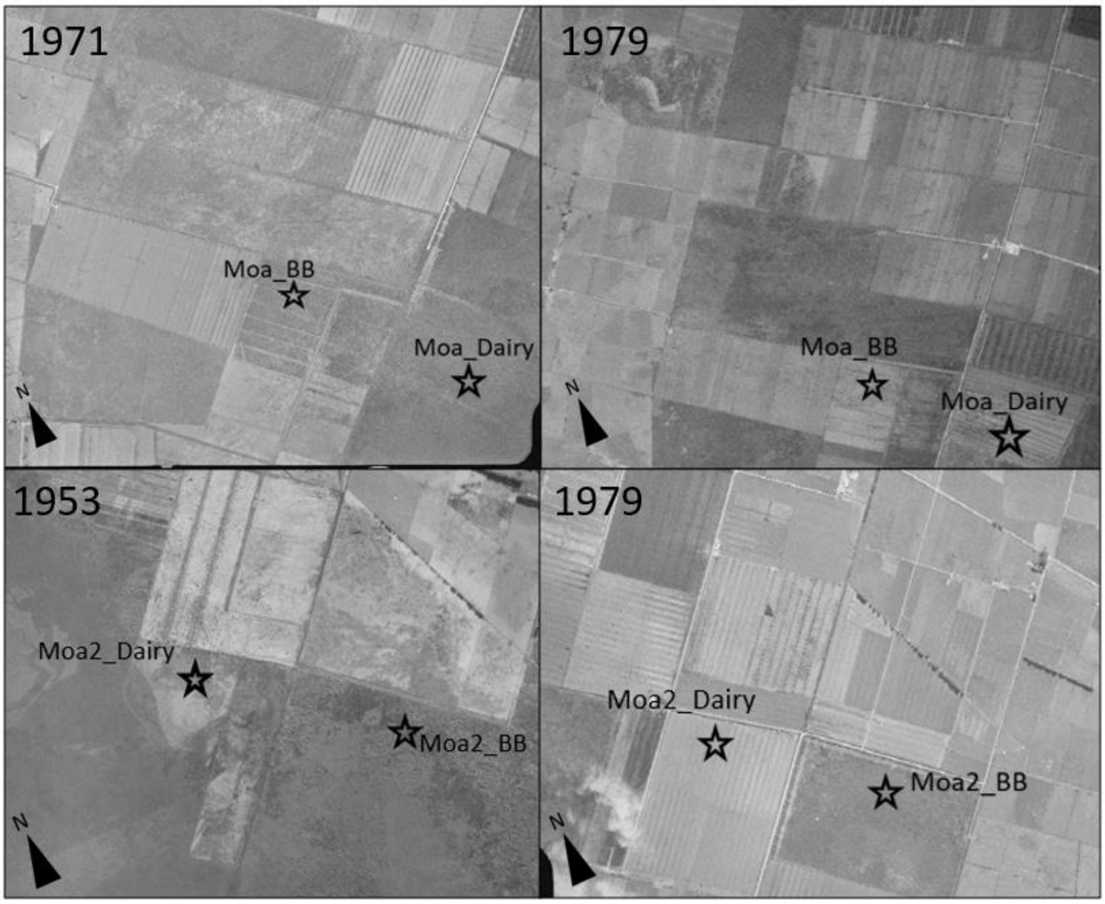

Figure 3.2 Aerial photographs of Moa_Dairy and Moa_BB (top - 1971 and 1979) and Moa2_Dairy and Moa2_BB (bottom - 1953 and 1971) (base images sourced from http://retrolens.nz, licensed by LINZ).

3.3.2 Rukuhia

The Rukuhia peatland is located approximately 3.5 km south of Hamilton in the Waikato region and covers an areas of approximately 6420 ha (64.2 km^2) (Davoren, 1978). The dominating vegetation of this bog was also *S. traversii* and *E. minus;* as a result, this peatland was also a restiad raised bog. *Sphagnum* mosses were minor components of this former peatland (Campbell, 1975). Radiocarbon dating cores have indicated that Rukuhia was mainly developed between 10, 000 to 12, 000 BP years ago and at a rate of 1.2 to 14 mm yr^{-1} (Hogg *et al.*, 1987). A historian search undertaken by Dr Joanna Bishop in 2015 for the Waikato Regional Council found the earliest mention of drainage ditches in a report that spanned 1914-1970 (Bishop, 2015). Drainage attempts had been reported as early as the late 1800s (Rayes, 1988 *in* Pronger et al., 2014). The Ruk_DS landowner website states that the farm area was first drained in the 1960s (Henderson & Henderson, 2022). Aerial photographs were again used to constrain dates, especially due to a lack of information for Ruk_Dairy and Ruk_BB. Ruk_DS and Ruk_Dairy were undrained in

1957 the next aerial image, in 1967, shows Ruk_DS and Ruk_Dairy under rough pasture so it is assumed drainage occurred midway between 1957 and 1967, in 1962. Ruk_BB was drained later in approximately 1971 (Figure 3.3).

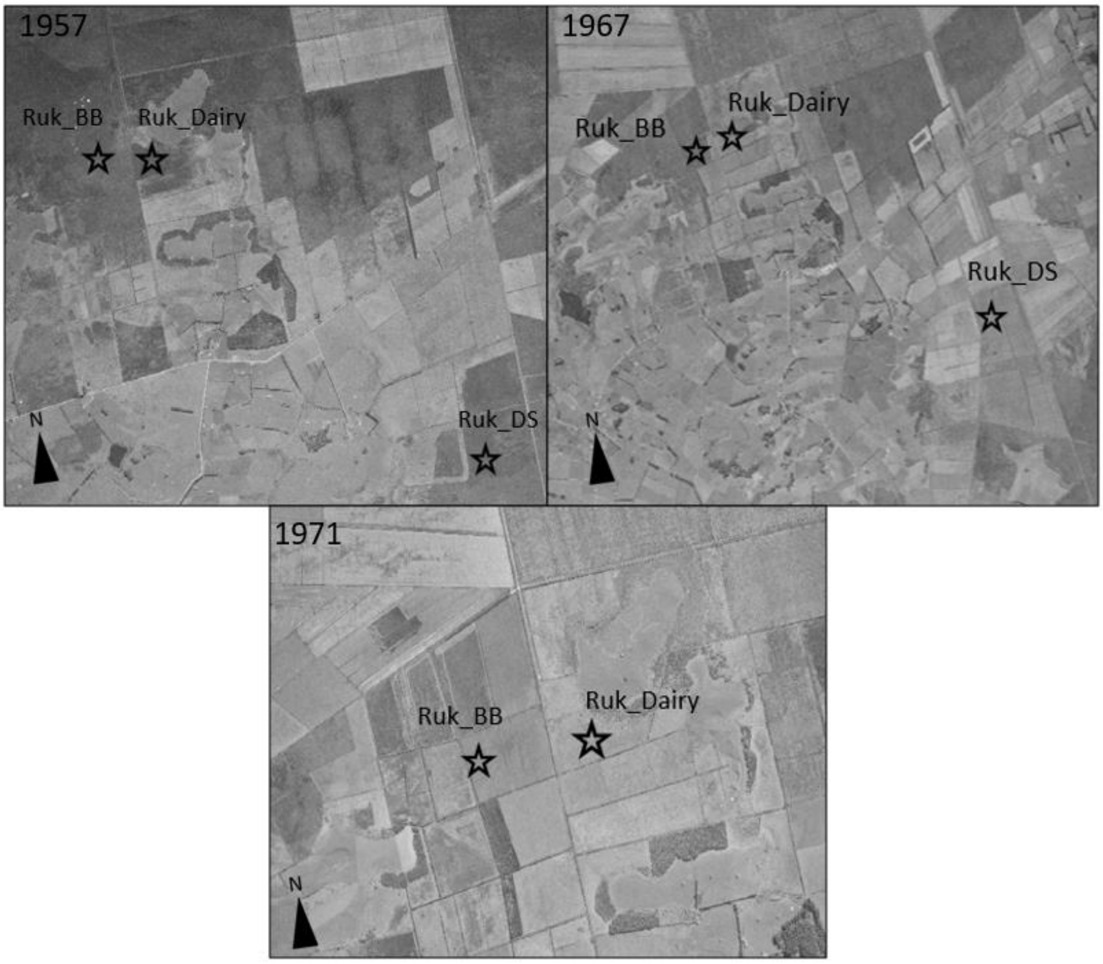

Figure 3.3 Aerial photographs of Ruk_Dairy, Ruk_BB and Ruk_DS for years 1957, 1967 and 1971 (Ruk_DS not visible in 1971) (base images sourced from http://retrolens.nz, licensed by LINZ).

3.3.3 Komakorau

The Komakorau dry stock site is located close to Woodlands Road near Gordonton. The former peatland was Komakorau, but in some historical documents, the area near Woodlands Road was referred to as part of the Piako Swamp (Bishop, 2015). It has also been referred to as Motumaoho restiad peat bog, with the dominant vegetation in the past being *E. minus,* as well as two other sedge species, *Schoenus brevifolius* and *Baumea teretifolium,* and some *S. traversii.* Like Moanatuatua, *Sphagnum* mosses were very minor components of the vegetation in this peatland (Campbell, 1964). It was difficult to find much other information on this site and therefore dates were confirmed via historic aerial photography (LINZ, n.d.).This analysis indicated a drainage date of between 1963 and 1969, as the images showed rough pasture in 1969 (Figure 3.4). Therefore, the median date of 1966 was assumed.

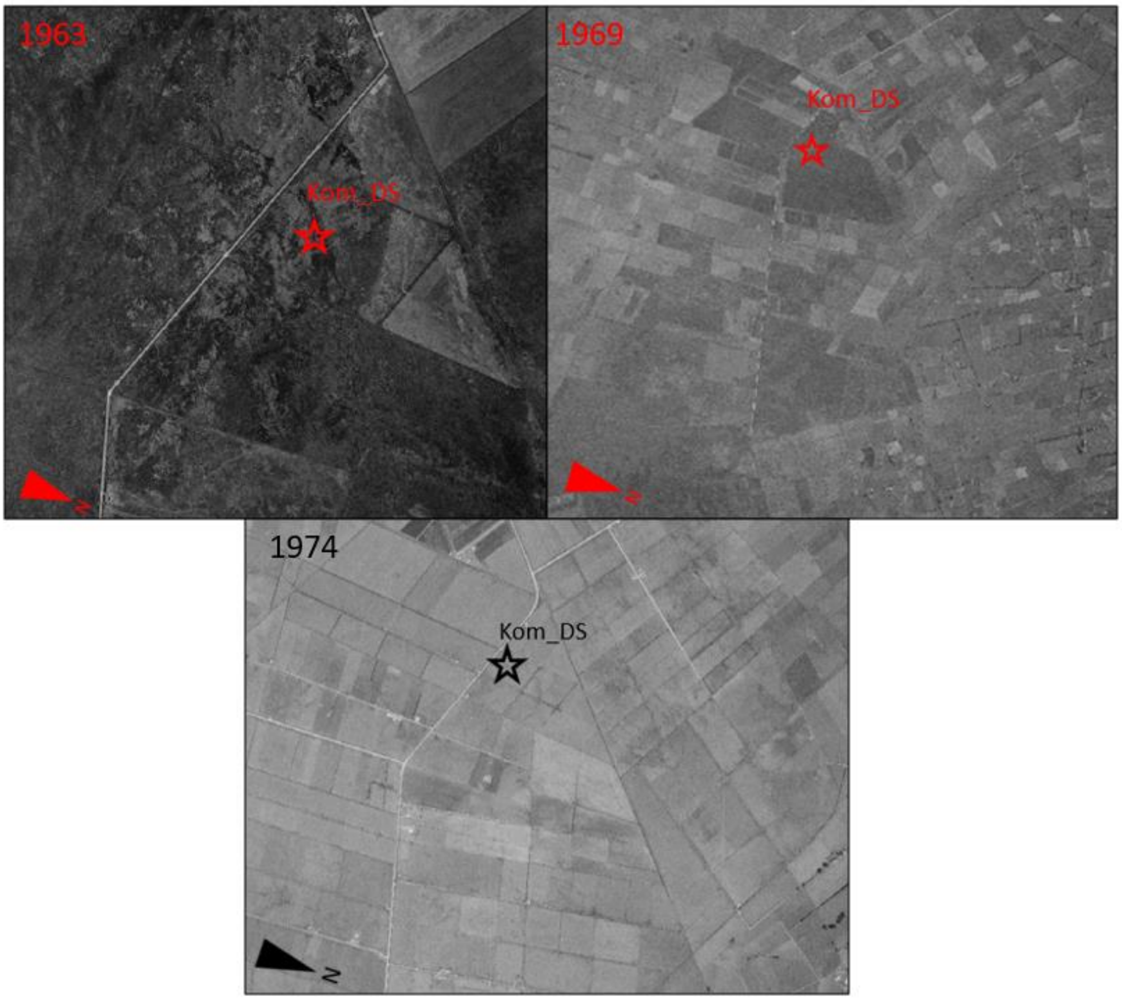

Figure 3.4 Aerial photographs of Kom_DS for years 1963, 1969 and 1974 (base images sourced from http://retrolens.nz, licensed by LINZ).

3.3.4 Torehape

The Torehape peatland is located within the Hauraki Plains peatland area, which comprises both intact and drained peatland areas (Davoren, 1978; Pronger et al., 2014). Davoren (1978) estimated the total area of both the undisturbed and drained peatland to be 2385 ha. The current remnant peatland are of Torehape is dominated by *Sporidanthus*, and *E. robustum* (Clarkson *et al.*, 2004; Wagstaff & Clarkson, 2012). There is evidence that part of the peatland was also dominated by *Sphagnum* mosses and there are previous reports of moss mining (Campbell, 1975; Russel, 1993). Initial formation of the peat bog is estimated to be 9360 BP, but this is from cores taken in Kopuatai, which is to the south east of Torehape. The PSO sites were on adjacent dairy farm and blueberry orchards on the former Pouarua peat dome, which is part of the Torehape peatland area west of the

Piako River. Many drains and canals have been dug in this area, especially in the vicinity of the Tor_Dairy and Tor_BB PSO monitoring sites. Drainage on the Hauraki Plains began under the Drainage act of 1908 and the Hauraki Plains Drainage Scheme (Bishop, 2015). The Torehape peatland appears to have the earliest intense drainage. Despite this, the drainage dates for the PSO sites located in Torehape were not much older than the sites at the other peatlands. Aerial photography indicated that Tor_Dairy was drained around 1969 (between 1966-1977). Tor_BB was drained earlier around 1966, which was also shown in aerial photography (Figure 3.5).

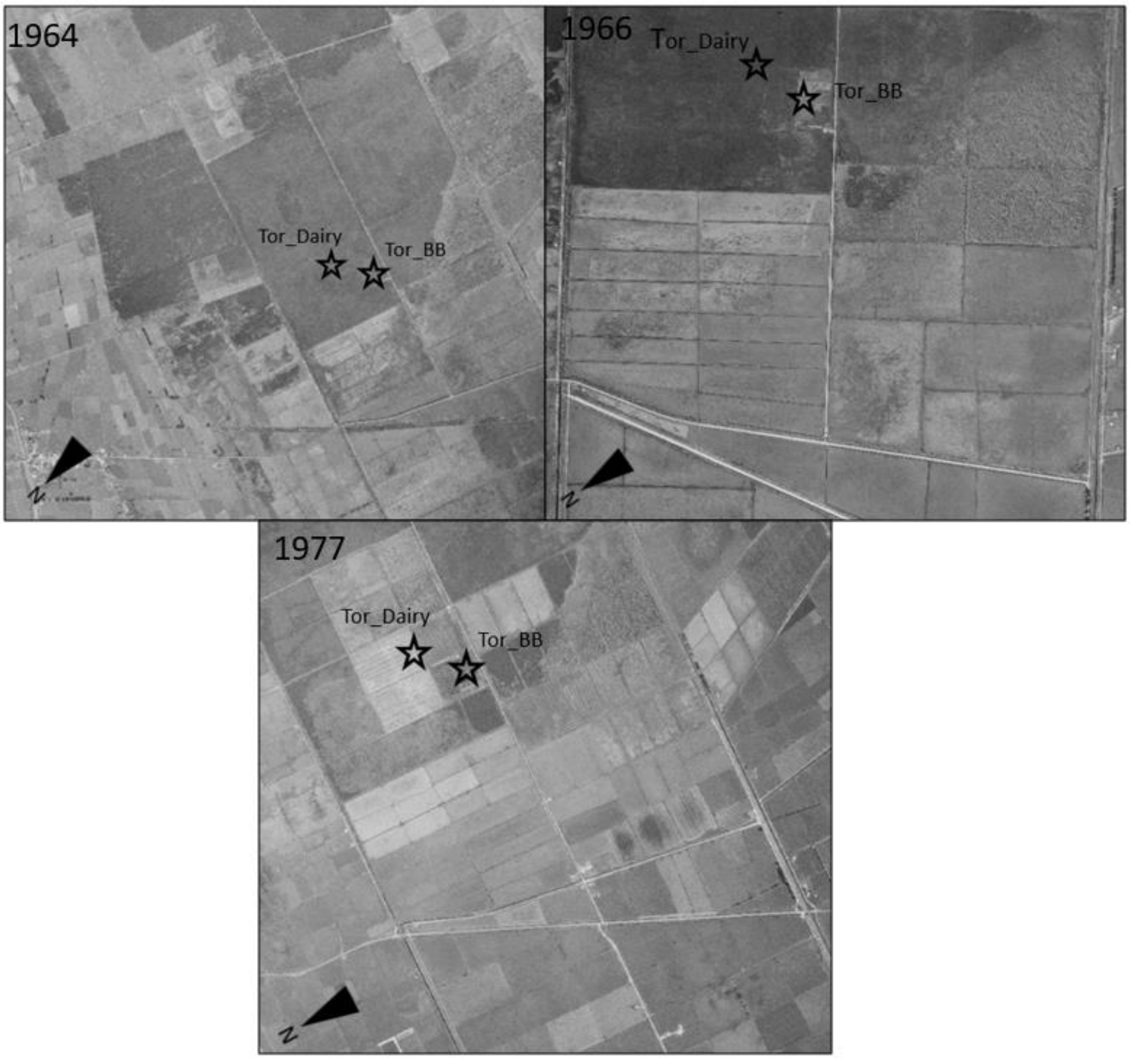

Figure 3.5 Aerial photographs of Tor_Dairy and Tor_BB sites for years 1964, 1966 and 1977 (base images sourced from: http://retrolens.nz, licensed by LINZ).

3.3.5 Motukaraka

Mot_Dairy is located in the former Motukaraka "Swamp", for which there is very little information regarding its formation and vegetation history, and drainage history.

However, local maps on the Waikato Regional Council website (2022) indicated that it is part of the Franklin drainage scheme. A report of the proceedings of a conference held in 1981 indicated that the drainage of the Motukaraka Swamp began in approximately 1967 (Tilsley & Findley, 1981). A record from the Auckland Council Libraries announces the opening of a screw-pump in The Motukaraka Swamp in November, 1974 (Auckland Council Libraries, 2004). Aerial photography indicated that the site was drained around 1966, since the photograph from 1966 appeared to show the site to be under rough pasture (Figure 3.6).

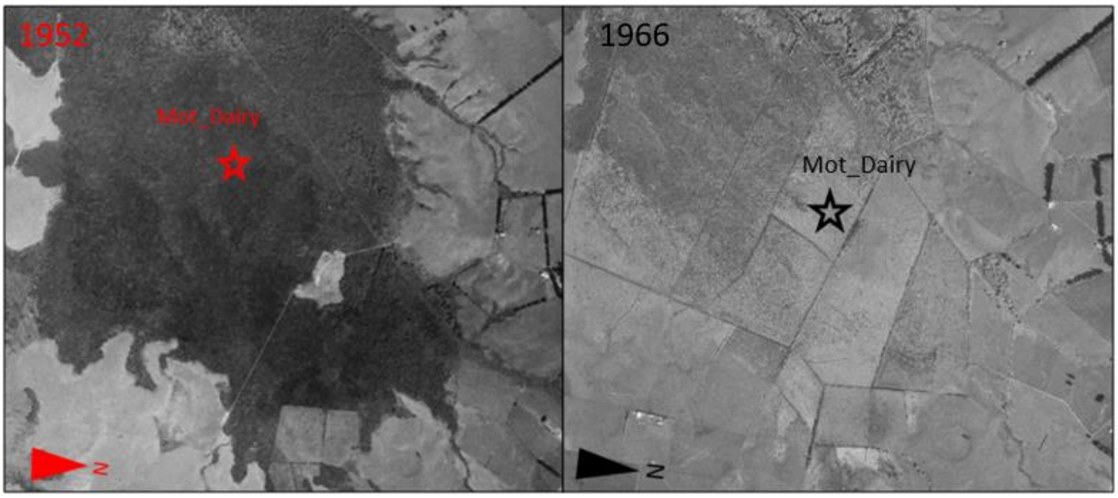

Figure 3.6 Aerial photographs of Mot_Dairy for years 1952 and 1966 (base images sourced from http://retrolens.co.nz, licensed by LINZ)

3.4 PSO measurements

3.4.1 PSO site set-up

The PSO sites were established during summer to autumn of 2020-2021, to measure water table depth and changes in peat surface elevation using the paired pressure transducer method adapted from Fritz et al. (2008) and Glover-Clark (2020). The site locations, set up and standard operating procedures are outlined in Glover-Clark (2021).

At each site, two logging water level transducers (Levellogger 5, Solinst, Georgetown ON Canada) were suspended from Kevlar cord and suspended in a PVC pipe dip-well. One of the probes was suspended from a steel rod (Figure 3.7), which was anchored into the mineral substratum beneath the peat, usually either sand or clay. Generally, the steel rod was hammered much deeper into the clay substratum (Tor_Dairy, ~ 6 m into marine clay) than the sandy substratum (Ruk_Dairy, ~ 2 m into sandy substrate). The sensor attached to the rod measured absolute water level (AWL), which is the water table depth relative to an absolute benchmark (the top of the steel rod). The elevation was measured using GNSS survey system (Viva GS16 Unlimited GNSS Smart Receiver, Leica Geosystems, Heerburg, Switzerland). The second sensor was attached to a galvanised steel mesh grid that was fixed to the peat surface using weed mat staples (Figure 3.7), and free to move with the peat. This sensor measured relative water level (RWL), which is the water table depth relative to the peat surface. A Solinst Barologger was also installed within each peatland group of sites for barometric correction of water levels in post-processing of the data. Rainfall data were obtained from weather stations near each location (Table 3.2).

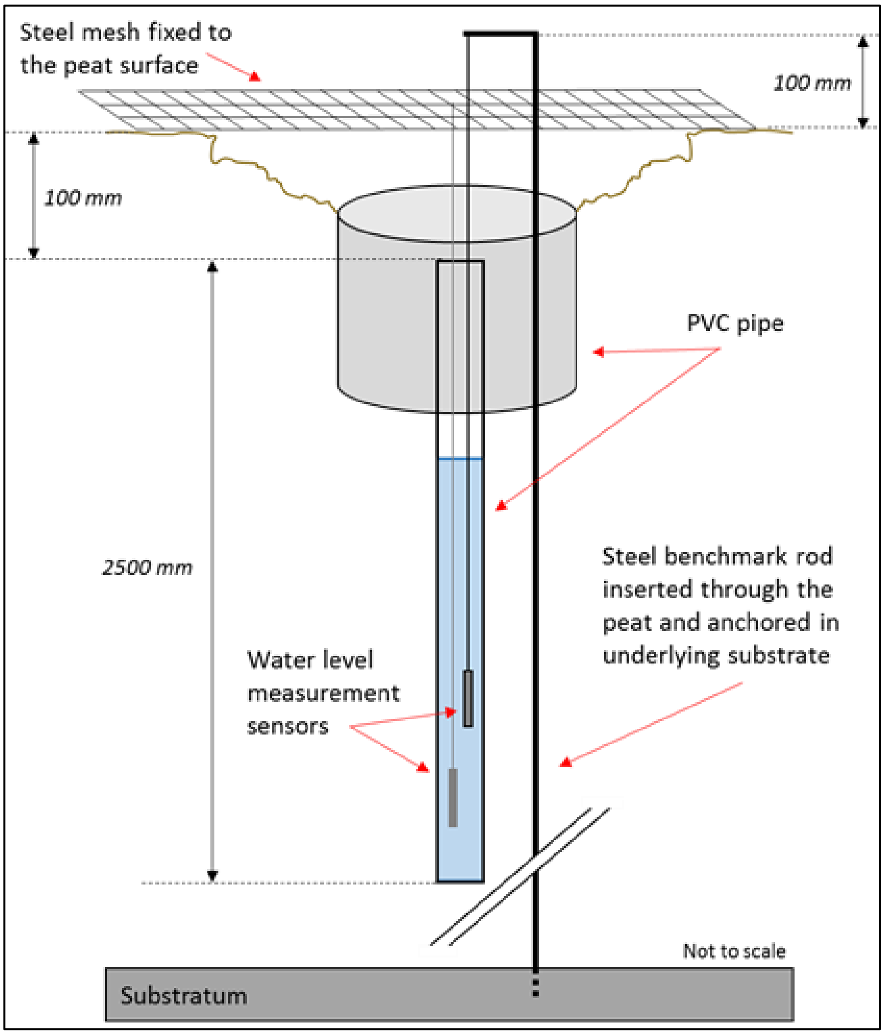

Figure 3.7 Diagram of PSO site set up, showing the paired transducer method with the steel rod inserted in the substratum for use as a benchmark and mesh fixed to the ground surface (adapted from Glover-Clark, 2021). Note that the upper 2.5 m of the steel benchmark rod ran through a 30 mm PVC pipe to prevent the surface peat from binding to the rod.

Figure 3.8 Photograph of aboveground hardware at the Moa_Dairy PSO site, showing the steel benchmark rod, horizontal bolt with AWL probe Kevlar cord attachment, steel mesh with RWL probe attachment and dipwell cap through which Kevlar lines ran. (Photo credit: David Campbell, 2021)

Table 3.2 Barologger and rain gauge locations for each peatland

Peatland	**Barologger location**	**Location of rain gauge**
Moanatuatua	Moa_Dairy	Moa_Dairy
Rukuhia	Ruk_Dairy	Moa_Dairy
Komakarau	Kom_DS	Ruakura, Hamilton Weather Station (NIWA)[a]
Torehape	Tor_Dairy	Maukoro Landing (Waikato Regional Council)
Motukaraka	Mot_Dairy	Control Station – Whangamarino River (Waikato Regional Council)

[a] Monthly and annual rainfall and temperature calculated from data from this station to compare with normals.

3.4.2 PSO downloads

Downloading PSO and barometric data occurred approximately every three months. Prior to removing the Levelogger probes for downloading data manual measurements of water table level (C) and distance from the top of the benchmark to the mesh (A) and the mesh to the top of the PVC pipe (B) were made (Figure 3.9). All raw RWL and AWL files were compensated for barometric correction using Solinst probe software. The resulting compensated data (.xle) files were then converted to text (.lev) files before being uploaded to the Hydroclimate database at the University of Waikato.

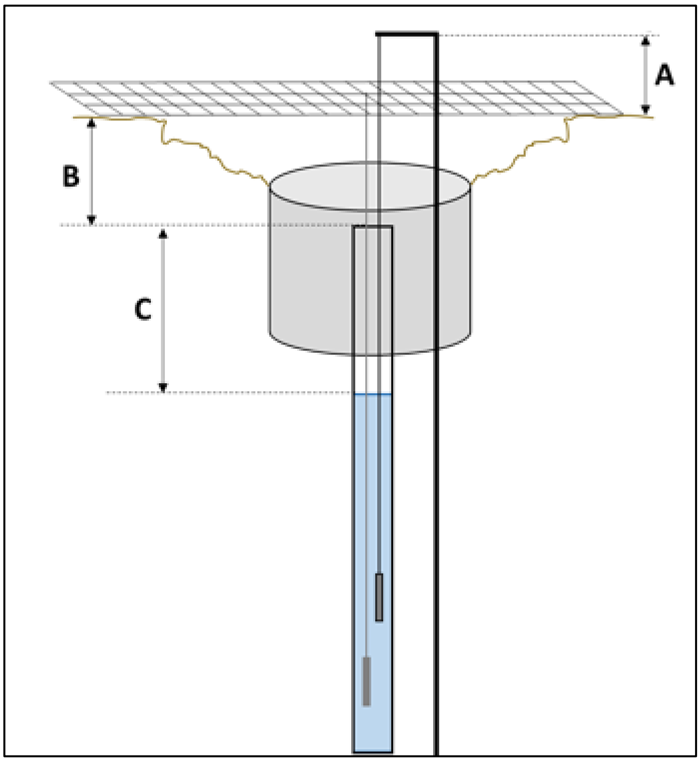

Figure 3.9 Guide for manual measurements when downloading data

3.4.3 PSO data processing

Date was further processed in custom MATLAB (The Mathworks, Inc) scripts developed in-house. Surface elevation was calculated from the difference between the two measurements, following Fritz et al, (2008):

$$SE = AWL - RWL \qquad (3.1)$$

where AWL is elevation above sea level (m) and RWL is defined as negative where then water table is below the soil surface.

The Solinst probes collected raw water level (and temperature) data at 30-minute intervals, which was stored in the database at this frequency after barometric compensation. The raw data were inspected for any anomalies such as spikes, these generally occurred during downloads when the Solinst probes were removed from the dipwells. At some sites and at some times, the 30-minute and daily mean data for calculated SE were often very noisy, as described in Appendix C, so for most of the analyses presented, 7-day running means were calculated.

The manual measurements of AWL, RWL and SE were used as a check on the performance of the Solinst probes (Appendix C). There were offsets to Solinst probe RWL and AWL measurements made based on comparisons made between the raw probe measurements and the manually-determined RWL and AWL, especially where constant offsets were evident between manual and automatic SE. Appendix C details the potential sources of errors causing these offsets.

The automatic measurements for the 30-minute period prior to probe downloads during site visits were compared to the manual measurements and means of offsets were calculated. Some manual measurements were not used if it was clear a gross error had been made. If drift was evident, offsets were not applied, as there are not sufficient manual data to indicate if it is a true drift or coincidence, an example is Tor_Dairy (Appendix C). It is also important to note that there was a very large offset at Mot_Dairy (-95.3 mm). Without this offset, SE was calculated to be at an elevation higher than the benchmark (Appendix C).

When comparing surface elevation regimes between sites, SE change (ΔSE) has been calculated as:

$$\Delta SE = SE_t - SE_{t=0} \qquad (3.2)$$

where *t* is time

The statistics calculated for RWL, including mean, max, min and total ranges were calculated in MATLAB from the daily means of the raw data. These stats were calculated for the annual 1 July 2021 to 30 June 2022, in line with IPCCC reporting on water table depths (Hiraishi *et al.*, 2014). The RWL and surface elevation ranges calculated for different periods of shrink and swell throughout the whole study were also calculated in MATLAB from 7-day running means of data in order to reduce the effect of short-term fluctuations such as noise in SE datasets (Appendix C). These were determined through finding the minimum and maximum values of surface elevation and RWL within defined periods. For the 2021 “swell” period, this was 1 April 2021 to 1 November 2021, for the 2021 – 2022 “shrink” period this was from 1 August 2022 to 1 July 2022, and for the 2022 swell period this, was from 1 April 2022 to 10 April 2022.

3.5 Field sampling

Collection of soil cores and grab samples from each monitoring site occurred between 4 November and 9 December 2021. 478 cores (Figure 3.10) were collected with 110 of these reserved for shrinkage analysis. The remainder were processed and analysed for bulk density, soil moisture, organic matter and mineral fraction, and C/N ratio. 165 grab samples were collected for pH measurement.

Figure 3.10 Example of soil cores collected in field (Photo credit: David Campbell, 2021)

Except for the Kom_DS site, samples were extracted from three different pits across the site. At all of the dairy and the Rukuhia dry stock sites, sampling pits were excavated at random locations along a transect at 90 degrees to the paddock drains close to the PSO site. The first pit was always within 10 m to the PSO site, while the other pits were located at random distances along the transect either side of the PSO site. At the blueberry sites, pits were excavated in gaps in the rows of blueberry bushes, or at the end of a row. This was to represent the location of the sensors, to avoid the lanes that were likely compacted and to avoid damage to the blueberry bushes. At the time of sampling the Komakarau dry stock site (Kom_DS) the peat was under a new maize crop. To avoid damage to the crop one pit was excavated next to the PSO site, and four replicate soil core samples at five depths were taken in two spots within the same pit. At all other sites three replicate samples were taken at each depth in each pit. At all sites, sampling depths were 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm and 40-50 cm. The samples were collected in stainless steel rings that were sharpened on one end, with dimensions of 100 × 75 mm. The cores chosen for the shrinkage analysis were kept in their steel core and wrapped in plastic film wrap. All other samples were extracted into zip lock bags and placed in insulated bins. Samples were stored in a refrigerator prior to laboratory processing, the bulk density cores were processed within one or two days of sampling. The shrinkage experiment cores and the pH grab samples were both processed within a month of sampling.

Soil cores at all but one site (Moa2_BB) were collected using a modified house jack mounted to the tow bar sleeve of the vehicle (Figure 3.11). This allowed the steel rings to be pressed into the soil with minimal compaction or other disturbance. At the Monavale blueberry site (Moa2_BB), soil rings were carved in with a knife, due to restricted vehicle access because of the organic certification status of the orchard.

Figure 3.11 Modified house jack used to press the stainless steel rings into soil without disturbance. The upper ring has tabs that fit over the lower sharpened sampling ring and acts as a “pusher ring”.

3.6 Laboratory Analyses

3.6.1 Bulk density and moisture content

Bulk density was determined first by weighing the soil cores of a known volume before and after drying at 105˚C until a constant weight was reached following McLay *et al.* (1992). The volumes (units of cm^{-3}) of every steel ring was accurately measured with electronic callipers and the steel ring associated with its corresponding soil sample was recorded. The difference between the field moist weight and oven-dry weight (in grams) was used to calculate dry bulk density (BD, units $g\ cm^{-3}$) and gravimetric moisture content (GMC, units $g\ g^{-1}$) the latter was used to calculate volumetric moisture content (VMC units $g\ cm^{-3}$).

The calculations followed McLay (1986):

$$BD = \frac{oven\ dry\ mass}{volume} \tag{3.3}$$

$$GMC = \frac{(fresh\ soil - oven\ dry\ soil)}{oven\ dry\ soil} \times 100 \tag{3.4}$$

$$VMC = GMC\ \times BD \tag{3.5}$$

3.6.2 Porosity

Porosity was calculated from bulk density and the particle density value of 1.55 g cm^{-3} reported in McLay (1986). This value was calculated as an average of particle densities determined for Torehape peat. This calculation gives an estimation of porosity of the samples at each site by assuming the particle density (PD) of peat was 1.55 g cm^{-3} (McLay, 1986).

$$Porosity = \frac{PD - BD}{PD} \times 100 \tag{3.6}$$

3.6.3 Organic matter fraction

Loss on Ignition (LOI) was used to determined the organic matter (OM) fraction of a sample, presented as a percentage (%). For LOI, approximately 1.5-5 g was subsampled after oven drying for BD. The sample was ground and sieved through a 2 mm sieve to produce a uniform sample. This was re-dried and cooled in a desiccator before being reweighed (± 0.5 g). The sample was then placed in a muffle furnace (Nabetherm INC., Delaware, USA) set to 550°C for 4 hours (Schwärzel *et al.*, 2002; Mustamo *et al.*, 2016; Wang *et al.*, 2021). The main assumption using this method for determining OM fractions is that all of the OM is burned off during incineration. The left over mineral material was then weighed. The OM fraction were calculated from the difference between the initial and final weights.

3.6.4 pH

Grab samples of peat for pH analysis were collected from every sampling pit at each for all sites. In the laboratory, 10 g of field-moist soil from each sample was weighed out into a 100 mL vial. 50 mL of distilled water was added to the vial, creating a 1:50 ratio of sample to extractant, after that the solution was stirred for 15 seconds using a milkshake mixer. Water is used as the extractant as it has a similar cation exchange capacity (CEC) to most soils found in New Zealand and is the standard in New Zealand for measurement of soil pH (Edmeades & Wheeler, 2012). A 1:50 ratio was used to allow for better separation of the solution and the soil. To promote separation samples were left overnight before being measured with a calibrated pH probe (Jenway, Cole-Parmer Ltd., Illinois, USA).

3.6.5 C/N Ratio

Peat carbon to nitrogen ratios (C/N) were analysed using an elemental analyser (Vario EL cube, Elementar, Langelsbold, Germany). Samples were prepared by grinding and passed through a 0.6 mm sieve until a homogenous sample was produced. ~10 mg of sample was then weighed into tin boats, which were then analysed using 120s of oxygen dosing.

3.6.6 Shrinkage experimentation

A simple experiment broadly based on the method of Gebhardt et al. (2010) was developed to measure shrinkage for each site and sample depth. However, water retention was not measured in this study due to both time and financial constraints. Instead, VMC was calculated for each drying stage based on weight changes and final oven dry weight and was used as the independent variable.

A press was used to remove intact soil cores from the sampling rings for the shrinkage experiment (Figure 3.12). This pressing device applied pressure equally to the surface of the core to enable the removal of a sample from its sampling ring with minimal disturbance. The extracted soil samples were placed onto pre-weighed plastic sheets, in trays and then weighed. The height of the core was measured using a frame placed over the core (Figure 3.13). The frame had holes drilled in the top, through which the end of a pair of digital callipers could be inserted to measure the height from the top of the frame to the top of the core. The height of the core was measured in a pattern with eight set points. The diameter was also measured with electronic callipers at six set points around the core (Figure 3.13).

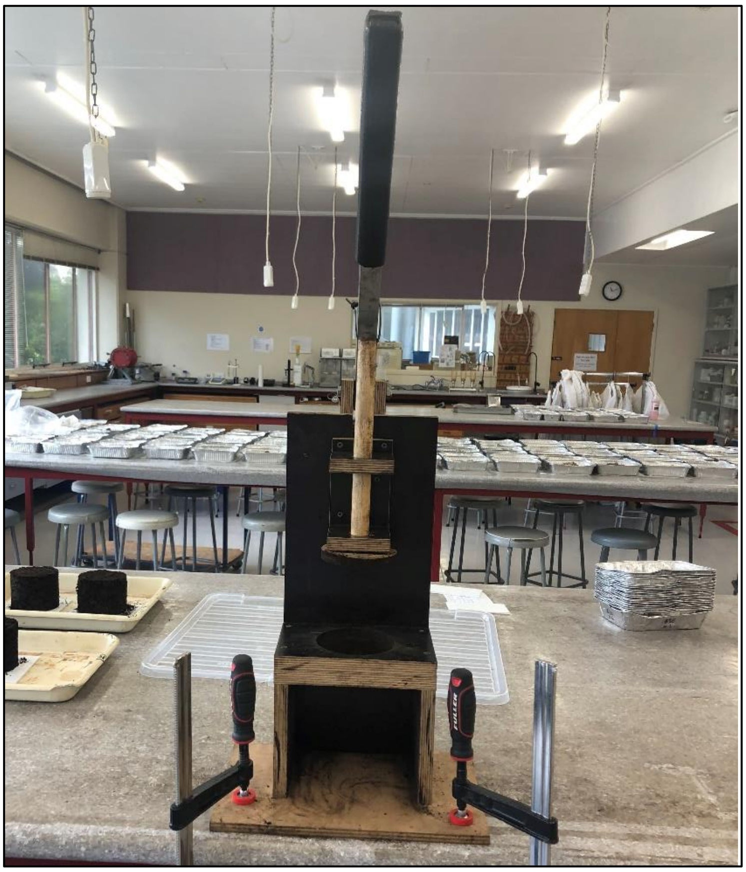

Figure 3.12 Device used to remove soil cores from the steel rings

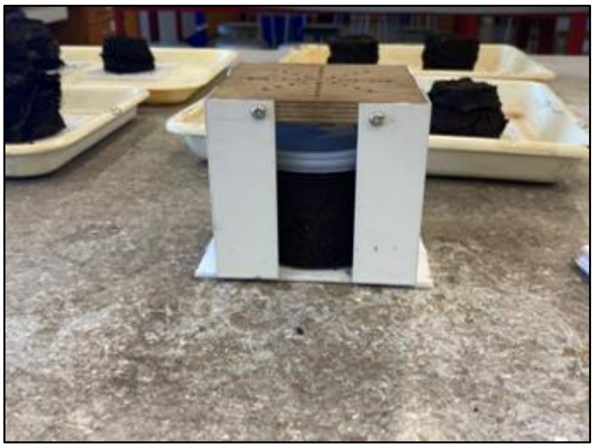

Figure 3.13 Shrinkage experiment measurement set up with the frame used to measure the soil core height.

