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Amendment incorporation to increase soil water retention

A thesis
submitted in partial fulfilment
of the requirements for the Degree of
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Dirk Fraser Wallace

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Amendment incorporation to increase soil water retention

by
Dirk Fraser Wallace

This thesis comprises two small core studies and two lysimeter studies, which are aimed at understanding how incorporation of soil amendments at cultivation can increase soil water retention in New Zealand's shallow stony soils. The overall objective was to determine the potential of this management practice to increase water retention of these vulnerable soils and to develop an understanding of the benefits and limitations of this practice in a spray irrigated system.

Experiment 1 (Chapter 3) - A lab based study was initially conducted to determine the potential of a range of amendments to increase soil water retention. This experiment involved incorporating organic (dairy shed manure (DSM), municipal compost (MC), sphagnum moss (SM) and biochar (BC)) and synthetic (polyacrylamide-based hydrogel (PM), silicate gel (SI) and starch gel (ST)) amendments in to a Templeton silt loam soil that had been under long term intensive cropping management. The amendment application rate was 1% and 0.1% on a mass by mass basis for the organic and synthetic amendments, respectively. The original hypothesis was that incorporation of these amendments would increase the water-retaining mesoporosity of a cultivated silt loam and that water repellence and carbon mineralisation would not be increased relative to the control. This experiment confirmed the original hypothesis for some amendments. Mesoporosity and total mesopore volume increased relative to the control in the order of PM>SM>DSM>BC, and the remaining amendments failed to produce a significant increase. Contrary to the original hypothesis, both water repellence and carbon mineralisation were significantly increased relative to the control by the incorporation of DSM, although no other amendment had a significant effect on these properties. From analysis of changes in soil physical properties such as bulk density, total porosity and the volume change due to the strain of amendment addition it was concluded that these changes in mesoporosity were caused by two modes of action that were unable to be separated: (1) inter-particle pore spaces were created through soil and amendment particle interaction, (2) the introduction of amendments bought new intra-particle pore spaces within the new particles which held water within the mesopore range.

The results and conclusions from this initial experiment allowed subsequent questions to be developed that contribute towards the original aim.

Experiment 2 (Chapter 4) - If the concentration and volume of water-retaining mesopores is controlled by the introduction of new inter-particle pore and intra-particle pore spaces, what effect would 1) modifying the maximum particle size of the amendment have? and 2) modifying the application rate have? For this experiment a readily available amendment (municipal compost) was selected, screened to three different maximum particle sizes and incorporated at four rates to determine if reducing particle size would allow water retention to be increased at lower application rates than traditionally recommended. Increasing MC application rate increased both the concentration and net volume of mesopores, and maximum mesoporosity was achieved with the smallest MC particle size (<0.25 mm) at the maximum application rate (80% wt/wt). It was concluded that reducing particle size of MC was an effective method of increasing water retention at lower (and potentially more economical) application rates.

Experiment 3 (Chapter 5) - The findings of Experiments 1 and 2 were expanded by answering the following question: Are the increases in water retention associated with sphagnum moss (SM) and polyacrylamide (PM) measured in Chapter 3 and municipal compost (MC) in Chapter 4 maintained under spray irrigation? What effect does spray irrigation application rate have on water retention and movement within the amended soil? This experiment identified that the incorporation of SM, MC and PM significantly increased soil mesopore volume and water retention compared to the control. The change in pore size distribution following amendment addition also resulted in an increase in the proportion of macrpores which increased water movment through the soil in lysimeters where MC and PM were incorporated. This experiment was unable to define any yield effect due to plants not becoming water stressed under the set irrigation schedule.

Experiment 4 (Chapter 6) - The final experiment builds on the findings of Chapter 5 by asking if increasing water retention can prolong plant water use, and whether this translates to an increase in dry matter production? To answer this question, rye-grass in the weighing lysimeters used in Chapter 5 was allowed to grow in non-irrigated conditions until plants had fully senesced. This experiment found that incorporation of MC and SM both increased dry matter yield and prolonged water use compared to the control. The results from this experiment were applied to a simple irrigation calculator and the increase in water retention equated to a potential irrigation saving of 30 mm (SM) or 20 mm (MC) over an irrigation season in Lincoln, Canterbury.

Keywords: Soil water retention, amendment incorporation, spray irrigation, porosity, pore volume, shallow soil

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Terms

The following terms are described as they have multiple definitions in the literature.

Macropores

Pores with diameters greater than 30 µm in diameter.

Macro-mesopores

Pores with diameters between 30 µm and 3 µm. This pore size is equivalent to readily available water capacity.

Mesopores

Pores with diameters between 30 µm and 0.2 µm. This pore size is equivalent to available water capacity.

Micropores

Pores with diameters less than 0.2 µm. This pore size is equivalent to permanent wilting point.

Soil water retention

Volume of water retained in the soil once drainage has ceased.

Drained upper limit/Field Capacity

Volumetric concentration of water retained in the soil when matric potential is equivalent to -10 kPa and free water has drained.

Available water capacity

Water available to plants and is equivalent to mesoporosity.

Readily available water capacity

Water that is easily available to plants and is equivalent to macro-mesoporosity.

Permanent wilting point

Volumetric concentration of water retained in the soil when matric potential is equivalent to -1500 kPa. Equivalent to microporosity.

Symbols

ρ_b	Bulk density (g cm^{-3})
ρ_{bS}	Soil bulk density (g cm^{-3})
ρ_{bA}	Amendment bulk density (g cm^{-3})
ρ_p	Soil particle density (g cm^{-3})
θ_v	Volumetric water content (cm^3 cm^{-3})
ψ	Matric potential (-kPa)
ϕ_t	Total porosity (cm^3 cm^{-3})
ϕ_p	Porosity of pore size p (cm^3 cm^{-3})
$\propto$	Proportional to
ε_B	Bulking strain
ε_N	Net strain
ε_R	Strain ratio
ε_D	Dilution strain
$\varepsilon c\phi_p$	Strain corrected porosity of pore size p (cm^3 cm^{-3})
$\lambda\phi_p$	Net pore volume factor of pore size p
λ_p	Net pore volume of pore size p (mm)
R_T	Water retention (mm)
D_I	Depth of incorporation (mm)
D_H	Depth of horizon (mm)
I_E	Effective infiltration (mm h^{-1})
A	Amendment application rate (g g^{-1})

Acronyms

SM	Sphagnum moss
PM	Polyacrylamide
MC	Municipal compost
BC	Biochar
SI	Silicate gel
ST	Starch gel
DSM	Dairy shed manure
DM	Dry matter (g)
C	Carbon
N	Nitrogen
P	Phosphorous
K	Potassium
S	Sulphur
WU	Water use (mm)
WE	Wetting efficiency
DUL	Drained upper limit (cm^3 cm^{-3})
FC	Field Capacity (cm^3 cm^{-3})
PWP	Permanent wilting point (cm^3 cm^{-3})
HAW	Horizon available water capacity (mm)
AWC	Available water capacity (cm^3 cm^{-3})
WUBP	Water use break point (mm)

Chapter 1 Introduction

Globally, fresh water scarcity is a significant problem as it is essential for the survival of humans and ecosystems (Gleick, 2013). Fresh water is required for food production, and irrigation has been identified as one of the key mechansims to help fill global yield gaps (Mueller et al., 2012). The increasing demand for food has resulted in 70% of global fresh water being allocated to agricultural irrigation, with much of this irrigation being developed on under-performing landscapes (Mueller et al., 2012).

New Zealand has followed global water use trends, with over 50% of the country's allocatable fresh water being used for irrigation (Ministry for Environment & Stats NZ, 2017). New Zealand's irrigated area has increased by 40% in the last 15 years; an expansion rate that is greater than any other country in the OECD (OECD, 2014). Agricultural irrigation is set to continue expanding, with a further 51% increase in irrigated areas planned for New Zealand's Canterbury region (New Zealand Government, 2012) with much of this expansion occuring on vulnerable shallow soils (Carrick et al., 2013). The arrival of irrigation to these previously un-irrigated areas represents an example of the pursuit of "sustainable intensification" (Mueller et al., 2012), whereby the aim is to increase agriculutral production while maintaining or decreasing the current environmental impacts. This approach presents a problem as shallow stony soils are not well suited to irrigation because they are characterised by low soil water retention and rapid permeability (Carrick et al., 2013), two characteristics that are strongly correlated with increased nutrient leaching (Wheeler et al., 2011) and inefficient water use (Hatfield et al., 2001; Howell, 2001). Increasing irrigation on these shallow stony soils may contribute to an increase in nutrient leaching and poor water use efficiency, which may cause more environmental harm than economic good.

Soil management options are available that may improve water retention in New Zealand's shallow stony soils, thereby minimising the adverse effects of irrigation on these soils. The importance of soil management on water retention has been well researched in regard to tillage practices both internationally (Ali and Talukder, 2008; Hatfield et al., 2001) and locally (Francis and Knight, 1993), with the general conclusion being that no-tillage practices improve water retention. Canterbury is New Zealand's primary arable region (Statistics NZ, 2012), which limits the adoption of no-till as high value, high water demand crops require conventional cultivation. An alternative soil management practice that has potential in arable systems is the incorporation of organic (Aggelides and Londra, 2000; Celik et al., 2004) or synthetic (Green et al., 2004; Hosseini et al., 2012) water retention amendments. Research from international studies has demonstrated the importance of soil texture (Akhter et al., 2004; Bauer and Black, 1992; Novak et al., 2012), climate (Khaleel et al., 1981) and standard agricultural management practices (Reynolds et al., 2003) on changes in soil water retention following amendment incorporation. Locally, amendment incorporation has primarily focussed on the nutrient value of the applied product and the resulting yield response (Horrocks et al., 2014; Stewart et al., 1998); however, in a water limited system, increasing soil water retention is likely to be of greater benefit than increasing nutrient input (Carter et al., 2004). Thus, if New Zealand hopes to use such amendements effectively to improve soil water retention, local studies are needed that consider whether this soil management practice has the potential to mitigate the risks associated with irrigating shallow stony soils.

This thesis focuses on determining if soil water retention can be increased through the incorporation of a soil amendment, thus reducing the environmental and economic risks of irrigating shallow stony soils. The main objectives are:

- To evaluate how a range of organic and synthetic amendments can modify soil physical characteristics for increased soil water retention, and to assess if these products have limitations that would restrict their adoption in irrigated agriculture;
- To determine if a commonly available waste stream (municipal compost) can be modified to increase soil water retention, and quantify the relationships between application rate and changes in soil physical properties;
- To assess how amendments modify soil water retention and movement within and through a shallow stony soil under spray irrigation, and
- To quantify whether the increase in soil water retention associated with amendment incorporation can change the relationship between plant water use and dry matter production.

This thesis contains seven chapters addressing these objectives. Following this introduction, Chapter 2 reviews the literature on the potential of amendment incorporation for increasing soil water retention, the limitations of this practice and the current research gaps. Chapters 3, 4, 5 and 6 present progressive hypotheses, methods and results from the experimental component of this thesis.

Chapter 3 presents the results of a laboratory experiment that determined how a range of amendments could alter soil pore size distribution in favour of water-retaining macro-mesopores and mespores. A combination of readily available organic and synthetic amendments were applied at rates recommended by the manufacturers. The hypothesis was that incorporation of municpal compost (MC), dairy shed manure (DSM), sphagnum moss (SM), biochar (BC), polyacrylamide (PM), starch gel (ST) or silicate gel (SI) into a cultivated Templeton silt loam soil would increase soil water retention by increasing the porportion of mesopores. A secondary hypotheses was that amendments would persist for the duration of a typical irrigation season and that there would be no effect of amendment incorporation on surface water repellence at a range of potential refilling points. The results showed that mesoporosity and total mesopore volume were both increased in the order of PM>SM>DSM>BC. All amendments decreased bulk density and increased total porosity. Water repellence and carbon mineralisation were both significantly increased by the incorporation of DSM, however, no other amendment had a significant effect on these properties. The changes in mesoporosity were caused by two modes of action: (1) pores were created through soil and amendment particle interaction, and (2) absorbance of water into the amendment caused pore creation through swell shrink action.

Chapter 4 presents the results of a second laboratory experiment which quantified the effect of maximum compost particle size and application rate on soil physical properties. This question was raised because there was no change in pore size distribution following incorporation of MC in Chapter 3. MC has great potential for use as a soil amendent as it is a readily available and economical product that has been shown to effectively increase soil water retention in previous international studies (Celik et al., 2004; Reynolds et al., 2015). The hypothesis was that MC would increase water retention and that this increase would be positively correlated with application rate and decreasing maximum particle size. The experiment confirmed this hypothesis. Increasing MC application rate increased both the concentration and net volume of mesopores, and maximum mesoporosity was achieved with the smallest MC particle size (<0.25 mm) at the maximum application rate (80% wt/wt). It was concluded that although application rate was positively correlated with increasing water retention, reducing particle size of MC was an effective method of increasing water retention at lower application rates.

Chapter 5 expanded on the results from Chapter 3 and Chapter 4 by building a small weighing lysimeter facility. This experiment aimed to determine if the increase in soil mesoporosity following incorporation of SM, PM and MC measured in Chapter 3 and 4 would persist when the soils were spray irrigated and managed according to conventional practices. Two rates of spray irrigation were applied to determine if there was an interaction between amendment and irrigation management that would result in an increase in overall irrigation efficiency. The hypothesis of this experiment was that incorpation of SM, PM and MC amendments would increase soil water retention and storage under two rates of spray irrigation (10 mm h^{-1} and 80 mm h^{-1}), and that the amendment-induced increase in soil water retention would increase rye-grass yield. This experiment identified that the incorporation of SM, MC and PM increased soil mesoporosity as well as the total volume of mesopores spaces. Amendment incorporation also increased the proportion of macropores in the MC and PM treatments leading to greater effective infiltration during spray irrigation. Plant water stress was not achieved in this experiment. In order to understand the changes produced a production benefit we conducted a second experiment with the lysimeter facility.

Chapter 6 further explored the results from Chapter 5 to determine if the increase in water retention could increase plant dry matter yield. The question this experiment aimed to answer was: Does incorporation of SM, MC and PM prolong water use and increase plant yield compared to an un-amended control? To answer this question, rye-grass in the weighing lysimeters used in Chapter 5 was allowed to grow in non-irrigated conditions until plants had fully senesced. This experiment found that incorporation of MC and SM increased dry matter yield and prolonged water use compared to the control. This experiment found that these changes could reduce irrigation requirement by as much as 30 mm (SM) or 20 mm (MC) over an irrigation season in a local field situation.

Chapter 7 summarises the experimental work and offers suggestions for future research work.

The thought progression from Experiment 1 onwards is presented in Figure 1.1.

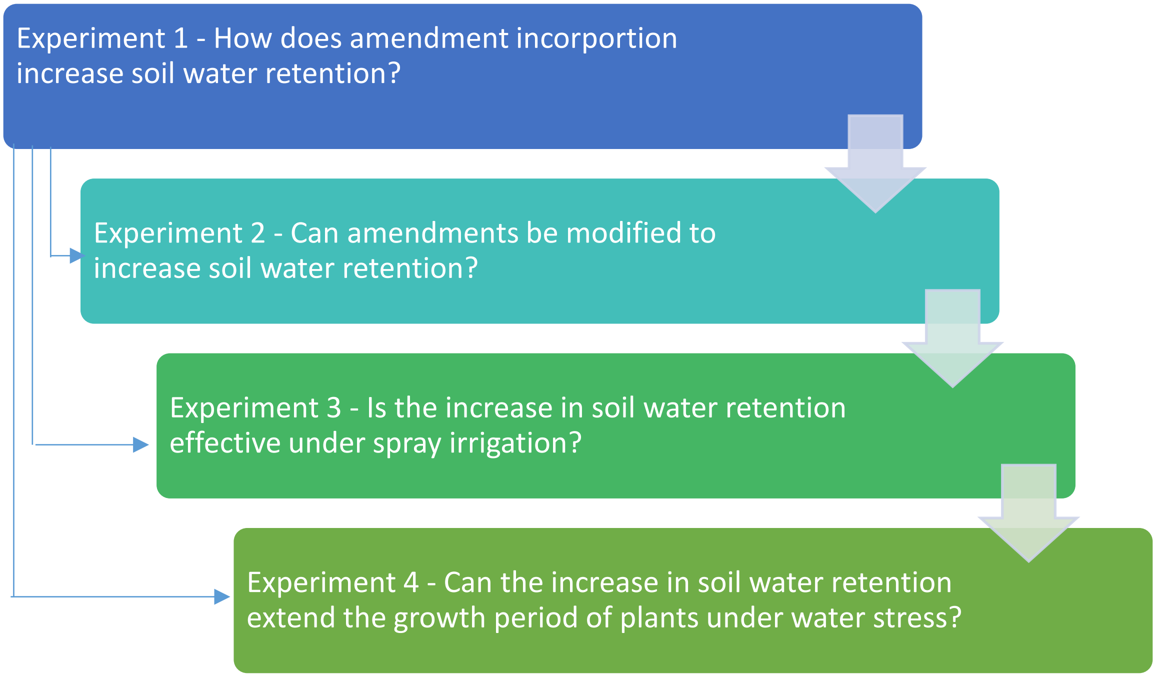


Figure 1.1 Thought progression of the thesis, highlighting the question which each experiment aimed to answer and how this relates to the original question.

Chapter 2 Literature review

2.1 Irrigation and stony soils

Globally, there is an increasing demand for fresh water (Gleick, 2003). Agriculture is the largest consumer of freshwater, with 70% of withdrawals used for agricultural production in developed countries (United Nations World Water Assessment Programme, 2014). New Zealand's water use reflects the global trends, with over 50% of allocated fresh water used by agricultural irrigation (Ministry for Environment & Stats NZ, 2017). Irrigation in New Zealand has expanded by approximately 40% between 2002 and 2017, the majority (74%) of this expansion taking place on the east coast of the South Island in the Canterbury region (Ministry for Environment & Stats NZ, 2017). Irrigation expansion is set to continue, as a further 51% increase in irrigated area is currently planned for Canterbury (New Zealand Government, 2012). Although the efficiency of irrigation infrastructure has improved with time (Brown, 2016), the expansion of this infrastructure is increasingly occuring on shallow stony soils which are poorly suited to irrigation (Carrick et al., 2013).

Shallow stony soils present a major challenge for irrigation as they are limited by depth of fine textured material (< 45 cm to gravels) and hydraulic characteristics (moderate to rapid permeability and low water retention) (Carrick et al., 2013). The low water retention of these soils (30 – 90 mm over a 1 meter profile depth) is especially challenging as they require more frequent irrigation to maintain maximum plant growth, and relatively low application volumes to avoid drainage and nutrient losses by leaching. These soils have been identified as being highly vulnerable to nutrient losses and there is a need for targeted research to determine how best to manage them under irrigation (Carrick et al., 2013). Nutrient losses could be reduced by increasing potential soil water retention as this has been positively correlated with reducing nitrate leaching (Wheeler et al., 2011). Increasing soil water retention also has positive effects on irrigation efficiency as more water retained following irrigation means more irrigation water can be applied in a single application without the risk of drainage losses. Thus, increasing soil water retention allows irrigation frequency to be reduced which can result in significant savings in irrigation cost and better management of individual water allocations (Bloomer et al., 2013). These benefits could compound to improve environmental and economic outcomes of irrigated systems. While there are a variety of soil management options that may reduce nutrient loss and improve water use efficiency, one potential mechanism for achieving these goals is modifying the water-retaining porosity of the soil. However, little attention has been given to modifying soil water-retaining porosity to improve irrigation management. Therefore, this review will focus on determining if soil physical characteristics can be modified to increase potential soil water retention.

2.2 Descriptors of soil water retention

When evaluating changes in water retention it is important to understand the various terminology involved. Points of water stress relating to plant water demand can be described as contents, limits and points, while the volume of water a soil can hold can be referred to as content, capacity or simply "water" (McQueen, 1993). The aim of this section is to clarify the two most common stress points (field capacity and permanent wilting point), and two common descriptors of a soils plant available water retention capacity: readily available water and available water. These stress points are related to soil pore sizes and their linkages will be discussed in Section 2.3.2.

2.2.1 Field capacity

Field capacity (FC) was originally defined by Veihmeyer and Hendrickson (1931) as "the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement has materially decreased". Although this definition is broadly applied (McLaren and Cameron, 1996), it can be easily criticised as it is not a true equilibrium water content, rather, it is a water content reached when the water flux out of the root zone has become negligible (Cassel and Nielsen, 1986). Therefore, the representation of FC as a specific matric potential (whereby equilibrium is reached) is not representative of a field situation. However, FC is commonly determined from intact soil cores that are saturated and then subjected to a tension or pressure to achieve equilibrium at a specific matric potential (Reynolds and Topp, 2007b).

The matric potential that best represents FC is still debated, however, Colman (1947) originally suggested that -33 kPa be applied to determine FC and this pressure has been consistently applied in international studies since (Kirkham, 2005). In New Zealand, the standard matric potential for FC is currently -10 kPa (McQueen, 1993); however, when Gradwell (1968) was initially reviewing the literature to determine an appropriate matric potential to apply for FC he reported values ranging from -4 kPa to -50 kPa had been used in the past. The decision of which matric potential to represent FC has a significant impact on the calculation of available water capacity (AWC) as it represents the upper limit of available water, and as such FC can also be referred to as the drained upper limit, particularly when measured in the field (Ratliff et al. 1983). It is important to note that although FC represents a point at which large pores have drained, this does not mean that the draining water is not readily available for plant use (Kirkham, 2005).

2.2.2 Permanent wilting point

Permanent wilting point (PWP) has been defined by Kirkham (2005) as “the amount of water per unit weight or per unit soil bulk volume in the soil, expressed in percent, that is held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt”. The PWP was initially set by determining the soil water content when a sunflower (*Helianthus annuus*) is grown in 500 g of soil in a metal can until the third pair of true leaves are formed. The can is then sealed with wax and the sunflower is grown until it is wilted. It is then transferred to a dark, humid chamber to recover. If recovery occurs, the plant is returned to the greenhouse until the plant remains wilted overnight in the humid chamber. The soil water content of the soil in the can is then considered to be the soils PWP (Veihmeyer and Hendrickson, 1927). This method is impractical and because of this, the water content of the soil when it has reached a matric potential of -1500 kPa is generally considered to be a good proxy for PWP (Kirkham, 2005). However, PWP is a plant-dependent variable and therefore the use of a single matric potential to describe it is questionable. To demonstrate the inaccuracy of -1500 kPa as representing PWP for all soil and plant combinations, Horne and Scotter (2016) calculated that the volumetric water content of PWP measured in the field for a silt loam under pasture was 0.07 cm^3 cm^{-3} lower than that measured at -1500 kPa. The uncertainty around these values indicates that to truly determine the effectiveness of amendment incorporation on soil water retention the process needs to be repeated under field conditions.

2.2.3 Available water capacity

Available water capacity (AWC) is defined simply as the difference between FC and PWP (McLaren and Cameron, 1996; McQueen, 1993). Profile available water can then be calculated from these measurements by multiplying AWC by the rooting depth of the plant. One major problem with this calculation is the fact that rooting depth is not constant for all plants and is strongly influenced by both the vigour of the plant and the soil and climatic conditions in which the plant is growing. To navigate this problem, an assumed total rooting depth of 30 inches or 760 mm is used for pasture (Horne and Scotter, 2016).

2.2.4 Readily available water capacity

Available water describes the total amount of water that can be stored in the soil; however, the water in this store is not equally available to plants (Lacey, 2017; McLaren and Cameron, 1996). To address this, the concept of non-limiting (Kirkham, 2005) or readily available (McQueen, 1993) water capacity has been introduced, which acknowledges that within the available water range there is a zone where water is more readily available to plants. This concept is particularly applicable to irrigated systems and is used in Australia (Lacey, 2017) and New Zealand (Foundation for Arable Research, 2010; Pratt et al., 1997) to define when to trigger an irrigation application. Australian agronomists have recommended matric potentials based on crop type with effective water retention at -20 kPa for vegetables and -100 kPa for annual pastures and other relatively hardy crops (Lacey, 2017). Locally, Webb and Wilson (1995) defined the matric potential of the lower limit readily available water as -1500 kPa in the 0-0.4 m layer and -100 kPa in the lower layers. Webb and Wilson (1995) also defined that readily available water holding capacity be measured via the tension table and pressure plate water-release methods defined by Gradwell and Birrell (1972). This definition was later simplified further by McQueen (1993) who recommended that readily available water be defined as the difference between volumetric water content at -10 kPa and -100 kPa . This definition has been used in subsequent studies of soil quality under a range of land uses (Ross et al., 2009; Sparling and Schipper, 2002).

2.3 Soil properties controlling water retention

The amount of water held in the soil matrix following wetting is governed by fixed and dynamic soil properties. Fixed, or inherent, soil properties include soil texture and horizon thickness, whereas dynamic properties - those readily modified by soil management - include aggregate size, structure, bulk density and organic matter content (Marshall and Holmes, 1988).

2.3.1 Inherent soil properties

Texture

The primary inherent soil property governing soil water retention is texture (McLaren and Cameron, 1996). Soil texture has been defined by McLaren and Cameron (1996) as the proportion of soil particles belonging to three size fractions (sand, silt, clay) in the less than 2 mm diameter fraction. These particles can be split into three main categories: sand, silt and clay, and the specific proportions of each component create the soils final texture. Texture governs soil water retention primarily due to the way water is stored within the soil matrix through adhesion, cohesion, and the combination of these two forces: capillarity (McLaren and Cameron, 1996). Water retention occurs due to adhesion of water to particles and capillarity of water infilling the spaces created between particles. Changing soil particle sizes as well as the sorting and packing of these particles can therefore lead to significant changes in water storage potential of the soil matrix (Bear, 1988). The relationship between soil particle size and soil water was initially discussed by Arya and Paris (1981) and was improved through the use of fractal mathematics by Tyler and Wheatcraft (1989). The reader is referred to these studies for further discussion on the importance of soil texture, sorting and packing on the final pore volume and pore size distribution. Traditionally, soil depth would also be included as an inherent property, however, amendment incorporation challenges this idea and is therefore discussed as a dynamic property in the following section (Section 2.3.2).