The eight height and six diameter measurements were averaged. The soil cores were kept in the laboratory to air dry over two weeks. For the first week, the weight, height and diameter of each core were measured every day. Some cores had a total of four measurements and some five due to time constraints. After another week of drying, the cores were then weighed and measured once more before being dried overnight at 105°C and then measured again to obtain a final volume. Cumulative volume change was calculated for each core.

3.6.7 Statistical analysis

Descriptive statistics for soil analyses (the mean, maximum, minimum, standard deviation and standard error, SE) were determined using Excel (Microsoft Office, 2016). Excel was also used to determine statistically significant differences between sites and depths through two-way, unequal variance student’s t-tests. The R-Software statistics package (stats) was used to perform an ANOVA and post-hoc Tukey HSD on bulk density, porosity and organic matter to analyse differences in means between the different land uses. It was performed on the data altogether (i.e. all sample depths) and on data grouped as near-surface peat samples (sample depths 0-10 cm and 10-20 cm) and deep peat samples (30-40 cm and 40-50 cm).

Chapter Four

Results

4.1 Introduction

This chapter presents the results of analyses of physical and chemical properties of the peat sampled from each PSO site, as well as the shrinkage experiment. Photographs of certain peat profile features at some of the sites are also presented. Tabulated results and results of significance tests for each of the properties are available in Appendix A.

4.2 Profile features of interest

During field sampling, we were unable to record full soil profile descriptions due to time constraints, however, several features were observed that may explain trends seen in the results of laboratory analyses. Any other profile images will be available in Appendix B The first of these features was quite common at most of the sites; this was the presence of large amounts of wood. This is illustrated by Tor_BB where large partially-decayed logs up to 5 cm diameter were found at depths 20-50 cm (Figure 4.1a). The second of these is the presence of volcanic tephra, in some sites this was more visible than in others. An example was at Tor_Dairy where there was a clearly-defined 1-2 cm thick layer of pale-coloured course sand-grained size tephra layer around 27-29 cm depth (Figure 4.1b). Kom_DS (Figure 4.1c), was a site that did not have visible wood or tephra and the profile was unusually uniform in both colour and texture compared to all other study sites. Lastly, Mot_Dairy (Figure 4.1d) was an oddity among the sites, in that the top 0-26 cm did not look like peat material at all being pale and greyish in colour. Blocky inclusions in the upper 20 cm that were very pale in colour, almost light and were light to hold. We are unsure if this site has had some other material deposited over the peat material. Below 27 cm depth, the peat appeared to look more like the other sites but a lighter brown colour with the peat fabric consisting entirely of visible plant fragments including kahikatea leaves (Figure 4.2).

Figure 4.1 Four profile images from different sites, a) Tor_BB, b) Tor_Dairy, c) Kom_DS, d) Mot_Dairy, displaying different features observed in the field

Figure 4.2 Layer of visible plant litter seen at Mot_Dairy

4.3 Physical properties

4.3.1 Bulk density

Across all of the sites, there was a trend of decreasing bulk density (BD) with depth[2] (Figure 4.3). There was a highly significant difference ($p<0.01$) in BD in the 5 cm depth compared to the 45 cm depth across all of the sites. There was a highly significant ($p<0.001$) difference in BD between the blueberry and dairy sites, and the blueberry and dry stock sites in the near-surface peat (5 cm and 15 cm), whereas there was no difference between the dairy and dry stock sites at the same depths ($p=0.838$) (Table 4.2). In the deeper peat (35 cm and 45 cm), there was a highly significant difference between the blueberry and the dry stock site ($p<0.001$) and a significant difference ($p<0.05$) between the dairy and dry stock site (Table 4.4). There was no significant difference in BD between the blueberry and dairy sites in the deeper peat ($p=0.153$). The greatest BD was at Mot_Dairy at 5 cm depth (0.570 ± 0.025 g cm^{-3}) (mean ± standard error), but this was only significantly higher ($p<0.05$) than the blueberry sites at this depth. The lowest BD occurred at Ruk_BB at 45 cm depth (0.110 ± 0.001 g cm^{-3}) (Figure 4.3c). The lowest BD at 5 cm depth occurred at Tor_BB (0.267 ± 0.010 g cm^{-3}) (Figure 4.3c), the highest BD at 45 cm depth was at Kom_DS (0.261 ± 0.007 g cm^{-3}) (Figure 4.3b). At the dairy farm sites, there was large variation in BD with the overall trend of decreasing BD with depth. Even sites that were located in the same peatland, e.g Tor_Dairy and Tor_BB, exhibited differences in BD patterns with depth.

The dairy sites displayed the most rapid decline in BD from 5 cm to 10 cm depth compared to the other two land uses. Across the two dry stock sites, depth-trends were similar until 35 cm depth where they diverged, with Ruk_DS BD decreasing further but Kom_DS increasing. Interestingly, at the blueberry sites Moa_BB and Moa2_BB, despite being in the same peatland, BD did not follow similar trends with depth. The blueberry sites had two definitive trends; Moa_BB and Ruk_BB had higher bulk densities (0.357 ± 0.006 g cm^{-3}, 0.332 ± 0.003 g cm^{-3}respectively) than Moa2_BB and Tor_BB (0.289 ± 0.007 g cm^{-3}, 0.267 ± 0.010 g cm^{-3} respectively) at 5 cm depth. At 15 cm depth, there was a "cross-over" where Moa2_BB and Tor_BB had higher bulk densities, which then decreased much less rapidly with depth than the other two dairy sites. Overall, there was a large amount of variation in patterns of bulk density with depth across and within the peatlands, as well as between and within the different land uses.

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[2] Depth reported as the midpoint of the sampling depths e.g 5 cm for a sampling depth of 0-10 cm

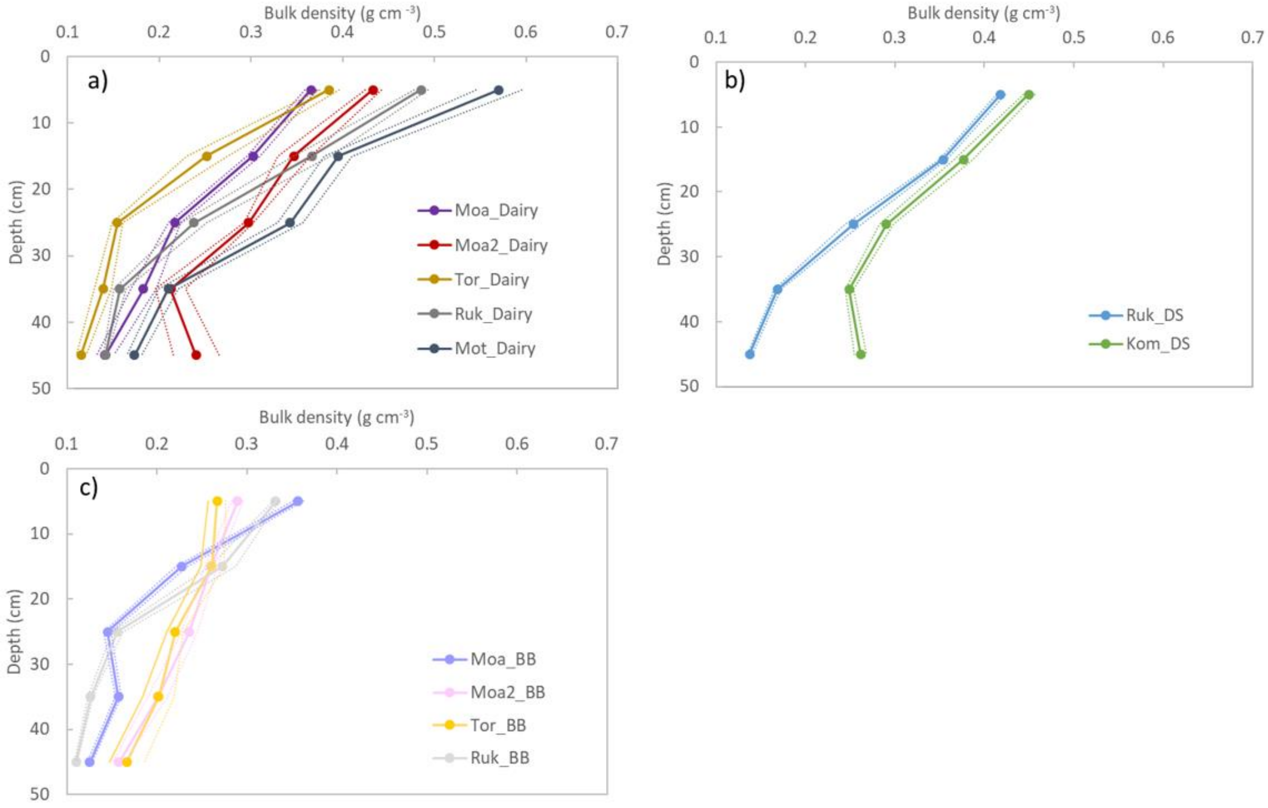

Figure 4.3 Trends in mean bulk density with depth grouped by land use:

a) Dairy, b) Dry stock, c) Blueberry. The dotted lines indicate ± one SE from the means.

Table 4.1 ANOVA for differences in soil physical and chemical properties between land uses for near-surface peat (5-15 cm depth) (OMf = organic matter fraction)

ANOVA	Bulk density	Porosity	OMf
p-value	$<2 \times 10^{-16}$	$<2 \times 10^{-16}$	3.2×10^{-4}

Table 4.2 Post-hoc p-values to determine significance of soil physical and chemical property differences between land uses for near-surface peat (5-15 cm depth) (OMf = organic matter fraction)

Tukey HSD	Bulk Density	Porosity	OMf
Blueberry vs dairy	$p<0.001$	$p<0.001$	$p<0.001$
Blueberry vs dry stock	$p<0.001$	$p<0.001$	0.095
Dairy vs dry stock	0.838	0.817	0.550

Table 4.3 ANOVA for differences in soil physical and chemical properties between land uses for deeper peat (35-45 cm) (OMf = organic matter fraction)

ANOVA	Bulk density	Porosity	OMf
p-value	3.9×10^{-4}	0.01	0.114

Table 4.4 Post-hoc p-values to determine significance of soil physical and chemical property differences between land uses in deeper peat (35-45 cm) (OMf = organic matter fraction)

Tukey HSD	Bulk Density	Porosity	OMf
Blueberry vs dairy	0.153	0.968	0.331
Blueberry vs dry stock	$p<0.001$	0.012	0.117
Dairy vs dry stock	0.022	0.019	0.635

4.3.2 Volumetric moisture content

Volumetric moisture content (VMC) is temporally variable and can change from day to day depending on the soil water balance. Some of the variation in VMC between the sites are likely due to samples not being taken on the same day or under the same environmental conditions. However, at 45 cm depth most of the sites were at or near saturation, therefore differences in VMC can be attributed to physical properties rather than differences in environmental conditions prior to sampling. The overall trend across all the study sites was an increase in VMC with depth (Figure 4.4). The site with the smallest VMC value was Mot_Dairy at 5cm depth (23.12 ± 0.688%) and Ruk_BB was the site with the greatest VMC at 45 cm depth (87.03 ± 0.675%) (Figure 4.4 a, c). The site that had the lowest VMC at 45 cm depth was Moa2_Dairy (55.41 ± 4.405%) and Moa_BB had the highest VMC at 5 cm depth (66.59 ± 1.263%) (Figure 4.4 a, c).

Moa2_Dairy had the lowest VMC of all the dairy sites at 5 cm depth whilst the highest VMC at the same depth of all the dairy sites was at Moa_Dairy (70.71 ± 0.727%). The highest VMC of all of the dairy sites was Ruk_DS had consistently higher VMC than Kom_DS down the entire profile (Figure 4.4). When comparing the blueberry sites, the lowest VMC was found at 5 cm depth at Moa2_BB (35.69 ± 1.053%) and the highest at the same depth was found at Moa_BB (66.59 ± 1.263%). At 45 cm depth, Tor_BB and

Moa2_BB had very similar VMC, and the lowest at this depth of the blueberry sites, VMCs (70.95 ± 3.185% and 70.97 ± 1.247%, respectively). Ruk_BB had the highest VMC of all the blueberry sites and this was at 45 cm depth (87.03 ± 0.675%).

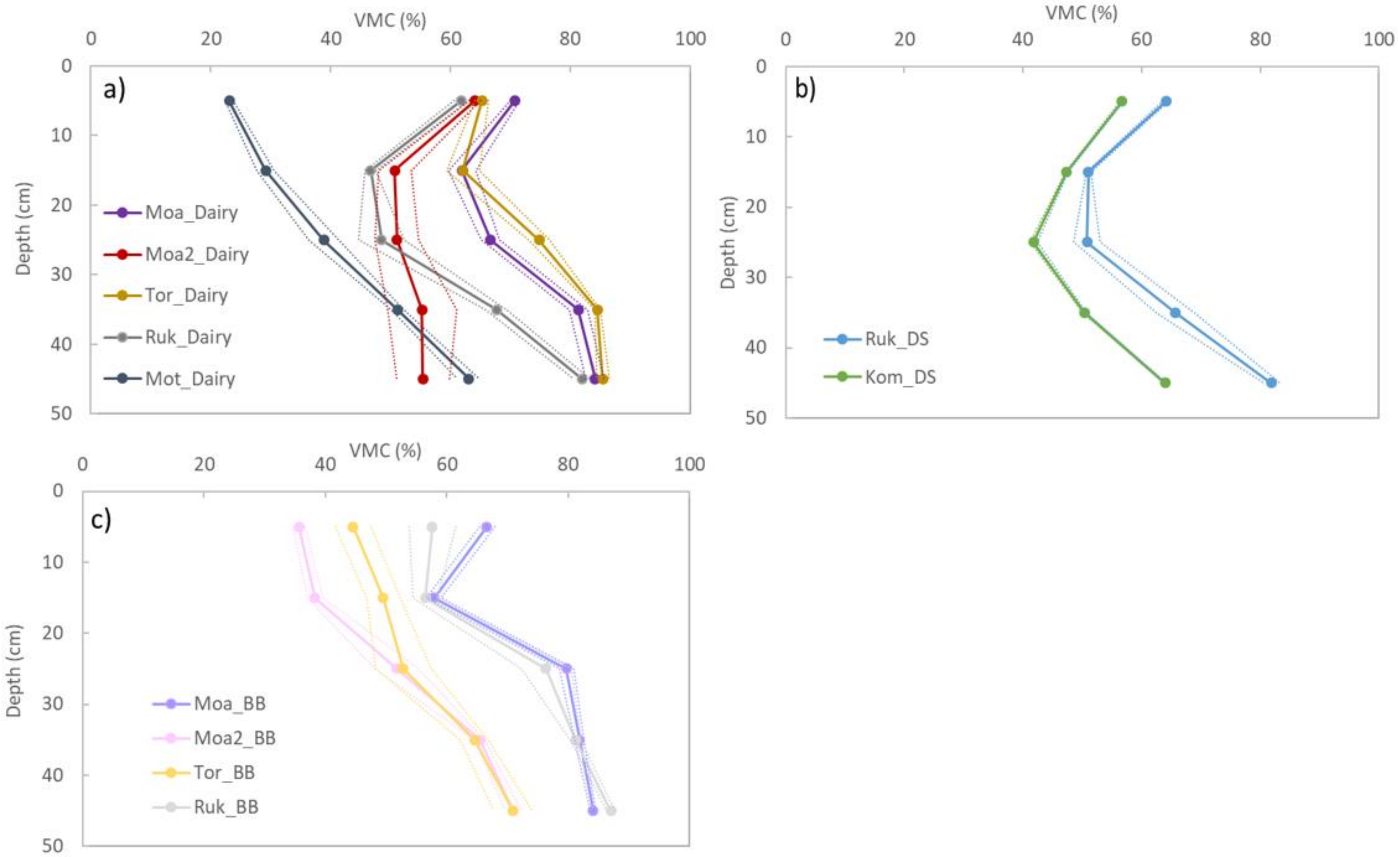

Figure 4.4 Trends in VMC with depth (%) grouped by land use: a) Dairy, b) Dry stock, c) Blueberry. The dotted lines indicate ± one SE from the mean.

4.3.3 Porosity

The overall trend across most of the study sites was that porosity increased with increasing depth. The highest mean porosity was at Ruk_BB at 45 cm depth (92.91 ± 0.091%), and this was significantly different ($p < 0.05$) compared to all sites except Moa_Dairy, Tor_Dairy, Ruk_DS and Tor_BB (Figure 4.5). The lowest mean porosity was at Mot_Dairy at 5 cm depth (63.21 ± 1.610%) (Figure 4.5a), this being only significantly lower ($p<0.05$) than the blueberry sites. Overall, porosity was variable across the different peatlands and land uses but had a general trend of increasing porosity with depth.

There was less variation in trends of porosity with depth than the other soil characteristics. The dry stock sites follow a very similar trend until 25 cm depth after which they diverged, Ruk_DS porosity continued to increase with depth whilst Kom_DS porosity began to decrease (Figure 4.5b). There were highly significant differences (p<0.001) in near-surface (5-15 cm) porosity between the blueberry and dairy sites, and between the blueberry and dry stock sites. There was no significant difference in porosity between the dry stock and dairy sites at the surface (p=0.817) (Table 4.2). There was a significant difference found when comparing the porosities of the blueberry and dry stock sites (p), and the dry stock and dairy sites in the deeper peat (p=0.019) (Table 4.3). There was no significant difference found between the porosities of the blueberry and dairy sites in the deep peat (p=0.968).

Of all the dairy sites, Mot_Dairy had the lowest mean porosity at 5 cm (63.21 ± 1.610%). Moa_Dairy had the highest porosity at 5 cm (76.43 ± 0.416%), which was significantly higher (p<0.05) than Moa2_Dairy, Ruk_Dairy and Mot_Dairy at this depth. The highest porosity was at 45 cm depth at Tor_Dairy (92.59 ± 0.341 %), but this was only significantly different to Mot_Dairy at this depth. The lowest porosity at the same depth was at Moa2_Dairy (84.52 ± 1.609%) which was significantly lower (p < 0.05) than all the other sites at this depth, with the exception of Mot_Dairy. Of the two dry stock sites, Ruk_DS had higher porosities than Kom_DS, which was significant (p<0.05) at 5 cm depth. When comparing the variation across the four blueberry sites, the highest porosity was at Ruk_BB at 45 cm depth (92.91 ± 0.091 %), and this was significantly higher (p<0.05) than Moa_BB and Moa2_BB. The lowest porosity of all the blueberry sites was at Moa_BB at 5 cm depth (74.50 ± 0.174%). At the same depth, Tor_BB had the highest porosity (82.80 ± 0.643%).

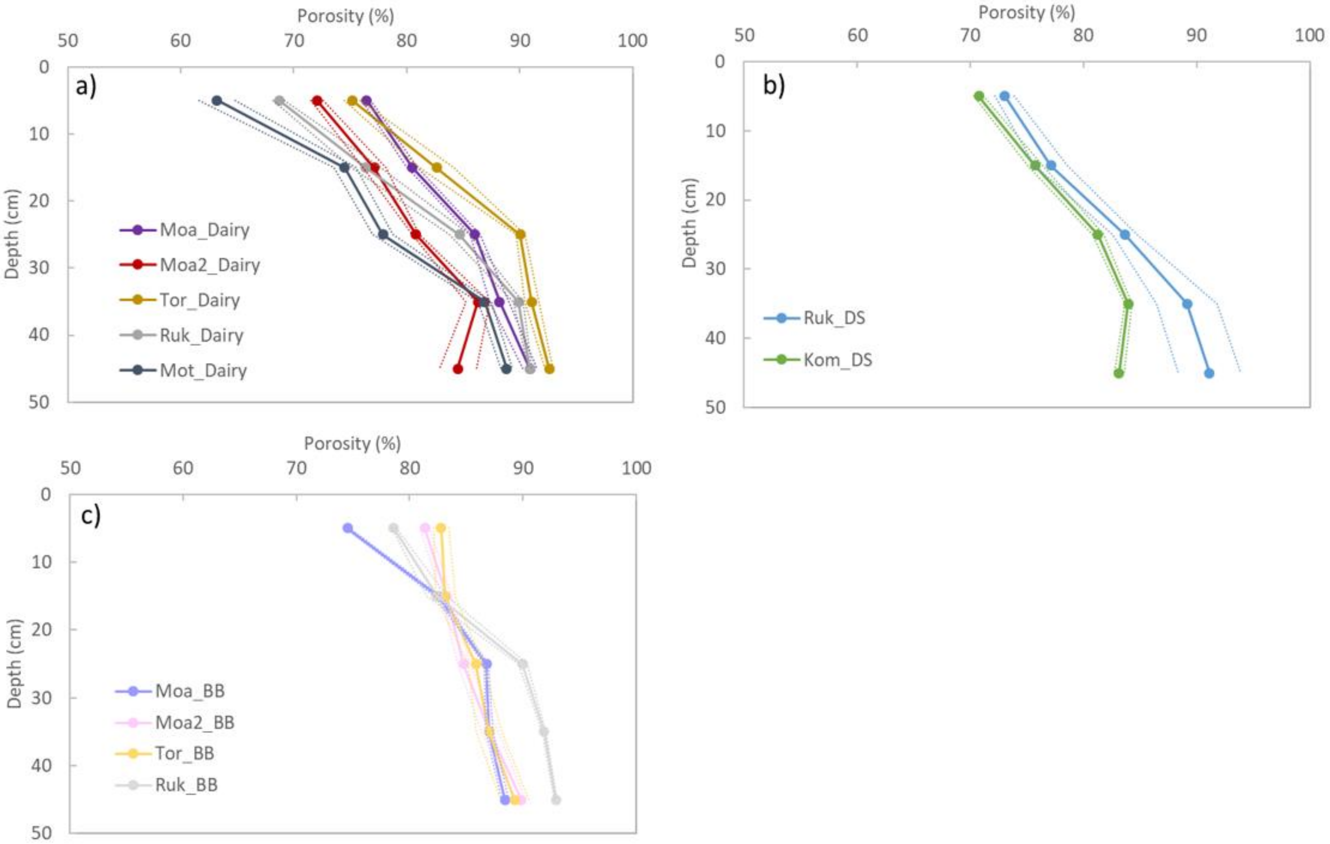

Figure 4.5 Trends in porosity (%) with depth grouped by land use: a) Dairy, b) Dry stock, c) Blueberry. The dotted lines indicate ± one SE from the mean.

4.4 Chemical properties

4.4.1 Organic matter fraction

The general trend in organic matter fraction (OMf) was an increase with depth but with notable exceptions (e.g Moa_Dairy and Moa_BB, 25-35 cm), where OMf decreased between some depths (Figure 4.6a). There was a high amount of variation even within the same peatland, for example Moa_Dairy, Moa2_Dairy, Moa_BB and Moa2_BB did not have similar trends despite being from the same peatland (Figure 4.6 a, c). The lowest OMf was at Mot_Dairy at 5 cm depth (57.20 ± 3.563%) (Figure 4.6a). The highest OMf was at Ruk_BB at 45 cm depth (97.36 ± 0.165%) (Figure 4.6c). The highest OM fraction at 5 cm depth was at Tor_BB (90.15 ± 1.314%), whilst the lowest OMf at 45 cm depth was at Kom_DS (61.12 ± 2.912%) (Figure 4.6 a, c). A statistically significant difference between OMf in the near-surface peat was only found between the blueberry and dairy sites, and this was highly significant ($p<0.001$) (Table 4.2). There was no statistical significance between any of the land uses in OMf at the deeper sampling depths (Table 4.4).

When comparing the trends of OMf between the five different dairy sites, Mot_Dairy had much lower OMf than the other sites at 5-15 cm depth, but this was not found to be particularly significant. Moa_Dairy had lower OMf at 35 and 45 cm depths than the other dairy sites, but this was not found to have statistical significance. The lowest OMf of the dairy sites was found at Mot_Dairy at 5 cm depth and at the same depth; Moa_Dairy (87.03 ± 0.706%) had the highest OMf. The highest OMf overall was at Tor_Dairy at 45 cm depth (95.56 ± 0.278%) which was only significantly higher than Mot_Dairy. When comparing the two dry stock sites, Kom_DS had lower OMf than Ruk_DS down the entire profile and this was significant ($p < 0.05$) at 5-25 cm depth. When comparing the four blueberry sites Ruk_BB had the highest OMf, which was at 45 cm depth (97.36 ± 0.165%). Moa_BB had the lowest OMf, which was at 35 cm depth (69.45 ± 5.715%). Overall, OMf was highly variable between and within all of the different peatlands and land uses.

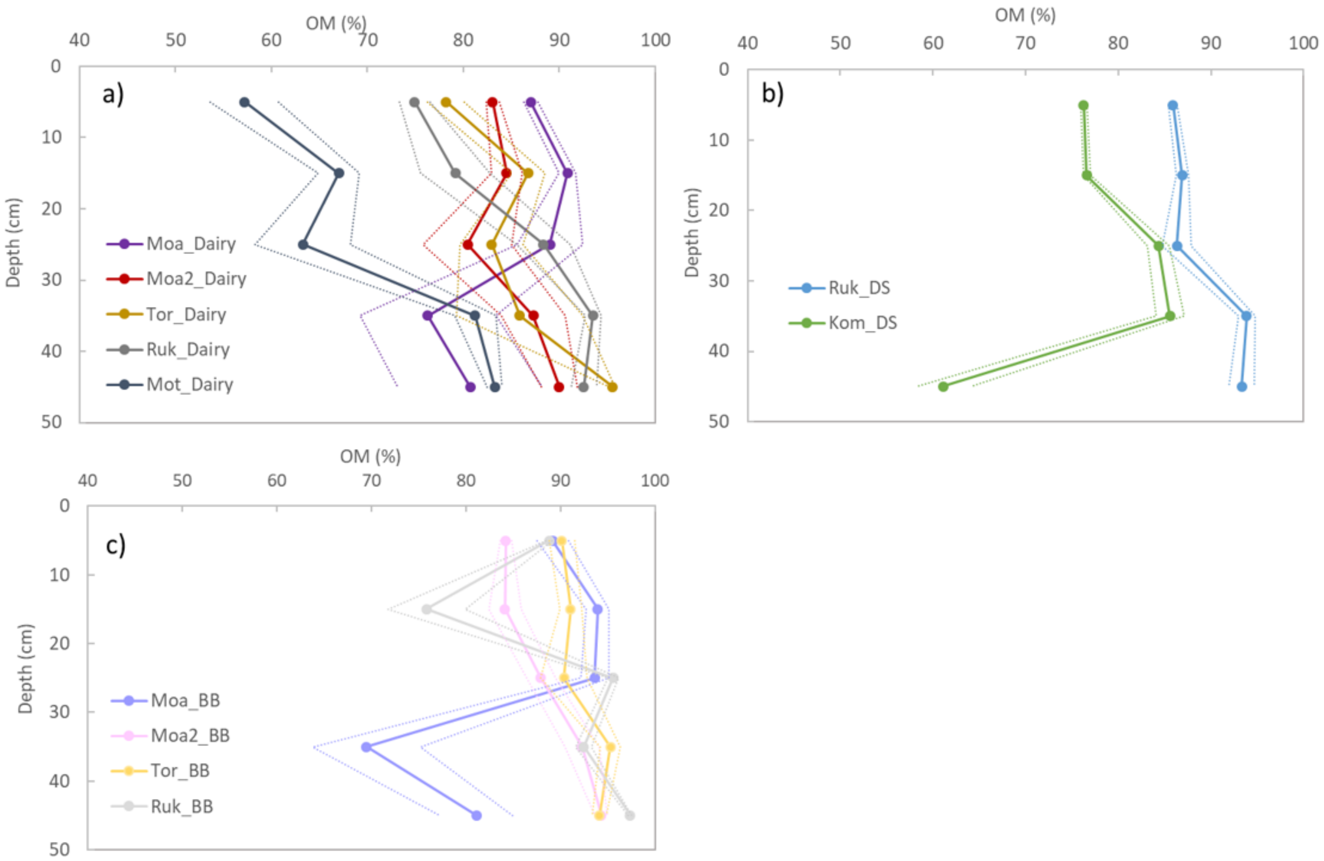

Figure 4.6 Trends in OM (%) with depth grouped by land use: a) Dairy, b) Dry stock, c) Blueberry. The dotted lines indicate ± one SE from the mean.

4.4.2 C/N Ratio

The overall trend across all the sites was an increase in C/N ratios with depth (Figure 4.7). The highest mean C/N ratio of all the sites was Tor_BB at 45 cm depth (46.49 ± 6.877) and this was not significantly different to other sites. The lowest C/N was at 5 cm depth where Mot_Dairy and Ruk_Dairy had very similar C/N ratios here (18.60 ± 0.368 and 19.11 ± 0.913 respectively) (Figure 4.7). The lowest C/N ratio at 45 cm depth was at Kom_DS (26.01 ± 0.247), whilst at 5 cm depth Tor_Dairy, Tor_BB and Moa2_BB had similar higher C/N ratios at 27.86 ± 4.226, 27.38 ± 1.268 and 27.00 ± 1.130 respectively (Figure 4.7). Ruk_Dairy and Tor_Dairy followed a similar trend with depth but Tor_Dairy generally had higher C/N ratios than Ruk_Dairy (Figure 4.7a).

When comparing C/N ratios across the different dairy sites, Ruk_Dairy and Mot_Dairy had similarly low C/N ratios at 5 cm depths (19.11 ± 0.913 and 18.60 ± 0.368, respectively) and Tor_Dairy had the highest mean C/N ratio (27.86 ± 4.226) at 5 cm. These sites were not significantly different to each other. The highest mean C/N ratio of the dairy sites was at 25 cm depth at Tor_Dairy (41.09 ± 1.597) and the highest C/N ratio at 45 cm depth was at Mot_Dairy (39.90 ± 3.545). Also at 45 cm depth, the lowest C/N ratio was at Ruk_Dairy (36.29 ± 3.436). Comparing the two dry stock sites, Ruk_DS had consistently higher C/N ratios than Kom_DS, but this was only significant at 35 and 45 cm depths. Out of the blueberry sites, the lowest mean C/N ratio was at Ruk_BB at 5 cm depth (23.38 ± 1.388), whilst the highest C/N ratio was at Tor_BB at 45 cm depth (46.49 ± 6.877), both of which were not statistically different to the other sites at their respective depths.

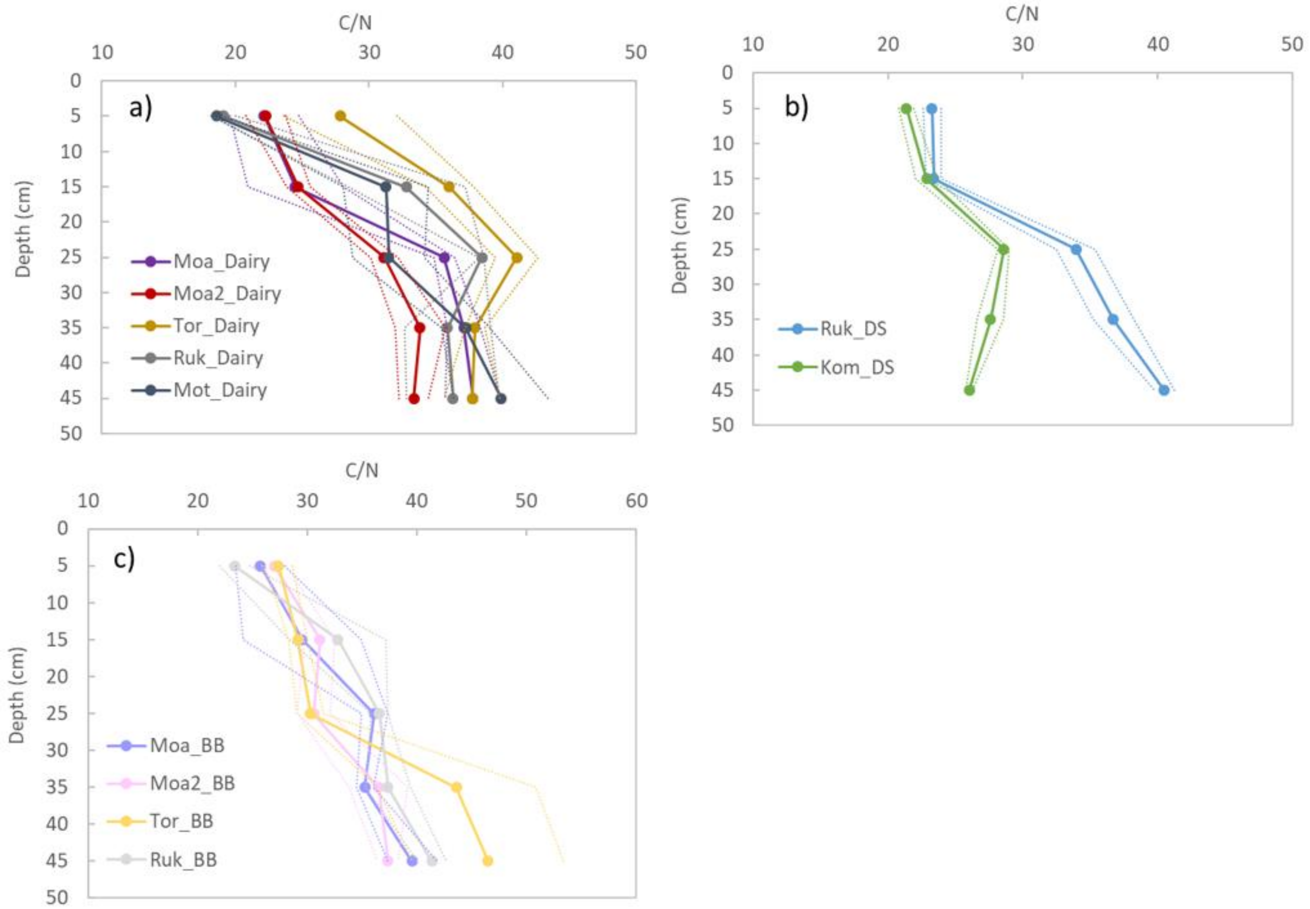

Figure 4.7 Trends in C/N ratios with depth grouped by land use: a) Dairy, b) Dry stock, c) Blueberry. The dotted lines indicate ± SE from the mean.

4.4.3 pH

Across all of the sites the general trend was that soil pH decreased with depth. The blueberry sites had lower pH values than the agricultural sites, and the least change down the profile (Figure 4.8). The lowest pH was at Mot_Dairy at 45 cm (3.82 ± 0.043) and the highest was at 5 cm at the Ruk_Dairy site (6.53 ± 0.162) (Figure 4.8a). Mot_Dairy at 45 cm was had a very low pH, but this did not have significance against most of the other sites. Ruk_Dairy had a high pH at 5 cm depth compared to the other sites. The highest pH at 45 cm was at the Kom_DS site (4.59 ± 0.012) and the lowest pH at 5 cm depth was at Tor_BB (3.83 ± 0.056). Ruk_Dairy had the greatest change with depth out of all the sites (figure4.8a) Ruk_DS had a more consistent decrease in pH with depth compared to Kom_DS, which had a more variable trend (Figure 4.8b)

When comparing the five different dairy sites, it was Ruk_Dairy (6.53 ± 0.162) that had the highest pH at 5 cm depth. At 45 cm depth Mot_Dairy (3.82 ± 0.043) had the lowest, which was significantly different compared to Tor_Dairy and Ruk_Dairy. The lowest pH at 5 cm depth was at Moa2_Dairy (5.73 ± 0.075) and the highest pH at 45 cm depth was at Moa_Dairy (4.440 ± 0.021). Of the two dry stock sites, Ruk_DS (5.894 ± 0.156) had a slightly higher pH than Kom_DS (5.50 ± 0.028) at 5 cm depth. At 45 cm depth this was reversed, with Kom_DS (4.591 ± 0.012) being less acidic than Ruk_DS (4.30 ± 0.059). The highest pH at the blueberry sites was at 5cm depth at Moa_BB (4.83 ± 0.117). The lowest pH of the blueberry sites was at 25 cm depth at Moa2_BB (3.68 ± 0.037).

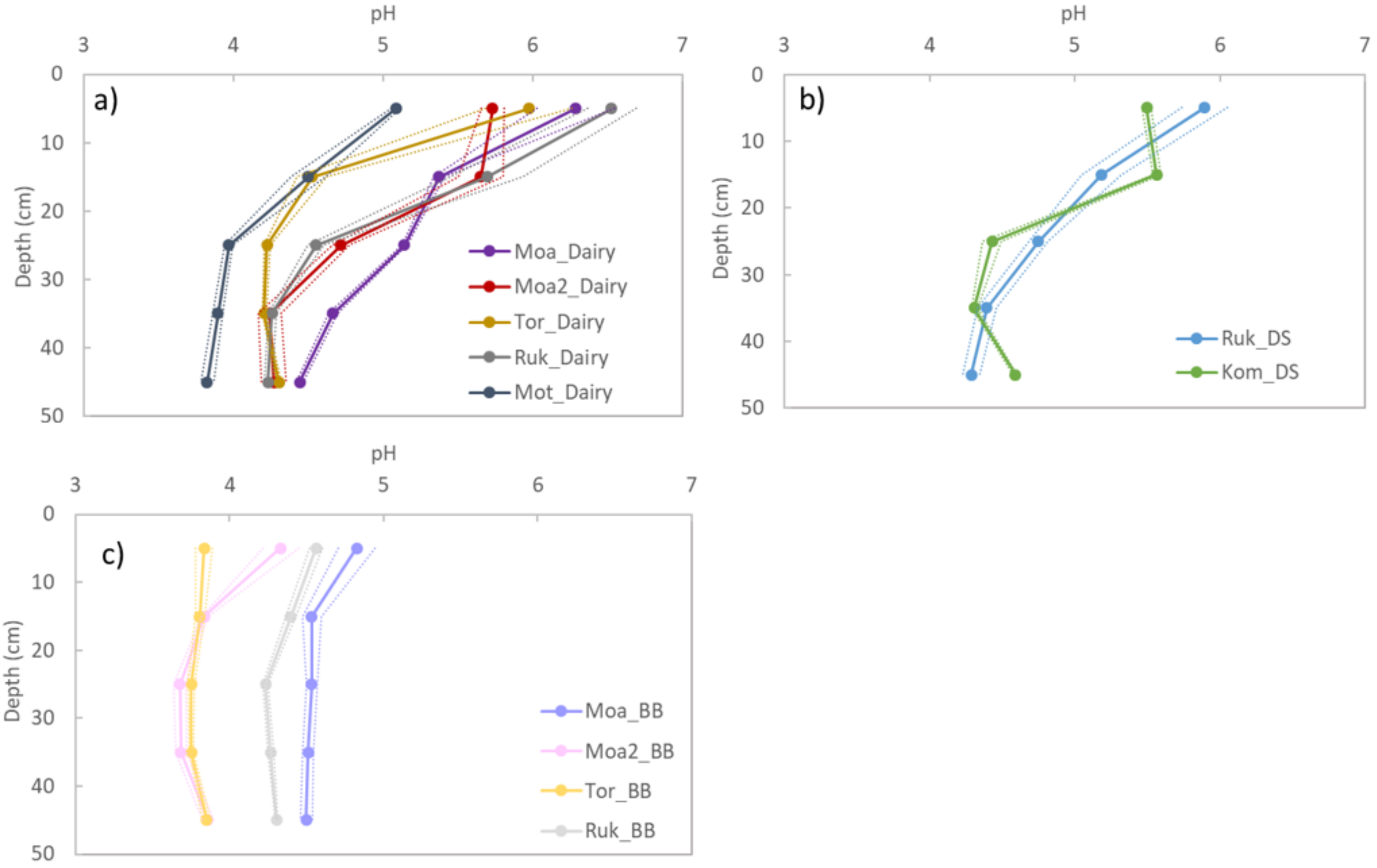

Figure 4.8 Trends in pH with depth grouped by land use: a) Dairy, b) Dry stock, c) Blueberry. The dotted lines indicate ± one SE from the mean.

4.5 Variation in bulk density and OM values

To investigate the variations in bulk density, the following graphs show the relationships between OM and bulk density. These graphs also show the wide range of variation across the different peatlands, land uses and depths. An overall trend at all sites was a weak negative relationship. Samples with the highest OM (>90%) also had the lowest bulk density values (~0.1 g/cm3) (Figure 4.9). The high variability of the data makes it hard to observe this negative relationship, particularly at many of the blueberry sites. There were some data points that stood out from this trend. For example, at 40-50 cm depth, Kom_DS had low OM fractions relative to similar bulk densities at other depths at both dry stock sites (Figure 4.9b). Moa_BB also appeared to have low OM fractions without a relative increase bulk density at 30-40 cm depth (Figure 4.9c).

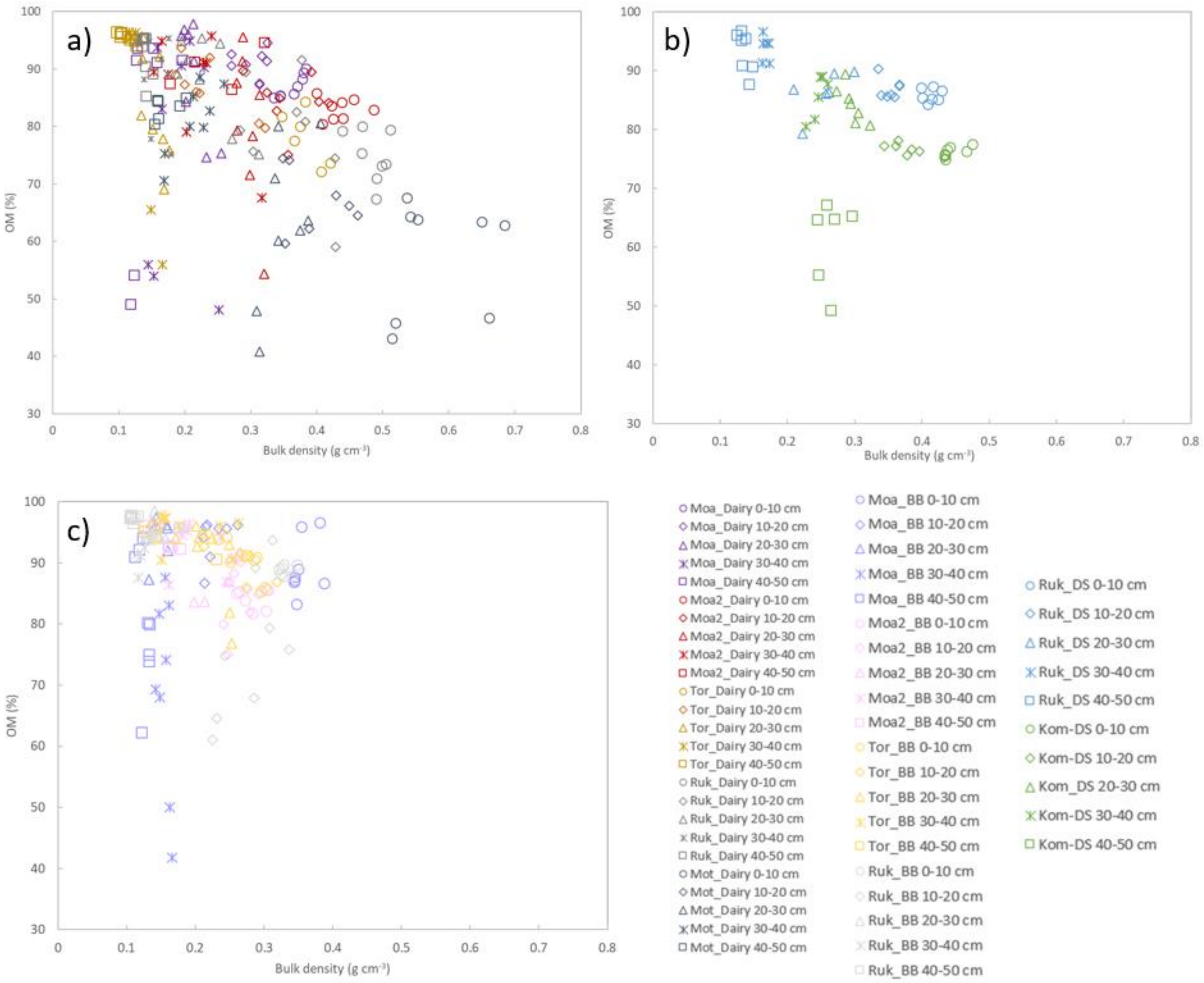

Figure 4.9 Scatterplot of relationship between bulk density (g/cm3) and OM (%) at each sampling depth grouped by sites a) Dairy, b) Dry stock, c) Blueberry

4.6 Shrinkage experiment

4.6.1 Shrinkage

The following graphs present the results of the shrinkage experiment on soils cores at each depth at each site. The change in volume will be described by sampling depth range e.g 0-10 cm, rather than the midpoint of the sampling depth due to the nature of the measurements. Overall, there was generally no change in volume until day 4 or 5 across all sites and depths. After this, the rate of volume change increased for most sites and depths.

At the dairy sites the greatest change in volume occurred in the cores taken from 20-30 cm depth and deeper (Figure 4.10). The sites all had similar trends in decreasing volume at 0-10 cm and 10-20 cm depths. Tor_Dairy had the greatest change in volume with drying at 20-30 cm depth, whilst Ruk_Dairy had the greatest change in volume at 30-40 cm depth. At 40-50 cm depth, the core with the greatest volume change was the Moa_Dairy core. Overall, the site with the least change in volume appeared to be Mot_Dairy, this site also had very minor changes in volume at most depths (Figure 4.10).

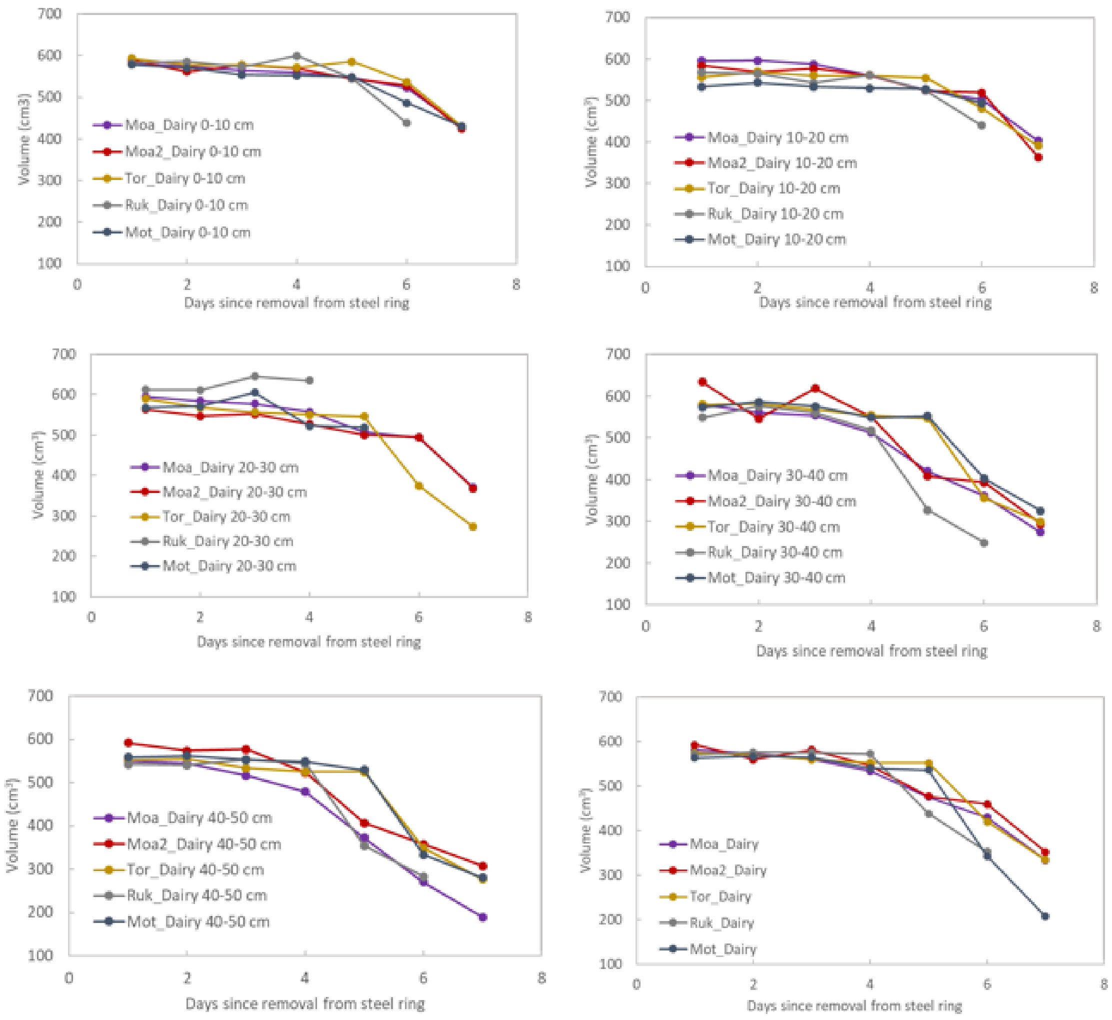

Figure 4.10 Change in volume (cm^3) over the period of drying (days) for the dairy sites, grouped by sampling depth a) 0-10, b) 10-20 cm, c) 20-30 cm, d) 30-40 cm, e) 40-50 cm, f) average across all depths.

The blueberry sites exhibited a great variation in shrinkage patterns (Figure 4.11). The 10-20 cm cores showed greater loss of volume (40%) than the dairy sites (26%) at the same depth. Moa_BB at 20-30 cm exhibited an extremely rapid and large change in volume between days 4-5. The other blueberry sites also had a rather rapid change in volume for the same time, but not as large (Figure 4.11c). Ruk_BB started to decrease in volume at all of the depths earlier than the other blueberry sites, decreasing rapidly from day 3 onwards (Figure 4.11). Ruk_BB experienced the greatest change in volume at 10-20 cm, 20-30 cm and 30-40 cm depth (Figure 4.11 b, c, d), whilst at 40-50 cm depth it was Moa2_BB that experienced the greatest volume change (Figure 4.11e).

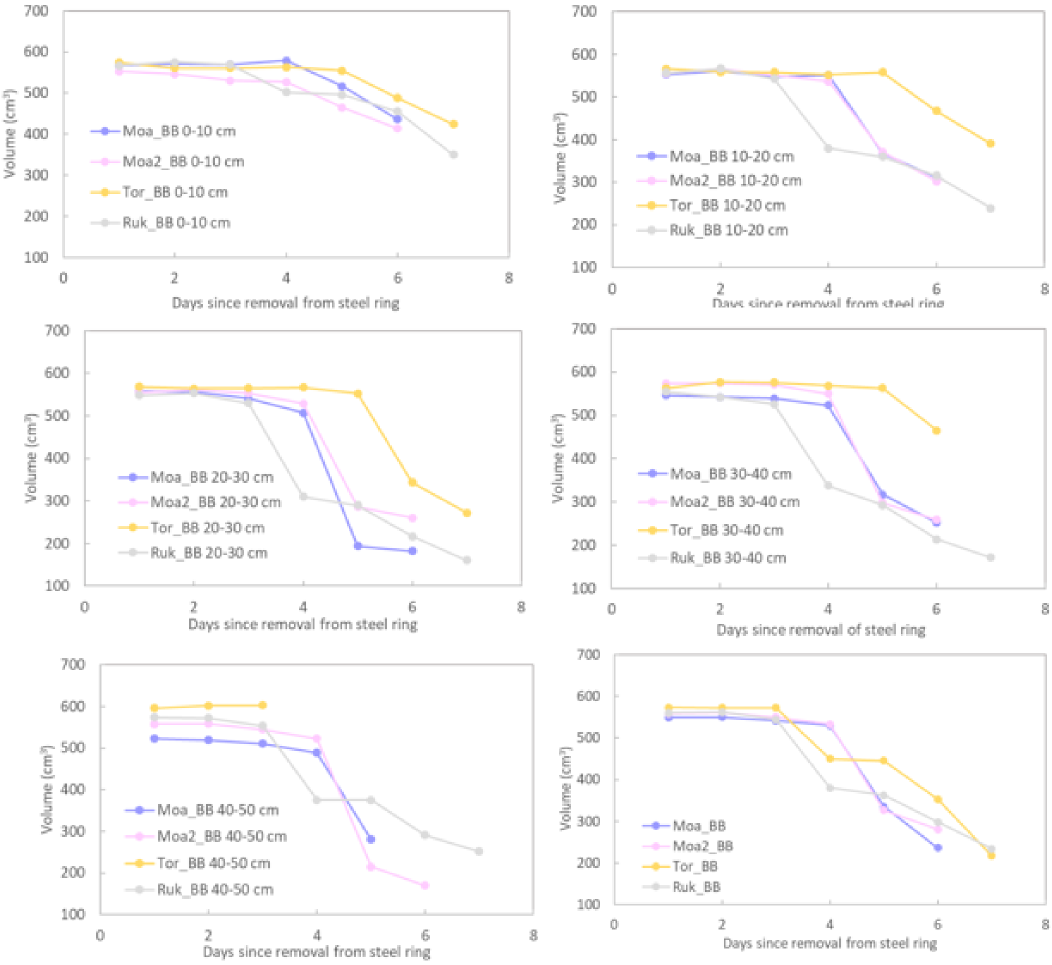

Figure 4.11 Change in volume (cm^3) over the period of drying (days) for the blueberry sites, grouped by sampling depth a) 0-10 cm, b) 10-20 cm, c) 20-30 cm, d)30-40 cm, e) 40-50 cm f) average across all depths

In comparison to the dairy and the blueberry sites, the dry stock sites did not display as much change in volume as drying progressed (Figure 4.12). The greatest change in volume for Kom_DS was at 30-40 cm depth from day 4 (Figure 4.12d), while the greatest change in volume for Ruk_DS was at 40-50 cm depth between day 3 and day 4 (Figure 4.12e).

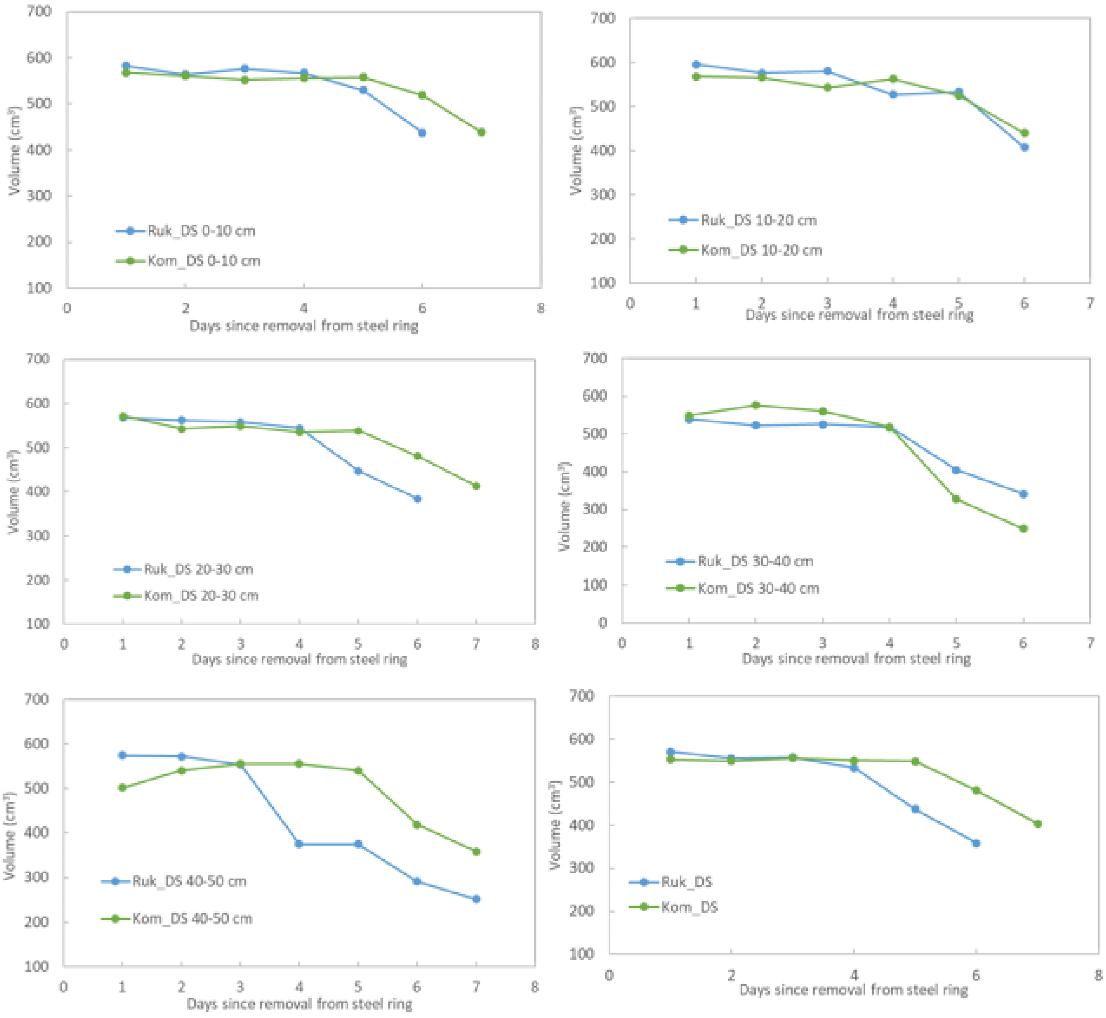

Figure 4.12 Change in volume (cm^3) over the period of drying (days) at the dry stock sites, grouped by sampling depth a) 0-10 cm, b) 10-20 cm, c) 20-30 cm, d) 30-40 mc, e) 40-50 cm, f) average across all depth.

The total percentage of volume change across all depths ranged from between 27.0% at Mot_Dairy to 58.1% at Ruk_BB (Table 4.5). Generally, the mean total percentage of volume change was greater at the agricultural sites than the blueberry sites. Moa_Dairy had the greatest change in volume across all the depths compared to the other dairy sites, with a mean percentage change of 41.8%. Mot_Dairy had low percentage changes at 10-20 cm and 20-30 cm, being 7.6% and 8.53% for each respective depth range. Tor_BB had a low change in volume compared to the other blueberry sites, having a mean percentage change of 31.6%, it is important to note that this site does not have data for 40-50 cm depth, due to the sample being lost at the beginning of the analysis. This also occurred for Ruk_Dairy at 20-30 cm depth. Tor_BB did have a very small percentage change in volume at 30-40 cm of 17.43%. Ruk_DS had consistently higher changes in volume than Kom_DS, particularly at 40-50 cm depth where Ruk_DS had a percent volume change of 69.5 % and Kom_DS had less than half of this, being only 28.6%.

Table 4.5 Total percentage change in volume at all sites, averaged across all depths
n/a were cores that had lost sample

	Change in volume (%)					
Site	**0-10 cm**	**10-20 cm**	**20-30 cm**	**30-40 cm**	**40-50 cm**	**Mean**
Moa_Dairy	26.1	32.4	37.7	52.6	65.6	42.9
Moa2_Dairy	27.9	37.7	34.7	53.6	48.0	40.4
Tor_Dairy	27.4	29.7	53.7	48.3	49.8	41.8
Ruk_Dairy	24.8	22.6	n/a	54.6	47.8	29.2
Mot_Dairy	25.6	7.6	8.53	43.2	49.8	27.0
Ruk_DS	24.9	31.6	32.4	36.6	60.8	37.3
Kom_DS	22.8	21.8	27.7	34.5	28.6	27.1
Moa_BB	23.0	43.6	67.3	53.8	46.3	46.8
Moa2_BB	25.2	45.7	53.0	55.0	69.5	50.0
Tor_BB	26.1	30.9	52.0	17.43	n/a	31.6
Ruk_BB	38.3	57.0	70.8	69.1	56.2	58.1

4.6.2 Cumulative water volume change during shrinkage experiments

The following graphs also present results of the shrinkage experiment on a water volume loss (cm^3/cm^3) basis rather than physical volume change. Overall, the general trend seen was very little loss of water until day 4 at almost all sites and depths. The trends at the dairy sites were quite variable but at 30-40 cm and 40-50 cm Ruk_Dairy and Moa_Dairy had similar trends (Figure 4.13, d, e). Mot_Dairy appeared to lose the least amount of water with drying especially at the 0-10 cm and 10-20 cm depth (Figure 4.13a,b). Moa2_Dairy lost less water volume than Moa_Dairy over the drying period (Figure 4.13).

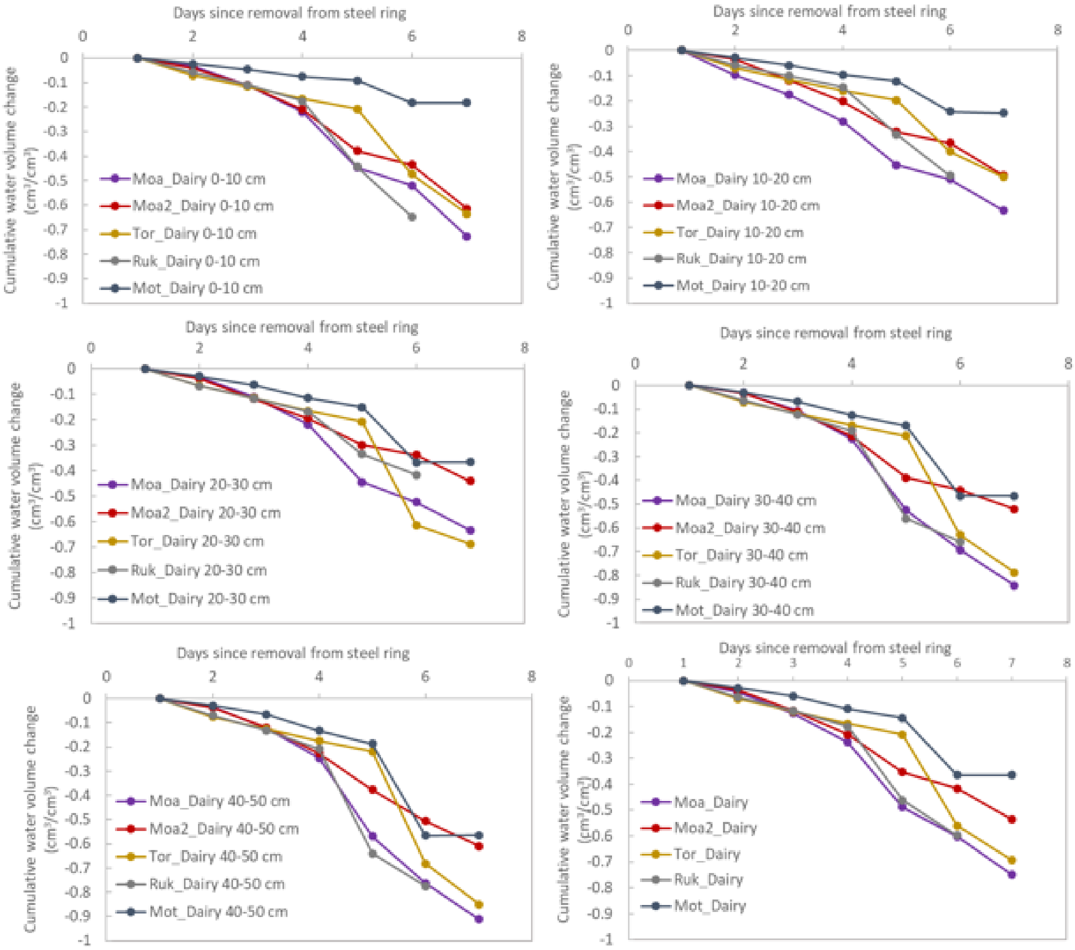

Figure 4.13 Cumulative water volume change (cm^3/cm^3) over period of drying (days) for the dairy sites, grouped by sampling depth a) 0-10 cm, b) 10-20 cm, c) 20-30 cm, d)30-40 cm, e) 40-50 cm, f) average across depths

The trends in cumulative water volume loss at the blueberry sites were also variable. At the 10-20 cm depth and 40-50 cm depth Moa_BB and Moa2_BB had similar patterns, but with Moa2_BB generally losing a little less water volume after day 4 than Moa_BB (Figure 4.14 b, e). Tor_BB had the least volume change of all the blueberry sites for depths 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm (Figure 4.14 a, b, c, & d)

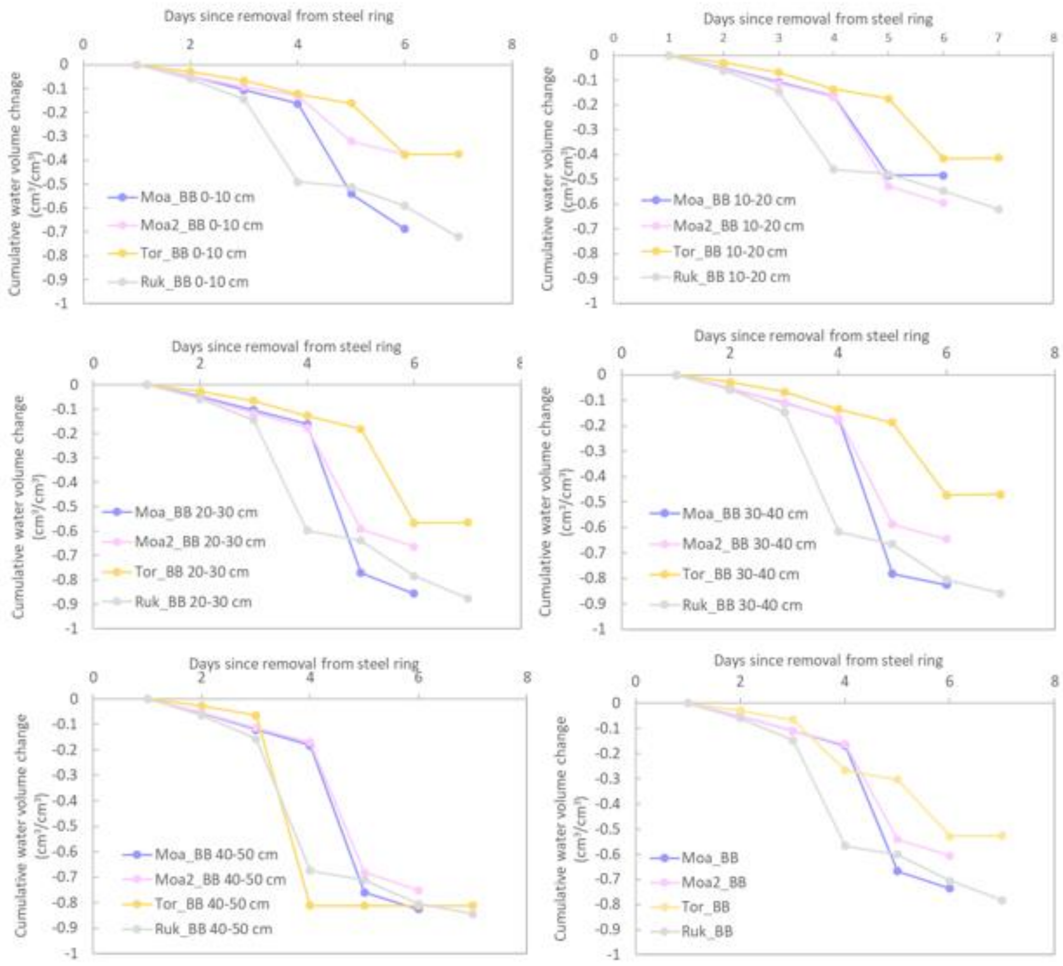

Figure 4.14 Cumulative water volume change (cm^3/cm^3) over period of drying (days) for the dry stock sites, grouped by sampling depth a) 0-10 cm, b) 10-20 cm, c) 20-30 cm, d) 30-40 cm, e) 40-50 cm f) average across all depths

At most depths, except for 30-40 cm depth, Ruk_DS and Kom_DS followed a similar trend up until day 4, after which Ruk_DS began to lose water volume rapidly (Figure 4.15). At 30-40 cm the two sites diverge at day 2 and Kom_DS appears to slightly increase until day 5 before rapidly losing water at day 5 (Figure 4.15e).

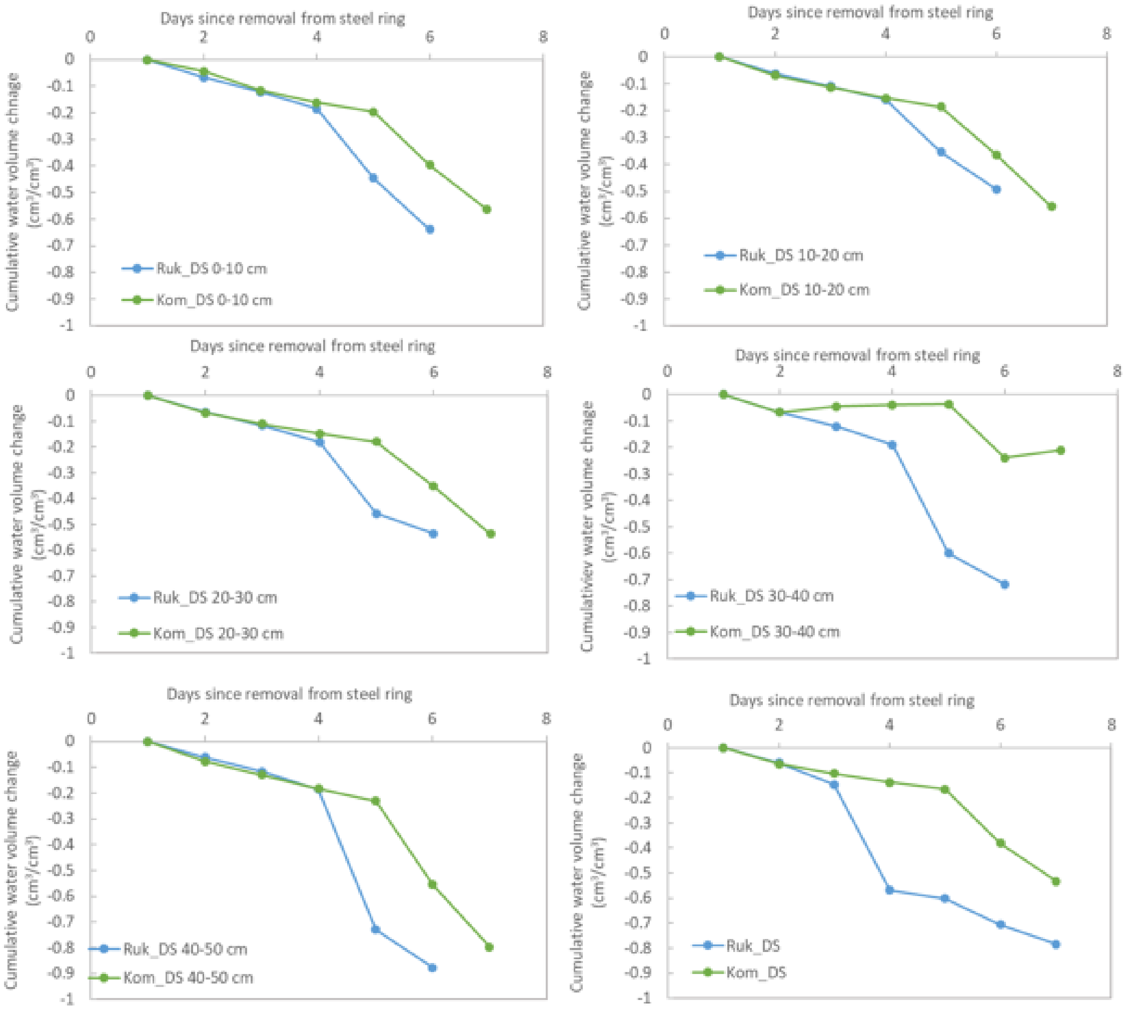

Figure 4.15 Cumulative water volume change (cm^3/cm^3) over period of drying (days) for the blueberry sites, grouped by sampling depth a) 0-10 cm, b) 10-20 cm, c) 20-30 cm, d) 30-40 cm, e) 40-50 cm, f) average across all depths.

Chapter Five

Hydrological and PSO regimes

5.1 Introduction

This chapter presents results from the measurements of relative water level (RWL),and peat surface elevation (SE). This includes seasonal trends in RWL and SE, as well as tables of statistics of annual RWL, and the major seasonal shrink and swell period ranges for SE and RWL over the full study period. RWL regimes are shown as daily means and SE shown as 7-day running means of SE change (ΔSE) based on the start of the study period. Figures showing daily means of data for RWL, AWL and SE are provided in Appendix C, along with manual check measurements.

5.2 Climate

The Ruakura climate station was chosen as a regionally representative site for rainfall, potential evaporation and air temperature data across the Waikato peatland regions (Figure 5.1 and 5.2). However, Ruakura is still relatively representative for the whole study area. Annual rainfall at Ruakura in 2021 was 1018 mm, which was 97% of the long term average (1991-2020) annual rainfall of 1118 mm (NIWA, 2022). Total rainfall for January to June 2022 was 518 mm, 99% of normal (Figure 5.1). Comparing Ruakura rainfall to rainfall measurements at sites chosen as representative of the regional peatland areas (Table 3.2), Moanatuatua had a notably greater cumulative rainfall than Ruakura in 2021, from April until December 2021 Moanatuatua had a cumulative rainfall of 1049 mm and Rukakura had 803 mm (Figure 5.2).

On average, air temperature was higher than normal, 0.7°C higher in January to December 2021, and 1.7°C higher for January to July 2022. The greatest difference was during October 2021 – January 2022 when air temperature was 2°C higher than normal (Figure 5.1).

During individual months February, April and May 2021 had 35%, 54% and 59% of their respective normal rainfall at Ruakura. January and April of 2022 had exceptionally low rainfalls compared to normal, with 8% (6.4 mm) in January 2022 and 16% (13 mm) in

April 2022 (Figure 5.1). Some months were much wetter, March 2021 had 194% of normal and September 2021 had 160% of rainfall. February 2022 was also a wet month with 174% of the normal rainfall, but was also hotter than the average by 2°C.

Between October 2021 and January 2022 there was a significant shortfall of rainfall (only 247 mm) compared to normal (351 mm), coupled with much higher air temperatures (18.0°C) than normal in these months (16.0°C). This meant that this period of the study was an exceptionally dry and hot period than what would normally be expected. The wettest period occurred between June to September 2021 with a total rainfall of 483 mm, 111% of normal (436 mm). May and June 2022 were also wet, with a total of 306 mm of rainfall, 144% of normal for these two months.

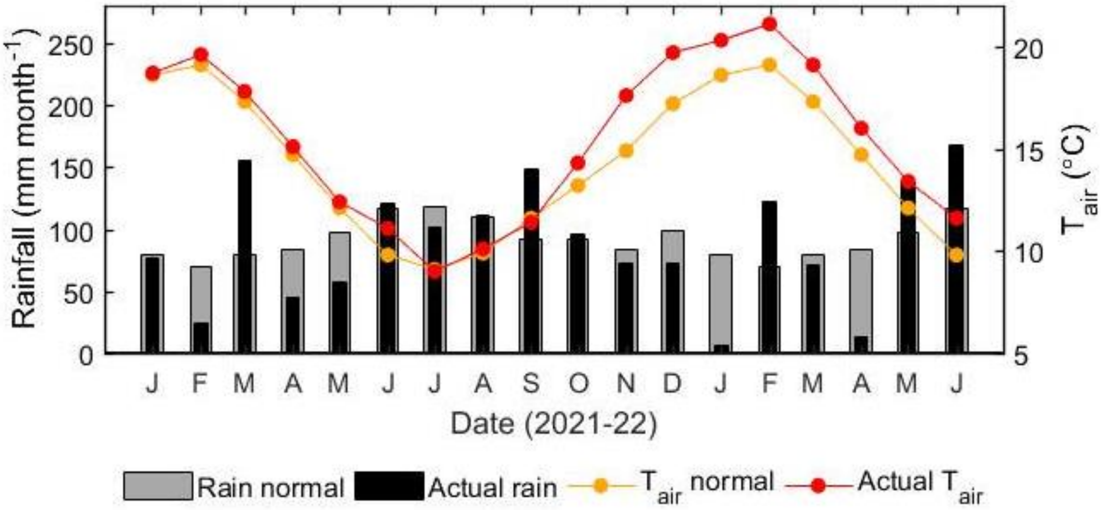

Figure 5.1 Monthly total rainfall measured at Ruakura for January 2021 to June 2022 compared to mean monthly rainfall totals (normals) for 1991-2020, and mean air temperature at Ruakura compared to air temperature normals for 1991-2020 (NIWA, 2022).

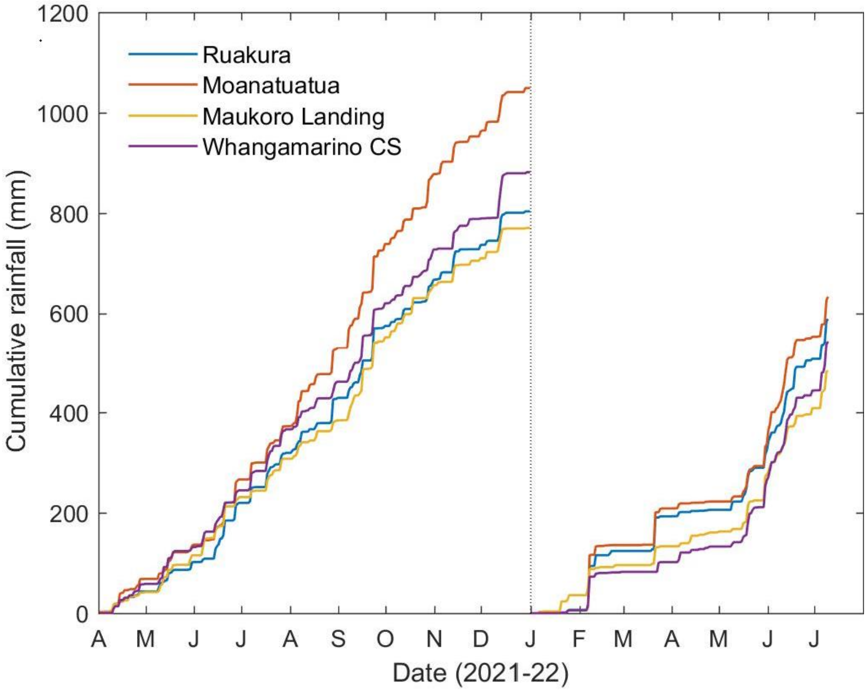

Figure 5.2 Cumulative rainfall in 2021 and 2022 for the rain gauge sites representing the regional PSO sites (see Table 3.2 and Figure 3.1)

From April 2021 through to late September 2021, there was a water surplus at Ruakura, where rainfall exceeded evaporation (Figure 5.3). Water deficits developed from early October 2021 to late January 2022, with the deficit exceptionally large in January due to both low rainfall and higher temperatures (Figure 5.1 and 5.3). Rainfall in February 2022 exceeded evaporation before evaporation again exceeded rainfall from March to mid-April 2022, after which a water surplus began to develop.