2.3.2 Dynamic soil properties

There are two main dynamic soil properties governing soil water retention: soil structure and soil porosity (McLaren and Cameron, 1996). In the case of amendment incorporation there is also likely to be a third dynamic property: soil depth.

Structure and Porosity

Soil structure refers to the shape, size and degree of aggregation of the primary soil particles and how these aggregates are arranged. The arrangement of aggregates produces pores which are best described as the voids between and within soil particles and aggregates (Hillel, 1998). Pores created between aggregates and particles can be described as contributing inter-particle pore space, while intra-particle pore space refers to the spaces within each individual aggregate or particle (Horn and Smucker, 2005). The combination of inter-particle pore and intra-particle pore space represents the soils total porosity which can be defined as the total volume of soil pore space per unit bulk volume of soil (Reynolds and Topp, 2007a). The soils porosity is highly important for soil water infiltration, retention, drainage, aeration and plant development (McLaren and Cameron, 1996). Total porosity can be split further in to three main pore categories which help to describe the soils potential for water movement and water retention. These categories are: macropores, mesopores and micropores. Macropores are soil pores that are considered to be empty of water at FC and are involved in the infiltration and transport of water and air through the soil matrix near saturation; mesopores are those that retain water against gravitational forces for plant production and are therefore the pores that describe AWC; and micropores are those that retain water that is inaccessible to plants, and hence water held at PWP and above. Of these categories, macropores are most readily influenced by soil management practices (Kay, 1998) and have strong control on the soils mechanical characteristics, aeration, water and solute flow, and root development. The relationship between saturated flow and macroporosity has been described by Beven and Germann (1982) who assumed that macropore flow is analogous to laminar Pouiselle flow through vertical tubes, where:

$$Q_s \propto {E_{ma}}^2$$

Where Q_s is the saturated flux density and E_{ma} is the porosity of the macropore system (Beven and Germann, 1982). Multiple sizes have been suggested to describe macropores, ranging from >1000 µm diameter (Luxmoore, 1981) to >29 µm diameter (Belyaeva and Haynes, 2012), however, the most common description is pores with a diameter of >30 µm (Kay, 1998). Macropores form by a range of processes including soil shrinkage, root growth and decay, activity of soil fauna and management practices such as tillage (Kay, 1998).

Compared to macropores, mesopores are less influenced by physical soil management, and the water held in these pores has been referred to as plant available water (Veihmeyer and Hendrickson, 1927). The mesopore range was first recommended by Luxmoore (1981) as a means of describing pore diameters of 10 – 1,000 µm, more recently, mesoporosity has been associated with AWC, as mesopores are considered to be water filled at matric potentials between -10 kPa to -1500 kPa, which corresponds to pore sizes of 30 – 0.2 µm (Kay, 1998). Mesopores can be created through multiple mechanisms, including the creation of microcracks in the soil matrix due to changes in volume, the collapse of macropores, infilling of macropores by new material, or changes in pore structure due to the development of root hairs and fungal hyphae (Kay, 1998).

Micropores are the least affected by soil management, as the water retained in these spaces is largely due to adhesion of water to soil particles. Therefore, microporosity is strongly correlated with soil texture (McLaren and Cameron, 1996). Oades (1984) defined micropores as those containing bound water unavailable for plants, and relating to pore diameters <2 µm. Although microporosity can be largely an inherent property, it has been proposed that micropores can be created by the collapse of mesopores or shrinkage of the soil matrix (Kay, 1998).

Soil depth

Soil depth has been traditionally thought of as an inherent soil property, however, the addition of large volumes of low density material during amendment incorporation is likely to make this property a dynamic one. Previous studies have identified that incorporating organic material reduces both the soil compaction potential (Soane, 1990) and bulk density (Eden et al., 2017; Rawls et al., 2003). It follows that the addition of a significant mass of amendment in to a cultivated layer, which lowers bulk density, will increase net soil volume. This increase in soil volume will present itself as an increase in soil depth, as the volume change is most likely to occur on the vertical plane as the amended layer is constrained by the uncultivated soil layer below and unconstrained above. Although the change in depth following amendment addition has been discussed (Chang et al. 2007), it has received little research attention as the potential changes are likely to be insignificant in most soils. However, when total water retention of a shallow stony soil has been reported to be as low as 30 mm, (Carrick et al., 2013) an increase in soil depth of 20 mm could represent a potential increase in plant available water retention of 17% due to the depth change alone (assuming AWC of 25%). Pursuing this theory further - in unison with changes in pore size distribution - should allow for a more complete view on the potential of amendment incorporation to increase soil water retention of these shallow stony soils.

2.4 Amendment incorporation to increase soil water retention

Soil management practices, such as no tillage, have been shown to modify porosity on Canterbury's stony soils (Francis and Knight, 1993). However, conventional tillage remains the dominant establishment method for high value irrigated crops in Canterbury, and therefore, a management practice that increases water retention while working with established methods will ultimately be the most successful option. Consequently, this literature review focusses on the efficacy of increasing water retention with soil amendments incorporated during conventional tillage. Furthermore, amendments are frequently used to improve other soil conditions such as soil fertility (e.g. addition of nitrogen (N), phosphorous (P) and potassium (K)), chemistry and physical properties (lime and gypsum), which further improves the likelihood of the adoption of this management practice.

2.4.1 Amendment selection

An effective amendment to improve soil water retention must have certain properties. These properties, summarised by Kay (1998), are: 1) the pore characteristics of the material and its capacity to absorb water; 2) the capability of the material to increase inter-aggregate porosity by the strengthening of pore walls or creating new secondary pore spaces; and 3) persistence of the material (recalcitrance or protection against attack by micro-organisms). If an amendment possesses these three properties, it may improve soil water retention by: 1) providing water absorbing porosity; or 2) infilling or stabilising pore spaces following cultivation.

A range of waste products and bespoke water retention amendments are currently available and have the potential to be incorporated during secondary cultivation to provide an instantaneous increase in water retention when high value, high water-demand crops are being planted. These products can be classified as organic products, when they are a naturally occurring waste product, or synthetic, when they have been developed specifically to increase water retention.

2.4.2 Organic amendments

The use of organic waste streams as a soil amendment offers a benefit to agriculture and the environment as agricultural production can be increased while diverting waste from landfills (Eden et al., 2017). Organic amendments that have been shown to improve soil water retention include unprocessed materials such as manure (Celik et al., 2004) and sphagnum peat (Li et al., 2004), along with processed products such as composts (Aggelides and Londra, 2000) and biochar (Atkinson et al., 2010). The majority of research on the incorporation of organic amendments has been conducted at long term amendment application sites (Eden et al., 2017) and focusses on plant response rather than the change in physical properties (Khaleel et al., 1981), with few studies reporting changes in soil water retention in the first year of application.

The few short-term studies that have assessed organic amendments such as manure, compost and biochar incorporation have indicated that soil water retention can be improved through a single incorporation event. Aggelides and Londra (2000) reported that incorporation of high rates of compost (39, 78, and 156 t ha^{-1}) on loam and clay soil increases soil water retention proportional to the amount applied. A similar study by Celik et al. (2004) compared the response of soil physical properties to the application of cattle manure, compost, mycorrhiza-treated compost and conventional fertiliser. Their field study found that the greatest increase in water retention was attributed to compost, followed by manure, with no significant difference in mesoporosity between the control, fertiliser and compost plus mycorrhiza treatment. Incorporating biochar to cropping soils as a means of sequestering carbon has received significant attention in recent years; however, the use of biochar is often considered in isolation. Novak and Watts (2013) compared incorporation of biochar and the un-pyrolised switchgrass feedstock to a loamy sand soil at a rate of 2% (equivalent to 40 t ha^{-1}) and found that both biochar and switchgrass increased water retention relative to the control, with no significant difference in the effects of biochar and uncharred switchgrass. However, Hardie et al. (2014) incorporated 47 t ha^{-1} in to a sandy loam and concluded that there was no evidence of biochar improving soil porosity and therefore no improvement in water retention. Blanco-Canqui (2017) reviewed the literature on the impact of biochar on soil physical properties and concluded that incorporating biochar reduces bulk density by 3% - 31%, increases total porosity by 14% - 64% and increases AWC by 4% - 134%. Although amendments such as biochar have received a lot of attention, others, which are locally available in Canterbury, such as sphagnum moss harvested on New Zealand's West Coast remain relatively unexplored. The decomposed and compressed form of sphagnum moss - sphagnum peat - has received some attention, with Li et al. (2004) reporting that incorporating sphagnum peat to a loamy sand increased water retention, decreased bulk density and increased total porosity.

Traditionally, changes in soil water retention following organic amendment incorporation have been attributed to the increase in organic carbon and the positive effects this has on soil structure, pore space and polysaccharide gel creation (Rawls et al., 2003). Emerson (1995) stated that the addition of organic matter can increase AWC by up to 13 g of water for every 1 g of incorporated organic carbon. This finding has been disputed by Haynes and Naidu (1998) who found that adding organic matter increases soil water content at both FC and at PWP, thereby causing no change to plant available water capacity. This apparent contradiction has continued, with a recent review on the effect of incorporating organic waste into agriculture soils by Eden et al. (2017), who concluded that "organic amendments generally induce beneficial effects on plant available water and other soil properties". Nonetheless, the review of Minasny and McBratney (2017) reported that an increase of 1% in soil organic carbon resulted in a negligible change in available water content of between 0.7% and 2%, with sandy soil being the most responsive to the addition of organic carbon. Although the importance of organic carbon addition on soil water retention is likely to receive further attention it is generally agreed that organic amendments change soil structure, which is frequently manifested as a lower bulk density and greater total porosity (Khaleel et al., 1981). The decrease in bulk density has been attributed to dilution of the largely silicate-derived soil matrix with less dense organic material (Khaleel et al., 1981; Soane, 1990), or an increase in soil aggregation and attendant pore spaces (Franzluebbers, 2002; Kay, 1998).

There has been little research regarding the effects of soil amendment on water retention of the vulnerable shallow stony soils of Canterbury. Much of the previous research in to the effects of incorporating composts into cropping soils in Canterbury has focussed on nutrients and the associated yield response. Stewart et al. (1998) reported physical soil changes following the incorporation of mushroom substrate into an arable soil in Canterbury, and found that this practice reduced bulk density and increased macroporosity after two years of application. In that study, an increase in mesoporosity and microporosity with increasing application rate was measured; however, these changes were not statistically significant. Additionally, Horrocks et al. (2014) applied municipal compost mixed with conventional fertiliser to an arable soil and found that the greatest yield benefit occurred when conventional fertiliser was applied with compost, the cause of this synergistic benefit was not clear and the authors concluded that the result was potentially due to the addition of other ingredients in the compost such as humic substances which improved N uptake. Another potential reason for the synergistic effect reported by Horrocks et al. (2014) may be the “non-nitrogen” effect of increasing water retention, which was originally proposed by Carter et al. (2004) who suggested that the potential increase in water retention associated with compost incorporation may be more important for crop yield than any potential nutrient benefit.

2.4.3 Synthetic amendments

Synthetic water retention amendments are typically designed to absorb water and release it within a specified range of matric potentials (Zohuriaan-Mehr and Kabiri, 2008). The most common forms of synthetic amendments are the hydrogels or super absorbent polymers. These amendments are created with internal anionic cross-linked chains which can absorb large amounts of water, causing the material to expand yet hold its original form (Zohuriaan-Mehr and Kabiri, 2008). These materials absorb water via a combination of three processes: 1) physical entrapment of water via capillary forces, 2) hydration of functional groups, and 3) dissolution and thermo-dynamically favoured expansion of the macro-molecular chains limited by cross-linkages (Zohuriaan-Mehr and Kabiri, 2008). A secondary synthetic amendment is silicate granules. Silicate granules are generally made from silicate based stone powders, carbon compounds and cellulose that attach to the surface of soil particles which increases the area available for nutrient and water adsorption (Farrell et al., 2013).

Despite these products being designed to improve water retention, assessments of their effectiveness have been mixed and few studies have addressed the response in the field. Field studies are important because the efficacy of these amendments has been demonstrated to reduce with repeated wetting and drying cycles and with increasing salinity of irrigation water (Akhter et al., 2004; Green et al., 2004). These conditions are typical in actively managed arable systems in Canterbury (i.e. frequency of irrigation and application of agrichemicals) and need to be considered in order to define the optimal use of these products.

Along with irrigation and agrichemical management, soil texture may also influence the success of synthetic amendments. A common conclusion amongst studies is that coarse textured soils produce the greatest water retention response to synthetic amendment incorporation. The effect of soil texture on hydrogel performance has been studied by Abedi-Koupai et al. (2008) who performed a soil column study where two hydrogels were applied at increasing rates (2, 4, 6, 8 g kg^{-1} soil) on three different soil textures (sandy loam, loam, clay) and reported that at the maximum application rate, water retention increased 1.8, 2.2 and 3.2 fold in clay, loamy and sandy loam soils, respectively. Similarly, Farrell et al. (2013) compared the effect of silicate granules and hydrogels incorporated into two different green roof mediums: scoria and crushed terracotta. The study found that silicate granules increased water retention of both growing mediums, however, the hydrogel was effective only in the coarser scoria mix. Both studies concluded that the reduced response in the finer textured soils was due to limited expansion of the hydrogel particles. The results from past research indicate that the potential of these amendments to increase soil water retention is soil, site and amendment specific. Therefore, targeted research is required to determine if synthetic amendments are a viable option to increase soil water retention of Canterbury’s shallow stony soils, and if so, by what mechanism.