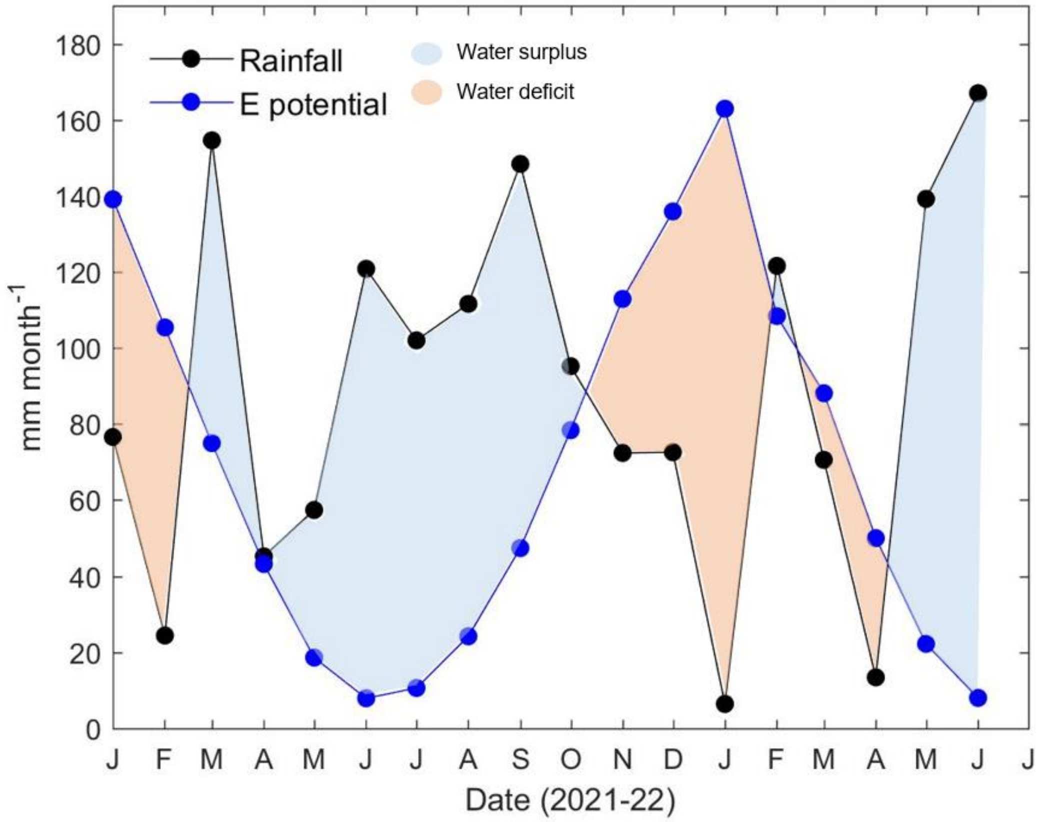

Figure 5.3 Monthly rainfall and potential evaporation (Priestley-Taylor method) totals from Ruakura weather station for 1 January 2021 to 30 June 20222. Shading represents period of water surplus (blue) and water deficit (red).

5.3 Water table regimes

Over the study period, all of the sites displayed similar seasonal patterns of RWL fluctuations as a response to changes in water inputs (precipitation) and outputs (evaporation) (Figure 5.4). At the beginning of the study period, relative water levels (RWL) at the sites were at their maximum depths due to the previous summer dry down. Between June and July 2021 RWLs began to rise as water inputs through precipitation increased, and then plateaued at the majority of the sites in early July 2021. RWLs stayed high and relatively stable from early July 2021 to November 2021 when they began to decline during the warm and dry summer season (Figure 5.4). This decline continued until late May to early June 2022 and during this time, there were short-term, rapid rises and falls due to rainfall events but RWL continued to decline. From early June 2022, precipitation increased and RWL began to rise again until the end of the study period in early July 2022.

RWL rises between June and July 2021 were rapid and relatively large at the Moanatuatua, Rukuhia and Komakorau peatland sites but RWL rises at the Torehape peatlands sites were comparatively smaller and more gradual (Figure 5.4). The sites with the greatest RWL rises during this period were Moa2_Dairy and Kom_DS, with 1.0 m and 1.1 m rise in RWL, respectively (Figure 5.4a,b). Data was not available for Mot_Dairy during the 2021 RWL rise but had a very slow rise in RWL during the 2022 wet season, despite having a responsive dry season RWL (Figure 5.4e).

The abrupt short-term responses in water tables to rainfall events between November 2021 and June 2022, were the most notable in early February and late March at the Moanatuatua and Rukuhia peatland sites. For example, Moa2_BB had a sharp rise in RWL of approximately 0.6 m at the beginning of February and Ruk_BB had a rise of approximately 0.8 m in late March (Figure 5.4a,b). These same rain events did not trigger such large RWL responses at Torehape (Figure 5.4c), however, Tor_BB had generally smaller responses to short-term rain events compared to Tor_Dairy.

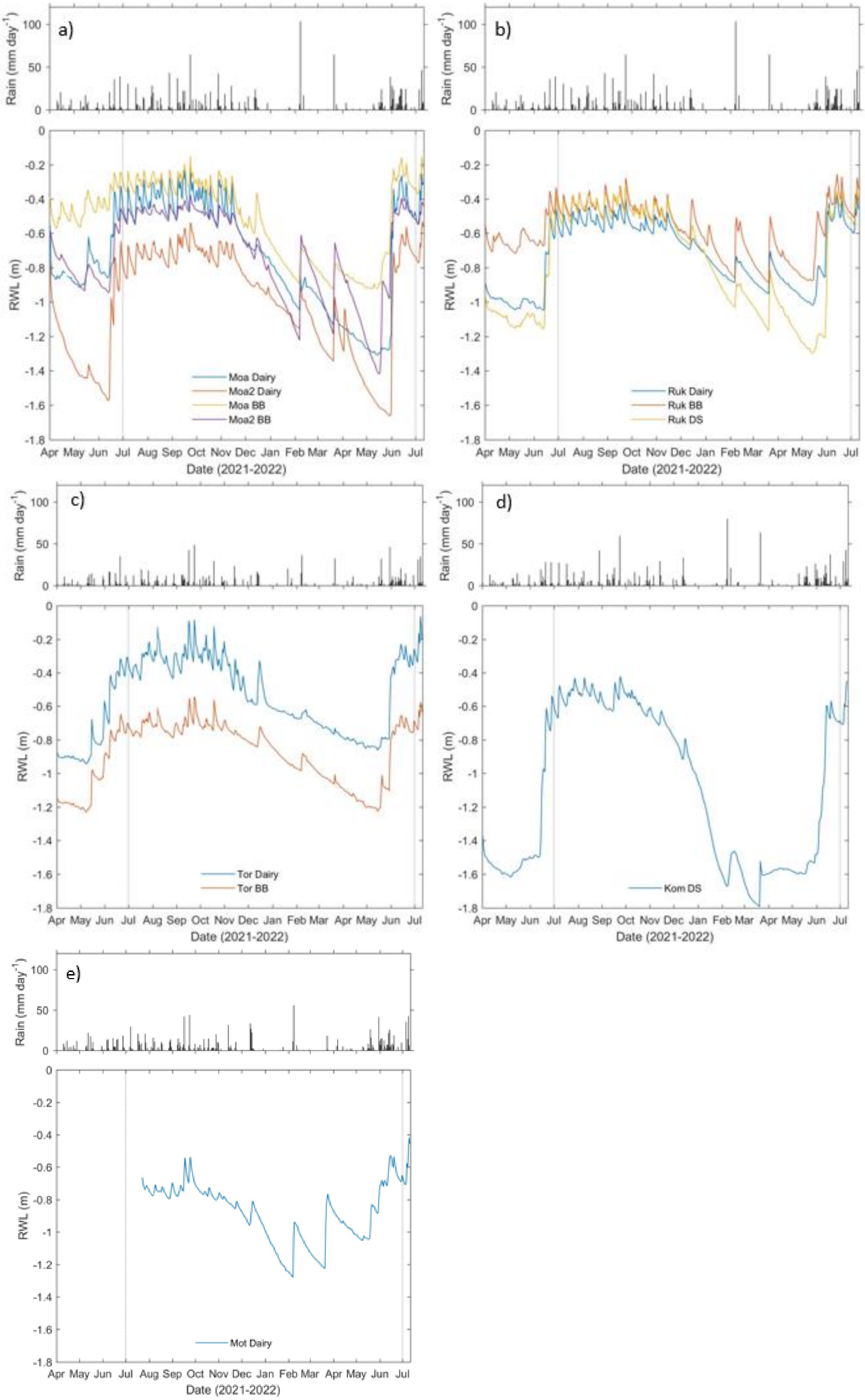

Figure 5.4 Time series' of RWL fluctuations for the entire study period, 1 April 2021 to 10 July 2022, grouped by peatland a) Moanatuatua, b) Rukuhia, c) Torehape, d) Komakorau, e) Motukaraka, vertical dashed lines on RWL panels indicative of annual period from 1 July 2021 to 30 June 2022. Note: Mot_Dairy was installed later than the other sites.

For the annual period 1 July 2021 to 30 June 2022, the site with the deepest mean RWL was Kom_DS (-1.029 m) and the shallowest mean RWL was Tor_Dairy (-0.514 m) and none of the sites had a water table that rose above the surface of the peat (Table 5.1). At Tor_Dairy, the daily mean RWL came closest to the surface with a maximum level of -0.084 m in July 2021 (Table 5.1, Figure 5.4c). Tor_BB had the deepest maximum RWL (-0.557 m), but Kom_DS had the deepest minimum RWL (-1.791 m). Ruk_BB had the smallest range of RWL (0.708 m) over the annual period and Kom_DS had the greatest RWL range (1.419 m), which was almost that of double Ruk_BB (0.708 m) (Table 5.1)

At the Moanatuatua and Rukuhia peatlands sites, RWL behaved in a similar manner during the July to November 2021 wet period (Figure 5.4a,b). At the Moanantuatua peatland, Moa2_Dairy RWL was notably deeper than at the other sites. From November 2021, at the Moanatuatua and Rukuhia sites, RWL regimes diverged markedly as they drew down during the dry summer period. As the water table began to rise again towards the 2022 winter maximum RWLs at the respective Moanatuatua and Rukuhia peatland sites began again to behave in a similar pattern and this was particularly notable at the Rukuhia peatland sites (Figure 5.5b). The two Torehape sites had very different RWL but followed very similar seasonal patterns, Tor_BB having a deeper RWL regime but a smaller range than Tor_Dairy (Figure 5.4c).

Table 5.1 Statistics for RWL at all sites for the annual period 1 July 2021 to 30 June 2022 (max = maximum, min = minimum, negative notation indicates RWL is below the peat surface)

Site	Mean RWL (m)	Min RWL (m)	Max RWL (m)	RWL range (m)
Moa_Dairy	-0.717	-1.308	-0.195	1.260
Moa2_Dairy	-0.958	-1.662	-0.538	1.221
Moa_BB	-0.543	-0.928	-0.152	0.903
Moa2_BB	-0.717	-1.420	-0.375	1.111
Ruk_Dairy	-0.682	-1.018	-0.378	0.815
Ruk_BB	-0.571	-0.886	-0.255	0.708
Ruk_DS	-0.720	-1.298	-0.312	1.066
Kom_DS	-1.029	-1.792	-0.423	1.419
Tor_Dairy	-0.514	-0.862	-0.084	0.848
Tor_BB	-0.859	-1.227	-0.541	0.786
Mot_Dairy	-0.882	-1.281	-0.529	0.777

Half-hourly RWL over the July 2021 to June 2022 annual period were sorted and plotted as depth-duration (exceedance probability) curves in order to better compare key characteristics of water table regimes across the study sites (Figure 5.5). Depth-duration curves are analogous to flow duration curves, which are commonly used for river flow regime analysis in hydrology. Here they show the percentage of time that a given RWL was equalled or exceeded and by eliminating the time variable, these curves eliminate the complexity of the time-series RWL plots (Figure 5.4). Flatter sections of the curves indicate stable portions of the RWL regimes whereas steeply sloping sections indicate parts of the RWL regimes where the water table rapidly transitions from shallow to deep.

The Rukuhia sites had strikingly similar stable RWL regimes during the wet season (0-40% exceedance), and this was reflected in similarities in water table behaviour in the wet seasons of the time series graphs (Figure 5.4b and 5.5b). However, above 50% exceedance, the RWL at Ruk_DS was deeper than the other two sites. At high exceedances Ruk_Dairy and Ruk_BB had very similar patterns, but Ruk_BB had a shallower RWL than Ruk_Dairy (Figure 5.5b).

The Moanatuatua peatland sites had three different patterns during the wet season, with Moa2_BB having a stable RWL at 0-40% exceedances as indicated by the flatness of the depth duration curve (Figure 5.5a). At higher exceedance values, the Moanatuatua sites with deeper RWLs had a much more rapid drawdown than the shallower sites, meaning that during the summer dry down the RWL regimes all displayed very different patterns. The RWL regimes at Kom_DS was distinctive compared to all of the other study sites as it was relatively stable during the wet season but during summer, RWL dropped rapidly before reaching a deep but stable level (Figure 5.4c) indicated by the large step in the RWL exceedance curve (Figure 5.5c). In contrast, Tor_BB and Mot_Dairy had very similar RWL depth-duration curves, especially between 20-60% exceedances, which displayed relatively stable RWL regimes.

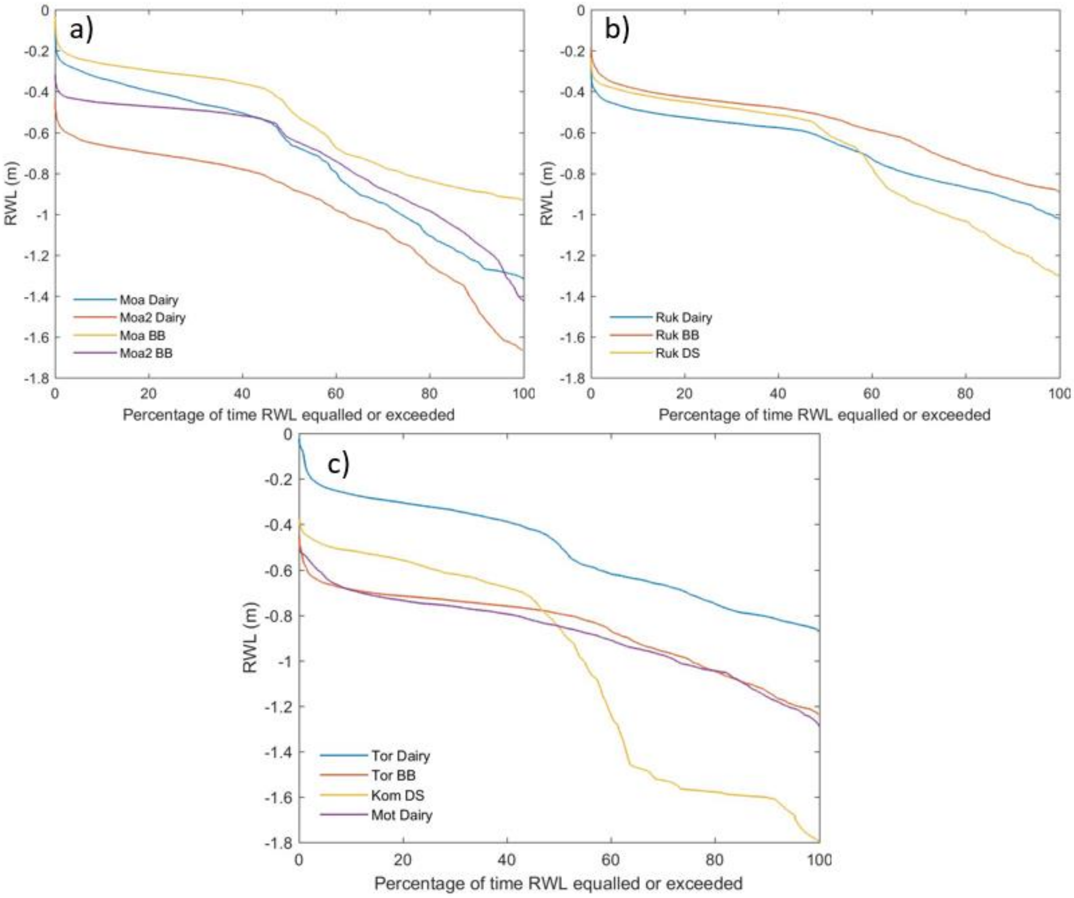

Figure 5.5 Depth-duration for RWL from 1 July 2021 to 30 June 2021, a) Moanatuatua peatland sites, b) Rukuhia peatland sites, c) Torehape, Komakarau and Motukaraka peatland sites.

2.1 Surface elevation changes

The peat surface elevation (SE) regimes during the study period are shown in Figure 5.5, in order to plot these at the same scale they are shown as a change relative to the initial elevation and are therefore denoted as change in SE or ΔSE. Actual SE data are shown in Appendix C plotted at the same scale as AWL. The change in surface elevation (ΔSE) graphs are presented as 7-day running means to reduce the impact of high-frequency noise (Appendix C).

All sites had similar seasonal patterns of changes in SE (Figure 5.6). In June 2021, the first swell period began as water inputs increased in early winter. Most of the sites reached their winter maximum SE between September and November 2021, although Kom_DS plateaued earlier than many of the other sites after a rapid initial increase in SE (Figure 5.6d). This site Kom_DS also had a rapid decrease in surface elevation between January and February 2022, whereas the other sites did not reach their summer minimum until May-June 2022. All sites reached their lowest ΔSE of the study period during the 2022 late summer-autumn. SE at all the sites began to rise again for the second swell period from early June 2022 until the end of the study period on 10 July 2022. It is not clear whether these data have captured the full peat surface elevation rise for the 2022 swell period.

The sites all exhibited a similar trend in swell and shrink periods, as a response to changes in the water balance but the variation in magnitudes of these responses was rather large. Tor_Dairy had exceptionally large changes in SE compared to Tor_BB (Figure 5.6c). In winter, the SE responses to single rain events were not as responsive at Moa2_BB and Kom_DS as the other sites (Appendix C).

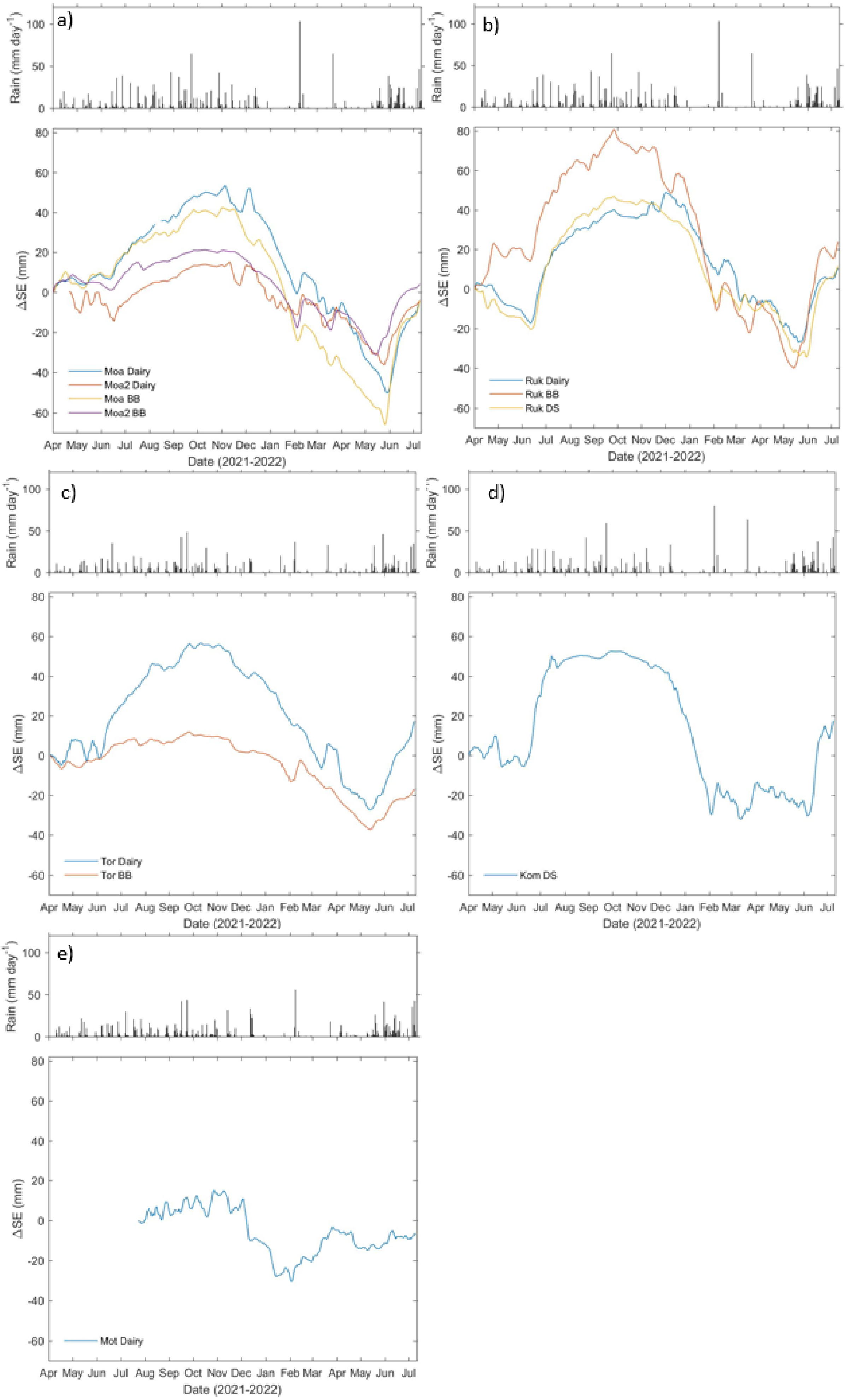

Figure 5.6 Surface elevation changes (ΔSE) for the entire period of study, grouped by peatland: a) Moanatuatua peatland, b) Rukuhia peatland, c) Torehape peatland, d) Komakorau, e) Motukaraka peatland.

The ranges of SE of the two swell periods and the single shrink period between 1 April 2021 and 10 July 2022 are presented in Table 5.2. The 2021 swell period ranges were calculated from the maximums and minimums of 7-day running means of SE between 1 April 2021 to 1 November 2021, and the shrink period for 2021-2022 was calculated between 1 August 2021 and 1 July 2022. This period captured the effect that a relatively dry summer had on SE (Figure 5.1). The second swell period was likely incomplete but was calculated from values between 1 April 2022 to 10 July 2022. It is unknown if the peak surface elevation was captured for the second swell period; however, preliminary comparisons can still be made with the 2021 swell period.

Ruk_BB had the largest overall SE range out of all the sites, for both the swell periods (80.9 mm and 64.1 mm) and for the shrink period (-121.0 mm). Mot_Dairy had the smallest SE range for the 2021-2022 shrink period (-45.1 mm) and the smallest recorded SE range for the 2022 swell for the dairy sites (25.9 mm). There was insufficient data to calculate the SE range for the 2021 swell period at Mot_Dairy; therefore, the site with the smallest SE range for this period was Tor_BB (18.5 mm). Out of the dairy sites, the smallest SE range for the 2021 swell period was Moa2_Dairy (28.4 mm). Tor_BB had the smallest 2022 swell out of all the sites (20.3 mm). This site also had the smallest SE range for the 2021-2022 shrink period (-49.1 mm). When comparing the dairy sites, Tor_Dairy had the greatest 2021 swell (61.5 mm), and Moa_Dairy had the greatest 2021-2022 shrinkage and 2022 swell (-101.7 mm and 47.6 mm, respectively). Comparing the two dry stock sites, Ruk_DS had greater changes in surface elevation for the 2021 swell and s021-2022 shrink period (67.4 mm and -81.5 mm, respectively) and Kom_DS had a greater 2022 swell of 49.5 mm than Kom_DS. The 2022 swell period at all the sites had not reached the same elevation as the previous swell period by the end of the study period. Overall, there were large variations in the magnitudes of SE changes observed across all the sites and the greatest changes in SE occurred between November 2021 and May/June 2022 (Table 5.2, Figure 5.6).

Table 5.2 Ranges of surface elevation (SE) and relative water level (RWL) for each swell and the one shrink period. These ranges have been calculated from 7-day running means of both RWL and SE for the full study period 1 April 2021 to 10 July 2022. Positive values denote relative increases and negative values denote relative decreases.

	2021 swell[3]		**2021- 2022 shrink[4]**		**2022 swell[5]**	
Site	**SE range (mm)**	**RWL range (mm)**	**SE range (mm)**	**RWL range (mm)**	**SE range (mm)**	**RWL range (mm)**
Moa_Dairy	51.3	595.4	-101.7	-992.2	47.6	978.5
Moa2_Dairy	28.4	958.7	-50.4	-1051.9	32.3	1056.3
Moa_BB	42.1	295.4	-108.2	-667.0	62.15	705.2
Moa2_BB	21.2	507.4	-52.6	-974.6	35.6	966.5
Ruk_Dairy	57.5	562.3	-67.0	-533.1	37.4	571.9
Ruk_BB	80.9	342.6	-121.0	-510.0	64.1	546.8
Ruk_DS	67.4	757.3	-81.5	-902.3	46.2	897.3
Kom_DS	58.3	1014.1	-84.3	-1310.4	49.5	1272.3
Tor_Dairy	61.5	715.4	-84.0	-629.6	44.7	708.1
Tor_BB	18.5	596.9	-49.1	-589.1	20.3	546.8
Mot_Dairy	n/a	n/a	-46.1	-644.1	25.9	772.7

5.4 Relationships between RWL and surface elevation change

When SE ranges for each period in the PSO cycle were plotted against the changes in RWL for the same periods (Table 5.2), there were no obvious relationships (Figure 5.7). There was a weak relationship during the 2022 swell period, where the sites, with the

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[3] Calculated from maximum and minimum between 1 April 2021 and 1 November 2021

[4] Calculated from maximum and minimum between 1 August 2021 and 1 July 2022

[5] Calculated from maximum and minimum between 1 April 2022 and 10 July 2022

exception of Ruk_BB and Moa2_BB, followed a trend where the sites with rather large RWL ranges had corresponding large SE ranges for example Kom_DS (Figure 5.7c). Another example is Tor_BB, where this site had a very small RWL range and corresponding SE range.

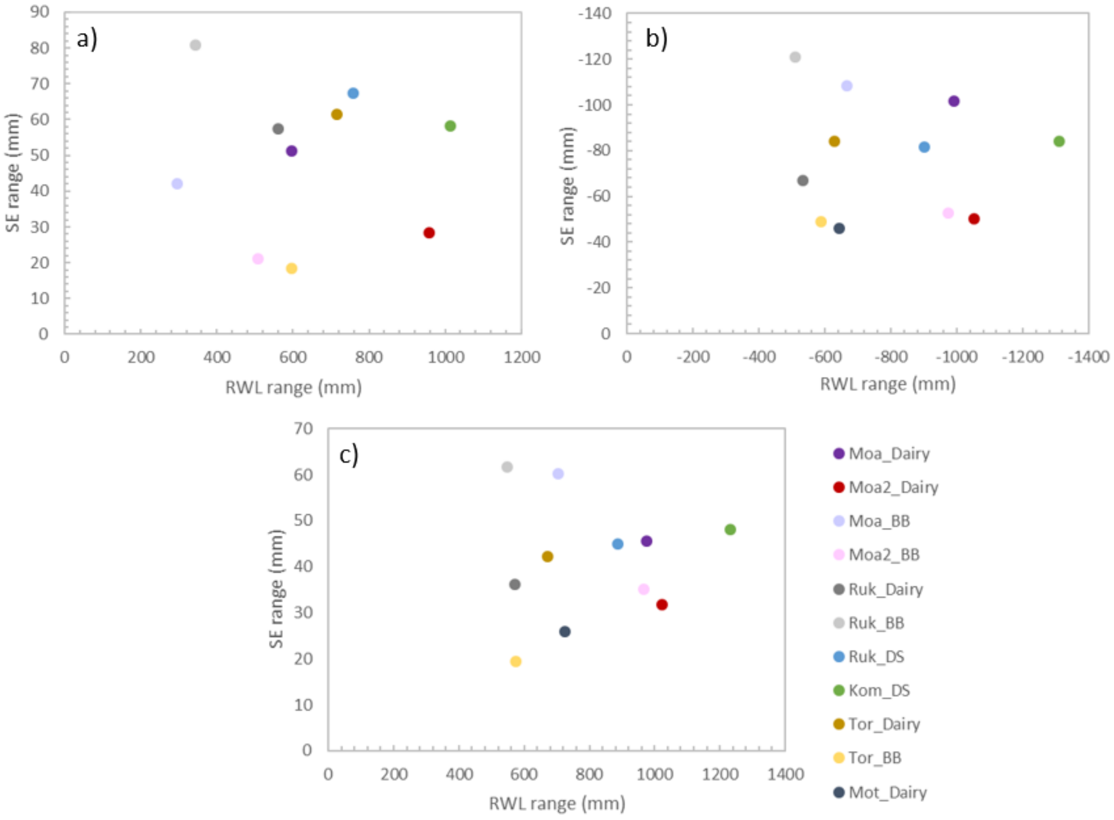

Figure 5.7 Changes in surface elevation vs changes in RWL for each swell or shrink period. a) 2021 swell, b) 2021-2022 shrink, c) 2022 swell. Note: No data point for Mot_Dairy in 2021 swell due to no data

Chapter Six

The influence of peat soil properties on PSO across different drained peatland sites

6.1 Introduction

This chapter provides a discussion of the results of the soil analyses and the peat surface oscillation (PSO) hydrological regimes of the eleven study sites, and attempts to determine the influence land management has on peat soil properties. Any relationship between land management and peat soil properties, as well as trends in water table regimes, are then assessed to determine their relative influence on the spatial variability of PSO regimes across the eleven study sites. There is also an assessment on the investigation in drainage histories and its relative successfulness in explaining differences in both peat soil properties and PSO regimes.

At the time of this study, we believe that this is the first of its kind globally that investigates high-resolution measurements of surface elevation and water table depth across a large spatial extent. It is also the first study in New Zealand to investigate physical and chemical properties across different drained peatlands under different land managements. This chapter also places the study results in the context of previous New Zealand studies and the international literature.

6.2 Spatial variability of physical properties of drained peat

6.2.1 Bulk density and porosity

There was a wide range of variation in patterns of bulk density (BD) and porosity with depths across and within peatlands, as well as between and within different land uses. Across all of the study sites, there was a trend of decreasing bulk density with depth (Figure 4.3) and an increase in porosity with depth (Figure 4.5). The bulk density-depth relationship found at the sites was in agreement with both similar studies in New Zealand and internationally for drained peatland sites (McLay *et al.*, 1992; Kechavarzi *et al.*, 2010; Mustamo *et al.*, 2016; Menberu *et al.*, 2021). The ranges and trends in porosity seen at the sites reflected the inverse relationship commonly observed between bulk density and porosity and was expected due to the methodology for calculating porosity at the sites (Liu & Lennartz, 2019; Menberu *et al.*, 2021). However, it has been suggested that porosity may not always decrease with increased bulk density due to the formation of secondary pore spaces, largely related to macroporosity (Lennartz & Liu, 2019; Liu & Lennartz, 2019). The calculation we used for determining porosity did not consider this factor, therefore total porosity is only discussed in accordance with its relationship to bulk density.

Many of the pastoral site results for bulk density agree with results of previous New Zealand studies by McLay *et al.* (1992) and Glover-Clark (2020). McLay *et al.* (1992) reported a mean (± standard error) bulk density of 0.30 ± 0.010 g cm^{-3} at 0-15 cm sampling depth and 0.11 ± 0.030 g cm^{-3} at 25-45 cm depth[6], from pastoral sites approximately 2-3 km south of the Torehape sites of the present study. The agricultural sites in the present study had bulk density that were generally similar at the surface layers, if not slightly higher. For instance, Moa_Dairy had a bulk density of 0.365 ± 0.006 g cm^{-3} and 0.302 ± 0.007 g cm^{-3} at 5 cm and 15 cm depth, respectively, and Tor_Dairy had 0.386 ± 0.011 g cm^{-3} and 0.252 ± 0.022 g cm^{-3} at the same respective depths. The exception to this was Mot_Dairy, which had a substantially higher bulk density of 0.57 g ± 0.025 cm^{-3} (Figure 4.3). However, all of the agricultural sites had higher bulk density in the deeper sampling depth compared to what McLay *et al.* (1992) found at the same depth, for instance Moa2_Dairy had bulk density of 0.212 ± 0.017 g cm^{-3} and 0.240 ± 0.025 g cm^{-3} at 35 and 45 cm depth, respectively. Many of the blueberry sites had lower bulk densities than McLay *et al.* (1992) in the surface layers but had higher bulk densities at greater depths. The only exception was Ruk_BB, which had a bulk density of 0.110 ±0.001 g cm^{-3} at 45 cm depth. Ruk_BB at this depth had a significantly lower bulk density than all of the other study sites except for Tor_Dairy (Figure 4.3).

Glover-Clark (2020) reported mean bulk density of 0.30 g cm^{-3} and 0.36 g cm^{-3} for depths of 2.5-7.5 cm, at two adjacent dairy farm sites in the Moanatuatua drained peatland. These values largely agree with the values obtained at the agricultural sites of the present study, although they were slightly greater at 5 cm depth. Most of the blueberry sites had lower bulk density, especially at the 15-25 cm depths than the mean bulk densities reported by

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[6] Note: Depths are reported as the midpoint of the sampling depths e.g 5 cm for 0-10 cm depth

Glover-Clark (2020) (Figure 4.3). Deeper in the profile, from 35 cm depth, all of the current study sites had lower bulk densities than those obtained by Glover-Clark (2020).

All of the current study sites at all depths and across all of the land uses and peatlands, had bulk densities much higher than typically found in natural peat-forming areas in New Zealand. Kopuatai, an intact raised bog, has bulk densities the are as low as 0.014 ± 0.002 g cm^{-3} (Lambie & Ratcliffe, 2020). For the remnant peatland area of the Moanatuata bog, which had been somewhat degraded because of unnaturally low water tables, Lambie & Ratcliffe (2020) reported bulk densities as low as 0.036 ± 0.002 g cm^{-3}. Even deeper in the profile, the lowest bulk density of the sites at Ruk_BB, 0.110 ± 0.001 g cm^{-3}, was still higher than reported by Lambie & Ratcliffe (2020) in intact New Zealand bogs (Figure 4.3). This comparison shows that all of the study sites have undergone severe degradation due to both drainage and the subsequent development for agricultural and horticultural land use.

The notably higher bulk densities in the surface layers, such as 0.433 ± 0.009 g cm^{-3} at 5 cm depth at Moa2_Dairy (Figure 4.3), indicate degradation has overtaken natural processes that would have occurred in the intact peatland. In the surface this is due to the effects of shrinkage, Price (2003) reported that peat nearest to the surface had greater shrinkage due to the development of greater negative potentials in the surface peat, which is why bulk densities are greater in the near-surface peat. In deeper peat it is consolidation that is driving increased bulk density due to peat being below the water table (Kennedy & Price, 2005; Nusantra *et al.*, 2018). Both of these processes are a direct result of drainage and explain why none of the current study sites have bulk densities, even at the deepest sampling depth, that are as low as that found in intact bogs (Figure 4.3).

When comparing international studies of peat properties in drained peatlands, there is an agreement in the relationship both bulk density and porosity have with depth. The bulk densities at many of the study sites, particularly the blueberry sites, are much lower than international values. For example, in Northern Finland, a bulk density range of 0.40-0.49 g cm^{-3} was obtained for a depth range of 0-30 cm (Mustamo *et al.*, 2016). Comparing this range to the current New Zealand study sites, only a few sites had bulk density values in a similar range, which were all agricultural sites. Only Mot_Dairy exceeded this range with a bulk density of 0.570 ± 0.025 g cm-3 at 5 cm depth (Figure 4.3). However, this was only at 5 cm depth for these sites and none of the blueberry sites had bulk densities this high. This same conclusion can be made when comparing other international studies, such as those undertaken in Germany or the UK (Schwärzel *et al.*, 2002; Kechavarzi *et al.*, 2010; Menberu *et al.*, 2021). Generally, the agricultural sites had bulk density values closer to international values for drained peatlands, and the blueberry sites were always lower. When comparing the deeper peats of the current studies to international studies, porosity and bulk density were comparable. For example, in England a “humified” peat at 35-50 cm depth had a bulk density of 0.17 g cm^{-3} and a porosity of 87.0% (Kechavarzi *et al.*, 2010). This is much closer to the values of the current study sites, especially at 45 cm depth. For example, Mot_Dairy had a bulk density of 0.173 ± 0.016 g cm-3 and a porosity of 88.9 ± 0.52% and Tor_BB, under a different land use, had a bulk density of 0.166 ± 0.002 g cm-3 and porosity of 89.3 ± 1.25%, both at 45 cm depth (Figure 4.3 and 4.5).

These international peatlands have likely been drained for a very long time, in Europe drainage for agriculture has occurred for centuries (Joosten *et al.*, 2012). Some places, such as the Netherlands, have been drained for thousands of years (Erkens *et al.*, 2016). This means that these European sites have been subjected to processes leading to increased bulk density and decreased porosity for much longer than the current study sites which have been drained for barely half a century (Table 3.1). This likely explains why in the surface layers the international sites have greater bulk density and lower porosity than the sites in the current study, which have been drained over a much shorter time scale. This likely also explains why deeper peat bulk density and porosity have greater similarities between the current study sites and the international studies (Kechavarzi *et al.*, 2010). Intact peatlands in the Northern Hemisphere also have been found to have higher bulk densities than intact peatlands in New Zealand. For example, Schwärzel *et al.* (2002) reported for a preserved reed-sedge peat horizon, bulk density was 0.140 ± 0.02 g cm^{-3} which is higher by 0.10 g cm^{-3} than Kopuatai (0.014 g cm^{-3}). An originally higher bulk density likely has contributed to higher bulk density in the international literature compared to the current study sites.

The blueberry sites generally had lower bulk density and higher porosity than the agricultural sites (dairy and dry stock farms) (Figure 4.3 and 4.5). This was found to be highly significant ($p<0.001$) at the near-surface peat (5-15 cm) and only significant between the blueberry and dry stock sites in the deeper peat (35-45 cm) (Table 4.2 and 4.4). This is likely due to differences in land management between land uses, with agricultural sites having greater amounts of compaction resulting from trampling by stock and heavy vehicle use year-round (Hooijer *et al.*, 2012). The agricultural sites likely also have greater frequency of ploughing and cultivation for renewal of pasture and additions to the surface of fertiliser such as lime. The significance tests indicate that this is largely concentrated in the surface layers and there is less of a difference in impacts between land uses further down the peat profile. This means that at the agricultural sites, compaction is occurring at a greater rate than at the blueberry sites, in conjunction with shrinkage, which is occurring due to drainage. These two processes often cannot be separated from each other which makes it difficult to determine the actual proportions of each process occurring at the different land uses (Hooijer *et al.*, 2012; Nusantra *et al.*, 2018).

Another reason for differences between land uses is likely due to bias introduced through the sampling strategy at the blueberry sites; samples were only taken under the blueberry bushes in the rows and not in the lanes to avoid highly trafficked areas. There is also a large unknown as to whether blueberry sites had previously been pastoral land. Moa2_BB from records (Monavale Blueberries, 2021), likely has only ever been under blueberry orchards but at the other blueberry sites, there is a large lack of information.

6.2.2 Volumetric moisture content

There was a high amount of variability in volumetric moisture content (VMC) across the different study sites (Figure 4.4). VMC did decrease with depth across all the sites, but at many sites, VMC at 5 cm depth was higher than 15 cm depth and below this depth VMC increased. For example, Moa_BB had a VMC of 66.5 ± 1.26% at 5 cm depth and this decreased to 57.8 ± 1.17% at 15 cm depth (Figure 4.4a). Comparison of VMC between the different sites, especially in the surface layers, was constrained due to the timing of sampling which spanned five weeks. The increase in VMC with depth at all the sites is likely to be due to increased proximity to the water table and possibly due to the act of capillary rise replenishing water in drained pores (McLay *et al.*, 1992; Campbell & Jackson, 2004; Nugraha *et al.*, 2017).

McLay *et al.* (1992) also reported a trend of increased VMC with depth in agricultural peats located in the former Torehape peatland. Campbell *et al.* (2021) and Glover-Clark (2020) reported extensive capillary fringes for two drained agricultural sites at the Moanatuatua drained peatland. They suggested this indicates saturation of pores at the near surface despite deep water tables. However, our sampling strategy for VMC measurements did not allow us to determine if the study sites had deep and large capillary fringes. This is because, as Campbell *et al.* (2021) and Glover-Clark (2020) reported, capillary fringes are more apparent in summer when water tables are low whereas we sampled when water tables were high.

6.3 Spatial variability of chemical properties of drained peat

6.3.1 Organic matter fraction

There were large variations in organic matter fractions (OMf) between and within the different peatlands and land uses; however, OMf generally increased with depth across all of the study sites (Figure 4.6).

The range of OMf were comparable to those reported by McLay *et al.* (1992), for the Torehape drained peatland in New Zealand, with OMf of 74.0% at 0-15 cm depth. Mot_Dairy (57.2% at 5 cm, 67.0% at 15 cm) had a much lower OMf, whilst Kom_DS had very similar values of 76.3% and 76.6% at 5 and 15 cm depth (Figure 4.6). The rest of the study sites, including the other dry stock sites, the dairy sites and all of the blueberry sites had greater OMf in a similar range of sampling depths. McLay *et al.* (1992) reported increased OMf of 81.1% at 15-45 cm depth. Moa_BB, Moa_Dairy, Mot_Dairy and Kom_DS either had very similar or lower OM fractions than this value, while the other sites, including all of the blueberry sites, had higher OMf. The trend of increasing OM fraction with depth reported by McLay *et al.* (1992) was consistent with all of the current study sites (Figure 4.6).

In comparison to international studies, the current study sites had greater OMf, especially when comparing the surface layers of the profile (Figure 4.6). The international sites reviewed were either previously or currently fens (Schwärzel *et al.*, 2002; Kechavarzi *et al.*, 2010; Mustamo *et al.*, 2016). In Finland, the mean OMf of a cultivated fen peat was 42% at 0-15 cm depth, 59% at 125-30 cm depth and 93% at 30-45 cm depth (Mustamo *et al.*, 2016). The only site that did not have a higher OM than this study was Mot_Dairy. A German study obtained higher OMfs of 77% in a degraded fen peat and 75% in a strongly degraded fen peat (Schwärzel *et al.*, 2002). This is closer to the ranges seen at the current study sites and higher than Mot_Dairy at 5cm depth. However, deeper in the profile the current study sites had much greater OMf than the Schwärzel *et al.* (2002) study. In England, a peaty loam from a fen peatland at 0-15 cm depth had OMf of 39% and 60.1% at 35-50 cm depth, which were a lot lower than at any of the current study sites (Kechavarzi *et al.*, 2010). All of these international studies reported a trend in increasing OM with depth, consistent with the trends we found at the current study sites.

Many of the current study sites had greater OMf than the international study sites and this can be attributed to three different reasons. The main reason is that the international studies investigated fen peat, which naturally has a greater mineral fraction than bog peat, which is what comprises the current study sites. Fen peat is also more susceptible to rapid degradation due to a greater availability of nutrients and high pH (Sorrell & Gerbeaux, 2004). Another reason is time since drainage; peatlands internationally, especially in European countries, have often been drained for centuries meaning that they have likely been subjected to oxidation for much longer than the current study sites. This is reflected in the lower OMf, particularly the very low OMf in the near-surface peat, in the international studies (Grønlund *et al.*, 2008). The last reason for lower OMf in the international studies is that many European peatlands have had mineral soils added to the surface, which is often then mixed with the peat through ploughing (Säurich *et al.*, 2019).

Lower near-surface OMf at all of the sites can be attributed to greater rates of aerobic decomposition in the surface layer caused by drainage (Leifeld *et al.*, 2020). At depth, high VMC helps to prevent oxygen from entering pores and therefore reduces the microbial decomposition of OM. The presence of tephra at some sites resulted in decreased OMf, for example at Moa_Dairy and Moa_BB at 25-30 cm depth.

The agricultural sites generally had lower OMf in the surface layers than the blueberry sites but there was less of a difference further down the profiles (Figure 4.6). For example, Tor_Dairy had lower OMf (78.2 – 86.8%) compared to Tor_BB (90.2-91.1%) at 5-25 cm depth, which is within a couple hundred metres of Tor_Dairy and has a similar drainage history. At 45 cm depth, Tor_Dairy and Tor_BB had very similar OMf, 96.6 ± 0.28% and 94.1 ± 0.75% respectively. Ruk_Dairy has much smaller near-surface OMf (74.9-88.4%) compared to Ruk_BB (75.8-95.6%) at 5-15 cm depth, these two sites (Figure 4.6). The blueberry and dairy sites had a significant difference in OMf ($p<0.001$) and only at the near-surface peat (Table 4.2). This indicates that land management has had an effect on the rate at which degradation occurs, especially because these sites have similar times since drainage. Aeration at the surface of the peat due to drainage at all of the study sites has led to increase aerobic decomposition of the organic matter in the peat, hence lower OMf in the near-surface peat (Kellner, 2003). Further down the peat profile the peat is less impacted by surface processes and there is an increase in soil moisture due to proximity to the water table (McLay *et al.*, 1992). Increased soil moisture means that there is less opportunity for oxygen to enter pore spaces and so aerobic decomposition is reduced (Leifeld *et al.*, 2011; Krüger *et al.*, 2015; Bader *et al.*, 2018), this is why OMf are greater deeper in the peat at all of the sites, with the exception being layers where tephra is present.

6.3.2 Carbon to nitrogen ratios

C/N also had a very large range across the sites, with a trend of increasing C/N with depth at all of the sites (Figure 4.7). There were few significant differences in C/N across the sites and this is likely due to the small sample size.

There have been few studies reporting C/N ratios in drained peatlands in New Zealand. However, one study on the drainage-affected Moanatuatua peat found a range of C/N ratios of 38 – 39 (Lambie & Ratcliffe, 2020), which is very similar to the results of the current study sites in the same peatland. Intact bogs in New Zealand have an average C/N of 48.5 at a depth of 0-10 cm being consistent with bogs being rain fed and therefore nutrient poor. Intact swamps in New Zealand have an average C/N of 18.0; consistent with the nutrient rich status of swamps (Clarkson *et al.*, 2003; Sorrell & Gerbeaux, 2004), with higher N inputs via minerotrophic water sources, and increased rates of organic matter decomposition.

All of the present study sites, across the different peatlands, land uses and all of the sampling depths had lower C/N than reported in intact bogs in New Zealand. The former Moanatuatua, Rukuhia, Komakarau and Torehape peatlands were classified as bogs. The sites in these peatlands have lower C/N due to drainage, which has resulted in increase rates of aerobic decomposition due to aeration leading to consumption of organic matter. The aerobic decomposition reaction, which is mediated by microorganisms, favours carbon over nitrogen leading to an enrichment of nitrogen, hence lowered C/N (Säurich *et al.*, 2019; Leifeld *et al.*, 2020; Szajdak *et al.*, 2020). All sites, except for Mot_Dairy and Ruk_Dairy at 5 cm depth (18.6 ± 0.368 and 19.1 ± 0.913, respectively), had substantially greater C/N than reported for New Zealand swamps (18.0) (Clarkson *et al.*, 2003; Sorrell & Gerbeaux, 2004) (Figure 4.7). This provides evidence that the majority of the peatlands sites are on former bogs. Historic reports have indicated that Motukaraka was formerly minerotrophic, alongside a notable layer of Kahikatea plant remains observed below 27 cm depth when field sampling (Tilsley & Findley, 1981) (Figure 4.1e), despite C/N results at Mot_Dairy in the deep peat suggesting otherwise. This could be because the former peatland was more of a fen-bog or swamp-bog complex rather than just purely minerotrophic.

A study of German fens and bogs reported C/N 52 ± 16 for intact bogs, 50 ± 16 for slightly disturbed bog peat and 26 ± 5 for moderately disturbed bog peat (Säurich *et al.*, 2019). The intact and slightly disturbed bog peats had much higher C/N than at any of the current study sites whereas the moderately disturbed bog peats had C/N similar to the values obtained in the surface layers (5-15 cm) of the current study sites (Figure 4.7). A study in Switzerland investigated C/N under different land uses in a former bog as well as in an intact bog (Leifeld *et al.*, 2020). Their cropland sites had an average C/N of 17.9, the grassland sites 19.6 and the natural bog 33.8 C/N from the disturbed sites were much lower than the C/N found at the majority of the sites in the current study. Mot_Dairy and Ruk_Dairy are the only two sites that had similar C/N to the cropland and grassland values, being 18.60 ± 0.368 and 19.11 ± 0.913 at 5 cm depth, respectively. C/N at our study sites in the deeper peat (e.g 25-45 cm depth) were much higher than the cropland

and grassland C/N. The intact bog value obtained by Leifeld *et al.* (2020) is closer to the values we obtained, especially deeper in the peat, and much smaller than what is commonly measured in New Zealand bogs. Their cropland and grassland C/N may be very low compared to our study sites because the original bog C/N itself is much lower than what the original values at our sites had likely been. For example, the Moanatutua peatland has C/N between 38-39 (Lambie & Ratcliffe, 2020).

The overall trend in increasing C/N with depth at all of the sites can be attributed to drainage and oxidation due to greater aeration of the near-surface peat leading to accelerated consumption of organic carbon (Bader *et al.*, 2018). Another reason for greater C/N ratios in the surface layers is the application of nitrogen-based fertilisers, especially in pastoral systems nitrogen (Bader *et al.*, 2018; Säurich *et al.*, 2019; Leifeld *et al.*, 2020). The use of fertiliser would lead to enrichment of nitrogen, particularly in the near-surface above the plough layer where the fertiliser would be concentrated (McLay *et al.*, 1992). Differences in C/N between land uses were not substantial enough to suggest that nitrogen based fertiliser was a major determiner of C/N. This may be because some fertiliser had also been applied at the blueberry sites, which may have contained some nitrogen as well.

6.3.3 pH

There was less variation in pH across the study sites but all of the sites exhibited an increase in acidity with depth. All of the sites had pH lower than 7 in the top 5-25 cm and lower than 5 at 35-45 cm depth (Figure 4.8). The decrease in pH with depth can be attributed to the use of lime to increase pH at the surface, but this is limited to the plough layer (McLay *et al.*, 1992). Higher lime inputs at the agricultural sites explains the generally higher pH in near-surface peat compared to the blueberry sites as pasture requires a higher pH, between 5-6 (Sparling *et al.*, 2008). Blueberry crops require pH of 4-5 (Hayes, 1988), therefore less lime is needed to increase the natural pH of peat when it is developed for blueberry cropping.

pH around 4.0 for intact bogs and 5.2 for intact swamps is common in New Zealand (Clarkson *et al.*, 2003; Sorrell & Gerbeaux, 2004). Many of the study sites had higher pH than is common for bogs at 5-15 cm depth, with some having higher pH at 5 cm than is common for swamps. This occurred more frequently at the dairy and dry stock sites than the blueberry sites. The sites had higher pH values than intact bogs because of the use of lime to increase pH. The pH values at the pastoral agricultural sites were much higher than intact bogs in comparison to the blueberry sites because blueberry crops survive well in acidic soils (Figure 4.8). Therefore, the differences in pH between the agricultural sites and the blueberry sites reflects the agricultural sites need for higher optimum pH.

6.4 Summary of physical and chemical properties

The key finding of this investigation into the physical and chemical properties of Waikato drained peats is that land management is a major contributor to increased degradation leading to changes in these properties. Near-surface peat at the agricultural sites had greater bulk densities than the blueberry sites and we suggest that this is because of accelerated shrinkage and compaction from animals, year-round use of vehicles and the intensity of the land use. For deeper peat, the main control on increased bulk density and decreased porosity is the process of consolidation following drainage. This likely explains why there is less of a difference in bulk density and porosity between land uses deeper in the peat. It also explains why all of the sites have higher bulk densities and lower porosities than intact peatlands.

6.5 Relationship between organic matter and bulk density as an indication of degradation

When OMfs were plotted against bulk densities, a weak negative relationship was determined (Figure 4.9). A negative relationship is expected because a decreased OMf is due to increased degradation and therefore increased bulk density (Szajdak *et al.*, 2020). However, there was a large amount of variation underlying this relationship and some sites did not display this relationship. Despite reductions in OMf at some sites, the expected increase in bulk density did not occur, for example, at Moa_BB and Kom_DS (Figure 4.9 b,c).

This unexpected pattern may be explained by the presence of tephra, which at the majority of the study sites occurred as 3-5 cm thick layers at 15-35 cm depth, for example, at

Tor_Dairy tephra was clearly visible between 27-29 cm (Figure 4.1b). At Moa_BB, the cores taken at 30-40 cm and 40-50 cm depths had visible tephra and so it is likely the Taupo Tephra in these cores that is attributed to a decrease in OMF but no increase in bulk density (Figure 4.9). Kom_DS, however, did not have any visible tephra layer in the 40-50 cm depth cores, which appeared to have a decrease in OMf but no increase in bulk density. It is largely unknown what may have caused this unusual pattern at Kom_DS, it may be OMf has less of an influence on bulk density than compaction does or OMf may just be a highly variable property.

6.6 Relationship between water table regimes and peat physical and chemical properties

Tor_Dairy, Moa_BB and Ruk_BB had shallow mean annual relative water levels (RWL) (-0.514 m, -0.542 m, and -0.570 m, respectively) (Table 5.1). Tor_Dairy had the lowest bulk density (0.115 ± 0.005 g cm^{-3}) and highest porosity (92.6 ± 0.341 %) of all the dairy sites at 45 cm depth and Ruk_BB had the lowest bulk density (0.110 ± 0.001 g cm^{-3}) and highest porosity (92.9 ± 0.091%) at 45 cm depth out of all of the study sites (Figures 4.3 and 4.4). Moa2_Dairy and Kom_DS had the deepest mean RWL (-0.958 m and -1.029 m, respectively) (Table 5.1) of all the sites and these two sites had high bulk densities and low porosities at 45 cm depth (Figures 4.3 and 4.4). This could indicate that shallow mean RWL may provide better protection against degradation for deeper peat, however shallow RWL may not provide this protection in the near-surface evidenced by severe degradation across all sites in the surface layers. Ranges of fluctuations are also important, stable water tables are a prerequisite for accumulation of peat material in peatlands (Ingram, 1983; Clymo, 1984). Sites with greater fluctuations in RWL will have greater amounts of peat subjected to unsaturation and therefore this encourages greater degradation of the peat through both shrinkage and oxidation.

Kom_DS had the deepest water table and greatest RWL fluctuations (total range, 1.419 m) (Table 5.1), which would indicate a decreased specific yield. This is reflected by a high bulk density at 45 cm depth (0.261 ± 0.433g cm^{-3}) compared to all of the other sites (Figure 4.3) (Price & Schlotzhauer, 1999). Glover-Clark (2020) also reported this in the Moanatuatua peatland, as her Site 2 had greater bulk densities alongside greater RWL fluctuations than the other adjacent site. There also appeared to be an association with depth to the water table and stability of the overall water table regimes, for example both Kom_DS and Moa2_Dairy had unstable water table regimes, as shown in the exceedance curves (Figure 5.5). These two sites also had mean water tables depths greater than 1 metre, and relatively high fluctuations in comparison to other sites; Moa2_Dairy was also a site with a high bulk density at 45 cm depth, being 0.240 ± 0.006 g cm^{-3}. Alongside this, these two sites had the lowest porosities of all the sites at 45 cm depth. This indicates a possible association of deep mean RWLs and large RWL fluctuations, to peat soil properties that indicate greater degradation. Drainage-induced lowering increases bulk density, reduces total porosity and decreases the proportion of macropores and so there are more smaller pores, this reduces specific yields which are observed as greater fluctuations in water tables compared to intact peatlands (Whittington & Price, 2006; Holden *et al.*, 2011).

Comparisons of water table regimes through exceedance analyses via depth-duration curves appears to be a relatively new way to compare RWL regimes in drained peatlands, but has been previously used to compare water table regimes between drained, restored and intact peatlands (Holden *et al.*, 2011) (Figure 5.5). The time series plots of RWL over the entire study period are complex and this can make it difficult to tease out major differences in regimes. Depth-duration curves simplify the key features of the water table regimes and make it easier to discern differences in both wet season water table behaviour and responses to drawdown. These also illustrated that at Kom_DS and Ruk_DS RWL rose and drew down rapidly compared to the other sites, indicated by unstable depth-duration curves (Figure 5.5).

6.7 Shrinkage characteristics

The deep layer cores[7] e.g 30-40 cm, 40-50 cm had a much greater change in volume and greater water loss than the surface cores e.g 0-10 cm, 10-20 cm (Figures 4.10, 4.11, 4.12, 13, 14 and 15).

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[7] Note: Due to how shrinkage characteristics were measured, volume changes are discussed based on depth ranges the cores were taken from rather than their midpoints.

There was an association between bulk density and porosity, and volume changes upon drying. This was first shown through the deeper cores having greater volume changes than the surface cores, bulk density decreased and porosity increased with depth at all of the sites. This indicates that lower bulk density and higher porosity allows for greater changes in volume when a core is dried and this has previously been reported in the literature (Gebhardt *et al.*, 2010; Waddington *et al.*, 2010). This association was also reflected between different sites that were more degraded than others at different depths, particularly in the near surface where differences between properties were more significant (Table 4.2 and 4.4). Sites with larger bulk densities and generally smaller porosities appeared to also have smaller changes in volume upon drying. For example, Mot_Dairy, Ruk_Dairy and the two dry stock sites all had very high bulk densities and low porosities in the surface layers (5 and 15 cm) and these sites had similar changes in volume at 0-10 cm depth during the shrinkage experiment (Table 4.5). For instance, Mot_Dairy had a shrinkage percent volume change of 25.6% and Ruk_Dairy 24.8% at 0-10 cm depth. Overall, the blueberry sites generally had greater mean percent changes in volume than the agricultural sites, reflecting the fact that these sites generally were less degraded as shown by their lower bulk densities and higher porosities in the near-surface peat (Figure 4.3 and 4.5, Table 4.5). The association between shrinkage capabilities and soil properties weakened with depth, likely due to the smaller impact land management has on properties deeper in the peat profile due to increased distance from the surface.

These relationships could suggest a correlation between peat soil structure and shrinkage capability, however, laboratory experiments do not fully represent what is occurring in the field (Paivanen, 1982). This means that although relationships between peat soil physical and chemical properties and shrinkage characteristics can be found in “ideal” conditions, this relationship may be complicated by other factors introduced in the environment. It is also important to acknowledge that some of the cores may have seemed to decreased by a large amount due to unavoidable loss soil material. This was reflected by the lack of observable relationship between surface elevation changes measured at each site and the volume changes measured in the lab, which are further discussed below. However, these results could suggest that the greatest amount of shrinkage occurring could be deeper in the profile, where porosity and soil moisture are higher resulting in a higher shrinkage capabilities.

6.8 Peat surface oscillation

All of the eleven study sites displayed seasonal changes in surface elevation that were at least partially reversible (Figure 5.6), meaning that peat surface oscillation (PSO) has occurred as reversible shrinkage is its defining factor (Fritz *et al.*, 2008). The changes in surface elevation at all sites appeared to follow a similar trend to the response of the water table to changes in the water balance. The magnitudes of surface elevation changes were variable, but at all sites the decrease in surface elevation during the 2021-22 summer shrinkage period exceeded the increase in surface elevation that occurred in swell periods of both 2021 and 2022 (Table 5.2). This suggests that there is a component on irreversible shrinkage occurring as the peat shrinks during summer, which is expected due to all of these site beings drained (Teatini *et al.*, 2004; Gebhardt *et al.*, 2010). Pronger *et al.* (2014) had previously determined that the current rates of subsidence, the irreversible component of shrinkage, was occurring at a rate of 19 mm y^{-1}.

It is important to note that although the 2021 swell period was not complete, the sites were likely near their winter equilibrium surface elevation. This is because precipitation inputs between June-July 2021 and June-July 2022 were very similar (Figure 5.4 and 5.6). Another important consideration is that the 2021-2022 summer draw down period was very dry (Figures 5.1, 5.2 and 5.3), and this likely led to a large proportion of the shrinkage period being composed of irreversible shrinkage, evidenced by the mean of the two swell periods being smaller than the mean of the shrink period. For instance, the mean swell across all of the sites was 45.4 mm, whereas the mean shrinkage was -76.9 mm, a difference of 31.5 mm. This is because the strain exhibited on the peat during the summer period was so high that the rise of the water tables in the proceeding wet season likely were unable to restore pore water pressure to pre-consolidation levels (Terzaghi, 1943 *in* Kennedy & price, 2005). High temperatures during this period coupled with very low rainfall may have also resulted in such severe drying at the surface that there was the development of hydrophobic behaviour, making rewetting particularly difficult (Szajdak & Szatylowicz, 2010; Perdana *et al.*, 2018).

The 2021-2022 shrinkage period, between November 2021 and June 2022, was the period within which the greatest range in surface elevations occurred. Moa2_Dairy had an SE range during the 2021-2022 shrinkage period (-50.4 mm) that was half of the range measured at Moa_Dairy (-101.7 mm) for the same period, even though both sites are under the same land use and in the Moanatuatua peatland. However, Moa_BB (-108.2 mm) had a similar shrinkage SE range to Moa_Dairy, and Moa2_BB (-52.6 mm) a similar SE range to Moa2_Dairy. It might be assumed that differences and similarities could be influenced by location, Moa_BB and Moa_Dairy are closer together than they are to either Moa2_Dairy or Moa2_BB. However, Tor_BB and Tor_Dairy, which are within 400 m of each other, had very different SE ranges to each other. Tor_BB only reached 58% (-49.1 mm) of the range reached by Tor_Dairy during the shrinkage period (-84.0) (Table 5.2, Figure 5.6c).

Glover-Clark & Campbell (2021) reported a maximum range of peat surface movement of -122.6 mm and -84.2 mm at two dairy sites located in the Moanatuatua peatland. Two of the Moanatuatua sites measured in the present study had similar magnitudes of shrinkage, these two sites were Moa_Dairy (-101.7 mm) and Moa_BB (-108.2 mm), Moa_Dairy is expected to be similar due to being the same location as Site 1. The other two sites, Moa2_Dairy and Moa2_BB, had rather small shrinkages compared to those reported by Glover-Clark & Campbell (2021) (-50.4 mm and -52.6 mm, respectively). Ruk_BB had a similar magnitudes of shrinkage (-121.0 mm) to Site 1, and Ruk_DS and Kom_DS had similar shrinkage magnitudes to Site 2 (-81.5 mm and -84.0 mm, respectively). The other sites in the current study had much smaller shrinkages than reported by Glover-Clark & Campbell (2021), which highlights how variable PSO can be.

Fritz et al. (2008) reported a maximum magnitude of PSO of 280 mm for an intact fen peatland in the lower Waikato, which was fully reversible. None of the current study sites had a magnitude this great, nor was the surface elevation changes observed at the current study sites fully reversible (Figure 5.6, Table 5.2). The site with the greatest magnitude of surface elevation change was Ruk_BB (-121.0 mm). This magnitude is still quite large (approximately 43% of Fritz et al. 2008) but only two other sites reached a similar magnitude, Moa_Dairy (-101.7 mm) and Moa_BB (-108.2 mm) (Table 5.2). This is a direct result of drainage, which has previously been shown to reduce hydrological functioning of peatlands due to decreased compressibility related to increased bulk density and lower porosity (Glover-Clark, 2020).

The international literature has reported a large range of SE changes as a response to seasonal inputs and outputs of water (Table 2.2). Howie & Hebda (2018) measured surface elevation changes across different undisturbed, harvested and rehabilitated plant communities in a Canadian bog. The surface elevation at this bog ranged from as little as 20 mm to 340 mm across their study period. This study found that the harvested sites had greater magnitudes of SE changes due to shallower water table as the near-surface peat had been removed. None of the study sites had a shrinkage SE range that was a similar magnitude to the greatest change measured by Howie & Hebda (2018). Schothorst (1977) reported the smallest measurement of SE changes in a Netherlands drained peatland, with a range of 2-8 mm. This is substantially smaller than any of the ranges of SE measured across our study. Another study of surface elevation changes in a drained bog in Canada reported that cutover peat had a maximum of 55 mm of movement (Kennedy & Price, 2005). This magnitude of surface elevation change is similar to more of the current study sites, such as Moa2_BB, Moa2_Dairy and Tor_BB (-52.6 mm, -50.4 mm, 49.1 mm) (Table 5.2). All of these measurements of PSO in drained peatlands internationally show how variable changes in surface elevation can be.

Our data shows that PSO is highly variable between sites, even within the same peatland (Figure 5.6). Despite a relationship between land use and near-surface peat properties, this does not appear to be reflected in the magnitude of SE changes. The literature suggests that sites that had been more degraded with higher bulk density and lower porosity would have less seasonal change in surface elevation (Price & Schlotzhauer, 1999; Waddington *et al.*, 2010). The significantly higher bulk densities in the near-surface peat at our grazing sites would then suggest that the agricultural sites should have reduced PSO compared to the blueberry sites. The SE measurements do not support this, indicating that the drivers of PSO in drained peatlands are extremely complex and many different factors other than just peat physical properties influence the magnitude of PSO that occurs in a drained peatland.

There did appear to be a slight association between peat depth and SE change. For instance, in the Moanatuatua peatland, Moa_Dairy and Moa_BB had the deeper peat, 7.0 m and 6.5 m, respectively, than Moa2_BB and Moa2_Dairy, which had depths of 4.7 m and 4.4 m, respectively (Table 3.1). Moa_Dairy and Moa_BB had greater SE shrink ranges than Moa2_BB and Moa2_Dairy (Figure 5.6, Table 5.2). This same association occurred when comparing the Rukuhia peatland sites, however, Ruk_Dairy, which had a depth of 9.5 m, had a smaller SE shrink (-67.0 mm) than Tor_Dairy (-84.0 mm), which had a smaller peat depth of 6.0 m. This indicates that multiple different factors likely interact at each site to drive individual PSO regimes and the strength of interactions between factors is likely more important than the individual strengths of the factors alone.

We do not know the intra-site variability of PSO and previous studies across transects have found that variability can be quite large for both intact and drained peatlands (Fritz *et al.*, 2008). At each of the current sites, the magnitude of PSO may be very different only a few metres from the PSO site. The influences on variation in PSO within a site include distance to drains, depth of drains and the types of drains, for example border and spinner drains (Glover-Clark & Campbell, 2021). Other influences include the original typography of the former peatland, for example, areas such as humps and hollow, as well as peat thickness, can cause variation of PSO in the intact peatland (Kellner & Halldin, 2002; Fritz *et al.*, 2008).

Although there was an association between volume change upon drying during the shrinkage experiment and the physical properties of the peat, there was no such relationship to surface elevation changes. For example, Ruk_DS had consistently lower bulk density, and higher porosity and OMf than Kom_DS (Figure 4.3, 4.5 and 4.6) and had greater changes in volume and loss of water upon drying (Figure 4.11 and 4.14). Despite significant differences in soil properties and shrinkage characteristics, the two sites had remarkably similar surface elevation changes (Figure 5.6, Table 5.2). A second example is of Mot_Dairy and Tor_BB, which had very similar 2021-2022 shrinkage (-46.1 mm and 49.1 mm, respectively) and 2022 swell (25.9 mm and 20.3 mm, respectively) surface elevation ranges. Mot_Dairy had greater bulk densities and lower porosity and OMf than Tor_BB across all of the sampling depths, as well as less volume change than Tor_BB upon drying (Figure 4.3, 4.5, 4.6 and 4.12). This highlights the difficulty in determining the main factors that may have a dominant influence on PSO regimes in drained peatlands. The process occurring during the drying of peat are likely unable to be replicated in a laboratory environment due to the complexity of the relationships between different environmental factors (Paivanen, 1982).

In the literature regarding PSO in both drained and intact peatlands, the water table has been widely reported to be a major driver of seasonal PSO (Camporese *et al.*, 2006; Fritz *et al.*, 2008; Waddington *et al.*, 2010; Howie & Hebda, 2018; Morton & Heinemeyer, 2019). Howie & Hebda (2018) reported that PSO had a strong negative relationship with maximum water table depth and Morton & Heinemeyer (2019) reported that water table depth is the dominant driver of PSO, having greater influence than both vegetation type and land management. Our study results are not consistent with these observations, as we were unable to find a strong relationship between RWL and the magnitude of SE (Figure 5.6). Although RWL and SE changes followed very similar seasonal patterns, it is possible that surface soil moisture has a greater influence on PSO regimes than RWL alone. We do not have sufficient VMC data to provide any evidence for this.

Glover-Clark (2020) reported the existence of extensive capillary zones in the drained Moanatuatua peatland, which suggested that saturation could still occur relatively close to the surface despite deep water tables. We do not have sufficient data to determine the thickness or depth of capillary zones at the current stud sites. However, capillary zones and their variability across the different sites may be an important factor in PSO regimes, particularly during shrinkage. The water in saturated pores in the capillary zone are held at negative pressures through matric suction, whereas water in saturated pores below the water table are held at positive pressures (Ingram, 1983). Therefore, the physical processes occurring during shrinkage may differ both from processes occurring in the unsaturated zone (shrinkage) as well as in the peat below the water table (consolidation). Previous studies have reported that after drainage, capillary rise increases due to a shift in pore size distribution towards smaller pores and this may further complicate processes of shrink and swell (Kellner, 2003; Price *et al.*, 2003). Reversible shrinkage might occur here due to the water being held under tension. Also, we do not know how the capillary zone may (or may not) have replenished surface soil moisture lost via evaporation (Nugraha *et al.*, 2017), which could further complicate PSO regimes

The results of this large data set of SE changes across different peatlands show how PSO may complicate efforts to measure long-term subsidence in drained peatlands. PSO has previously been reported to confound measurements of ongoing subsidence due to its seasonal cycle, which makes it difficult to determine what is irreversible and what is reversible (Teatini *et al.*, 2004; Camporese *et al.*, 2006). The large variation in PSO regimes, even within the same peatland, show that cycles of PSO must be taken into account when measuring subsidence. Large differences in magnitude can lead to overestimation or underestimation of long-term subsidence across a large and varied study area. These data provide important detail that has not previously been investigated into short-term responses of surface elevations to seasonal changes in the water balance across both different peatlands and different land uses.

6.9 Summary of peat surface oscillation

All of the study sites exhibited seasonal SE changes as a response to changes in the water balance, these changes were partially reversible meaning that PSO occurred at all sites during the period of this study. There was also clear evidence of irreversible shrinkage occurring as a result of drainage. SE changes were highly variable across the different peatlands and land uses, and it was difficult to determine the main driver of PSO at each site. There did not appear to be an association with land use, peat soil physical or chemical properties or water table depths to magnitudes of SE change. Through the results of this study we believe that the factors influencing PSO in drained peatlands are more complicated compared to the drives of PSO in intact peatlands.

6.10 Time since drainage

Time since drainage is an important factor in the extent of subsidence within a peatland and this should be reflected by both peat soil physical and chemical properties (Ewing & Vepraskas, 2006; Pronger *et al.*, 2014). In this study, a relationship between measured peat properties and time since drainage was difficult to determine. This is largely because many of the sites have very similar drainage histories, making any differences likely small. Some sites that have similar drainage histories did not have similar properties either at the surface or deeper in the profile. The design of the regional PSO monitoring network also did not allow for an investigation in the effects drainage histories have on PSO regimes. This is because there was a focus on differences between land uses through paired sites, and therefore is why many of the sites have similar drainage histories because of their proximity to each other.

The oldest drained site, Moa2_Dairy did not have the greatest bulk density near the surface nor in the deepest part of the profile, this site also did not have the smallest change in SE. The youngest site, Moa2_BB likewise did not have the lowest bulk density at the surface nor at 45 cm depth and did not have the greatest change in SE across the study period. Tor_BB, one of the older sites (drained ~56 years), had the lowest bulk density at 5 cm depth but did have a rather small change in SE (-49.1 mm). Mot_Dairy had been drained for a similar amount of time to Tor_BB yet had the highest bulk density at 5, 15 and 25 cm depth (0.570 ± 0.025 g cm^{-3}, 0.395 ± 0.015 g cm^{-3}, 0.343 ± 0.014 g cm^{-3}, respectively) (Figure 4.3). Mot_Dairy had a similar change in surface elevation (-46.1mm) to Tor_BB during the 2021-2022 shrink period.

The main reason that the influence of drainage histories has on peat soil properties because of the major impact land management has on peat. Land management had a highly significant ($p<0.001$) effect on bulk density and porosity, especially for shallow peat (Table 4.2, Table 4.3). This therefore could confound any differences between sites that may be caused by differences in drainage histories.

Overall, it is difficult to determine the role of drainage histories on PSO behaviours. It is likely that land management and water depths have a more profound effect on peat physical and chemical properties as these may accelerate any effect drainage may have over time. The similarities in age between the sites and the unsuitability of the PSO network design for investigations into influences of drainage histories is also likely why there is no obvious relationship between drainage history and PSO regimes.

Chapter Seven

Conclusions and recommendations

7.1 Introduction

This study investigated the peat physical and chemical properties of eleven study sites across the Hamilton Basin, Lower Waikato and Hauraki Plains as part of a regional peatland subsidence monitoring plan. Also reported were the surface elevation changes and water table regimes that were measured at each site from 1 April 2021 to 30 July 2022. The study sites located across five different peatlands, allowed us to determine the spatial variation of peat surface oscillation (PSO). Paired sites across three different land uses were investigated in order to determine land management effects on peat soil properties and PSO. We compared patterns of PSO, relative water level (RWL) and the depth- and spatial trends in physical and chemical properties in order to try to determine the main drives of PSO in drained Waikato peatlands. This is the first study of its kind investigating high-resolution peat surface elevation changes across multiple different drained peatlands.

7.2 Main findings

7.2.1 Spatial variation of peat soil physical and chemical properties in drained peats under different land uses

There was a great amount of spatial variation in both physical and chemical properties across the eleven different study sites. All of the sites showed a strong bulk density-depth relationship, with bulk density decreasing with increasing depth. Porosity, organic matter fraction (OMf) and C/N also all increased with depth at all of the study sites.

The agricultural sites (dairy and dry stock) had greater bulk densities and lower porosities than the blueberry sites in the near-surface peat. The site with the highest bulk density at 5 cm depth was Mot_Dairy, whilst the site with the lowest at this same depth was the blueberry site Tor_BB. There was less of a difference in these properties between land uses deeper in the peat, and this indicates that land management has a major effect on peat properties near the surface. The agricultural sites had higher bulk densities and lower porosities than the blueberry sites due to compaction, which is caused by stock treading, heavy vehicle use and, likely, the frequency of cultivation for pasture renewal and lime incorporation. The blueberry sites are not affected by stock trampling and vehicle use is restricted to only a few times a year, therefore less compaction has occurred at these sites. All of the sites have undergone both shrinkage and compaction caused by drainage, evidenced by bulk densities that are much higher, even deeper in the peat profile, than what is reported for intact bogs in New Zealand (Lambie & Ratcliffe, 2020). Porosities and OMf are also much lower than what is reported in intact peatlands such as Kopuatai.

Both C/N and OM increased with depth at all of the sites, with both properties being lower than average values reported for New Zealand bogs (Sorrell & Gerbeaux, 2004). These two chemical properties were reduced in the near-surface peat due to oxidation as a direct result of drainage. This is because in the near-surface peat there is a greater ability for oxygen to enter peat soil pores and rates of aerobic decomposition increase (Kellner, 2003; Leifeld *et al.*, 2020). Oxidation favours carbon over nitrogen and therefore as organic matter is consumed, enrichment of nitrogen in the top soil occurs (Säurich *et al.*, 2019). This also occurs at the near surface due to effect of use of nitrogen based fertilisers, which were likely used at all of the land uses, hence why C/N was reduced in the near-surface peat. OMf increased with depth likely due to increased proximity to the water table, which could mean greater proportions of pores are water-filled, preventing aeration and therefore slowing oxidation rates.

The results of this investigation into physical and chemical properties are in agreement with other studies on drained peatlands in New Zealand (McLay *et al.*, 1992; Glover-Clark, 2020), but compared to international studies there is an indication that the current study sites are less degraded (Schwärzel *et al.*, 2002; Kechavarzi *et al.*, 2010; Mustamo *et al.*, 2016). This is likely because internationally, and particularly in places in Europe such as the Netherlands, peats have been drained for much longer than the current study sites have. Also many international studies had a focus on fen peats, which have higher mineral contents, naturally higher bulk densities and have a greater susceptibility to degradation (Sorrell & Gerbeaux, 2004).

Time since drainage did not appear to have a strong association with peat soil physical or chemical properties. This is likely because land management has a strong influence on near surface properties and because many of the sites have similar drainage histories, making determination of its influence on properties difficult.

7.2.2 Spatial variability of water table regimes

At all of the study sites, RWL followed seasonal changes due to changes water inputs and outputs. There was considerable spatial variation in mean annual RWL depths and ranges, even between sites that were separated by short distances such as Tor_BB and Tor_Dairy. Depth duration curves were used to simplify key characteristics of the water table regimes across the sites, these highlighted that at Kom_DS and Ruk_DS the RWL did not sit at intermediate levels for long period compared to the rest of the sites.

In the deeper peat, there was an association between higher bulk density, lower porosity and large ranges of RWL, whereas in the near-surface peat there was no such association. This could suggest that sites with large fluctuations in RWL and corresponding high bulk densities in the deeper peat have reduced specific yields. The association between deep peat properties and fluctuations with RWL could also suggest that sites with smaller fluctuations in RWL and shallow mean annual RWL have greater protection against shrinkage and oxidation, resulting in lower bulk density and higher porosity at depth.

7.2.3 Drivers of spatial variability of peat surface oscillation in drained peatlands

All of the study sites exhibited peat surface oscillation (PSO), because they showed partially-reversible seasonal trends in surface elevation change. The surface elevation changes followed seasonal changes to water inputs and outputs, the surface decreased as the water deficit developed during the dry period (November 2021 to mid-May 2022), and rose as water inputs increased at the start of the wet season (mid-June to July 2021 and 2022).

The aim of this research was to determine both the spatial variation and drivers of PSO regimes in drained peatlands at a regional scale. This aim was partially fulfilled, as the network of monitoring sites revealed a large variation in magnitudes of PSO but that all of the sites generally followed the same seasonal trend. The drivers of PSO in drained peatlands were much more difficult to determine, it did not appear that land management had a greater influence on magnitudes of PSO. This is because both the agricultural sites and the blueberry sites exhibited large and small surface elevation changes. For example, Ruk_BB had a very large change in surface elevation during the shrinkage period (-121.0 mm), but Tor_BB had very little change in surface elevation for the same period (-49.1 mm). Moa_Dairy also had a rather large change in surface elevation during the shrink period (-101.7 mm) but Mot_Dairy had the smallest change in surface elevation for the same period (-46.1 mm). This indicates that land management is not a major driver in determining differences in magnitudes of PSO despite having an impact of near surface peat properties.

The water table has been reported in the literature to be a major drive of PSO; however, the results of this study do not support this. Although the largest surface elevation changes appeared to occur at sites that also had the largest range of RWL, this did not occur at all of the sites. We suggest that soil moisture content may be the proximal driver of PSO in drained peatlands, but we do not have enough data to determine this. Glover-Clark (2020) reported deep capillary zones in two dairy sites in the Moanatuatua peatland, which they suggested could indicate that soil moisture could be high near the surface despite increased depth of the water table. We do not know the depths of the capillary fringe nor how it may vary on a temporal basis; therefore, we are unable to determine the influence the capillary fringe may have on changes to surface elevation. It is unknown where in the profile reversible shrinkages is occurring during seasonal PSO, but the results of the shrinkage experiments suggest that it likely is occurring primarily in the deeper peat layers.

There was evidence from the surface elevation measurements that irreversible subsidence was occurring at all of the sites when we compared the 2021 and 2022 swell periods. There was a mean difference of 31.5 mm between the mean shrink and total mean swell across all of the study sites. The 2022 swell period was incomplete so this observation is tentative, as we do not know if we have captured the 2022 winter maximum.