2.4.4 Mechanisms that modify water retention

Incorporation of amendments can increase soil water retention by multiple mechanisms; the most common being inherent amendment properties or interaction between soil and amendment. Organic amendments bring inherent porosity (Kinney et al., 2012) and additional surface area (Novak et al., 2012; Novak and Watts, 2013), which can increase water retention, while synthetic amendments can absorb up to 1000 times their weight in water (Zohuriaan-Mehr and Kabiri, 2008). A mechanism that involves interaction between the amendment and the soil, for example, is when the organic matter provided by manure and compost stabilises aggregates created following tillage (Pagliai et al., 2004). This in turn creates more inter-particle pore spaces in which water can be stored. Although inter-particle pore creation has been defined as mechanism to change soil porosity, few studies have investigated how amendment particle size could influence the resultant inter-particle pore space in soil. Recently Liu et al. (2017) reported a relationship between biochar particle size and changes in pore size distribution following amendment incorporation, however, there is a need for similar studies on more readily available amendments such as composts. Organic amendments are also known to decrease bulk density and increase total porosity by diluting dense soil mineral particles with a low density solid (Khaleel et al., 1981), however, the decrease in bulk density could also be the result of new pores being created by amendment-soil interaction. The latter effect has received little attention, but this and other changes to soil physical properties may help explain the success, or lack thereof, of soil amendments to increase soil water retention.

2.4.5 Limitations of amendment incorporation

Although amendment incorporation can improve soil water retention, limitations to this practice do exist. The primary limitations of interest for an irrigator are the length of time an amendment is effective for and the potential of the amendment to increase water repellence and therefore reduce irrigation efficiency. Firstly, the persistence of the amendment has been discussed by Kay (1998) as a key consideration in appropriate amendment selection. The persistence of various organic amendments has been evaluated by Bernal et al. (1998) who concluded that the less stable the incorporated amendment the greater the rate of decomposition; manure broke down more quickly than composted products. This indicates that the persistence of an individual organic amendment is likely to be dependent on climate, land management, inherent soil properties and plant amendment interactions. Therefore, site specific research is required to assess their suitability as amendments to increase soil water retention.

Secondly, the onset of water repellence has been observed when manure (Olsen et al., 1970) and biochar (Briggs et al., 2012; Kinney et al., 2012) are incorporated in to the soil surface. However, few studies have measured the persistence of surface water repellence following amendment incorporation, so there is little information from which to draw conclusions about the length or magnitude of the effects. Determining the extent of these limitations alongside the potential improvement in soil water retention would enhance the understanding regarding the suitability of soil amendments for irrigated systems.

2.5 Plant response to amendments

The previous section of this review identified the potential of amendment incorporation for increasing soil water retention. In order for this soil management practice to be viable it would either need to increase income via increased harvestable yield or reduce costs via less frequent irrigation.

Plants have been shown to respond both positively and negatively to the addition of organic amendments. Mamo et al. (2000) found that applying 270 t ha^{-1} of solid waste compost to a sandy loam led to an increase in plant water stress in the first year due to the salt loading associated with such a large application. However, in the second year, water retention increased and this was associated with an increase in yield. Applying compost at lower rates has had positive plant impacts, with Carter et al. (2004) reporting that compost incorporated into a sandy loam at a rate of 29 t ha^{-1} increased potato tuber yield by 13% relative to the un-amended control. Similarly, Nguyen et al. (2012) reported a compost-amended sandy soil had greater root and shoot growth of tomato plants relative to a control, although, when these plants were drought stressed they wilted earlier in the amended soil.

Plant response to synthetic amendments has also been variable. Agaba et al. (2011) conducted a large pot study investigating the water use efficiency of a sandy soil following amendment with a polyacrylamide-based hydrogel at a rate of 0.2% and 0.4% compared to a non-amended control. The main finding was that water use efficiency was dramatically increased with the addition of the hydrogel, with water use efficiency being 1.56 g, 2.75 g and 13.7 g of dry matter per litre of water use for the control, 0.2% hydrogel application and 0.4% hydrogel application, respectively. Abedi-Koupai and Asadkazemi (2006) performed a similar pot study and found that incorporating 0.4% hydrogel reduced the amount of water required to grow an ornamental plant by 33%. The results of these pot studies contradict the field results of Green et al. (2004) who found no improvement in corn yield or water use efficiency when two comparable rates of hydrogel were applied.

Although work has been done to determine the effect of amendment incorporation on income (plant yield), few studies have considered the benefit of increased water retention on potential yield benefit. This form of research, which considers the economic benefit not only of increased income through yield gains but also of decreasing irrigation costs due to less frequent irrigation application, may allow the full economic benefit of this practice to be determined.

2.6 Scope for further research

This chapter has covered the expansion of irrigation in New Zealand and highlighted the need for a management practice that can increase soil water retention in order to improve the irrigation suitability of shallow stony soils. A summary of how water retention could be increased through the incorporation of a water retention amendment, how this would work and how plants are likely to respond was then presented.

This literature review has identified the following research gaps:

- What is the comparative effectiveness of a range of amendments, both organic and synthetic, on increasing water retention of an arable silt loam?
- Does this practice have associated limitations such as increasing water repellence or C mineralisation of the soil?
- Can the selection of appropriate amendment particle size and application rate modify soil pore size distribution?
- Does the potential change in soil volume following amendment incorporation increase water retention?
- Can amendments increase water retention of a spray irrigated silt loam?
- What is the potential of amendment incorporation to improve plant yield due to increased water retention?

Chapter 3 Modifying soil porosity for enhanced water storage using organic and synthetic amendments

3.1 Introduction

Agriculture is the largest consumer of fresh water globally, with 70% of fresh water withdrawals used for agricultural production in developed countries (United Nations World Water Assessment Programme, 2014). New Zealand has had one of the world's highest rates of agricultural land intensification over recent decades (OECD/FAO, 2015) which has largely been fuelled by an 88% increase in irrigated area between 2002 and 2017 (Ministry for Environment & Stats NZ, 2017). The majority of this irrigation expansion has occurred in the Canterbury region which now accounts for 74% of the country's irrigated area (Brown, 2016). Much of Canterbury's future irrigation expansion will be on shallow stony soils, which are limited by both poor water retention and rapid permeability making the management of optimal soil water content difficult and increasing the risk of nutrient leaching (Carrick et al., 2013).

To prevent production losses, these soils require frequent low volume irrigation applications, which makes maintaining optimal soil moisture difficult. Water retention following rainfall and irrigation is controlled by a soil's mesopores (pores 30 – 0.2 μm in diameter) and the plant rooting depth. To increase water retention and potential productivity, a soil management practice is required that could: 1) increase soil mesoporosity, 2) increase the plant rooting depth, or 3) a combination of both. One potential solution for growing cultivated crops is to incorporate a soil amendment during cultivation that directly increases water retention by increasing the concentration or total volume of mesopores. Amendments are frequently used to improve other soil conditions such as soil fertility through organic or synthetic fertiliser (e.g. nitrogen, phosphorus, potassium) and pH, or to overcome limiting structural properties (e.g. lime, gypsum), therefore, the incorporation of an amendment that can significantly increase soil mesoporosity has the potential to be readily adopted.

Amending soil with a range of organic products such as compost, manure (Celik et al., 2004), sphagnum moss (Li et al., 2004) and biochar (Atkinson et al., 2010) have been shown to effectively increase soil mesoporosity. These studies investigated long-term applications of high rates of organic products on soil physical properties, however, there are few studies that consider the immediate effects on mesoporosity.

Several mechanisms have been reported to be responsible for increases in soil water retention following amendment incorporation. Principally, soil water retention is increased due to 1) the pore characteristics of the material added and its capacity to absorb water, which can be referred to as the addition of intra-particle pore spaces, and 2) the capability of the material to create new pore spaces through interaction of amendment and soil particles, which can be referred to as the addition of inter-particle pore spaces (Kay, 1998; Liu et al., 2017).

Organic amendments have often been reported to reduce bulk density due to a “dilution” effect, whereby the addition of a low density amendment dilutes the dense mineral fraction of the soil (Khaleel et al., 1981). This effect could improve soil porosity, aeration, root penetration, water and nutrient use, and microbial activities.

Synthetic amendments such as polyacrylamide gel (Sojka et al., 2007), silicate gel (Farrell et al., 2013) and starch gel (Woodhouse and Johnson, 1991) are designed to absorb water. These products have an advantage over organic amendments in that they can increase soil water retention at much lower application rates. However, the majority of research in to these products has taken place on sandy soils, which are not comparable to the silt loam textured soils of interest in this thesis.

Although amendment incorporation has the potential to improve soil water retention, it can also have limitations for irrigated agriculture. Water repellence or hydrophobicity is produced by hydrophobic organic substances accumulating on soil surfaces (Müller and Deurer, 2011) and has been observed when organic material in the form of manures (Olsen et al., 1970) and biochars (Briggs et al., 2012; Kinney et al., 2012) are applied to cultivated soils. Carbon mineralisation has also been reported to increase following the incorporation of organic materials (Bernal et al., 1998), which may indicate rapid amendment decomposition (Ajwa and Tabatabai, 1994).

The objectives of this study were to: 1) determine if incorporating sphagnum moss (SM), municipal compost (MC), biochar (BC), dairy shed manure (DSM), polyacrylamide (PM), silicate gel (SI) and starch gel (ST) can increase the mesoporosity of a cultivated silt loam and 2) determine if amendments increased soil water repellence and C mineralisation.

3.2 Materials and Methods

3.2.1 Soil and amendments

The soil used in this study was a Templeton silt loam (Typic Immature Pallic Soil; Hewitt, 2010) collected from a depth of 0-10 cm at a research site located in Chertsey, Canterbury, New Zealand (43°47' S, 171°57'E). The soil texture was 23% clay, 70% silt and 7% sand; total C was 2.58% and total N was 0.22%. The site had been intensively cultivated (single pass of mouldboard plough and two passes with power harrow) every year for the previous 10 years.

Seven amendments were incorporated with soil: dairy shed manure (DSM), municipal compost (MC), sphagnum moss (SM), biochar (BC), polyacrylamide gel (PM) (Trade name: Broadleaf P4, Broadleaf Industries, USA), silica gel (SI) (Trade name: Sanoplant, Sanoway GmbH, Austria) and starch gel (ST). The DSM was sourced from a Canterbury dairy farm, which operated a solids separator with a 0.5 mm screen; effluent was pumped from the holding pond and passed through the solids separator which separated the liquid and solid components of the sludge. The MC (certified organic, aged 21 weeks) was sourced from Living Earth, Christchurch, New Zealand. The SM, originally harvested on the West Coast of the South Island, New Zealand, was purchased from a landscape supply store; the BC was sourced from Bishop Research Ltd, Palmerston North, New Zealand, and was made from a feed stock of air-dried *Pinus radiata* forestry residue, which was pyrolysed in a stainless-steel rotary drum at a maximum temperature of 450°C for 80 minutes. The PM was sourced from Transplant Systems New Zealand. The SI was sourced from Sanoway Australia and is produced by granulating silica, carbon and cellulose (Hosseini et al., 2012). The ST was sourced from the Bio Polymers Research Group at the New Zealand Institute for Plant & Food Research. Physical and chemical properties of these products are presented in Table 3.1.

Table 3.1 Particle density (ρ_p), un-packed bulk density (Un-packed ρ_b), total C and total N of Control (Con), Dairy Shed Manure (DSM), Municipal Compost (MC), Sphagnum Moss (SM), Biochar (BC), Polyacrylamide (PM), Silicate Gel (SI) and Starch Gel (ST). *Note the un-packed bulk density of Con was not measured as this was packed to a pre-determined target bulk density.

Treatment	ρ_p (g cm^{-3})	Un-packed ρ_b (g cm^{-3})	Total C (%)	Total N (%)
Con	2.65	1.18*	2.58	0.22
DSM	0.57	0.05	47.03	0.97
MC	2.04	0.56	25.07	2.28
SM	0.57	0.04	45.77	0.67
BC	1.07	0.20	78.71	0.34
PM	1.00	0.66	42.19	11.32
SI	2.57	0.80	13.33	2.07
ST	1.98	0.46	39.64	0.01

3.2.2 Sample preparation

Soil was sieved to ≤8 mm in the field to simulate a seed bed cultivation before being gently mixed in a trough. Soil and all amendments were then air dried at 25°C for 7 days. The amendments were then homogenised using a food processor and sieved to ≤4 mm. Subsamples of the soil and amendments were oven dried at 105°C to determine initial gravimetric water content prior to mixing.