These results showed that PSO regimes in drained peatlands are highly variable at a regional scale and compared to drained peatlands, determination of the main drivers of PSO is difficult. The lack of overlying trends across the study sites indicates that interactions of different factors are complex and differ substantially from site to site.

7.3 Implications for land management

The results of this study show that land management has an influence on the peat physical and chemical properties but it is largely restricted to the near-surface peat. The implication for this is that the peat at the surface of the agricultural sites may degrade at an accelerated rate in comparison to the blueberry sites and hence mitigation strategies to slow this degradation are recommended. The main mitigation strategy for reducing compaction is through reducing the loads on top of the peat surface. This would require removing stocks from paddocks to herd homes and a shift to a cut and carry system. This likely would be very expensive and there would likely be a hesitancy towards moving to this sort of system. It is important to note that compaction and shrinkage occur together and cannot be measured separately, shrinkage may still occur despite decreased loads due to the collapse of previously water-filled pore spaces (Hooijer *et al.*, 2012). Oxidation may also continue to be ongoing, leading to a loss of the peat substrate and long-term subsidence despite efforts to reduce land management impacts.

Although agricultural sites show greater degradation, blueberry orchards still cause negative changes to peatland functioning. Blueberry orchards still require relatively dry conditions compared to the natural state of the peatland and drainage is required for this. Drainage comes with the cost of a loss of peatland function and subsidence, which will eventually lead to a complete loss of the peat organic substrate through oxidation (Pronger *et al.*, 2014). Raising the water table has previously been reported to be effective for reducing further degradation of peat (Holden *et al.*, 2004; Young *et al.*, 2017). Rewetting of peatlands through raising the water table could reduce aeration and reduce the area of the peat profile that is periodically unsaturated due to seasonal changes in water inputs. This is important because this could reduce the amount of pores that are drained and prevent aeration from occurring. Keeping as much of the peat profile saturated as possible could help to safeguard against further oxidative losses deeper in the profile.

Avoiding deepening of drains and reducing frequency of drain cleaning can help safe guard against further lowering of the water table (Environment Waikato, 2006). Raising water tables can be achieved through drain blocking and water table levels monitored so that farming can still occur whilst keeping water tables shallow enough to protect peat. This is not a perfect solution, as subsidence will continue at slower rates and flooding will become more of an issue in the future. Already frequent flooding has become more common in places such as the Netherlands, which require large pump drainage schemes to avoid severe flooding due to large parts of the land being below sea level because of subsidence (Joosten *et al.*, 2012). It may be a particularly large issue in the Hauraki Plains due to these areas being close to sea level and being affected by sea level rise. As subsidence continues, more areas of the Hauraki Plains will be prone to flooding and become unsuitable for traditional agriculture or horticultural use (McLeod *et al.*, 2004).

A new option for reducing impacts of peat drainage but still keeping peatlands as economically viable land is through paludiculture. The research surrounding paludiculture is very limited and it may not be enough to protect peatlands against ongoing damage. It may not be possible in New Zealand due to the nature of the environmental conditions of the peatlands found here. The current European research regarding paludiculture has an emphasis on fens and swamps providing conditions for growing reeds and grasses for use as textiles and construction materials (Wichtmann & Joosten, 2007; Parish *et al.*, 2008; Tanneberger *et al.*, 2022), in this study the majort of the sites were previously rain-fed bogs. There needs to be more research into the possibility of paludiculture in New Zealand peatland environments and it may be that it is not economically valuable. Much of the drained peatlands in the Waikato is under dairy farming, which poses challenges to replace at scale with something like paludiculture that likely will not produce food sources.

The best solution for protecting the remaining peat in these drained peatlands is the complete rehabilitation of peatland plants after restoring water table levels. Restoring peatland vegetation alongside complete rewetting may allow for accumulation to occur again (Joosten *et al.*, 2012). It is important that before restoration begins, there is sufficient knowledge to produce a successful result (Holden *et al.*, 2004). This knowledge includes seasonal hydrological and PSO regimes and the current peat soil physical and chemical properties alongside knowledge of the prior environmental conditions. Holden et al. (2004) acknowledged that the environmental conditions of the present day are very different to the conditions in which peatlands formed. This is something that needs to be considered when restoring peatlands, as with a changing climate it may not be easy to restore the ecosystem functions of drained peatlands.

Howie & Hebda (2018) previously reported on the effect restoration of water tables may have on PSO regimes. They concluded that for PSO to be restored to magnitudes seen in intact peatlands, rewetting must occur quickly after drainage otherwise PSO would not recover. It may be that even after rewetting this hydrological behaviour may not be restored. All of the study sites indicated reduced magnitudes of PSO in comparison to intact peatlands, with only three of the eleven study sites reaching half of the surface elevation change that was reported by Frit *et al.* (2008). Due to the long time frames since initial drainage, it is highly likely that reduced PSO is permanent, highlighting how important it is to protect what remains of this self-regulatory behaviour. Overall, protecting intact peatlands, such as Kopuatai bog against drainage and development is currently the most productive way to mitigate future environmental issues.

7.4 Implications for future monitoring of drained peatlands

Continued monitoring of the current sites in the regional monitoring network will further develop understanding of how PSO overlays ongoing subsidence. This will help in determining the best seasonal timing for Lidar flights, which will help improve estimates of ongoing rates of subsidence through providing data for when the peat surface is at regionally-stable levels. This will help to remove any distortion that PSO has on subsidence estimates and the aerial Lidar surveys will provide more useful information regarding rates of shrinkage between land uses.

The large variation in PSO regimes across the different sites even within the same peatland suggests that it is difficult to accurately estimate PSO regimes from singular peatland measurements. This means that if future accurate monitoring of peatlands is required, simply estimating PSO or subsidence from previous data may provide widely inaccurate results. It is important to consider that we do not know the intra-site variability, so PSO may be very different even within the same site, particularly if close to areas with drains. PSO regimes closely followed the RWL regimes at each site, increasing RWL monitoring sites would be particularly useful as RWL can be measured much more accurately than measurements of surface elevation for PSO. This could help provide useful information for subsidence monitoring, as well as for purposes of greenhouse gas inventory work. Installing more RWL monitoring sites likely would also be of more use at farm-scale.

The mean annual RWL (water table depths) for all the current study sites were much deeper than 0.3 m below the surface. This means that, according to the IPCC 2013 Wetland Supplement, all of the current study sites fall under deeply-drained classification, therefore this will affect any future methodologies regarding emission factors from drained peatlands (Hiraishi *et al.*, 2014). Currently the agricultural sector in New Zealand follows the 2006 IPCC guidelines, which does not need measurements of water table depth. If New Zealand wants to move to using more higher-tier and New Zealand-specific emission factors there will be a requirements for drastically improved understanding of water table regimes nation-wide.

7.5 Future research

One of the objectives of this study was to determine the influence time since drainage had on peat soil properties and magnitudes of PSO but the current monitoring network design did not allow for detection of this factors influence. This due to both a lack of accurate knowledge regarding histories of specific sites, as well as a similarity in drainage histories between the study sites. The strong influence of land management, particularly in the near surface peat, likely overshadows any influence time since drainage may have had on peat soil properties and PSO regimes. A suggestion for future research is an investigation of the effect of time since drainage by comparing sites within the same peatland and under the same land uses in order to minimise confounding variables. This could be done at Moanatuatua peatland because drainage dates are reasonably well-established and there are many possible sites with different drainage histories but under the same land use.

There are two major questions that have arisen as the result of this study. The first of these is that it is unknown exactly where in the peat profile shrinkage occurs. It would be beneficial for future work to include investigations into where in the profile the greatest amount of shrinkage occurs in drained peatlands. This would provide further information on what is driving PSO in drained peatlands. The second question is how the capillary fringe influences PSO There may have been a large variation is depths and thickness of the capillary fringes between the different sites, which would have also been temporally variable. The capillary fringe is a zone where pores are saturated despite being above the water table and therefore being held under suction (Ingram, 1983). Shrinkage processes in this zone may differ from consolidation occurring below the water table and shrinkage occurring in the unsaturated zone above the water table. Determining depths of capillary fringes at different sites, alongside investigating where in the profile that the majority of shrinkage occurs would provide better information to further understand differences in PSO across drained peatland sites. This knowledge may also help explain how PSO differs in drained peatlands compared to intact peatlands and is important for future restoration measures.

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Appendix A

A.1 Physical properties statistics

Note: the depths reported in the tables are the midpoint of the sampling depths e.g. 5 cm for a sampling depth of 0-10 cm.

Table A.1 Statistics for bulk density (g cm^{-3}) at each depth at the dairy sites (max = maximum, min = minimum, SE = standard error, n = sample size)

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_Dairy	5	0.365	0.387	0.335	0.006	9
	15	0.302	0.326	0.271	0.007	9
	25	0.217	0.255	0.194	0.007	9
	35	0.183	0.251	0.142	0.014	8
	45	0.141	0.195	0.118	0.009	8
Moa2_Dairy	5	0.433	0.486	0.400	0.009	9
	15	0.347	0.418	0.256	0.018	9
	25	0.298	0.320	0.279	0.005	9
	35	0.212	0.317	0.153	0.017	9
	45	0.240	0.320	0.177	0.025	5
Tor_Dairy	5	0.385	0.429	0.347	0.011	8
	15	0.252	0.372	0.186	0.022	9
	25	0.154	0.176	0.134	0.006	8
	35	0.139	0.187	0.116	0.009	8
	45	0.115	0.146	0.097	0.005	9
Ruk_Dairy	5	0.485	0.511	0.438	0.008	9
	15	0.366	0.431	0.284	0.020	9
	25	0.238	0.312	0.188	0.014	9
	35	0.157	0.180	0.129	0.007	8
	45	0.141	0.153	0.135	0.002	9
Mot_Dairy	5	0.570	0.684	0.474	0.025	9
	15	0.395	0.462	0.349	0.015	9
	25	0.343	0.406	0.278	0.014	9
	35	0.210	0.260	0.169	0.011	9
	45	0.173	0.202	0.136	0.008	9

Table A.2 Statistical values for bulk density (g cm^{-3}) at each depth at the dry stock sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Ruk_DS	5	0.418	0.447	0.399	0.005	9
	15	0.354	0.367	0.335	0.004	9
	25	0.253	0.299	0.210	0.009	9
	35	0.169	0.190	0.151	0.004	8
	45	0.137	0.148	0.125	0.003	9
Kom_DS	5	0.450	0.475	0.434	0.006	8
	15	0.376	0.433	0.344	0.010	8
	25	0.290	0.323	0.250	0.008	8
	35	0.249	0.265	0.228	0.005	7
	45	0.261	0.296	0.244	0.007	7

Table A.3 Statistics for bulk density (g cm^{-3}) at each depth at the blueberry sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_BB	5	0.357	0.387	0.344	0.006	8
	15	0.227	0.261	0.212	0.006	8
	25	0.145	0.160	0.132	0.004	9
	35	0.157	0.170	0.142	0.003	9
	45	0.125	0.133	0.112	0.003	8
Moa2_BB	5	0.289	0.309	0.260	0.007	9
	15	0.260	0.292	0.231	0.007	9
	25	0.236	0.264	0.198	0.009	8
	35	0.201	0.245	0.162	0.011	7
	45	0.157	0.178	0.124	0.006	9
Tor_BB	5	0.267	0.300	0.219	0.010	9
	15	0.261	0.318	0.210	0.013	9
	25	0.220	0.252	0.172	0.009	9
	35	0.202	0.270	0.151	0.018	9
	45	0.166	0.274	0.126	0.019	8
Ruk_BB	5	0.332	0.348	0.321	0.003	8
	15	0.273	0.336	0.225	0.014	9
	25	0.156	0.184	0.137	0.006	9
	35	0.126	0.138	0.116	0.003	9
	45	0.110	0.116	0.105	0.001	9

Table A.4 Statistics for VMC (%) at each depth at the dairy sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_Dairy	5	70.71	72.95	66.86	0.727	9
	15	61.92	71.21	52.10	2.285	9
	25	66.68	75.89	60.70	1.487	9
	35	81.31	87.46	72.05	1.516	9
	45	84.10	90.50	76.46	1.532	8
Moa2_Dairy	5	64.04	66.99	60.27	0.913	9
	15	50.72	59.99	35.19	2.722	9
	25	51.04	66.76	40.51	3.590	9
	35	55.27	80.63	33.73	5.744	9
	45	55.41	66.61	41.96	4.405	5
Tor_Dairy	5	65.24	69.58	60.80	1.122	8
	15	62.07	70.61	50.11	2.685	9
	25	74.80	82.05	6840	1.742	9
	35	84.52	85.85	83.25	0.410	7
	45	85.42	90.75	82.67	1.012	9
Ruk_Dairy	5	61.78	67.54	54.96	1.190	9
	15	46.64	50.78	42.68	0.960	9
	25	48.49	67.52	34.65	3.821	9
	35	67.65	76.61	60.12	1.719	8
	45	81.96	86.60	76.33	1.388	8
Mot_Dairy	5	23.12	26.39	20.66	0.688	9
	15	29.20	36.23	24.63	1.437	9
	25	38.83	46.32	28.63	2.432	9
	35	51.14	55.27	45.06	1.037	9
	45	63.02	68.82	53.59	1.751	9

Table A.5 Statistics for VMC (%) at each depth at the dry stock sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Ruk_DS	5	64.10	67.07	62.16	0.553	8
	15	51.05	52.58	49.16	0.360	8
	25	50.79	63.05	43.26	2.171	9
	35	65.69	74.99	51.27	3.166	9
	45	81.87	87.72	75.99	1.367	8
Kom_DS	5	56.67	61.07	54.31	0.855	8
	15	47.40	55.63	43.46	1.441	8
	25	41.81	47.09	38.17	1.106	8
	35	50.37	63.38	38.86	2.689	8
	45	63.94	79.62	56.97	2.728	8

Table A.6 Statistics values for VMC (%) at each depth at the blueberry sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_BB	5	66.59	72.51	61.43	1.263	9
	15	57.91	63.93	54.14	1.173	9
	25	79.75	85.55	75.06	1.250	8
	35	81.90	85.01	77.64	0.717	9
	45	84.13	86.38	82.49	0.460	8
Moa2_BB	5	35.69	39.74	29.17	1.053	9
	15	38.26	46.31	35.36	1.275	8
	25	51.74	66.39	41.14	3.574	8
	35	65.47	66.95	62.89	0.772	5
	45	70.97	76.64	65.66	1.247	9
Tor_BB	5	44.61	58.76	32.49	2.936	9
	15	49.54	59.48	38.91	2.721	9
	25	52.86	73.80	34.77	4.517	9
	35	64.61	73.00	54.72	2.315	9
	45	70.95	79.84	53.58	3.185	8
Ruk_BB	5	57.64	72.05	39.10	3.869	9
	15	56.46	64.00	47.35	2.076	9
	25	76.39	88.79	60.45	4.070	8
	35	81.23	85.84	77.75	0.871	8
	45	87.03	89.54	84.33	0.675	9

Table A.7 Statistics for porosity (%) for each depth at the dairy sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_Dairy	5	76.43	78.38	75.02	0.416	9
	15	80.49	82.52	78.99	0.457	9
	25	86.02	87.46	83.53	0.434	9
	35	88.20	90.84	83.78	0.854	9
	45	90.91	92.42	87.39	0.599	8
Moa2_Dairy	5	72.05	74.22	68.63	0.558	9
	15	77.12	83.51	73.03	1.043	9
	25	80.82	82.03	79.36	0.324	9
	35	86.29	90.10	79.545	1.072	9
	45	84.52	88.56	79.36	1.609	5
Tor_Dairy	5	75.15	77.62	72.31	0.700	8
	15	82.64	87.98	76.00	1.519	9
	25	90.05	91.32	88.64	0.377	8
	35	91.05	92.51	87.912	0.602	8
	45	92.59	93.75	90.57	0.341	9
Ruk_Dairy	5	68.69	71.73	67.02	0.492	9
	15	76.37	81.68	72.17	1.280	9
	25	84.64	87.85	79.85	0.895	9
	35	89.87	91.65	88.42	0.427	8
	45	90.89	91.30	90.12	0.142	9
Mot_Dairy	5	63.21	69.41	55.85	1.610	9
	15	74.50	77.48	70.17	0.970	9
	25	77.88	82.09	73.80	0.876	9
	35	86.89	89.11	84.62	0.555	9
	45	88.85	91.20	86.98	0.519	9

Table A.8 Statistics for porosity (%) at each depth at the dry stock sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Ruk_DS	5	73.03	74.26	71.17	0.312	9
	15	77.13	78.39	76.32	0.288	8
	25	83.66	86.48	80.71	0.579	9
	35	89.13	90.25	87.73	0.256	8
	45	91.14	91.95	90.43	0.169	9
Kom_DS	5	70.75	71.99	69.37	0.403	8
	15	75.71	77.80	72.07	0.660	8
	25	81.26	83.90	79.19	0.501	8
	35	83.95	85.30	82.93	0.297	7
	45	83.14	84.24	80.92	0.433	7

Table A.9 Statistical values for porosity (%) at each depth at the blueberry sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_BB	5	74.50	75.39	73.91	0.174	7
	15	82.51	83.14	80.95	0.277	8
	25	86.76	87.62	86.08	0.192	8
	35	87.01	89.02	86.08	0.302	9
	45	88.42	89.56	86.71	0.303	8
Moa2_BB	5	81.35	83.24	80.08	0.424	9
	15	83.24	85.13	81.14	0.432	9
	25	84.78	87.22	82.95	0.561	8
	35	87.05	89.57	84.23	0.727	7
	45	89.85	91.98	88.50	0.400	9
Tor_BB	5	82.80	85.90	80.62	0.643	9
	15	83.15	86.46	79.46	0.839	9
	25	85.84	88.93	83.71	0.666	8
	35	87.00	90.26	82.58	1.141	9
	45	89.28	91.86	82.33	1.245	8
Ruk_BB	5	78.60	79.29	77.55	0.209	8
	15	82.40	85.49	78.30	0.911	9
	25	89.95	91.14	88.10	0.390	9
	35	91.87	92.52	91.09	0.165	9
	45	92.91	93.24	92.51	0.091	9

A.2 Chemical property statistics

Table A.10 Statistics for OM (%) at each depth at the dairy sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_Dairy	5	87.03	90.08	85.04	0.706	8
	15	90.84	94.53	87.27	0.878	8
	25	89.01	97.80	74.64	3.417	8
	35	76.30	94.87	48.08	7.074	8
	45	80.69	93.69	49.13	7.534	7
Moa2_Dairy	5	83.04	85.84	80.39	0.669	8
	15	84.50	89.64	75.08	1.611	8
	25	80.44	95.52	54.32	4.611	8
	35	87.27	95.75	67.64	3.331	8
	45	89.98	94.70	86.49	1.884	4
Tor_Dairy	5	78.22	84.26	72.18	1.916	6
	15	86.75	93.70	79.75	1.739	8
	25	82.94	95.33	69.11	3.269	8
	35	85.87	96.41	55.91	6.578	7
	45	95.56	96.43	94.12	0.278	8
Ruk_Dairy	5	74.91	80.06	67.39	1.599	8
	15	79.14	91.61	59.08	3.571	8
	25	88.35	95.37	75.20	2.752	8
	35	93.51	95.92	90.81	0.786	7
	45	92.53	95.46	85.30	1.342	8
Mot_Dairy	5	57.20	67.58	43.09	3.563	8
	15	67.02	74.42	59.68	2.132	7
	25	63.25	80.53	40.87	4.976	8
	35	81.22	88.60	70.63	2.163	8
	45	83.25	84.98	80.39	0.771	6

Table A.11 Statistics for OM (%) at each depth at the dry stock sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Ruk_DS	5	85.88	87.30	84.32	0.430	7
	15	86.91	90.34	85.57	0.659	7
	25	86.31	89.77	79.33	1.545	6
	35	93.85	96.62	91.21	0.877	6
	45	93.30	96.87	87.68	1.324	7
Kom_DS	5	76.27	77.52	74.96	0.332	7
	15	76.61	78.13	75.20	0.383	7
	25	84.35	89.40	80.74	1.163	7
	35	85.58	89.00	80.55	1.504	6
	45	61.12	67.25	49.30	2.912	6

Table A.12 Statistics for OM (%) at each depth at the blueberry sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_BB	5	89.15	96.63	83.24	1.656	8
	15	93.92	96.23	86.72	1.203	8
	25	93.60	97.43	87.27	1.493	8
	35	69.45	87.61	41.79	5.715	8
	45	81.08	94.07	62.23	3.860	8
Moa2_BB	5	84.21	85.70	81.73	0.629	7
	15	84.10	90.15	75.05	1.733	8
	25	87.92	91.50	83.58	1.520	6
	35	92.25	96.44	86.39	1.799	6
	45	94.31	96.44	92.29	0.652	8
Tor_BB	5	90.15	94.30	85.37	1.314	7
	15	91.07	94.80	86.00	1.140	8
	25	90.34	96.06	76.82	2.474	8
	35	95.26	97.81	90.47	1.056	8
	45	94.11	96.42	90.59	0.745	8
Ruk_BB	5	88.77	89.65	87.90	0.294	7
	15	75.82	93.75	61.11	4.050	8
	25	95.56	98.51	94.04	0.559	7
	35	92.44	95.35	87.60	0.852	8
	45	97.36	97.86	96.50	0.165	7

Table A.13 Statistics for CN for each depth at the dairy sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_Dairy	5	22.18	26.16	17.42	2.550	3
	15	24.49	29.05	17.45	3.569	3
	25	35.63	37.13	34.60	0.768	3
	35	37.12	39.11	34.86	1.234	3
	45	37.79	40.93	33.80	2.101	3
Moa2_Dairy	5	22.28	24.40	19.40	1.490	3
	15	24.71	26.49	23.76	0.893	3
	25	31.14	32.97	29.35	1.045	3
	35	33.83	36.09	30.08	1.886	3
	45	33.36	34.44	32.28	1.082	2
Tor_Dairy	5	27.86	34.63	20.09	4.226	3
	15	36.03	39.16	32.97	1.786	3
	25	41.09	44.27	39.31	1.597	3
	35	37.94	39.00	36.51	0.742	3
	45	37.75	40.43	33.63	2.088	3
Ruk_Dairy	5	19.11	20.79	17.66	0.913	3
	15	32.80	40.91	25.78	4.402	3
	25	38.45	38.61	38.28	0.166	2
	35	35.89	41.51	30.42	3.202	3
	45	36.29	39.99	29.42	3.436	3
Mot_Dairy	5	18.60	19.19	17.92	0.368	3
	15	31.29	34.87	24.95	3.178	3
	25	31.48	36.75	27.71	2.715	3
	35	37.24	39.21	33.67	1.791	3
	45	39.90	43.79	32.82	3.545	3

Table A.14 Statistics for CN for each depth at the dry stock sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Ruk_DS	5	23.27	24.56	22.57	0.643	3
	15	23.39	27.43	22.69	0.588	3
	25	33.95	35.92	31.18	1.429	3
	35	36.71	38.52	33.73	1.499	3
	45	40.50	41.55	39.11	0.725	3
Kom_DS	5	21.35	21.94	20.76	0.591	2
	15	22.86	23.63	22.09	0.774	2
	25	28.57	29.02	28.13	0.446	2
	35	27.61	28.59	26.63	0.979	2
	45	26.01	26.26	25.76	0.247	2

Table A.15 Statistics for CN for each depth at the blueberry sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_BB	5	25.71	30.07	22.73	2.226	3
	15	29.54	37.97	29.54	11.327	3
	25	36.12	38.11	33.87	19.557	3
	35	35.24	36.55	33.89	19.564	3
	45	39.57	42.45	35.24	2.205	3
Moa2_BB	5	27.00	28.23	24.75	1.130	3
	15	31.16	33.90	29.36	1.391	3
	25	30.59	32.72	27.65	1.517	3
	35	36.49	40.79	31.63	2.660	3
	45	37.37	39.26	36.20	0.954	3
Tor_BB	5	27.38	29.08	24.90	1.268	3
	15	29.14	30.75	27.75	0.872	3
	25	30.30	32.69	28.75	1.214	3
	35	43.59	57.98	35.21	7.225	3
	45	46.49	58.89	35.14	6.877	3
Ruk_BB	5	23.38	25.14	20.64	1.388	3
	15	32.80	40.91	25.78	4.402	3
	25	36.59	37.80	35.16	0.768	3
	35	37.36	41.43	34.95	2.043	3
	45	41.34	43.83	39.21	1.345	3

Table A.16 Statistics for pH at each sample depth at the dairy sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_Dairy	5	6.28	6.80	5.96	0.260	3
	15	5.37	5.43	5.31	0.036	3
	25	5.14	5.17	5.12	0.016	3
	35	4.67	4.70	4.61	0.027	3
	45	4.44	4.47	4.40	0.021	3
Moa2_Dairy	5	5.73	6.06	5.47	0.075	9
	15	5.65	6.25	5.14	0.148	9
	25	4.72	4.93	4.55	0.056	9
	35	4.24	4.56	4.02	0.078	9
	45	4.27	4.53	4.06	0.083	6
Tor_Dairy	5	5.97	7.27	5.12	0.290	9
	15	4.52	5.07	4.25	0.100	9
	25	4.22	4.32	4.13	0.022	9
	35	4.20	4.25	4.13	0.015	9
	45	4.30	4.40	4.23	0.017	9
Ruk_Dairy	5	6.53	6.96	5.57	0.162	9
	15	5.70	6.59	4.72	0.240	9
	25	4.55	4.77	4.37	0.052	9
	35	4.26	4.26	4.20	0.025	9
	45	4.23	4.23	4.13	0.026	9
Mot_Dairy	5	5.08	5.21	4.96	0.028	9
	15	4.50	4.91	4.00	0.116	9
	25	3.97	4.08	3.86	0.025	9
	35	3.89	4.01	3.72	0.033	9
	45	3.82	4.01	3.69	0.043	9

Table A.17 Statistics for pH at each sample depth at the dry stock sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Ruk_DS	5	5.89	6.63	5.40	0.156	9
	15	5.19	6.31	5.24	0.137	9
	25	4.75	5.00	4.53	0.065	9
	35	4.40	4.64	4.12	0.065	9
	45	4.29	4.52	4.07	0.059	9
Kom_DS	5	5.50	5.55	5.45	0.028	3
	15	5.57	5.62	5.53	0.029	3
	25	4.43	4.54	4.31	0.066	3
	35	4.31	4.35	4.29	0.022	3
	45	4.59	4.62	4.58	0.012	3

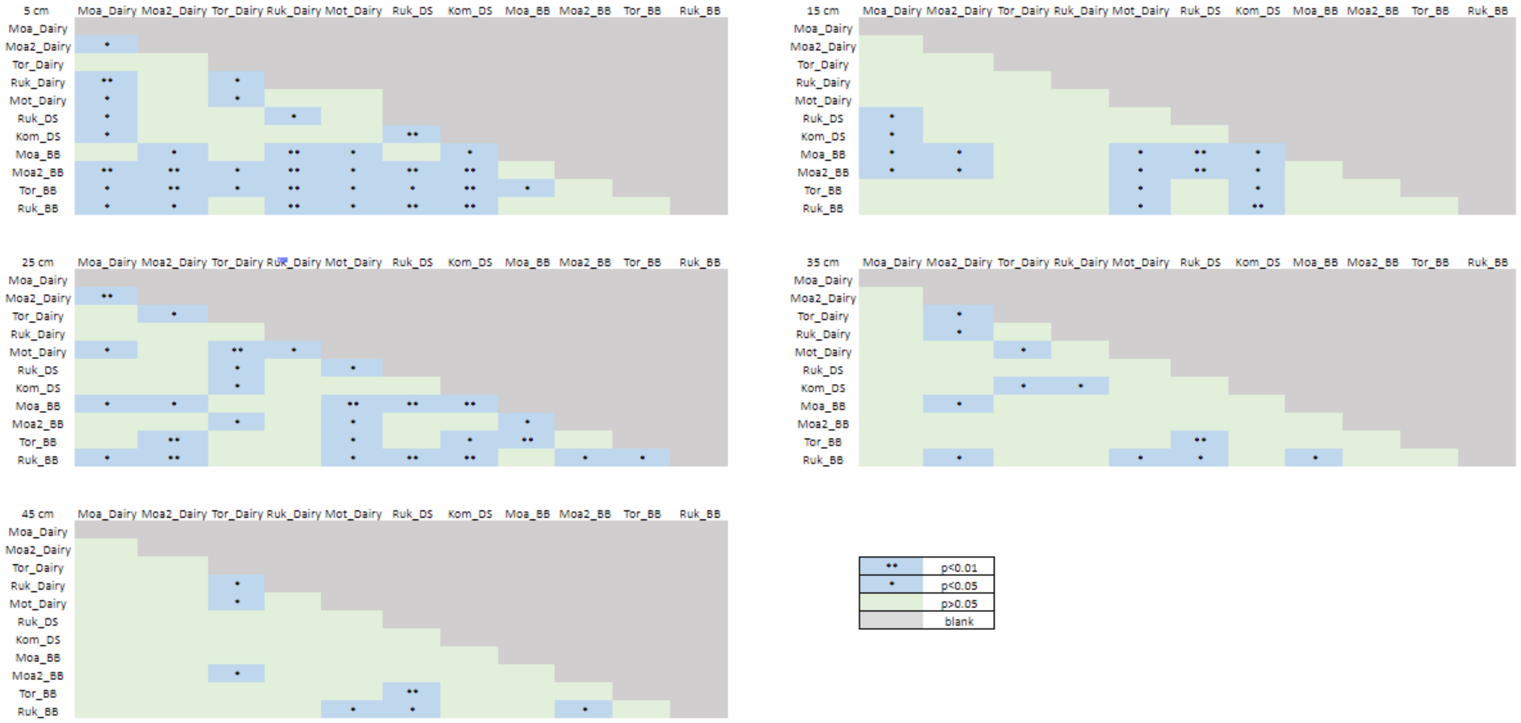
Table A.18 Statistics for pH at each sample depth at the blueberry sites

Site	Depth (cm)	Mean	Max	Min	SE	n
Moa_BB	5	4.83	5.15	4.31	0.117	9
	15	4.53	4.85	4.29	0.060	9
	25	4.53	4.55	4.28	0.034	9
	35	4.51	4.64	4.37	0.035	9
	45	4.50	4.63	4.35	0.038	9
Moa2_BB	5	4.33	4.99	4.03	0.114	9
	15	3.84	3.93	3.78	0.018	9
	25	3.68	3.79	3.49	0.037	9
	35	3.69	3.81	3.54	0.034	9
	45	3.86	4.02	3.70	0.035	9
Tor_BB	5	3.83	4.15	3.70	0.056	9
	15	3.81	3.89	3.70	0.028	9
	25	3.75	3.83	3.65	0.020	9
	35	3.75	3.79	3.66	0.014	9
	45	3.85	3.91	3.71	0.023	9
Ruk_BB	5	4.56	4.83	4.42	0.042	9
	15	4.40	4.54	4.28	0.032	9
	25	4.23	4.28	4.15	0.014	9
	35	4.27	4.38	4.19	0.021	9
	45	4.30	4.34	4.27	0.007	9

A.3 Significant tests

Significance tests of differences between sites and depths were carried out using either ANOVA or two-way, unequal variance t.tests. VMC was not investigated due to its temporal variability and the sampling strategy making it difficult to determine actual variation or variation caused by changes in rainfall. Some tests could not be performed on C/N due to lack of replicates or unmatched data.

A.3.1 Significance between sites for all physical and chemical properties



5 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy	•										
Tor_Dairy											
Ruk_Dairy	••		•								
Mot_Dairy	•		•								
Ruk_DS	•			•							
Kom_DS	•					••					
Moa_BB		•		••	•		•				
Moa2_BB	••	••	•	••	•	••	••				
Tor_BB	•	••	•	••	•	•	••	•			
Ruk_BB	•	•		••	•	••	••				

15 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS	•										
Kom_DS	•										
Moa_BB	•	•			•	••	•				
Moa2_BB	•	•			•	••	•				
Tor_BB					•		•				
Ruk_BB					•		••				

25 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy	••										
Tor_Dairy		•									
Ruk_Dairy											
Mot_Dairy	•		••	•							
Ruk_DS			•		•						
Kom_DS			•								
Moa_BB	•	•			••	••	••				
Moa2_BB			•		•			•			
Tor_BB		••			•		•	••			
Ruk_BB	•	••			•	••	••		•	•	

35 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy		•									
Ruk_Dairy		•									
Mot_Dairy			•								
Ruk_DS											
Kom_DS			•	•							
Moa_BB		•									
Moa2_BB											
Tor_BB						••					
Ruk_BB		•			•	•		•			

45 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy			•								
Mot_Dairy			•								
Ruk_DS											
Kom_DS											
Moa_BB											
Moa2_BB			•								
Tor_BB						••					
Ruk_BB					•	•			•		

••	p<0.01
•	p<0.05
🟩	p>0.05
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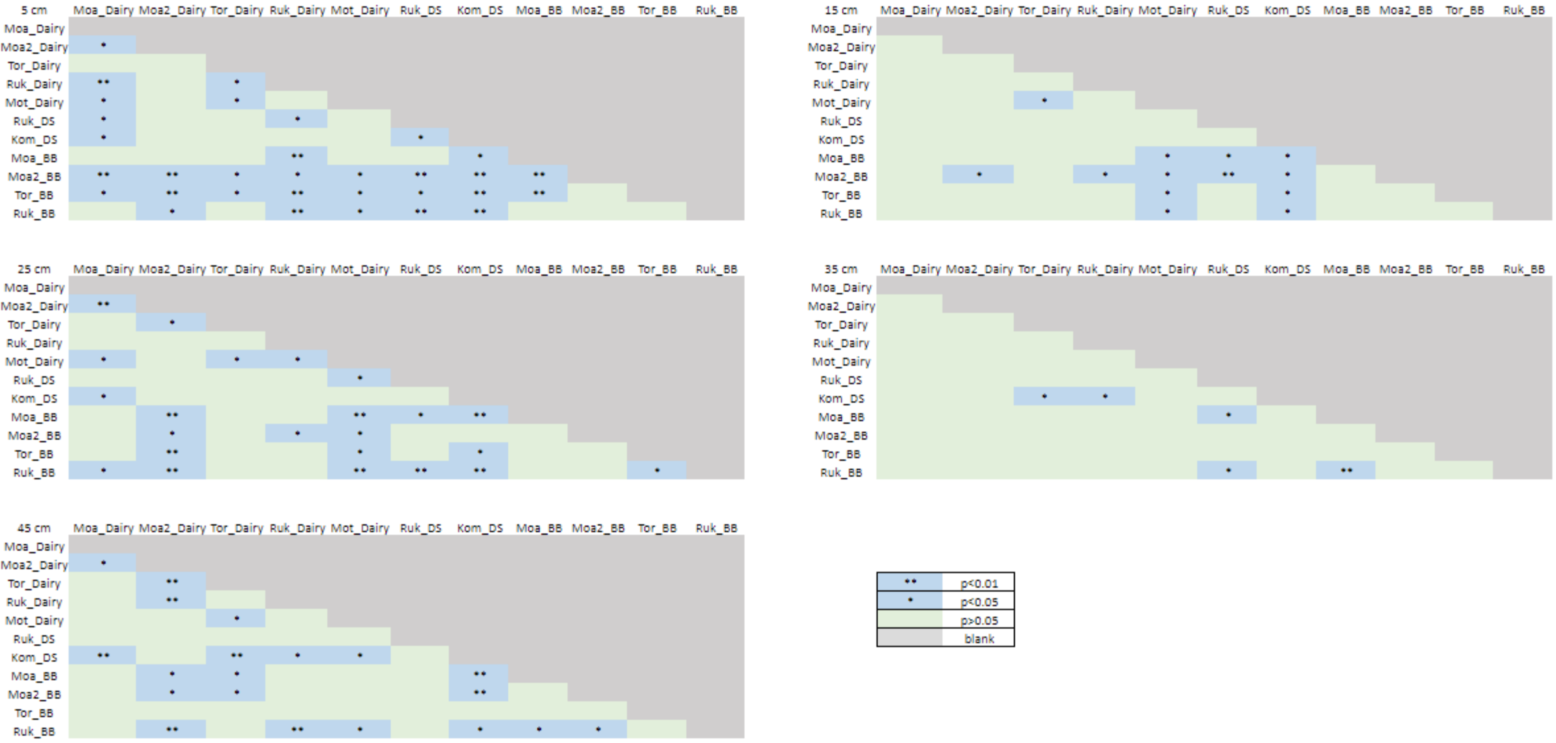
Figure A.1 Statistical significance of differences in bulk density between sites, split into depths, a) 5 cm, b) 15 cm, c) 25 cm, d) 35 cm, e) 45 cm



5 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy	*										
Tor_Dairy											
Ruk_Dairy	**		*								
Mot_Dairy	*		*								
Ruk_DS	*			*							
Kom_DS	*					*					
Moa_BB				**			*				
Moa2_BB	**	**	*	*	*	**	**	**			
Tor_BB	*	**	*	**	*	*	**	**			
Ruk_BB		*		**	*	**	**				

15 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy			*								
Ruk_DS											
Kom_DS											
Moa_BB					*	*	*				
Moa2_BB		*		*	*	**	*				
Tor_BB					*		*				
Ruk_BB					*		*				

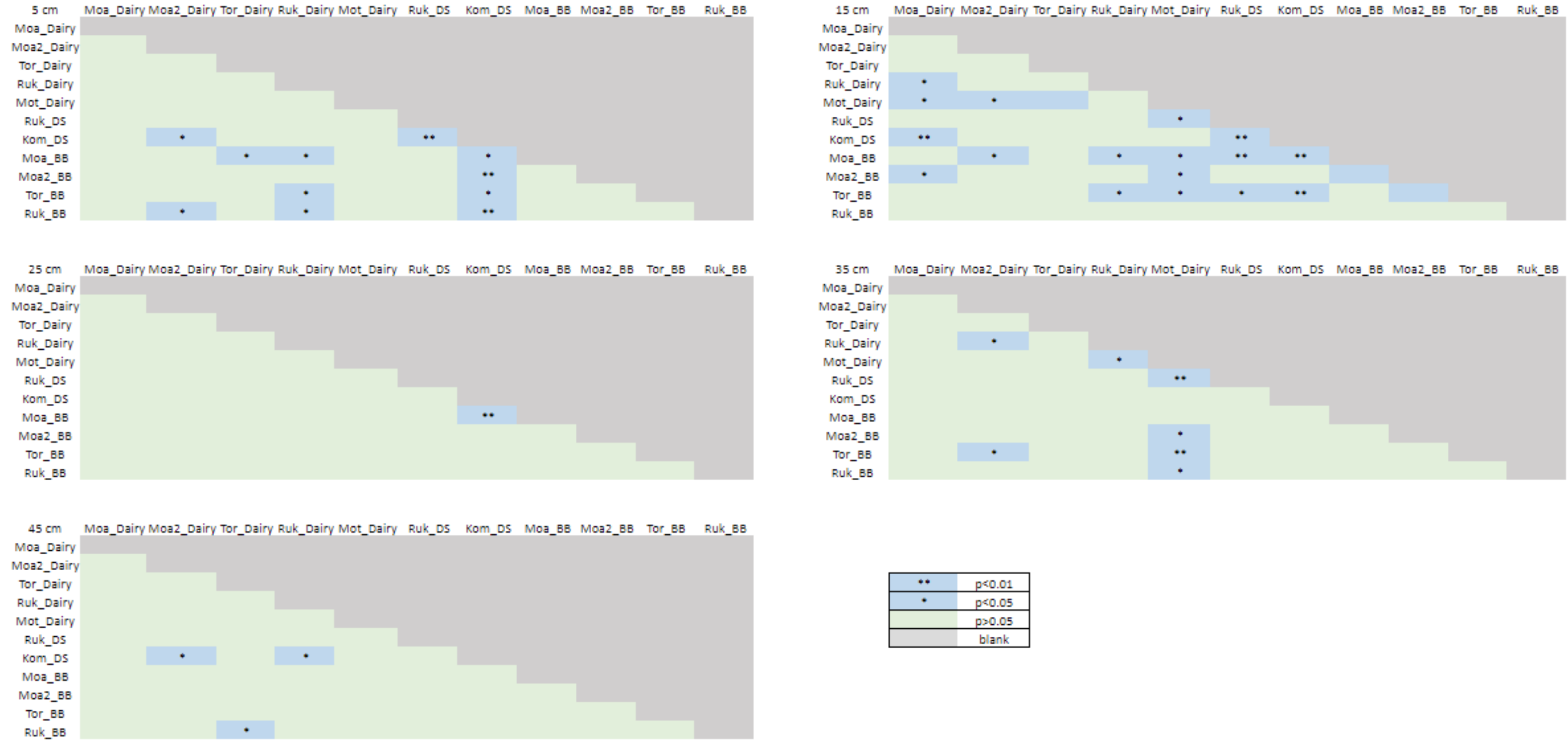
25 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy	**										
Tor_Dairy		*									
Ruk_Dairy											
Mot_Dairy	*		*	*							
Ruk_DS					*						
Kom_DS	*										
Moa_BB		**			**	*	**				
Moa2_BB		*		*	*						
Tor_BB		**			*		*				
Ruk_BB	*	**			**	**	**			*	

35 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS											
Kom_DS			*	*							
Moa_BB						*					
Moa2_BB											
Tor_BB											
Ruk_BB						*		**			

45 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy	*										
Tor_Dairy		**									
Ruk_Dairy		**									
Mot_Dairy			*								
Ruk_DS											
Kom_DS	**		**	*	*						
Moa_BB		*	*				**				
Moa2_BB		*	*				**				
Tor_BB											
Ruk_BB		**		**	*		*	*	*		

**	p<0.01
*	p<0.05
🟩	p>0.05
▨	blank

Figure A.2 Statistical significance of differences in porosity between sites, split into depths, a) 5 cm, b) 15 cm, c) 25 cm, d) 35 cm, e) 45cm.



5 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS											
Kom_DS		*				**					
Moa_BB			*	*			*				
Moa2_BB							**				
Tor_BB				*			*				
Ruk_BB		*		*			**				

15 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy	*										
Mot_Dairy	*	*									
Ruk_DS					*						
Kom_DS	**					**					
Moa_BB		*		*	*	**	**				
Moa2_BB	*				*						
Tor_BB				*	*	*	**				
Ruk_BB											

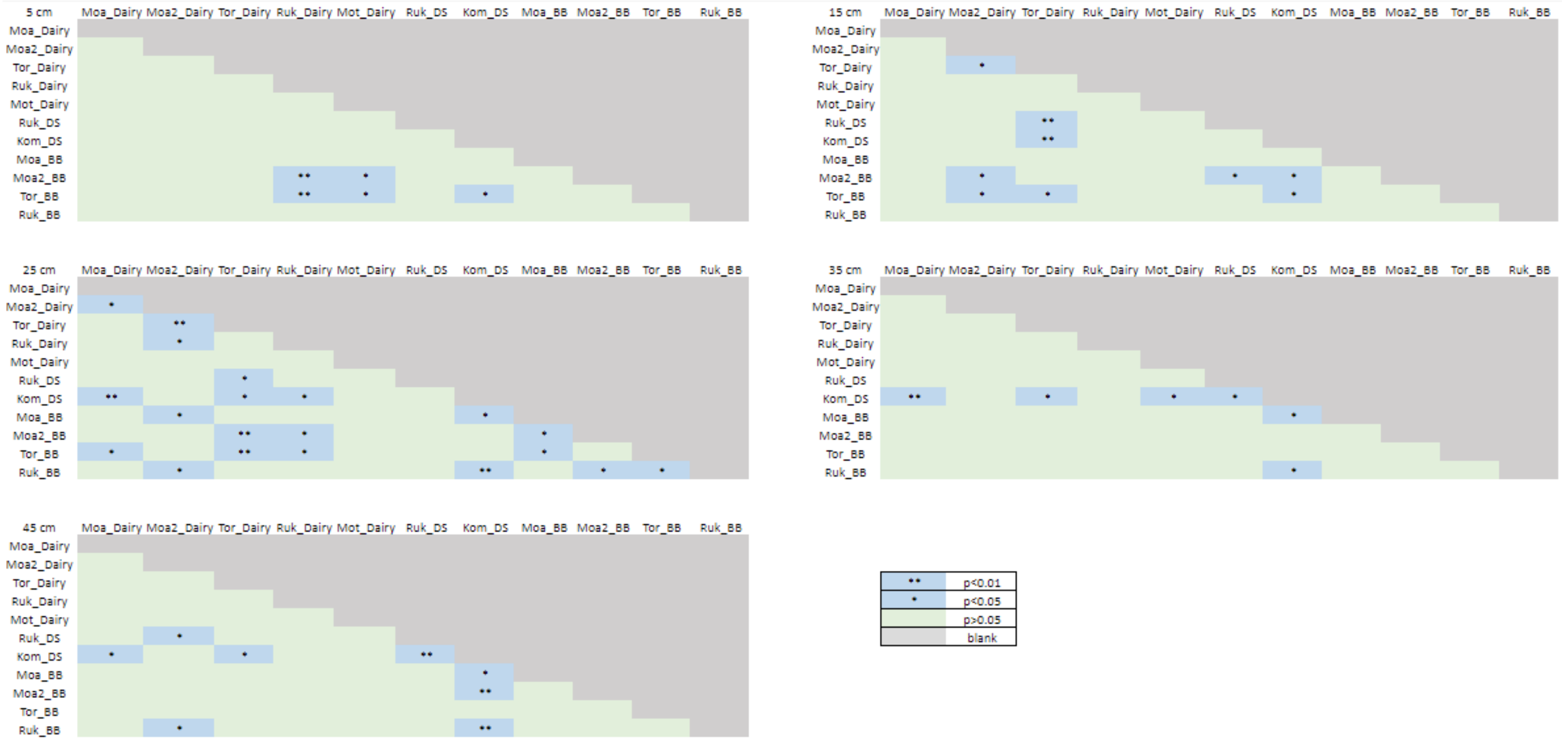
25 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS											
Kom_DS											
Moa_BB							**				
Moa2_BB											
Tor_BB											
Ruk_BB											

35 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy		*									
Mot_Dairy				*							
Ruk_DS					**						
Kom_DS											
Moa_BB											
Moa2_BB					*						
Tor_BB		*			**						
Ruk_BB					*						

45 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS											
Kom_DS		*		*							
Moa_BB											
Moa2_BB											
Tor_BB											
Ruk_BB			*								

**	p<0.01
*	p<0.05
🟩	p>0.05
▨	blank

Figure A.3 Statistical significance of differences in OM between sites, split into depths, a) 5 cm, b) 15 cm, c) 25 cm, d) 35 cm, e) 45cm.



5 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS											
Kom_DS											
Moa_BB											
Moa2_BB				**	*						
Tor_BB				**	*		*				
Ruk_BB											

15 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy		*									
Ruk_Dairy											
Mot_Dairy											
Ruk_DS			**								
Kom_DS			**								
Moa_BB											
Moa2_BB		*				*	*				
Tor_BB		*	*				*				
Ruk_BB											

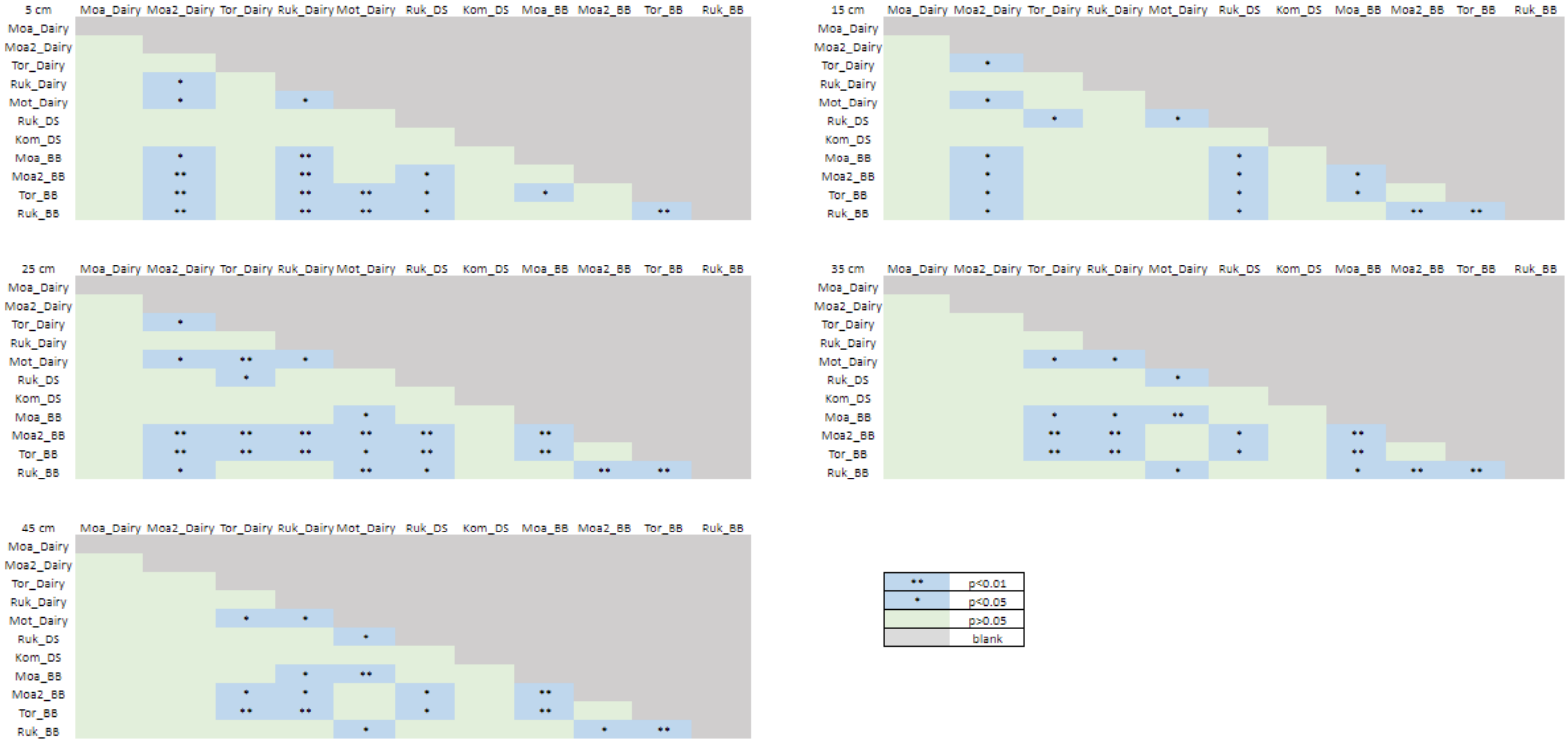
25 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy	*										
Tor_Dairy		**									
Ruk_Dairy		*									
Mot_Dairy											
Ruk_DS			*								
Kom_DS	**		*	*							
Moa_BB		*					*				
Moa2_BB			**	*				*			
Tor_BB	*		**	*				*			
Ruk_BB		*					**		*	*	

35 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS											
Kom_DS	**		*		*	*					
Moa_BB							*				
Moa2_BB											
Tor_BB											
Ruk_BB							*				

45 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy											
Ruk_DS		*									
Kom_DS	*		*			**					
Moa_BB							*				
Moa2_BB							**				
Tor_BB											
Ruk_BB		*					**				

**	p<0.01
*	p<0.05
🟩	p>0.05
⬜	blank

Figure A.4 Statistical significance of differences in C/N ratios between sites, split into depths, a) 5 cm, b) 15 cm, c) 25 cm, d) 35 cm, e) 45cm.



5 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy		*									
Mot_Dairy		*		*							
Ruk_DS											
Kom_DS											
Moa_BB		*		**							
Moa2_BB		**		**		*					
Tor_BB		**		**	**	*		*			
Ruk_BB		**		**	**	*				**	

15 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy		*									
Ruk_Dairy											
Mot_Dairy		*									
Ruk_DS			*		*						
Kom_DS											
Moa_BB		*				*					
Moa2_BB		*				*		*			
Tor_BB		*				*		*			
Ruk_BB		*				*			**	**	

25 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy		*									
Ruk_Dairy											
Mot_Dairy		*	**	*							
Ruk_DS			*								
Kom_DS											
Moa_BB					*						
Moa2_BB		**	**	**	**	**		**			
Tor_BB		**	**	**	*	**		**			
Ruk_BB		*			**	*			**	**	

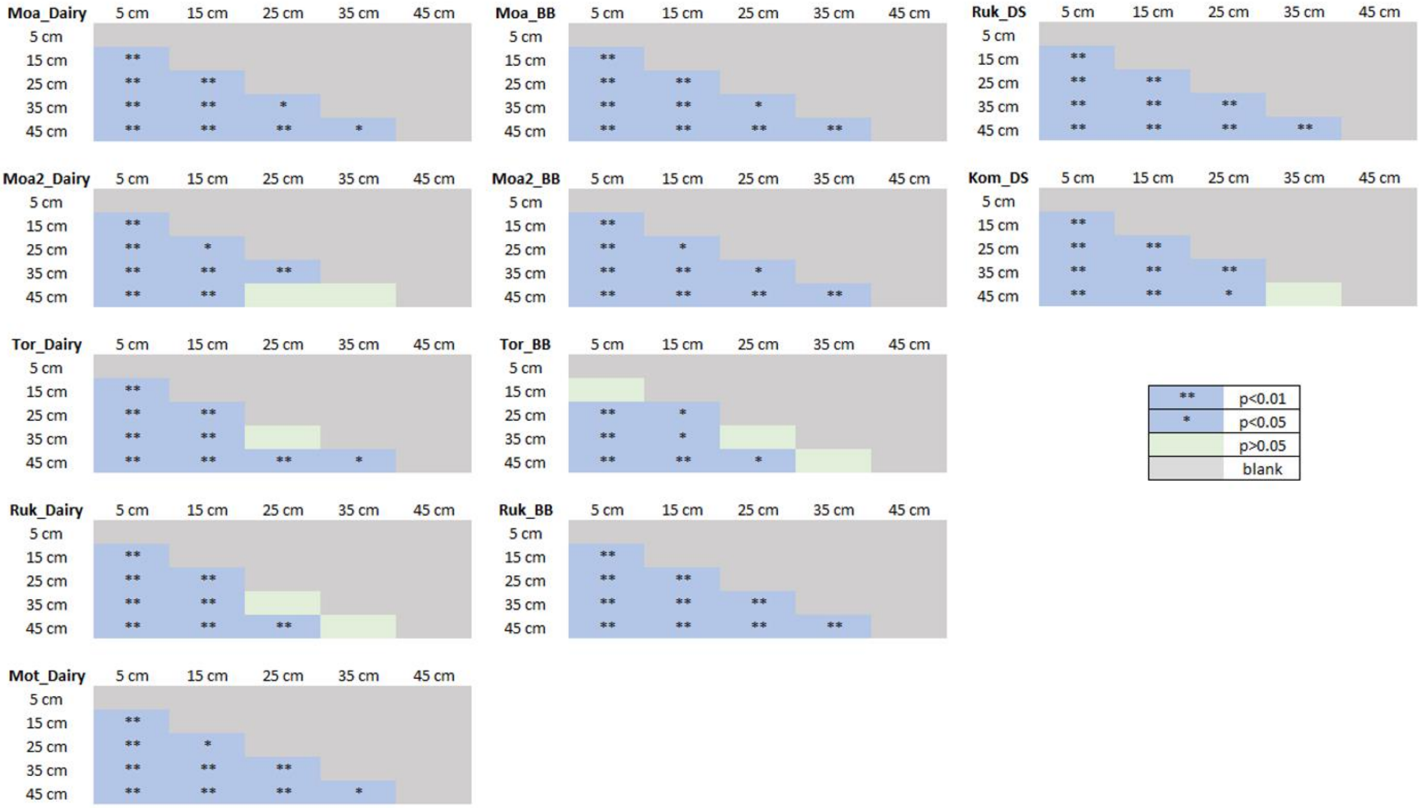
35 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy			*	*							
Ruk_DS					*						
Kom_DS											
Moa_BB			*	*	**						
Moa2_BB			**	**		*		**			
Tor_BB			**	**		*		**			
Ruk_BB					*			*	**	**	

45 cm	Moa_Dairy	Moa2_Dairy	Tor_Dairy	Ruk_Dairy	Mot_Dairy	Ruk_DS	Kom_DS	Moa_BB	Moa2_BB	Tor_BB	Ruk_BB
Moa_Dairy											
Moa2_Dairy											
Tor_Dairy											
Ruk_Dairy											
Mot_Dairy			*	*							
Ruk_DS					*						
Kom_DS											
Moa_BB				*	**						
Moa2_BB			*	*		*		**			
Tor_BB			**	**		*		**			
Ruk_BB					*				*	**	

**	p<0.01
*	p<0.05
🟩	p>0.05
⬜	blank

Figure A.5 Statistical significance of differences in pH between sites, split into depths, a) 5 cm, b) 15 cm, c) 25 cm, d) 35 cm, e) 45cm.

A.3.2 Significance of changes in physical and chemical properties with depth at each site



Moa_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	*		
45 cm	**	**	**	*	

Moa_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	*		
45 cm	**	**	**	**	

Ruk_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	**	

Moa2_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	*			
35 cm	**	**	**		
45 cm	**	**	🟩	🟩	

Moa2_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	*			
35 cm	**	**	*		
45 cm	**	**	**	**	

Kom_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	*	🟩	

Tor_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	**	*	

Tor_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	*			
35 cm	**	*	🟩		
45 cm	**	**	*	🟩	

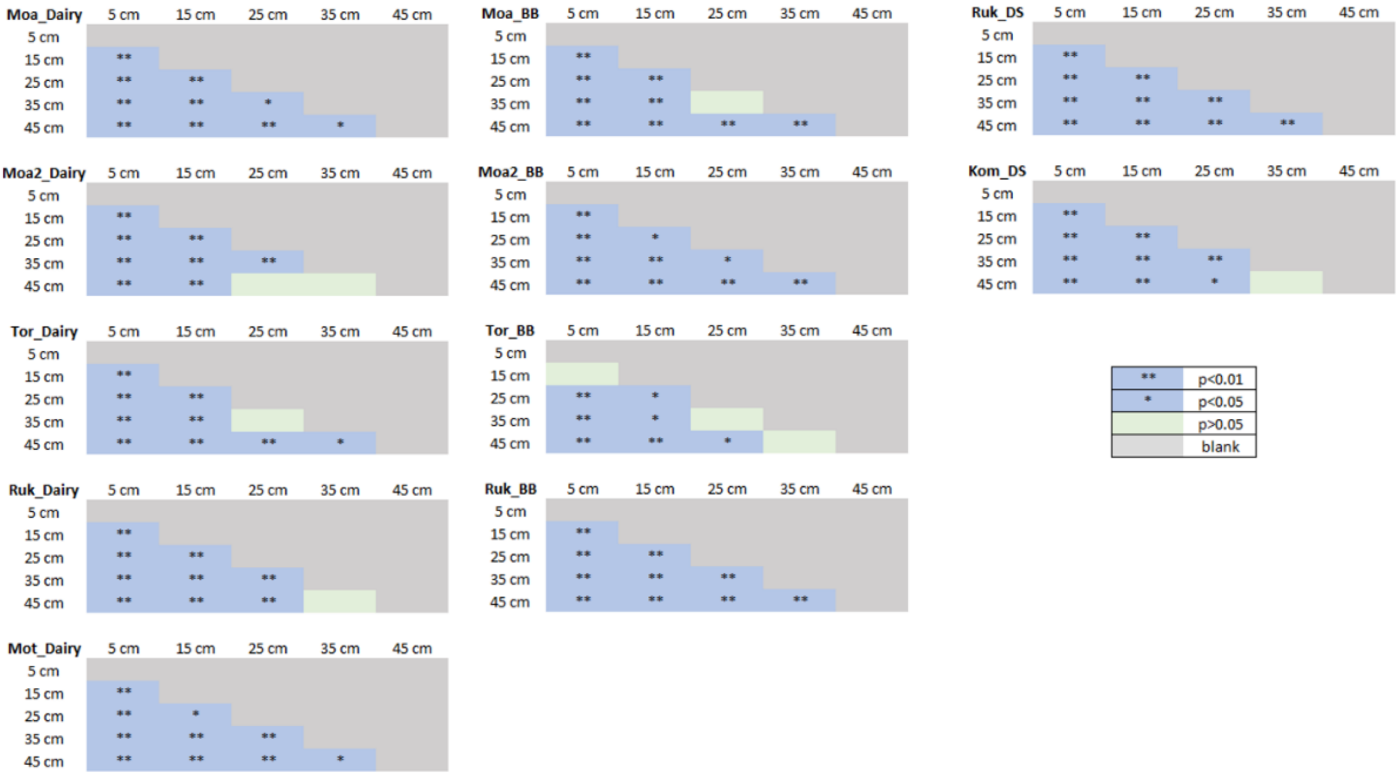
**	p<0.01
*	p<0.05
🟩	p>0.05
	blank

Ruk_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	**	🟩	

Ruk_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	**	

Mot_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	*			
35 cm	**	**	**		
45 cm	**	**	**	*	

Figure A.6 Significance of differences in bulk density (g cm^{-3}) between depths at each site.



Moa_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	*		
45 cm	**	**	**	*	

Moa_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	**	**	

Ruk_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	**	

Moa2_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	🟩	🟩	

Moa2_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	*			
35 cm	**	**	*		
45 cm	**	**	**	**	

Kom_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	*	🟩	

Tor_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	**	*	

Tor_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	*			
35 cm	**	*	🟩		
45 cm	**	**	*	🟩	

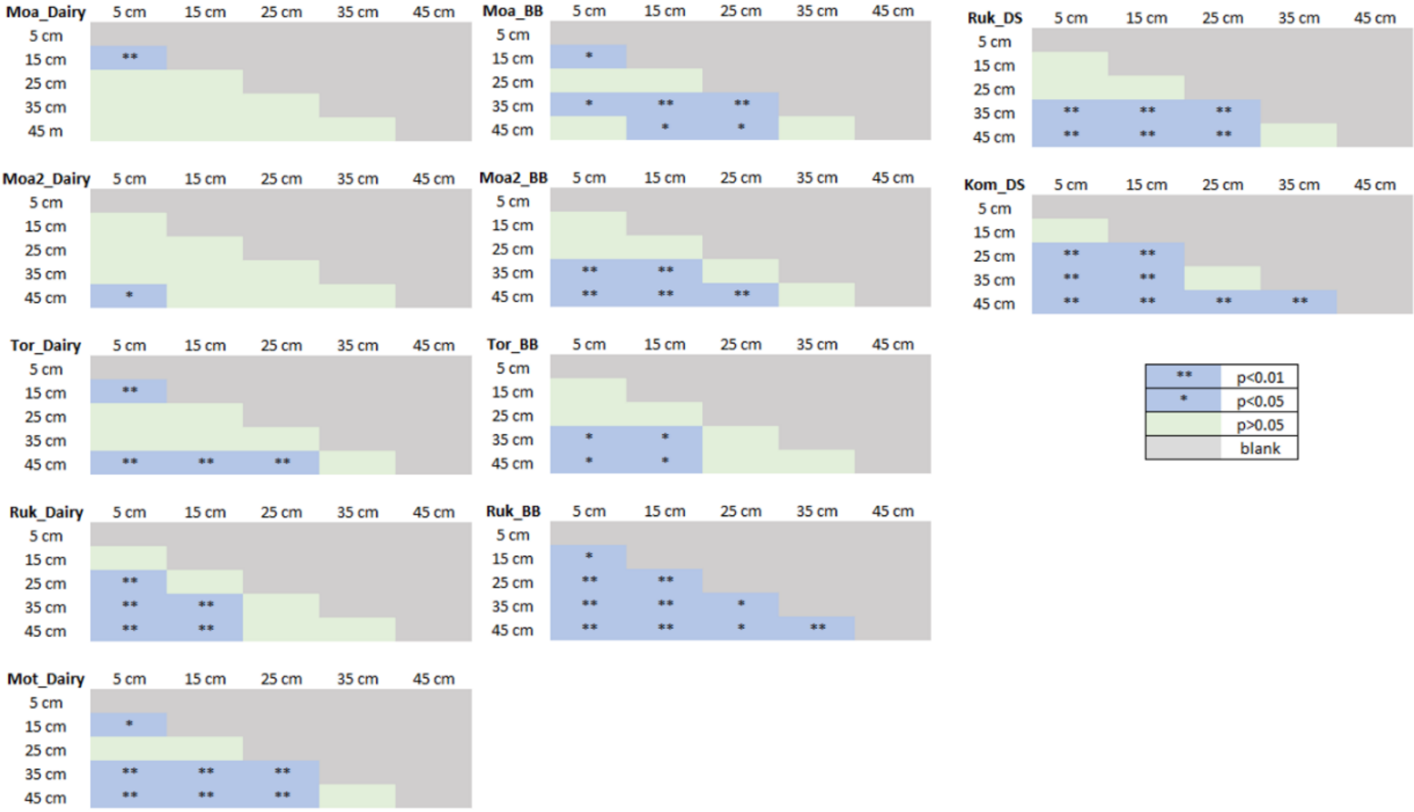
**	p<0.01
*	p<0.05
🟩	p>0.05
	blank

Ruk_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	🟩	

Ruk_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	**	

Mot_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	*			
35 cm	**	**	**		
45 cm	**	**	**	*	

Figure A.7 Significance of differences in porosity (%) between depths at each site.



Moa_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	🟩	🟩			
35 cm	🟩	🟩	🟩		
45 m	🟩	🟩	🟩	🟩	

Moa_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	*				
25 cm	🟩	🟩			
35 cm	*	**	**		
45 cm	🟩	*	*	🟩	

Ruk_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	🟩	🟩			
35 cm	**	**	**		
45 cm	**	**	**	🟩	

Moa2_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	🟩	🟩			
35 cm	🟩	🟩	🟩		
45 cm	*	🟩	🟩	🟩	

Moa2_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	🟩	🟩			
35 cm	**	**	🟩		
45 cm	**	**	**	🟩	

Kom_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	**	**	

Tor_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	🟩	🟩			
35 cm	🟩	🟩	🟩		
45 cm	**	**	**	🟩	

Tor_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	🟩	🟩			
35 cm	*	*	🟩		
45 cm	*	*	🟩	🟩	

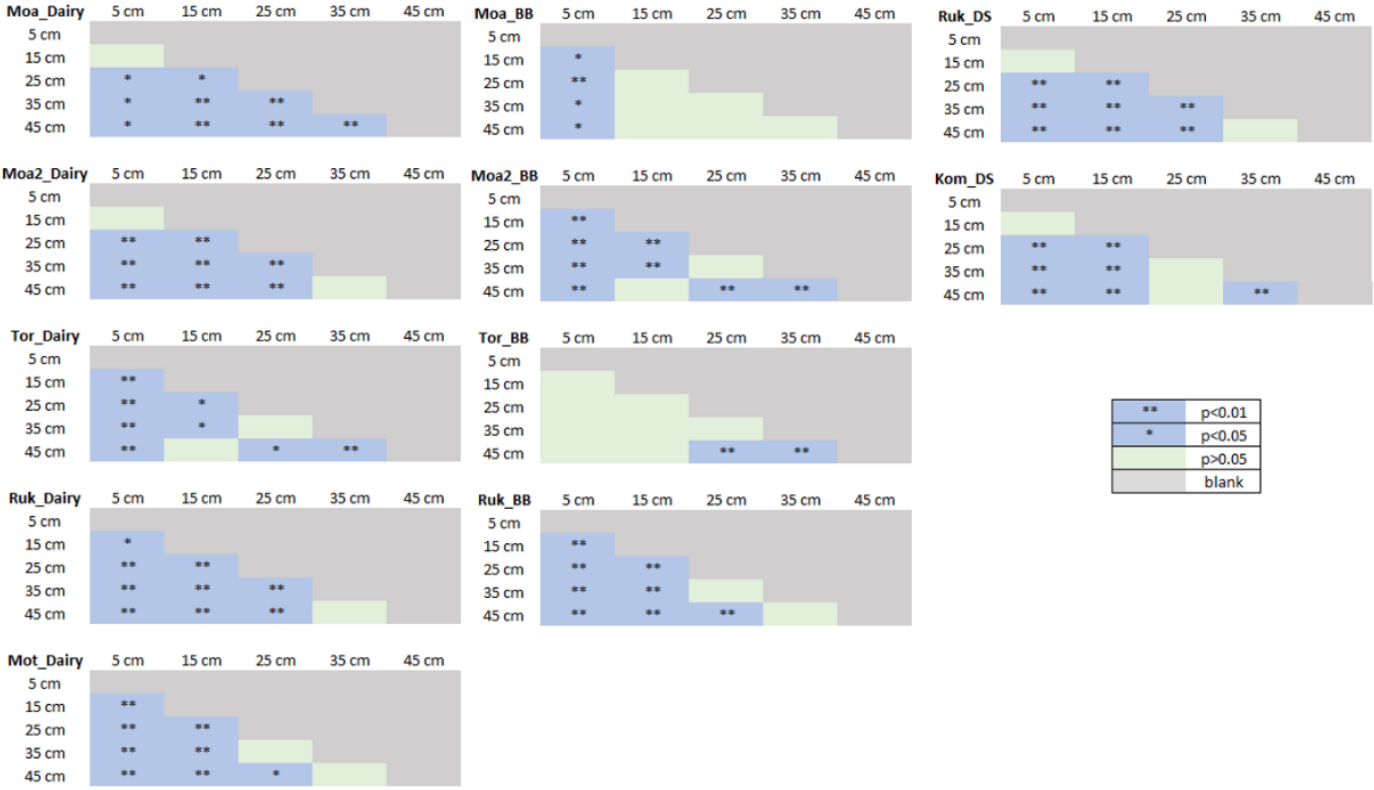
Ruk_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	🟩			
35 cm	**	**	🟩		
45 cm	**	**	🟩	🟩	

Ruk_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	*				
25 cm	**	**			
35 cm	**	**	*		
45 cm	**	**	*	**	

Mot_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	*				
25 cm	🟩	🟩			
35 cm	**	**	**		
45 cm	**	**	**	🟩	

**	p<0.01
*	p<0.05
🟩	p>0.05
	blank

Figure A.8 Significance of differences in OM (%) between depths at each site.



Moa_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	*	*			
35 cm	*	**	**		
45 cm	*	**	**	**	

Moa_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	*				
25 cm	**	🟩			
35 cm	*	🟩	🟩		
45 cm	*	🟩	🟩	🟩	

Ruk_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	🟩	

Moa2_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	🟩	

Moa2_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	🟩	**	**	

Kom_DS	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	🟩	**	

Tor_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	*			
35 cm	**	*	🟩		
45 cm	**	🟩	*	**	

Tor_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	🟩				
25 cm	🟩	🟩			
35 cm	🟩	🟩	🟩		
45 cm	🟩	🟩	**	**	

Ruk_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	*				
25 cm	**	**			
35 cm	**	**	**		
45 cm	**	**	**	🟩	

Ruk_BB	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	**	🟩	

Mot_Dairy	5 cm	15 cm	25 cm	35 cm	45 cm
5 cm					
15 cm	**				
25 cm	**	**			
35 cm	**	**	🟩		
45 cm	**	**	*	🟩	

**	p<0.01
*	p<0.05
🟩	p>0.05
	blank

Figure A.9 Significance in differences in pH between depths at each site.

Table A.19 ANOVA for land uses of peat soil properties for the entire profile

ANOVA	**Bulk density**	**Porosity**	**OM**
p-value	1.6e-10	6.46e-07	32.e-06

Table A.20 Post-hoc to determine significance of peat soil proerties between land uses for the entire profile

Tukey HSD	**Bulk Density**	**Porosity**	**OM**
Blueberry vs dairy	p<0.01	p<0.01	p<0.01
Blueberry vs dry stock	p<0.01	p<0.01	p<0.01
Dairy vs dry stock	p>0.05	p>0.05	p>0.05

Appendix B

Figure B.1 Images of peat profiles from the dairy sites a) Moa_Dairy (pit 1), b) Moa2_Dairy (pit 2), c) Tor_Dairy (pit 3), d) Ruk_Dairy (pit 1), e) Mot_Dairy (pit 1)

Figure B.2 Images of peat profiles from the dry stock sites a) Ruk_DS (pit 1), b) Kom_DS (pit 1)

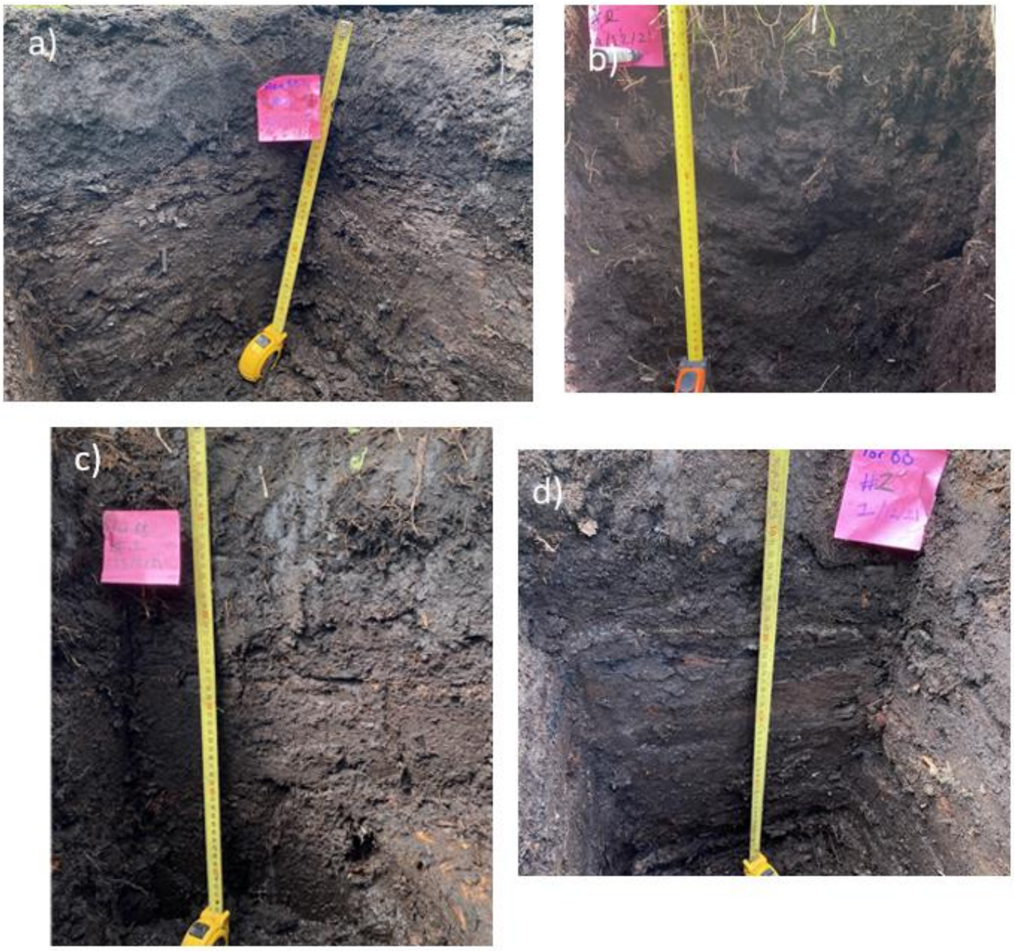


Figure B.3 Images of peat profiles from the blueberry sites a) Moa_BB (pit 1), b) Moa2_BB (pit 2), c) Ruk_BB (pit 1), d) Tor_BB (pit 2)

Appendix C

Presented here are daily means of relative water level (RWL), absolute water level (AWL) and surface elevation (SE) compared to their respective manual measurements.

Manual measurements of PSO site geometry (distances, A, B,C) (Figure 3.9) were used to calculate RWL, AWL and SE independent of the Solinst water level probes. These provided important visual checks on the continuous measurements from the Solinst probes. In particular, two large values (AWL and RWL) are subtracted to give a small difference (SE), so small errors in water level measurement can lead to potentially large errors in SE calculation. Some sites have been adjusted due to an offset present in the probes found when comparing the manual measurements to the Solinst probe measurements (Table C.1).

There can be errors in the Solinst probe-derived water levels and the manual measurements. The errors in Solinst probe-derived water levels can be caused by:

- Incorrect determination of the distance at which the Solinst probes are hanging below attachment points (this leads to constant offsets).
- Potential offsets in probe depth values, which includes differences between Leveloggers and Barologgers. These also lead to constant offsets.
- A drift in the calibration of the probe, which will lead to non-constant offsets e.g. Tor_Dairy.

The errors in manual measurements can be caused by:

- Different personnel using slightly different methods for measurements.
- Transcription errors during measurement.
- Failing to account for offsets from the zero position when measuring water table (distance C) with the bubbler.

These errors have been accounted for in both the graphs of RWL, AWL and SE, and in calculations for RWL statistics, SE ranges and RWL ranges.

Table C.1 Offsets applied to Levelogger depth measurements

Site	AWL offset (mm)	RWL offset (mm)
Moa_Dairy	-22.6	33.5
Moa_BB	0.0	0.0
Moa2_Dairy	0.0	0.0
Moa2_BB	-16.1	6.2
Ruk_Dairy	0.0	0.0
Ruk_BB	-5.7	5.9
Ruk_DS	11.0	17.3
Tor_Dairy	0.0	0.0
Tor_BB	7.9	15.5
Kom_DS	-30.8	-22.6
Mot_Dairy	-95.3	0.0

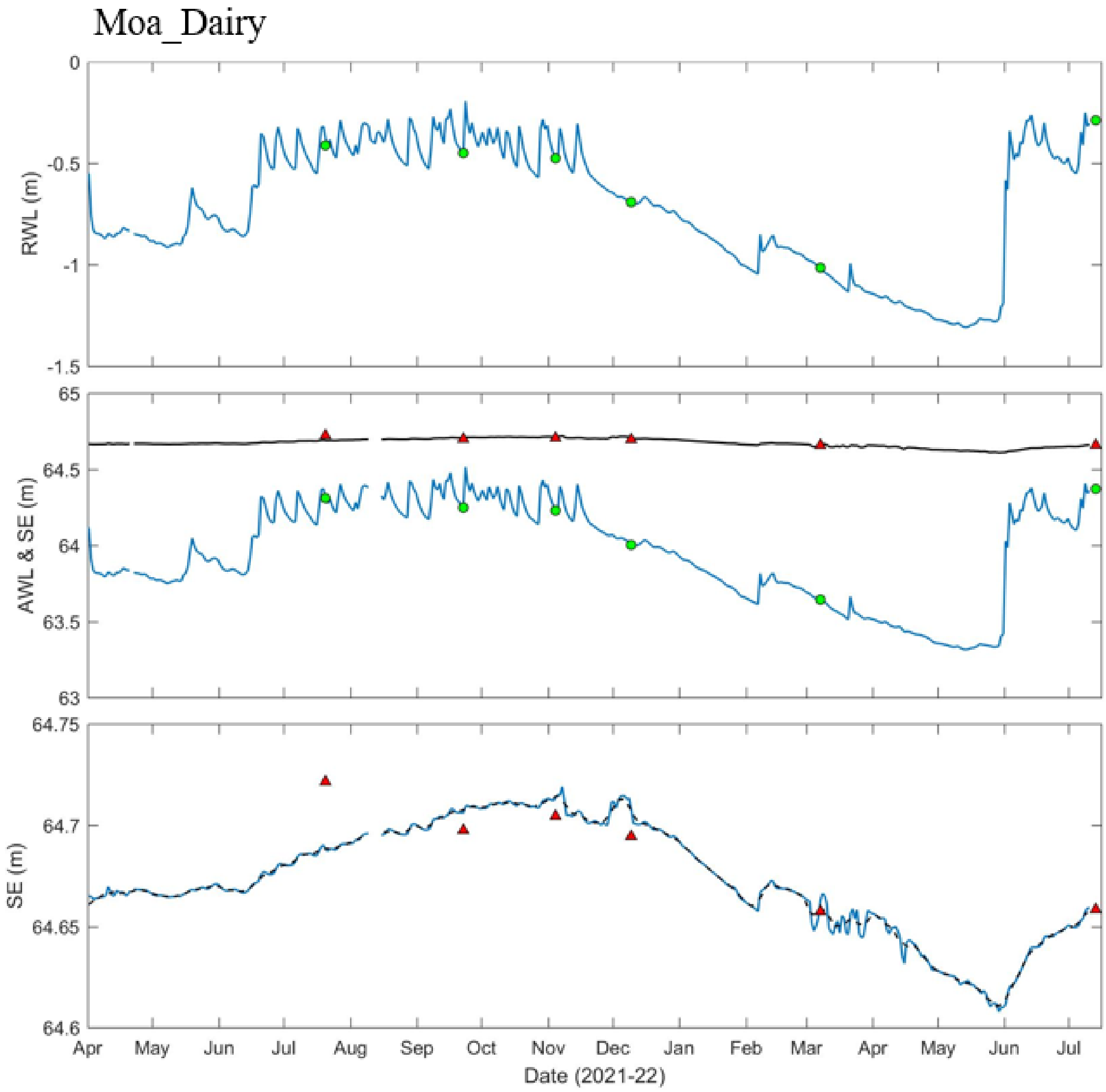


Figure C.1 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Moa_Dairy. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).