The DSM, MC, SM and BC were applied at a rate of 1% (g amendment per g soil), while PM, SI and ST were applied at 0.1%. A standard application rate of 1% for organic amendments was used based on manufacturer recommendations and previous studies that incorporated sphagnum (Parent et al., 2000), cattle manure (Miller et al., 2002), compost (Naeini and Cook, 2000; Taban and Naeini, 2006) and biochar (Laird et al., 2010). Synthetic amendments have been applied at a rate of 0.1% in other studies of polyacrylamide (Taban and Naeini, 2006) and silicate powders (Farrell et al., 2013), and this rate also is in line with the recommendation provided by the manufacturers.

Individual soil and amendment samples were mixed in a sealed container for 30 minutes using a tumbler. The mixed sample was then packed in 1 cm deep increments into brass cores (5.4 cm internal diameter by 3 cm in height, base covered with 15 µm nylon gauze) with eight replicate cores prepared for each treatment. Control soil cores were packed in 1 cm increments to a target bulk density of 1.18 g cm^{-3} using a hand operated steel piston with a 5 cm diameter. Amending the soil adjusted the volume of the sample. To correct for this the packed bulk density was adjusted according to the calculated bulking strain (ε_B) (see section 3.2.5 – Bulking strain) which accounted for the un-packed bulk density of the amendment, and the mass of amendment added. Un-packed bulk density of each amendment was measured as the oven dry mass of material that would fill a 59 cm^3 container. Soils amended with DSM, MC, SM, BC, PM, SI and ST were packed to 1.07, 1.15, 0.97, 1.12, 1.03, 1.17 and 1.13 g cm^{-3} respectively.

3.2.3 Density, total porosity, total carbon and nitrogen

Settled bulk density (ρ_b) was determined from soil volume measured at -10 kPa and oven dry soil mass measured at the start of the experiment. In all cases the soil shrunk following initial saturation. A comparable change in ρ_b has been noted in previous studies; Lu et al. (2004) measured shrinkage of five soils following saturation and found that optimal ρ_b for volumetric calculations is at a tension of -7 kPa. Particle density (ρ_p) was estimated by the pycnometer method (Gradwell and Birrell, 1972), and the total porosity (ϕ_t) according to Equation 3.1. Total C and N of both soil and amendments were measured using a LECO TruSpec CN analyser (LECO Corporation, Michigan, USA).

$$\phi_t = 1 - \frac{\rho_b}{\rho_p} \qquad 3.1$$

3.2.4 Soil water retention

Packed cores were slowly saturated from the base; 1 cm of water was added every 24 hours for 72 hours. Cores were then placed on silica sand tension tables and covers were placed over the tension tables to reduce evaporation. The soil physics laboratory was kept at 20° C. Soil water content was determined after core mass had equilibrated at a matric potential of -10 kPa (approx. 10 days), which was used to define the upper limit of macroporosity. Each tension table contained two replicates and the position of the cores was randomised to reduce the effects of any within-table variability.

Cores were then transferred to ceramic plates in pressure chambers (Soilmoisture Equipment Corporation, USA), which were set at a pressures of 33 kPa and 100 kPa (equivalent to matric potential of -33 kPa and -100 kPa). Following equilibration at each matric potential core weight was recorded. Smaller cores (3 cm diameter by 1 cm deep) were then carefully carved from the original larger core and placed in the pressure chambers at a pressure of 1500 kPa (equivalent to matric potential of -1500 kPa). Once the final pressure was reached, each core was oven dried at 105°C for 48 hours. The oven dry weight was used to calculate the gravimetric water content at each matric potential. The settled bulk density was then used to calculate volumetric water content. Volumetric water content was used to calculate pore volume by converting matric potential to effective pore diameters using the Young – Laplace equation (Equation 3.2).

$$D = \frac{30}{\psi_m} \qquad 3.2$$

Where D is the effective pore diameter in µm and ψ_m is the tension/pressure in meters. These results were used to calculate the concentration of macropores (>30 µm pore diameter), macro-mesopores (30 - 3µm pore diameter), mesopores (30 – 0.2 µm pore diameter) and micropores (<0.2 µm pore diameter) following the approach of Kay (1998).

3.2.5 Strain and pore volume

The incorporation of an amendment affects the soil volume and porosity, and thereby exerts a strain on the soil, by two main effects. First, an amendment changes the volume according to the rate of mass added (g g^{-1} soil) and the bulk density of that mass (g cm^{-3}); this change can be referred to as the bulking strain (ε_B) which is described in Equation 3.3. Second, the addition of amendment particles modify the size, shape and connectivity of pore spaces that contribute to total pore volume. The addition of coarse particles can modify the packing of adjacent soil aggregates and particles creating large inter-particle pore spaces, whereas the addition of fine particles may infill inter-particle pore spaces and result in decreased pore sizes. We are unable to separate the creation and infilling of inter-particle pore spaces, and therefore assess changes following packing as a strain ratio (ε_R) (Equation 3.11).

Bulking strain

Bulking strain (ε_B) is the strain predicted if no soil and amendment mixing occurs (Figure 3.1 and Equation 3.3) and was calculated using Equation 3.7.

$$\varepsilon_B = \frac{V_{sb}}{V_s} \tag{3.3}$$

where V_{sb} is the bulked volume which is the sum of the un-amended soil and the un-packed amendment (Equation 3.4), which provides a predicted volume prior to packing. V_s is the volume of un-amended soil (Equation 3.5).

$$V_{sb} = V_s + \frac{M_s\, A}{\rho_{bA}} \tag{3.4}$$

$$V_s = \frac{M_s}{\rho_{bS}} \tag{3.5}$$

where M_s is the mass of soil, ρ_{bS} is soil bulk density (g cm^{-3}), ρ_{bA} is un-packed amendment bulk density (g cm^{-3}) and A is the mass rate of amendment addition (g g $^{-1}$ soil).

Therefore, the bulking strain can be calculated (Equation 3.6)

$$\varepsilon_B = \frac{V_s + \frac{M_s\, A}{\rho_{bA}}}{V_s} = 1 + \frac{M_s}{V_s}\,\frac{A}{\rho_{bA}} \tag{3.6}$$

which simplifies to Equation 3.7

$$\varepsilon_B = 1 + \frac{\rho_{bS}}{\rho_{bA}}\, A \tag{3.7}$$

This calculation assumes that the voids that are apparent when the un-packed bulk density of the amendment is measured are maintained when the soil and amendment are mixed.

Net strain

The measured net strain (ε_N) describes the resulting strain following the addition of amendment mass and the resulting modification of inter-particle pore volume (Figure 3.1 and Equation 3.8) This strain is the ratio of the measured volume of the amended soil (V_{sA}) following amendment and the volume of the un-amended or control soil (V_s);

$$\varepsilon_N = \frac{V_{sA}}{V_s} \tag{3.8}$$

Therefore ε_N can be calculated using Equation 3.9

$$\varepsilon_N = \frac{\frac{M_s(1+A)}{\rho_b}}{\frac{M_s}{\rho_{bS}}} = \frac{M_s\,(1+A)}{\rho_b}\,\frac{M_s}{\rho_{bS}} \tag{3.9}$$

which can be simplified to Equation 3.10

$$\varepsilon_N = (1+A)\,\frac{\rho_{bS}}{\rho_b} \tag{3.10}$$

where ρ_b is the bulk density of the amended soil (g cm^{-3}).

Strain ratio

The strain ratio (ε_R) is the ratio between the measured net strain, ε_N, and the predicted bulking strain, ε_B. This ratio provides a metric for exploring the nature of the interaction between amendment and soil following packing. When the strain ratio is greater than 1 (ε_R>1) the interaction between amendment and soil has created pores, whereas when the strain ratio is less than 1 (ε_R<1) interaction has resulted in a reduction in pores. The ε_R is calculated as follows:

$$\varepsilon_R = \frac{\varepsilon_N}{\varepsilon_B} \tag{3.11}$$

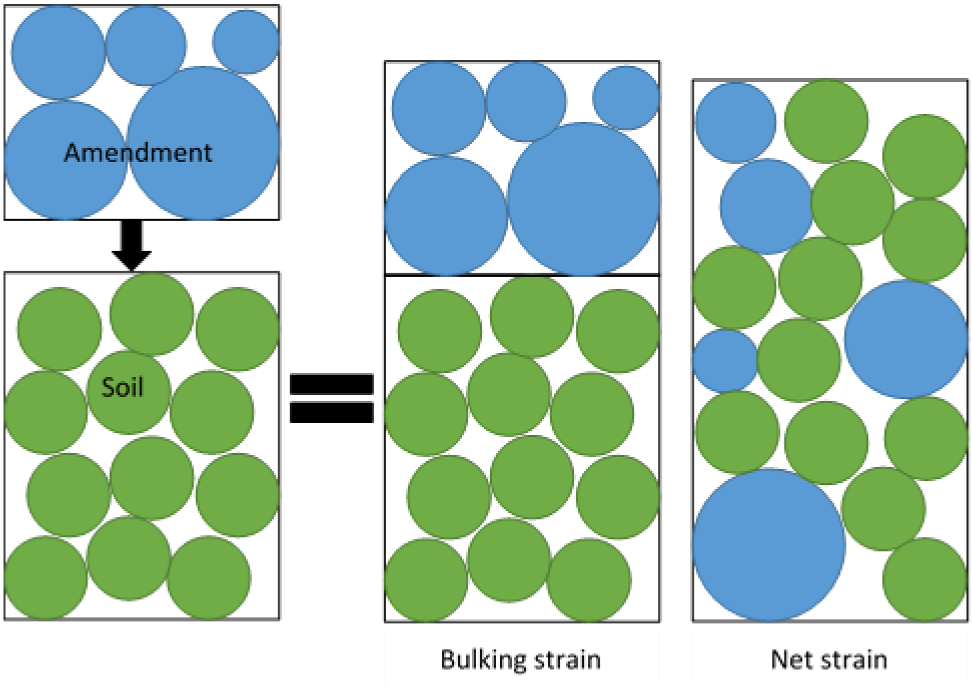


Figure 3.1 Representation of each strain and associated assumptions. Green circles are soil, blue circles are amendment.

Strain corrected porosity

As a result of strain due to amendment additions, the original soil pores in a particular size fraction are distributed across a greater volume. To account for this change in volume, the strain corrected soil porosity of an amended core, $\varepsilon c\phi_p$, in a particular pore size fraction, p, due solely to ε_N was calculated. To calculate $\varepsilon c\phi_p$, ε_N is first converted from a factor to a fraction which can then be multiplied by the porosity of the soil in size range p (Equation 3.12). This accounts for the volumetric dilution of the original (control) soil porosity by the volumetric expansion (net strain).

$$\varepsilon c\phi_p = \phi_{s,p}\left(\frac{1}{\varepsilon_N}\right) \tag{3.12}$$

where $\phi_{s,p}$ is the measured porosity of the un-amended control in size range p, and $\varepsilon_{N,}$ is the net strain of the amended soil of interest.

Net pore volume factor

To determine the absolute change in pore volume following amendment, the net pore volume factor, $\lambda\phi_p$, was calculated. This factor quantifies the volume of pores of size range *p* relative to an un-amended soil. This is achieved by accounting for the change in pore concentration (cm^3 cm^{-3}) and the change in net strain (ε_N) due to amendment incorporation. The net pore volume factor is then applied in the following way: if 1 cm^3 of soil has α cm^3 of pores of size range *p*, then after amendment the expanded volume would have a volume (cm^3) of pores of size range *p* given by $\alpha\lambda\phi_p$. Accordingly, the net pore volume factor is calculated as;

$$\lambda\phi_p = \frac{\phi_{As,p}}{\phi_{s,p}}\varepsilon_N \qquad 3.13$$

where $\phi_{A,p}$ is the porosity (cm^3 cm^{-3}) of pore size range *p,* in the amended soil.

3.2.6 Water repellence

Water repellence of each treatment was measured at matric potentials of -10, -33 and -100 kPa to simulate a range of potential re-wetting points in an irrigated system. The method used was the water drop penetration time (WDPT) from Letey (1969) as described by Caron et al. (2007). This method involved applying a 10 µL water droplet to the soil surface using a transfer pipette and recording the time taken for the droplet to disappear, this was repeated 10 times to determine the average WDPT of each core. The WDPT was used to determine the hydrophobic state as defined by Dekker and Jungerius (1990) where hydrophilic is <5 seconds (s), weakly hydrophobic is 5-60s, highly hydrophobic is 60-600s, severely hydrophobic is 600s -1 hour (h) and extremely hydrophobic is >1 h.

3.2.7 Carbon mineralisation

To understand if the selected amendments could persist for a typical irrigation season, the carbon (C) mineralisation rates of soils and amendments following amendment incorporation were determined. Soil cores were prepared according to the method detailed in section 3.2.2; polyvinyl chloride cores with perforated bases (5.7 cm diameter by 3 cm deep) were used. Each treatment was replicated six times resulting in 48 cores. Packed cores were brought up to field capacity (FC, volumetric water capacity at -10 kPa determined on tension tables) using a Rainin pipette (Mettler Toledo International Incorporated, Port Melbourne, Australia) on titrate mode before being covered with perforated film to reduce evaporation.

The cores were placed in gas-tight glass jars with a headspace of 1132 cm^3, and placed in an incubator set at 22 °C. The jars were randomised across three shelves of the incubator in the same experimental layout as on the tension table apparatus, as described in Section 3.2.4.

Headspace CO_2 concentrations were measured by drawing three 20 mL samples (30 seconds between samples) through a rubber septum and analysing these samples using an infrared gas analyser (Model 7000, Li-Cor, Lincoln, Nebraska USA) on day 1, 3, 7, 12, 18, 25, 32, 39, 46, 51, 60, 67. Core mass was recorded every week to determine evaporative loss and water was re-applied as required to maintain cores at FC. Initial total C was estimated from measured total C for each amendment and soil (Table 3.1) and known oven dry mass of soil and amendment in each core.

3.2.8 Statistical analysis

All results were analysed using general analysis of variance (ANOVA) implemented in GenStat 17 (GenStat, 2016) to determine if the amendment produced a significant change compared to the control. Water repellence was assessed by running ANOVA on the average water drop penetration time of each core. Significant differences where noted when $p<0.05$ and the mean of the amendment was 1 LSD different from the mean of the control.

3.3 Results

3.3.1 Bulk density and porosity

Amendments had a significant effect on bulk density (ρ_b), total porosity (ϕ_t), net strain (ε_N) and strain ratio (ε_R) as presented in Table 3.2. Compared to the control ρ_b reduced ($p<0.001$) and ϕ_t increased ($p<0.001$) by the incorporation of SM, PM, DSM, BC, ST and MC (Table 3.2). All amendments except SI resulted in ε_N significantly greater than 1, with the greatest ε_N being produced by incorporation of SM, followed by PM, DSM, BC, ST, and MC. The strain ratio presented in Table 3.2 indicated that new pores were created ($\varepsilon_R>1$) when PM and ST were incorporated while the addition of SM and DSM caused pore collapse infilling following packing ($\varepsilon_R<1$).

Macroporosity increased ($p<0.001$) compared to the control (0.17 cm^3 cm^{-3}) with incorporation of SM, PM, DSM and ST as shown in Table 3.3. Strain corrected soil macroporosity ($\varepsilon c\phi_{Macro}$) decreased ($p<0.001$) following incorporation of SM, PM, DSM and BC, indicating the creation of new macropores in SM, PM and DSM (Table 3.3). The macropore volume factor ($\lambda\phi_{Macro}$) was increased ($p<0.001$) by incorporation of SM, DSM, ST and PM, however, addition of BC, MC and SI was not different to the control.

Macro-mesoporosity increased with incorporation of SM, PM and DSM compared to the control (0.13 cm^3 cm^{-3}), but decreased when ST ($p<0.001$) was added (Table 3.3). Strain corrected soil macro-mesoporosity ($\varepsilon c\phi_{Mac\text{-}mes}$) decreased ($p<0.001$) compared to the control indicating the creation of new macro-mesopores when SM, PM and DSM where added (Table 3.3). An increase in the macro-mesopore volume factor ($\lambda\phi_{Mac\text{-}mes}$) occurred when amendments SM, PM and DSM were applied.

Mesoporosity increased ($p<0.001$) compared to the control (0.21 cm^3 cm^{-3}) with incorporation of PM, SM, DSM and BC (Table 3.3). Strain corrected soil mesoporosity ($\varepsilon c\phi_{Meso}$) decreased ($p<0.001$) following incorporation of all amendments with the exception of SI, indicating that new mesopores were created in the PM, SM, DSM and BC treatments. An enhancement of mesopore volume factor ($\lambda\phi_{Meso}$) resulted from incorporation of PM, SM, DSM and BC ($p<0.001$), however, MC, SI and ST failed to produce a significant change compared to the control.

Microporosity reduced ($p<0.001$) compared to the control (0.17 cm^3cm^{-3}) through incorporation of SM, PM, DSM and BC (Table 3.3). The strain corrected microporosity ($\varepsilon c\phi_{Micro}$) decreased ($p<0.001$) following incorporation of all amendments with the exception of SI compared to the control (Table 3.3) and there was no enhancement of total micropore volume factor ($\lambda\phi_{Micro}$). The lack of difference between microporosity and $\varepsilon c\phi_{Micro}$ indicates that no new micropores were created, rather, the original micropores were distributed across a greater volume.

Table 3.2 Physical properties of the Control (Con), Dairy Shed Manure (DSM), Municipal Compost (MC), Sphagnum Moss (SM), Biochar (BC), and Polyacrylamide (PM), Silicate Gel (SI) and Starch Gel (ST) treatments. Where A is application rate, ρ_{bA} is bulk density of the amendment, ρ_b is packed bulk density at -10 kPa, ϕ_t is total porosity, ε_B is the bulking strain, ε_N is the net strain and ε_R is the strain ratio. Bold indicates a significant difference from the control.

Treatment	A $g\ g^{-1}$	ρ_{bA} $g\ cm^{-3}$	ρ_b $g\ cm^{-3}$	ϕ_t $cm^3\ cm^{-3}$	ε_B	ε_N	ε_R
Con	0.000	1.18	1.18	0.55	1.00	1.00	1.00
SM	0.010	0.04	**0.97**	**0.63**	1.30	**1.23**	0.95
PM	0.001	0.66	**1.03**	**0.61**	1.00	**1.14**	**1.14**
DSM	0.010	0.05	**1.07**	**0.59**	1.24	**1.12**	0.91
BC	0.010	0.20	**1.12**	**0.57**	1.06	**1.06**	1.00
MC	0.010	0.56	**1.15**	**0.56**	1.02	**1.04**	1.02
SI	0.001	0.80	1.17	0.55	1.00	1.01	1.01
ST	0.001	0.46	**1.13**	**0.57**	1.00	**1.05**	1.05
LSD (P)			0.03 (0.001)	0.01 (0.001)		0.034 (<0.001)	0.032 (<0.001)

Table 3.3 Changes in porosity (ϕ), strain corrected porosity ($\varepsilon c\phi$) and pore volume factor ($\lambda\phi$) in the Control (Con), Dairy Shed Manure (DSM), Municipal Compost (MC), Sphagnum Moss (SM), Biochar (BC), and Polyacrylamide (PM), Silicate Gel (SI) and Starch Gel (ST) treatments. Bold indicates a significant difference from the control.

	Macroporosity			Macro-mesoporosity			Mesoporosity			Microporosity		
Treatment	ϕ_{Macro} cm^3 cm^{-3}	$\varepsilon c\phi_{Macro}$ cm^3 cm^{-3}	$\lambda\phi_{Macro}$	$\phi_{Mac\text{-}mes}$ cm^3 cm^{-3}	$\varepsilon c\phi_{Mac\text{-}mes}$ cm^3 cm^{-3}	$\lambda\phi_{Mac\text{-}mes}$	ϕ_{Meso} cm^3 cm^{-3}	$\varepsilon c\phi_{Meso}$ cm^3 cm^{-3}	$\lambda\phi_{Meso}$	ϕ_{Micro} cm^3 cm^{-3}	$\varepsilon c\phi_{Micro}$ cm^3 cm^{-3}	$\lambda\phi_{Micro}$
Con	0.17	0.17	1	0.13	0.13	1.00	0.21	0.21	1.00	0.17	0.17	1.00
SM	**0.25**	**0.14**	**1.83**	**0.17**	**0.10**	**1.63**	**0.24**	**0.17**	**1.43**	**0.14**	**0.14**	1.03
PM	**0.22**	**0.15**	**1.32**	**0.17**	**0.11**	**1.54**	**0.26**	**0.18**	**1.51**	**0.14**	**0.14**	0.96
DSM	**0.21**	**0.15**	**1.44**	**0.15**	**0.11**	**1.35**	**0.23**	**0.19**	**1.22**	**0.15**	**0.15**	1.02
BC	**0.19**	**0.16**	1.25	**0.14**	**0.12**	1.14	**0.23**	**0.20**	**1.14**	**0.15**	**0.15**	0.97
MC	**0.19**	0.17	1.18	0.13	**0.12**	1.07	0.21	**0.20**	1.07	**0.16**	**0.16**	1.03
SI	0.17	0.17	1.09	0.13	**0.12**	1.08	0.22	0.21	1.01	0.17	0.17	1.04
ST	**0.21**	0.17	**1.35**	**0.12**	**0.12**	0.96	0.20	**0.20**	1.01	**0.16**	**0.16**	0.98
LSD (P)	0.024 (<0.001)	0.01 (<0.001)	0.27 (<0.001)	0.01 (<0.001)	0.004 (<0.001)	0.15 (<0.001)	0.02 (<0.001)	0.01 (<0.001)	0.12 (<0.001)	0.01 (<0.001)	0.01 (<0.001)	0.08 (0.270)

3.3.2 Water repellence

Water drop penetration time (WDPT) increased as soil matric potential decreased (Table 3.4). At -10 kPa WDPT was 1.7 seconds for the control, which was significantly (p<0.001) increased by BC and ST to 2.5 seconds and reduced by SM to 1 second. Although the WDPT was significantly altered by the addition of amendments at -10 kPa, all treatments were hydrophilic as defined by Dekker and Jungerius (1990), where hydrophilic is <5 seconds (s), weakly hydrophobic is 5-60s, highly hydrophobic is 60-600s, severely hydrophobic is 600s -1 hour (h) and extremely hydrophobic is >1 h. At a matric potential of -33 kPa the WDPT increased; however, all treatments remained in the hydrophilic category and there were no significant differences between treatments. At -100 kPa the soil and amendments became more hydrophobic. WDPT of the control was 10.5 seconds and was significantly increased by the incorporation of DSM, which increased WDPT to 27.5 seconds; at this matric potential all treatments were weakly hydrophobic.

Table 3.4 Average water drop penetration time (WDPT) in seconds at matric potentials of -10 kPa, -33 kPa and -100 kPa in the Control, Dairy Shed Manure (DSM), Municipal Compost (MC), Sphagnum Moss (SM), Biochar (BC), and Polyacrylamide (PM), Silicate Gel (SI) and Starch Gel (ST)treatments. Bold indicates significant difference from control.

		WDPT (s)	
Treatment	-10 kPa	-33 kPa	-100 kPa
Control	1.7	3.9	10.5
MC	1.7	3.6	12.1
DSM	1.6	4.3	**27.5**
SM	1.0	2.8	8.5
BC	**2.5**	3.8	12.1
PM	1.7	3.1	9.35
ST	**2.5**	4.1	10.4
SI	1.6	4.4	10.4
LSD (p value)	0.4(<0.001)	0.8 (0.233)	4.8 (0.002)

3.3.3 Carbon mineralisation

Carbon (C) loss was significantly greater from DSM and ST amended soil compared to the control amendments (Table 3.5). Cumulative C mineralisation was significantly increased ($p<0.001$) when DSM (3.8 g C kg^{-1} soil), SM (2.7 g C kg^{-1}) and ST (2.7 g C kg^{-1}) compared to the control (2.5 g C kg^{-1} soil). Carbon mineralisation in the control was 9.7% of the initial total C. This was increased ($p<0.001$) to 12.6% by incorporation of DSM and reduced to 7.1% by incorporation of BC. The addition of amendments produced significant increases in total C even though the amounts added were relatively small. The initial C content of the control was 25.8 g C kg^{-1} soil, which increased with the addition of BC (32.8 g C kg^{-1} soil), SM (30.4 g C kg^{-1} soil), DSM (30.1 g C kg^{-1} soil) and MC (27.9 g C kg^{-1} soil).

Table 3.5 Cumulative CO_2-C loss and the percentage of initial total carbon evolved over a 60 day incubation period in the Control (Con), Dairy Shed Manure (DSM), Municipal Compost (MC), Sphagnum Moss (SM), Biochar (BC), and Polyacrylamide (PM), Silicate Gel (SI) and Starch Gel (ST) treatments. Bold indicates a significant difference from the control.

Treatment	Initial total C (g C kg^{-1} soil)	Cumulative CO_2-C loss (g C kg^{-1} soil)	Total C evolved (%)
Control	25.8	2.5	9.7
MC	**27.9**	2.5	8.9
DSM	**30.1**	**3.8**	**12.6**
SM	**30.4**	**2.7**	8.9
BC	**32.8**	2.4	**7.2**
PM	26.2	2.5	9.6
ST	26.1	**2.7**	10.2
SI	25.8	2.5	9.5
LSD (p)	0.5 (<0.001)	0.2 (<0.001)	0.7 (<0.001)

3.4 Discussion

Results from this experiment show that incorporation of both organic and synthetic amendments increased the concentration and volume of water-retaining macro-mesopores and mesopores relative to the control. Macro-mesoporosity was significantly increased when SM, PM, DSM and BC were incorporated, respectively, and decreased when ST was incorporated. Mesoporosity was significantly increased when PM, SM, BC and DSM were incorporated, and decreased when ST was incorporated. The remaining amendments failed to have a significant effect on mesoporosity despite previous studies finding that SI (Farrell et al., 2013) and ST (Woodhouse and Johnson, 1991) can increase water retention when applied at similar rates to those used in the current study. As expected, the addition of amendments reduced bulk density and increased total porosity with the exception of SI. Although adding a mass of amendment to a soil often results in changes in pore concentration and bulk density (Haynes and Naidu, 1998); relatively few studies have acknowledged that this may increase the net soil volume and therefore have implications for the water retention of the soil. Chang et al. (2007) suggested that the addition of an amendment is likely to increase the net elevation of a soil layer; if valid, this effective increase in soil depth is likely to have important implications for the shallow stony soils of interest in this thesis. To address changes in soil volume or elevation a method was introduced to quantify the net strain produced when a specific amendment is incorporated in to the soil. The application of this net strain, in conjunction with measurements of pore concentration, allow the pore volume factor to be calculated. The application of this method found that macro-mesopore volume factor ($\lambda\phi_{Mac\text{-}Mes}$) increased in order of SM, PM and DSM, while mesopore volume factor ($\lambda\phi_{Meso}$) was increased following incorporation of PM, SM, DSM and BC compared to the control. As this is a novel approach and changes in total volume of soil have almost exclusively focussed on the reduction of soil volume due to shrinkage and compaction (McGarry and Malafant, 1987; Mitchell, 1991) rather than expansion due to the addition of mass and reduction of density, there are few sources to compare against the $\lambda\phi_{Mac\text{-}Mes}$ and $\lambda\phi_{Meso}$ results.