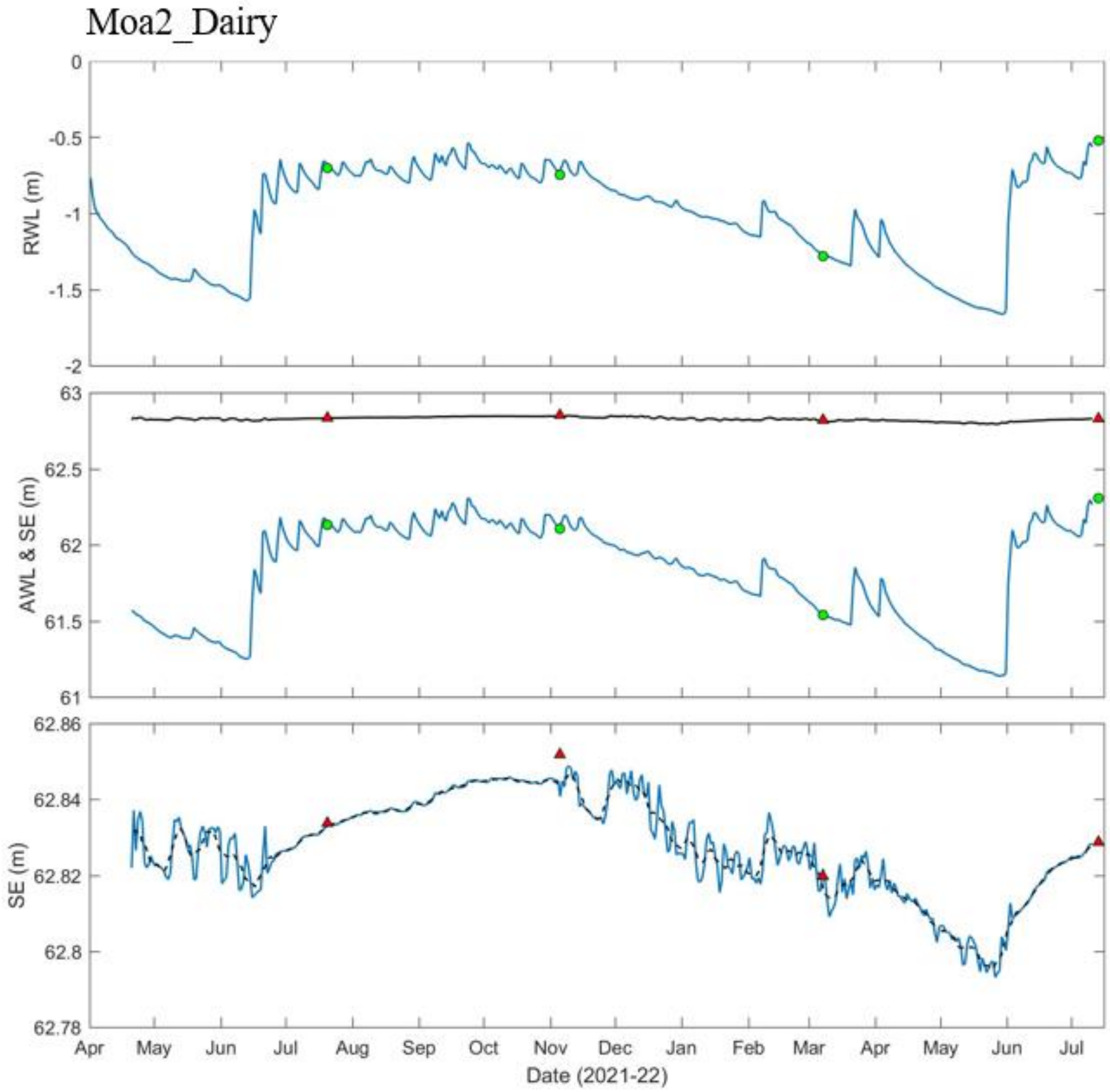


Figure C.2 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Moa2_Dairy. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means.

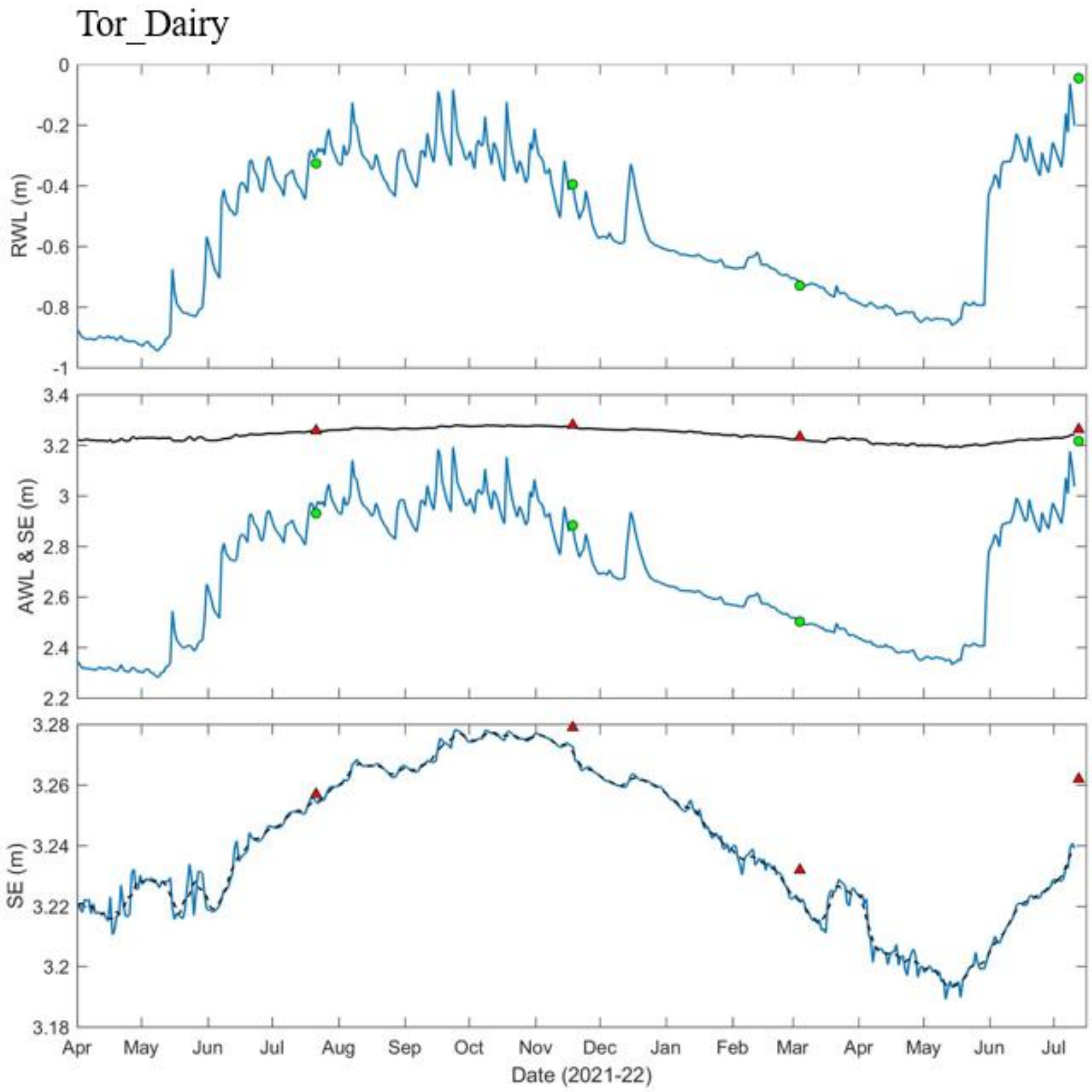


Figure C.3 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Tor_Dairy. Green circles and red triangles are manual measurements. Dashed line on SE panel is the 7-day running means.

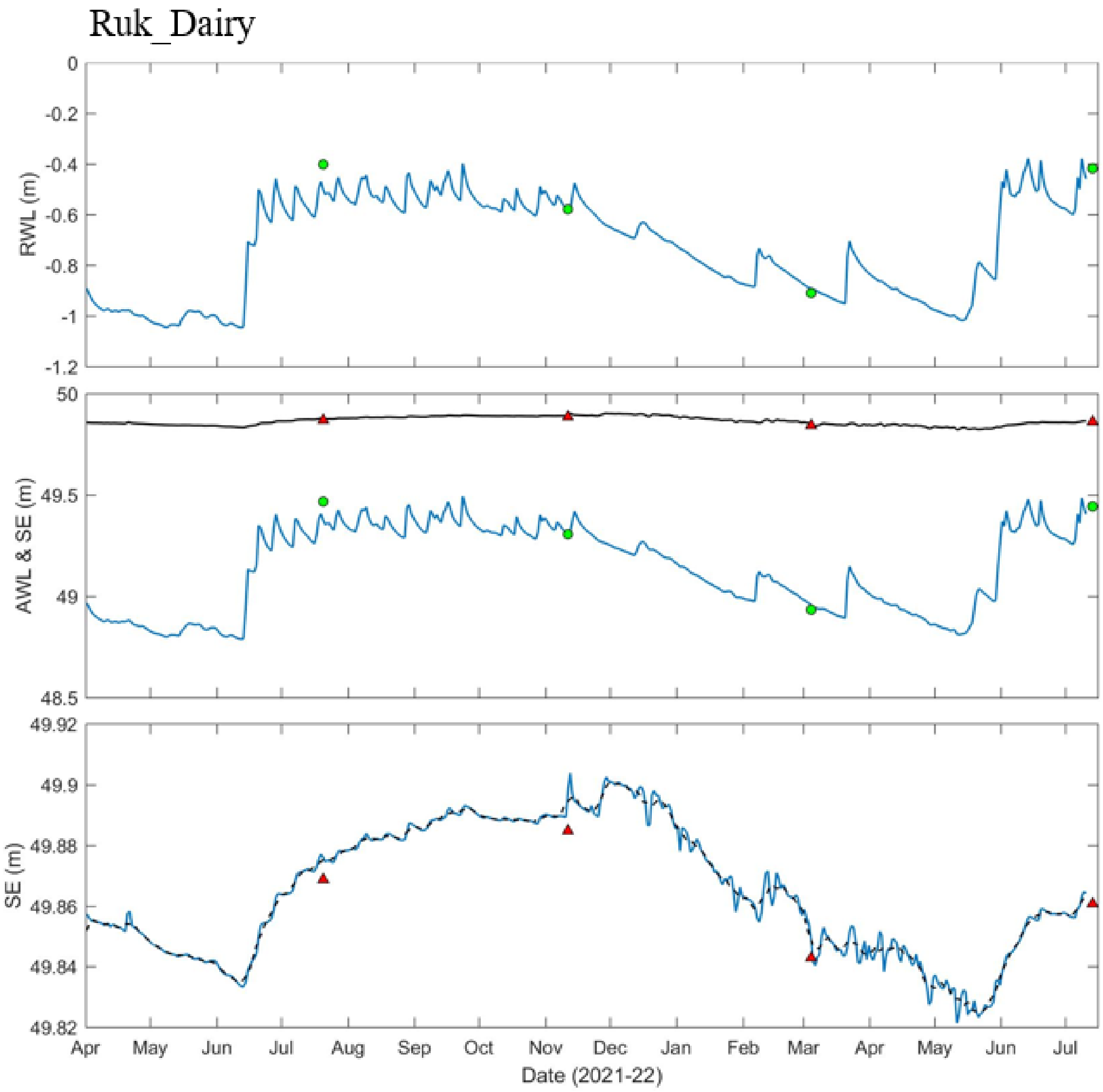


Figure C.4 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Ruk_Dairy. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means.

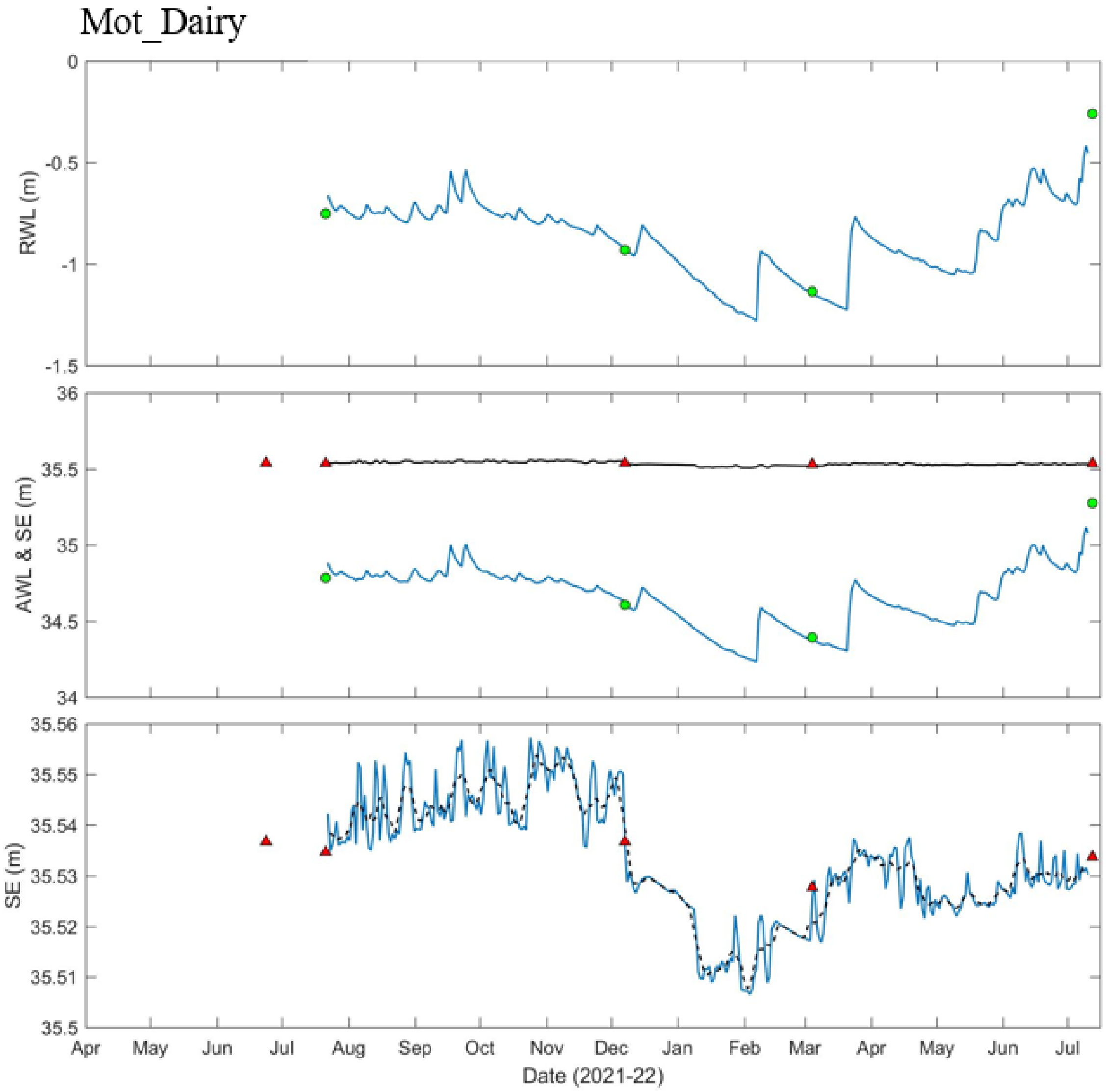


Figure C.5 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Mot_Dairy. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).

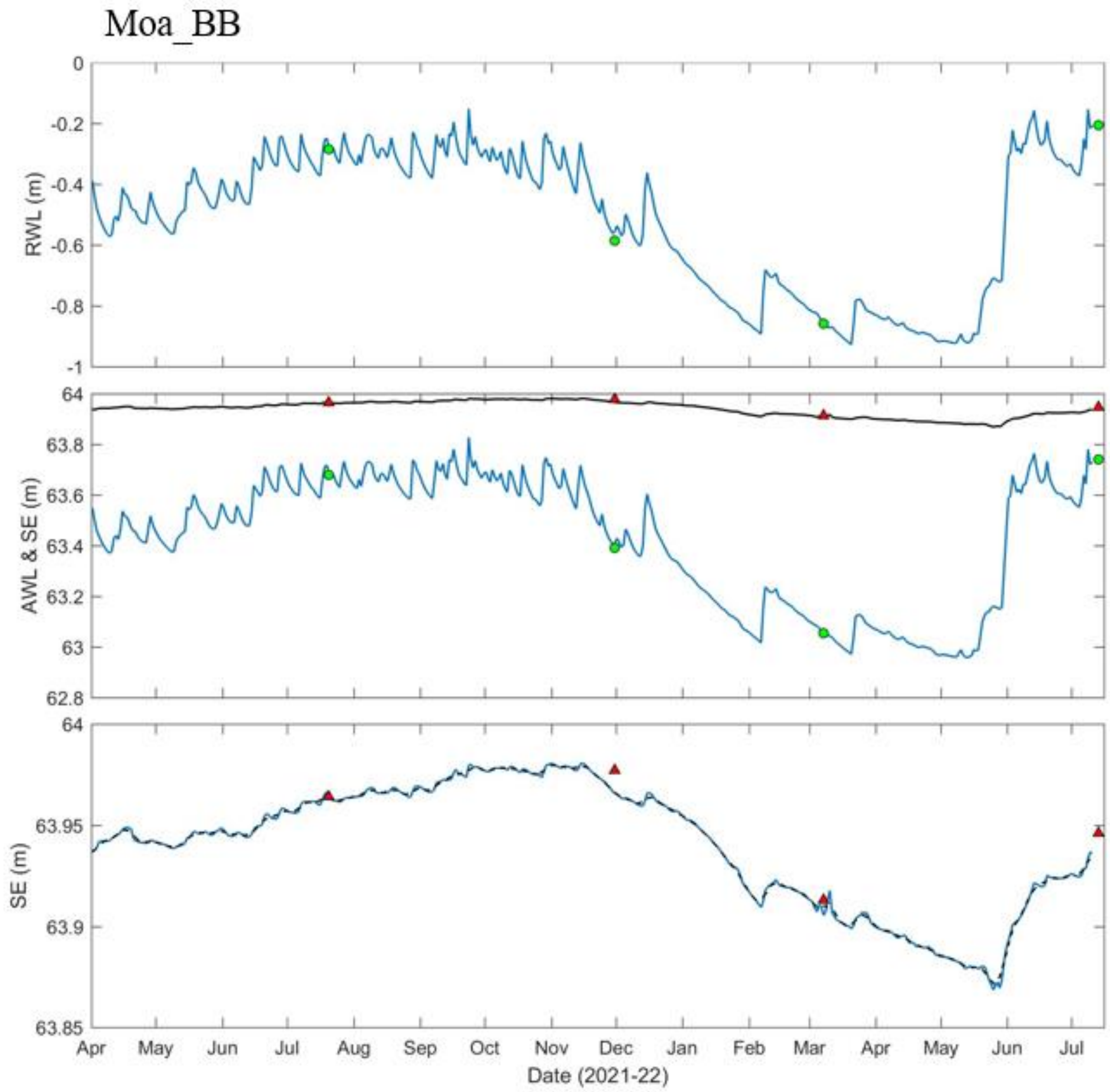


Figure C.6 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Moa_BB. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means.

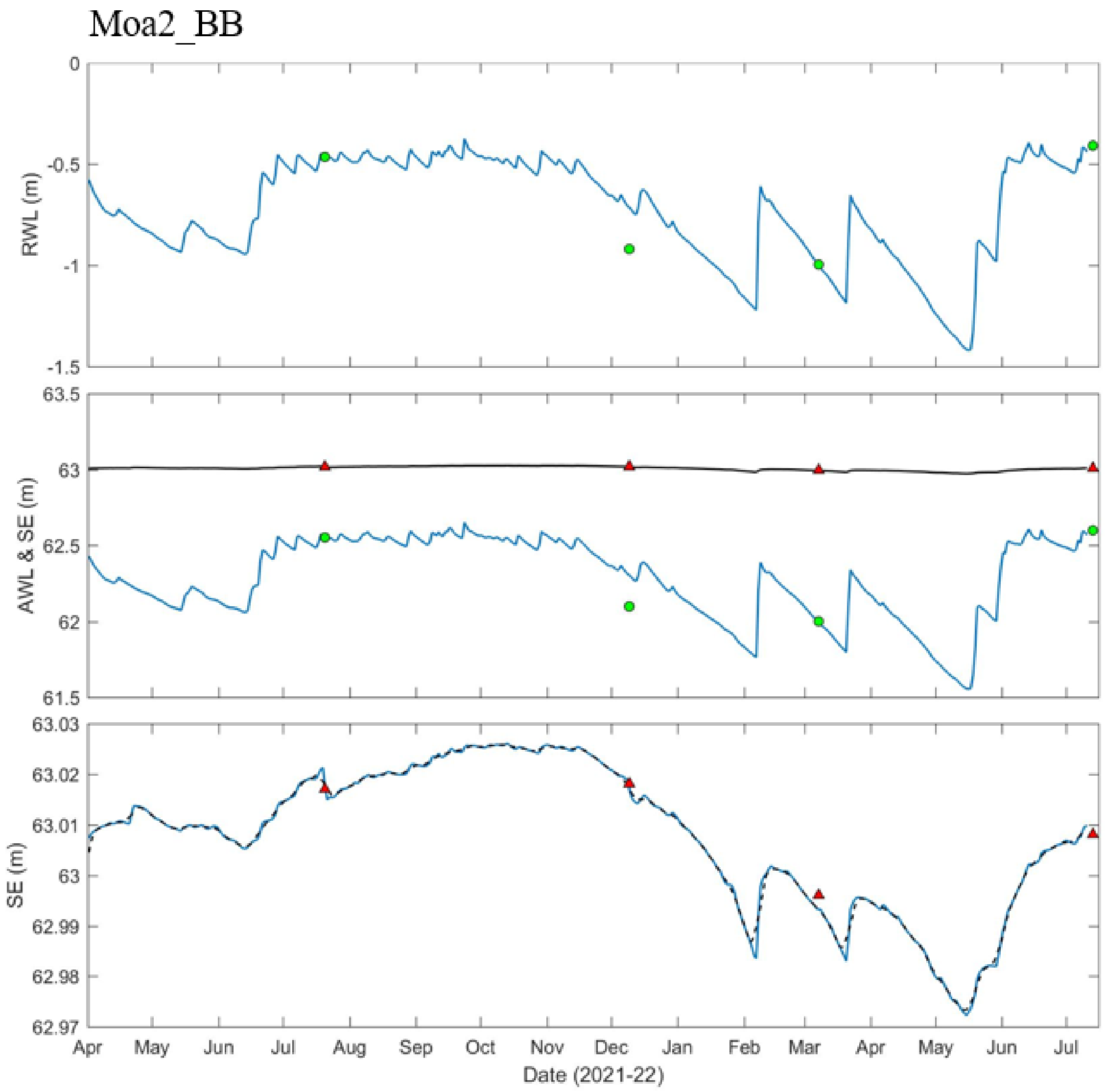


Figure C.7 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Moa2_BB. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).

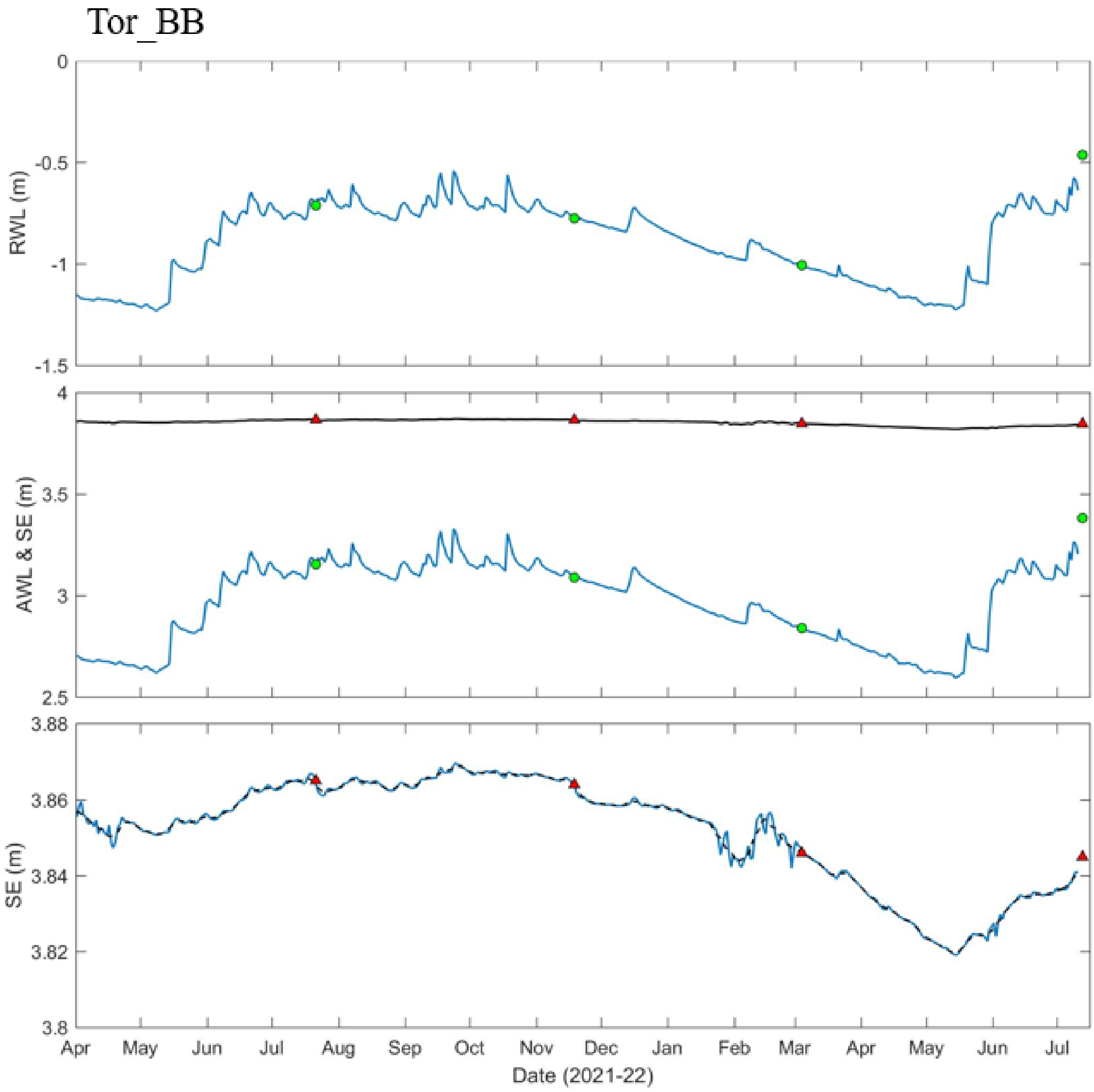


Figure C.8 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Tor_BB. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).

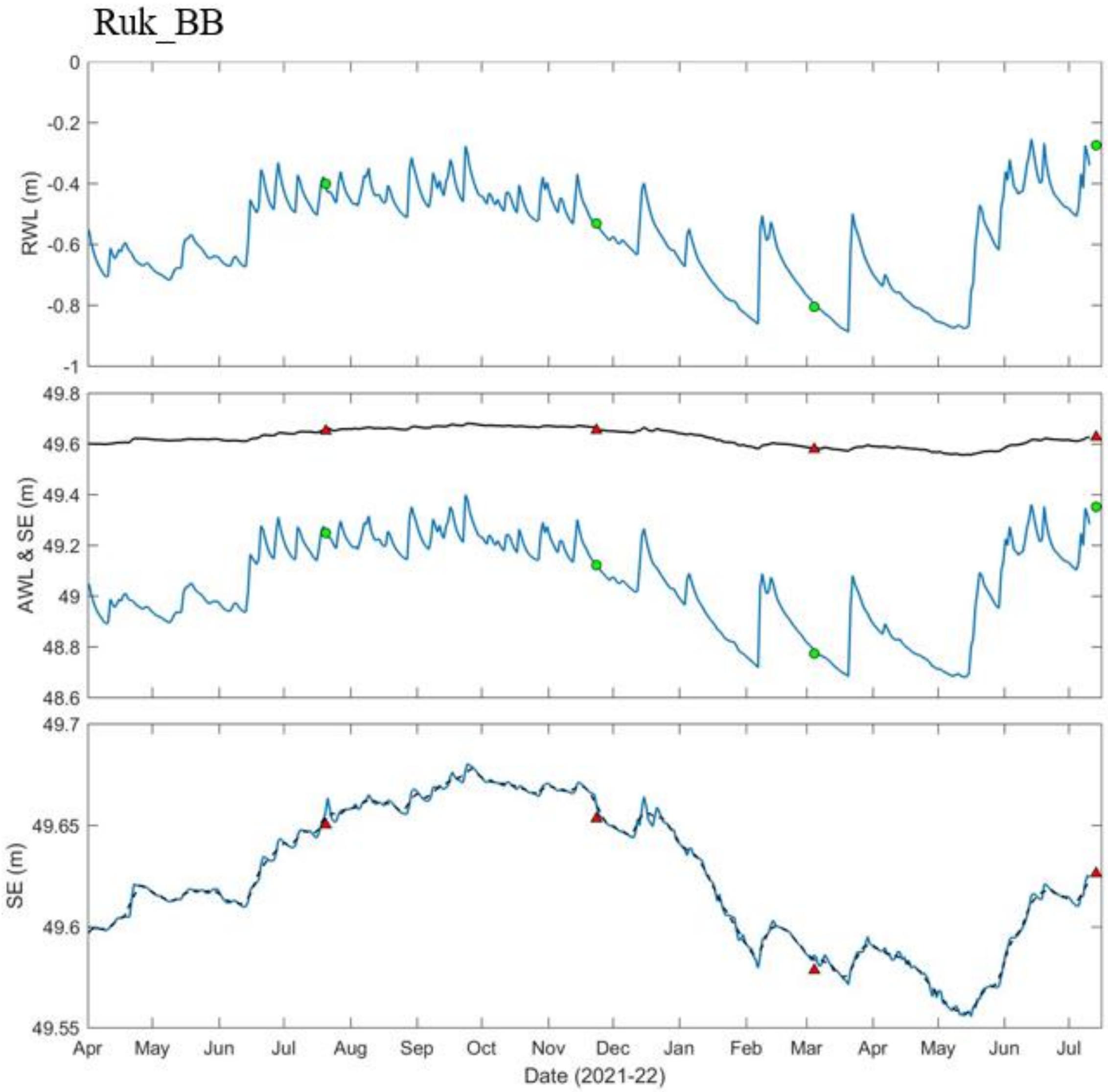


Figure C.9 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Ruk_BB. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).

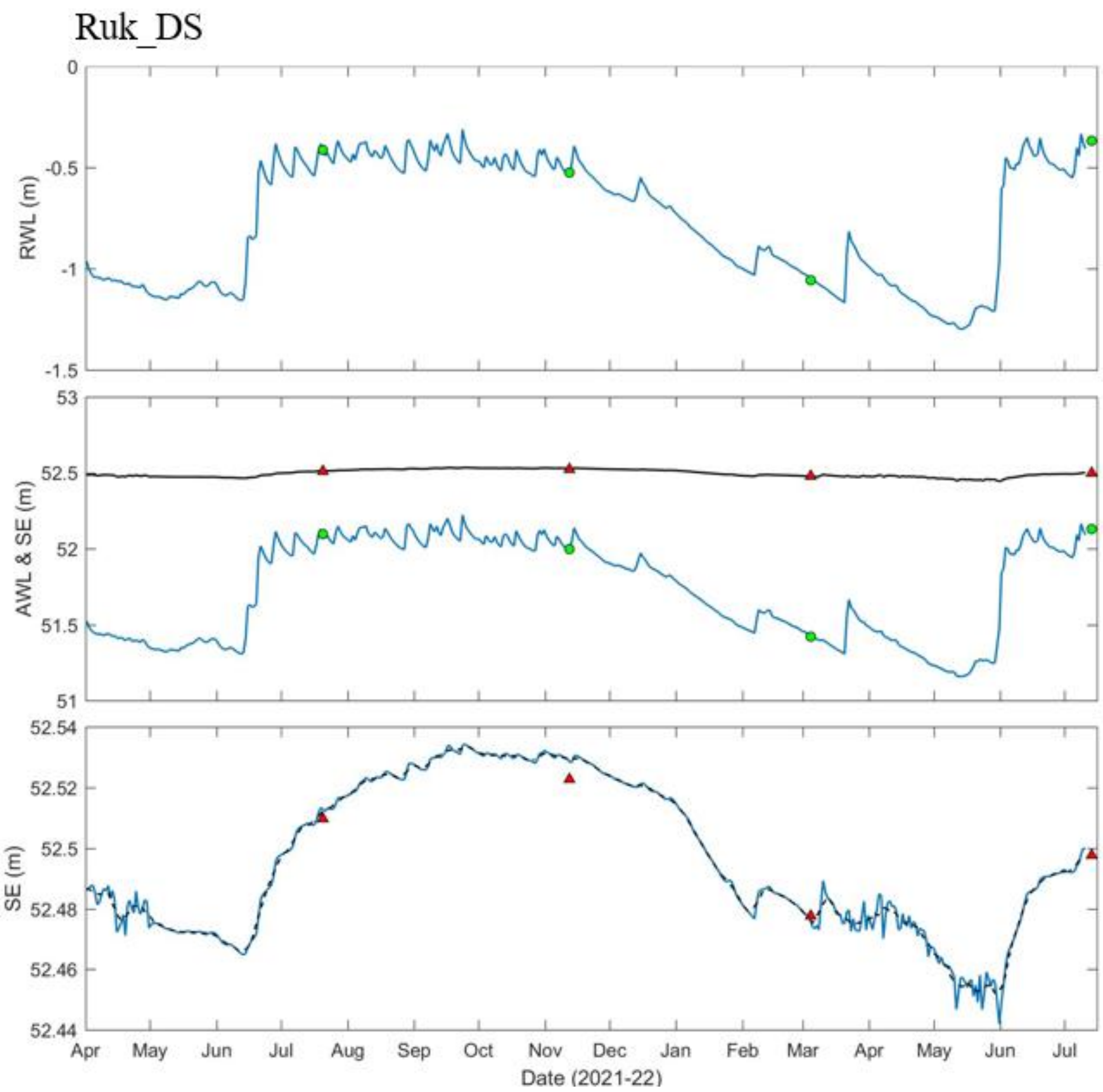


Figure C.10 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Ruk_DS. Green circles and red triangles are manual measurements. Black dashed line on SE panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).

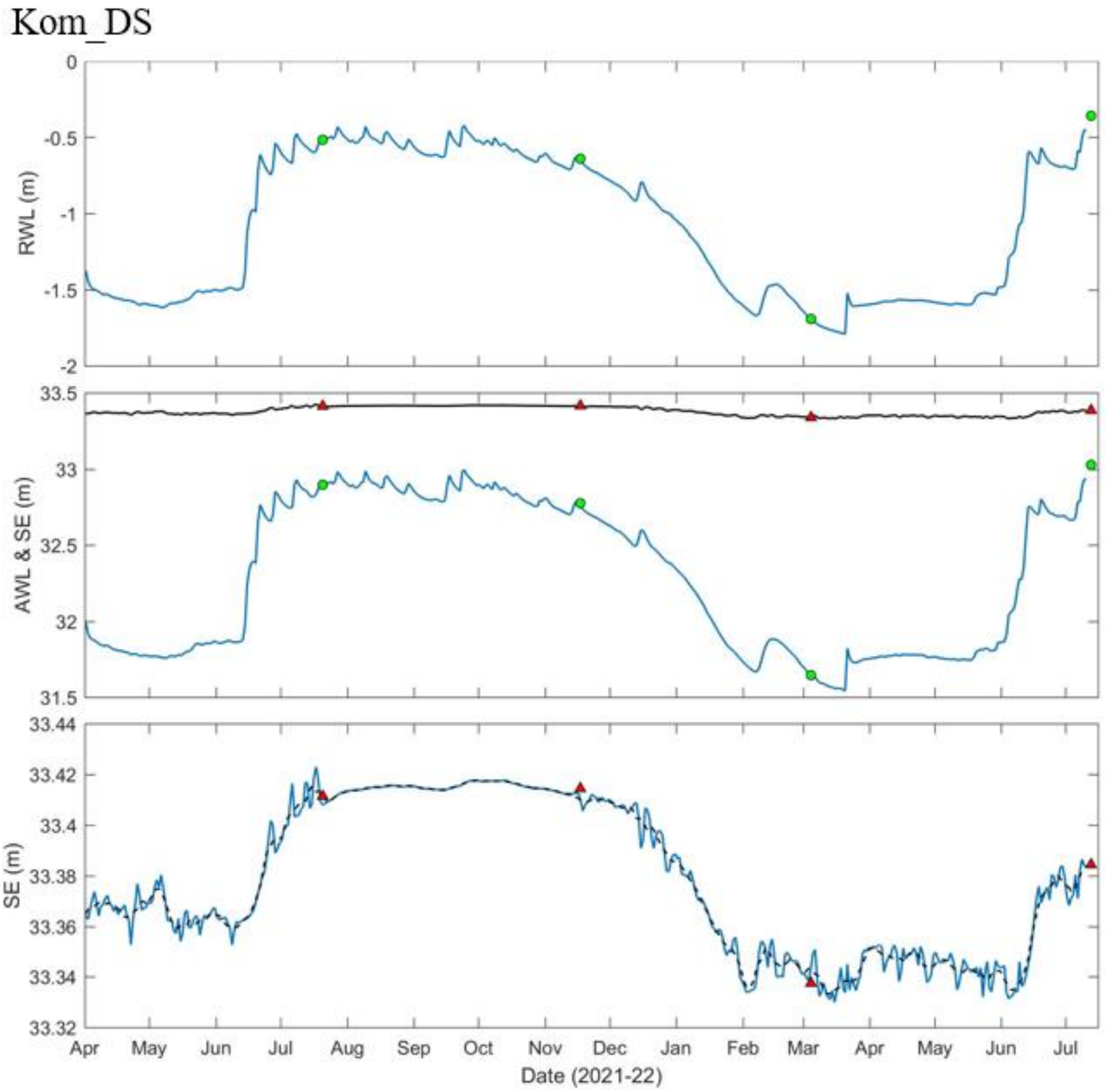


Figure C.11 Daily means of RWL (top panel), AWL (blue line) & SE (black line) (middle panel) and SE (bottom panel) at Kom_DS. Green circles and red triangles are manual measurements. Black dashed line on bottom panel is the 7-day running means. This site has been adjusted for probe offsets (Table C.1).