The significant finding from this analysis is that SM, PM, DSM and BC can increase the concentration and relative volume of plant water-retaining macro-meso and mesopores. SM produced the greatest increase in macro-mesoporosity, which would be beneficial for irrigated systems, as macro-mesopores hold readily available water for plants (McLaren and Cameron, 1996). Although SM is commonly available in New Zealand, the majority of research in to its use to change soil pore size distribution has applied sphagnum peat moss (Bigelow et al., 2004; Li et al., 2004; Parent et al., 2000), which is a decomposed and compressed version of the SM used in the current study with different hydraulic properties (Boelter, 1964). This finding highlights the need for further research with this product in conjunction with spray irrigation to determine if it has any potential for field application.

Application of PM in this study produced the second greatest increase in macro-mesoporosity and the greatest increase in mesoporosity. The use of PM to increase soil water has been well researched internationally; however, results vary according to 1) the formulation of polyacrylamide and 2) the inherent soil properties. Issue 1) has been highlighted by Johnson (1984) who incorporated three different PM products into silica sand at a rate of 0.1% and found mesoporosity to increase by 432%, 129% or 61% proportional to the control depending on the PM product used. In relation to soil properties, Agaba et al. (2011) found incorporation of 0.1% PM increased mesoporosity by approximately 100%, 20% and 10% for a sand, silt loam and clay soil, respectively. These combined effects make the comparability with our results difficult as the majority of studies apply PM to sandy soils with very low initial mesoporosity (Abedi-Koupai et al., 2008; Sivapalan, 2006), or test products that are not readily available in New Zealand (Johnson, 1984; Woodhouse and Johnson, 1991).

The application of DSM produced a consistent increase in macro-mesoporosity and mesoporosity. DSM is a practical, readily available product for New Zealand growers, which may make it a more attractive alternative to SM and PM. The increase in mesoporosity is supported by the results of longer term field studies (Celik et al., 2004; Hati et al., 2008); however, there are few data on the effect of incorporation of DSM in the first year after application. The effectiveness of DSM to increase mesoporosity has been disputed in the review of Haynes and Naidu (1998) who stated that typically, although there is an increase in the concentration of pores with a diameter of <30 µm, the concentration of pores of <0.2 µm increases commensurately under long term manure application, which results in no net gain in mesoporosity. In contrast, the current study found that DSM decreased microporosity (>0.2 µm diameter pores), but had no effect on the micropore volume factor ($\lambda\phi_{Micro}$) indicating that the difference in microporosity may have simply been a by-product of the net strain produced by adding DSM.

Incorporation of BC also increased macro-mesoporosity and mesoporosity compared to the control, which agrees with the results of Liu et al. (2017) who conducted a similar core scale study with sandy soil and a biochar application rate of 2% (wt./wt. oven dry soil). They found mesoporosity increased relative to the control by 17% to 122% depending on the size of biochar particle used. These increases are greater than the 10% increase in mesoporosity measured in the current study. This difference is likely to be driven by 1) the application rate, 2) the biochar type used, and 3) the soil used by Liu et al. (2017) which had a mesoporosity of 0.18 cm^3 cm^{-3}, whereas the Templeton silt loam used in the current study had a mesoporosity of 0.21 cm^3 cm^{-3}. These differences are likely to exaggerate any potential change in mesoporosity. The results from the current study contrast the field generated results of Hardie et al. (2014) who reported no measurable effect on soil mesoporosity when biochar was incorporated at a rate of 4% under apple trees. Although this study found significant increases in macro-meso and mesoporosity when PM, SM, DSM and BC were incorporated, macroporosity and microporosity were also modified by the incorporation of amendments.

Macroporosity was increased by incorporation of SM, followed by PM, DSM, ST, BC and MC. To determine the magnitude of macropore creation, the strain corrected macroporosity ($\varepsilon c\phi_{Macro}$) was first calculated. The $\varepsilon c\phi_{Macro}$ component was almost universally less than the original macroporosity because the original macropore volume was distributed across a larger soil volume due to amendment. The total volume of macropores, quantified by the factor $\lambda\phi_{Macro}$, was significantly greater in soils amended with SM, DSM, ST and PM than in the control. The significant increase in macroporosity may prove problematic for shallow soils as if these pores are connected, water loss due to drainage is likely to increase.

Microporosity decreased when SM, PM, DSM and BC were incorporated. Although previous studies have found that amendment incorporation can modify microporosity, this study found that $\varepsilon c\phi_{Micro}$ was equivalent to the measured microporosity. This finding is important as it provides evidence that the measured decrease in microporosity was likely a result of the change in soil volume following amendment incorporation.

Along with changes in porosity and pore volume, the incorporation of all amendments - except for SI - significantly altered bulk density (ρ_b) and total porosity (ϕ_t). The greatest reduction in bulk density was due to the addition of SM, followed by PM, DSM, BC, ST and MC. Reductions in bulk density following amendment incorporation are frequently reported when organic amendments such as biochar (Hardie et al., 2014), sphagnum peat (Li et al., 2004), compost and manure (Celik et al., 2004) are incorporated into soil. The reduction in bulk density is due to either the creation of additional pore spaces or the addition of mass which has a lower density than that of the original soil. The changes in bulk density and total porosity in our study are likely a product of the first mechanism as the volume of macropores also increased significantly ($p<0.001$).

The reduction in bulk density following amendment incorporation produced an increase in soil volume which is represented by the net strain (ε_N). The reason for this is that amendment application rate and therefore the addition of mass was small in comparison to the change in bulk density. Therefore, trends in ε_N were similar to those for bulk density, with SM producing the greatest increase in ε_N, followed by PM, DSM, BC, ST and MC, with no effect of SI. Although all amendments other than SI increased ε_N, the cause of this increase varied. To determine the cause of ε_N, the strain ratio (ε_R) was calculated, which indicates if pores have been created or destroyed due to soil and amendment particle interaction following packing. The greatest ε_R values were produced by PM, followed by ST, indicating that these amendments created new pores following packing, which was likely due to these synthetic products absorbing water following saturation and causing soil swelling which would increase ε_N. The ε_R in PM and ST was likely to be exaggerated as there was no initial increase in bulking strain (ε_B); however, ε_N was significantly >1 following soil saturation indicating that new pore spaces were created following saturation either due to the intra-particle pore spaces of these amendments becoming filled with water or the mechanical expansion altering the surrounding soil structure. The greatest decrease in ε_R was caused by incorporation of fibrous amendments such as DSM and SM, indicating that there was consolidation of pore spaces following wetting. The MC was the only organic amendment to produce a ε_R significantly >1 indicating that MC created new pores due to the interaction of soil and MC particles; however, the increase in ε_R was not significant.

To understand if the incorporation of these amendments would be practical in a field situation, we sought to understand if they would 1) increase soil water repellence at potential irrigation trigger points, or 2) persist for a length of time which is at least equivalent to an irrigation season when exposed to microbial decomposition in the soil. Water repellence has been reported when organic amendments such as manure (Olsen et al., 1970) and biochars (Briggs et al., 2012) have been incorporated in to soil. The current study found that incorporating DSM did increase water repellence at a matric potential of -100 kPa; however, all treatments at this matric potential, including the control, were in the weakly hydrophobic category defined by Dekker and Jungerius (1990). Although the increase in water repellence produced by DSM suggests that irrigation efficiency would be reduced, this would need to be tested under spray irrigation to understand if the increase in macroporosity produced by DSM minimises or exaggerates the effects of water repellence. It is likely the increase in macroporosity will have a significant impact on water infiltration, and this potential limitation is explored further in Chapter 5. To address the second limitation of this practice, a carbon mineralisation assay was performed. This assay concluded that carbon mineralisation was significantly increased by DSM and reduced by MC, SM and BC compared to the control. This result is supported by the findings of Ajwa and Tabatabai (1994) and Bernal et al. (1998) who both found that amending soil with less stable organic materials caused the greatest rates of carbon mineralisation when mixed with soil. Although carbon mineralisation increased, the rates that were measured indicate that it is unlikely that any amendment would be unable to persist for the length of a four month irrigation season.

Previous work has criticised the use of sieved repacked soils for studying soil physical properties (Hardie et al., 2014) as repacking changes the inherent soil physical properties. These changes have been described by Reynolds et al. (2003) who found that granulating soil and repacking it in to soil cores decreased the mesoporosity of a clay loam from 0.22 cm^3 cm^{-3} for an *in-situ* core to 0.17 cm^3 cm^{-3}. Although this change in soil physical properties is important, the use of repacked soils in the current study allowed the relative effect of amendments on pore size ranges of a cultivated soil to be compared. Because the focus of this study involves incorporation of amendments at the time of cultivation, this limitation is likely to be insignificant as the re-structuring resulting from soil and amendment mixing is similar to that which would happen following cultivation.

3.5 Conclusions

The results from this experiment demonstrate that SM, PM, DSM and BC can all effectively increase the concentration and net volume of water-retaining soil pores, with the most effective of these products being SM and PM. The changes in macro-mesoporosity and mesoporosity are likely produced by the creation of new inter-particle pore spaces (SM and DSM) or the absorbance of water due to the introduction of intra-particle pore spaces (PM). The incorporation of DSM resulted in an increase in carbon mineralisation and water repellence, although these limitation are unlikely to impact the performance of DSM in irrigated systems, it is recommended that further investigation is performed prior to field application. Although BC significantly increased macro-meso and mesopore volume and concentration, these changes were relatively small compared to the other amendments. Therefore, the conclusion from these results is that SM and PM should be further considered because they induced large increases in water retention without any associated limitations for a spray irrigated system. Further work on a larger scale is recommended to determine if PM and SM can effectively increase water retention under spray irrigation, and whether or not there are any associated negative effects such as increased drainage due to increases in macroporosity or water repellence.

Chapter 4 Reducing compost particle size and increasing application rate increases soil water retention

4.1 Introduction

This experiment was completed to build on the findings of Experiment 1, Chapter 3, where it was determined that the incorporation of Sphagnum moss (SM), Polyacrylamide (PM), Dairy shed manure (DSM) and Biochar (BC) all increased the volume of macro-mesopores and mesopores. Although these amendments significantly increased macro-meso and mesoporosity, only DSM is likely to be readily available in commercial quantities for field application. Furthermore, this product was found to increase water repellence and C mineralisation, which may limit its potential under spray irrigation. Municipal compost (MC) was found to have no significant effect on macro-mesopores or mesopores; a result that may have been due to the low application rate used (Reynolds et al., 2003) or the compost particle size (Liu et al., 2017). An advantage of applying MC is that it is readily available in commercial quantities in Canterbury. Locally, MC incorporation has been shown to increase nitrogen availability (Horrocks et al., 2014), however, the effect of increasing mesoporosity may have more benefit to plant yield than any potential increase in nitrogen availability (Carter et al., 2004) yet this benefit has not been fully investigated.

The modification of soil porosity has been shown to be correlated with MC application rate. Reynolds et al. (2003) reported that as compost application rate increased from 3.8% to 20%, mesoporosity increased by 5% to 23%. Hence, it appears that increases in mesoporosity from MC application may require a higher application rate than the 1% rate used in Chapter 3. Maximum particle size is also likely to have an effect on the volume of macro-mesopores and mesopores because larger particles are more likely to create inter-particle pore spaces when soil and MC are mixed and may also have differing intra-particle pore space compared to smaller particle sizes. The relationship between amendment particle size and soil porosity has been noted recently in the biochar study of Liu et al. (2017); while Haynes et al. (2015) have reported that carbon content increases with green waste (the feed stock for MC) particle size as larger particles have a high proportion of lignified woody material, whereas smaller particle sizes have a greater concentration of green stems, leaves and soil. This difference in MC feed stock is likely to influence the intra-particle porosity, density and shape of MC particles; however, the effect of MC particle size on porosity has received little attention. Practically speaking, MC produced commercially typically involves screening (Haug, 1993), therefore, modifying the maximum particle size of MC would not involve significant engineering challenges and may have the potential to produce an MC that is targeted at increasing soil water retention.

Changes in soil porosity are commonly attributed to a dilution effect (Khaleel et al., 1981; Reynolds et al., 2003) whereby the addition of a low density amendment dilutes the dense mineral fraction of the soil. The concept of a dilution effect suggests that the amendment particle size, shape and density are likely to have an influence on the modification of pore size. However, few studies have reported how this dilution effect is likely to influence the net volume of water-retaining pores. Chang et al. (2007) noted that the incorporation of a soil amendment is likely to increase the net soil volume and should therefore be accounted for when sampling. However, few data exist to quantify this. Although other research areas such as the quantification of soil carbon stocks have taken volume change in to account (Fraser et al., 2010), soil “pore” stocks are still typically reported on a concentration basis where the soil surface is the datum rather than the layer that is unaffected by management practice (e.g. implement depth). Accounting for this volume change would allow greater understanding of the net volume of soil pores and the dilution effect which follows the addition of amendment (Khaleel et al., 1981). This may address issues such as reported increases in the concentration of pores (porosity) at both the drained upper limit and permanent wilting point which lead to no significant difference in AWC (Haynes and Naidu, 1998).

To address these gaps the primary objective of this study was to evaluate the importance of MC particle size and application rate on resulting soil mesoporosity and mesopore volume following amendment. To achieve this objective we tested the following hypothesis; reducing MC particle size and increasing application rate will significantly increase soil mesopore concentration and volume.

4.2 Materials and Methods

4.2.1 Soil

The soil used for this experiment was Templeton silt loam (Typic Immature Pallic (Hewitt, 2010)) which had been under long term (>15 years) conventional cropping management. The site was managed by Plant & Food Research and situated approximately 2 km South East of Lincoln University, Canterbury, New Zealand (43°62’ S, 172°47’E). Soil was removed from 0-10 cm depth and sieved to ≤4 mm. Textural analysis found the soil to contain 22% clay, 66.5% silt and 11.5% sand. Soil pH was 5.7, total C was 2.9% and total N was 0.24%.

4.2.2 Compost

Municipal compost (certified organic, aged 21 weeks) was sourced from Living Earth Limited, Christchurch. Municipal compost was produced from domestic green waste from curb side collection and council park waste.

4.2.3 Sample preparation

Municipal compost was initially homogenised and then screened to produce composts with maximum particle sizes of <4 mm (MC4), <2 mm (MC2) and <0.25 mm (MC0.25) in diameter. Sieving altered the initial particle density (ρ_p), bulk density (ρ_b), total carbon (C) and total nitrogen (N) (Table 4.1).

Table 4.1 Particle density (ρ_p), un-packed bulk density (ρ_b), total C and total N for municipal compost size fractions MC4 (<4 mm), MC2 (<2mm), MC0.25 (<0.25mm) and the soil control. Note the un-packed bulk density of the control was not measured as this was packed to a pre-determined target bulk density of 1.06 g cm^{-3}.

Treatment	ρ_p (g cm^{-3})	Un-packed ρ_b (g cm^{-3})	Total C %	Total N %
MC4	2.04	0.49	24.06	2.31
MC2	2.06	0.49	23.45	2.42
MC0.25	2.25	0.79	19.36	2.2
Soil	2.63	*1.06*	2.9	0.24

Each compost type was then incorporated into a constant mass of field moist soil (θ_v = 0.30 cm^3 cm^{-3}), which had been sieved to ≤4 mm. Compost was incorporated at rates of 0% (control), 5%, 25%, 50% and 80% wt./wt. oven dry soil. Incorporation was performed by an automatic tumbler for 30 minutes to ensure an even distribution of compost and soil. These 15 treatments (three particle sizes by five application rates) were replicated four times resulting in 60 soil cores (5.4 cm diameter by 3 cm deep).

Un-amended control soil cores were packed in 1 cm increments to a target bulk density of 1.06 g/cm^3 using a hand operated, 5 cm diameter steel piston. The volume of the sample and hence bulk density was adjusted according to 1) the un-packed bulk density of the compost and 2) the mass of compost added. This correction is given by the bulking strain (Equation 4.3).

4.2.4 Density, total porosity, total carbon and nitrogen

Bulk density of the cores was measured at -10 kPa by measuring the distance from the soil surface to the top of the core. The assessment of the volume associated with ρ_b was made at -10 kPa because settling of the soil following packing resulted in a dynamic ρ_b. A matric potential of -10 kPa was selected as no significant settling was measured after this point, a decision supported by Lu et al. (2004) who reported that -7 kPa was the optimal tension to measure settled ρ_b in repacked soils. The volume of headspace in the core at -10 kPa was subtracted from the core volume to give the soil volume. Soil bulk density (ρ_b) was then determined by dividing the known oven dry mass of material by the soil volume. Un-packed bulk density was measured as the oven dry mass of material that would fill a 59 cm^3 container. Particle density (ρ_p) was estimated by the pycnometer method (Gradwell and Birrell, 1972), and the total porosity (ϕ_t) according to Equation 4.1. Total C and N of both soil and amendments were measured using a LECO TruSpec CN analyser (LECO Corporation, Michigan, USA).

$$\phi_t = 1 - \frac{\rho_b}{\rho_p} \qquad 4.1$$

4.2.5 Soil water retention

Packed cores were saturated incrementally from the base up with 1 cm of water added every 24 hours for 72 hours. Cores were then placed on silica sand tension tables and soil water content was determined after core mass had equilibrated at a matric potential of -10 kPa (Reynolds and Topp, 2007b). Cores were then transferred into pressure chambers (Soilmoisture Equipment Corporation, USA) and pressures equivalent to a matric potential of -100 kPa were applied. Smaller cores (3 cm diameter by 1 cm deep) were then carefully carved from the original larger core and placed inside a pressure chamber which was set at a pressure equivalent to a matric potential of -1500 kPa.

Once the final pressure was reached each core was oven dried at 105°C for 48 hours to determine the gravimetric water content at each matric potential. Bulk density was then used to calculate volumetric water content. The Young-Laplace equation was used to estimate effective maximum diameter of pores filled by water at a given matric potential (Equation 4.2).

$$D = \frac{30}{\psi_m} \tag{4.2}$$

where D is the effective pore diameter in µm and ψ_m is the tension/pressure in meters. These results were used to calculate the volume of macropores (>30 µm pore diameter), macro-mesopores (30 - 3µm), mesopores (30 – 0.2 µm pore diameter) and micropores (<0.2 µm pore diameter) as defined by Kay (1998).

4.2.6 Strain and pore volume

The incorporation of MC affects both the soil volume and porosity, and thereby exerts a net strain (ε_N) on the soil, by three effects. Firstly, MC incorporation changes the volume according to the product of mass rate (g g^{-1}) at which MC is added and the inherent bulk density of the MC; referred to as a bulking effect (ε_B). Secondly, inter-particle pore spaces are created by the physical interaction of MC particles and soil aggregates. Thirdly, the process of adding MC may collapse or infill existing inter-particle pore spaces within weak aggregates. Previously (Chapter 3), the strain ratio (ε_R) was used to describe the interactions of the second and third mechanism. As this experiment involves a single amendment source and there is greater confidence in measured amendment particle density (ρ_{pA}), the dilution strain, ε_D, has been calculated to describe the changes in the inter-particle pore space due to the addition of low density material.

Bulking strain

Bulking strain (ε_B) is calculated assuming soil and amendment do not interact and that the amendment maintains its un-packed bulk density. The bulking strain is calculated using Equation 4.3.

$$\varepsilon_B = 1 + \frac{\rho_{bS}}{\rho_{bA}} A \tag{4.3}$$

where ρ_{bS} is soil bulk density (g cm^{-3}), ρ_{bA} is amendment (MC) bulk density (g cm^{-3}) and A is the mass rate of MC addition (g g^{-1}).

Net strain

The measured net strain (ε_N) describes the resulting strain following the addition of amendment mass and the resulting modification of inter-particle pore space (Equation 4.4).

$$\varepsilon_N = (1 + A)\,\frac{\rho_{bS}}{\rho_b} \tag{4.4}$$

where A is the amendment application rate (g g^{-1}), ρ_{bS} is the bulk density of the control soil (g cm^{-3}) and ρ_b is the bulk density of the amended soil (g cm^{-3}).

Dilution strain

The change in soil bulk density and total porosity when organic amendments are incorporated has been proposed to be due to a "dilution effect" (Khaleel et al., 1981), which results from strain due solely to the volume of the amendment particles. To account for this effect, the dilution strain (ε_D) has been calculated (Equation 4.5).

$$\varepsilon_D = \frac{V_{sd}}{V_s} \tag{4.5}$$

where, V_s is the volume of soil and V_{sd} is the diluted soil volume which is calculated using Equation 4.6.

$$V_{sd} = V_s + \frac{M_s A}{\rho_{pA}} \tag{4.6}$$

where M_s is the mass of soil (g), A is the application rate of amendment relative to the mass of soil (g g^{-1}), V_s is the un-amended soil volume (cm^3) and ρ_{pA} is the particle density (g cm^{-3}) of the incorporated amendment. Substituting produces Equation 4.7.

$$\varepsilon_D = \frac{V_s + \frac{M_S\,A}{\rho_{pA}}}{V_s} = 1 + \frac{M_s\,A}{V_s\,\rho_{pA}} = 1 + A\,\frac{\rho_b}{\rho_{pA}} \tag{4.7}$$

Strain ratio

The strain ratio (ε_R) which is the ratio between the measured net strain, ε_N and the predicted bulking strain, ε_B. The strain ratio provides a metric for exploring the nature of the interaction between amendment and soil following packing (Equation 4.8). When the ratio is greater than 1 (ε_R>1) it is assumed that interaction between amendment and soil has created pores, whereas when the strain ratio is less than 1 (ε_R<1) it is assumed the interaction has resulted in a reduction in pores.

$$\varepsilon_R = \frac{\varepsilon_N}{\varepsilon_B} \tag{4.8}$$

Strain corrected porosity

As a result of strain due to amendment addition, the original soil pores in a particular size fraction are distributed across a greater volume of material. To account for this change in volume the strain corrected soil porosity of an amended core, $\varepsilon c\phi$, in a particular pore size fraction, *p*, due solely to ε_N was calculated (Equation 4.9).

$$\varepsilon c\phi_p = \phi_{s,p}\left(\frac{1}{\varepsilon_N}\right) \tag{4.9}$$

where $\phi_{s,p}$ is the measured porosity of the control in size range *p*,(cm^3 cm^{-3}) and ε_N, is the net strain of the amended soil of interest.

Amendment porosity contribution

The direct contribution of the amendment to porosity, $\phi_{a,p}$, of size range, *p*, can then be estimated from the strain corrected porosity for an amended soil (i.e. what we expect if the increase in volume was the only change mechanism) and the measured porosity of the amended soil (i.e. what we get when amendment is incorporated) using Equation 4.10.

$$\phi_{a,p} = \phi_{As,p} - \varepsilon c\phi_p \tag{4.10}$$

where $\phi_{As,p}$ is the measured porosity of the amended soil in size range, *p* (cm^3 cm^{-3}).

Net pore volume factor

To determine the change in pore volume after amendment, the net pore volume factor ($\lambda\phi_p$) has been calculated (Equation 4.11), which quantifies the volume of pores of size range, *p,* relative to an un-amended soil. This is achieved by accounting for the change in pore concentration (cm^3 cm^{-3}) and the net strain (ε_N) due to amendment incorporation. The net pore volume factor is then applied in the following way; if 1 cm^3 of soil has α cm^3 of pores of size range, *p*, then after amendment incorporation the expanded volume would have a volume of pores (cm^3) of size range *p* given by $\alpha\lambda\phi_p$.

$$\lambda\phi_p = \frac{\phi_{As,p}}{\phi_{s,p}}\varepsilon_N \tag{4.11}$$

4.2.7 Compost porosity

Compost porosity was determined via the water desorption method using tension tables and pressure chambers described in section 4.2.5. To perform this analysis MC4, MC2 and MC0.25 were packed to a bulk density of 0.4 g cm^{-3}, 0.4 cm^{-3} and 0.63 g cm^{-3} respectively, in to small cores (1 cm deep by 5.4 cm diameter) with four replicates per particle size. Porosity was then determined through the pressure tension method previously discussed in section 4.2.5 and these results were used to calculate the inherent macroporosity, macro-mesoporosity, mesoporosity and microporosity of pure compost.

4.2.8 Statistical analysis

All reported data were analysed using general analysis of variance (ANOVA) performed in GenStat 17 (GenStat, 2016). Post-hoc least significant differences were used to define significant differences between means. Treatment differences were considered to be significant when $p<0.05$.

4.3 Results

4.3.1 Bulk density, total porosity and strain

Incorporation of MC4, MC2 and MC0.25 increased total porosity (ϕ_t) (Figure 4.1B) and reduced bulk density (ρ_b) (Figure 4.1A) relative to the control soil ($p<0.001$), as shown in Table 4.2. There was a significant interaction effect ($p<0.001$) between application rate and particle size whereby changes in ϕ_t and ρ_b were greater for MC2 and MC4 than MC0.25 (Figure 4.1). There was also an interaction between application rate and particle size on ε_N and ε_D ($p<0.001$), with ε_N increasing with increasing application rate and particle size so that MC4>MC2>MC0.25, while ε_D followed a similar trend at rates greater than 5% (Table 4.2). The strain ratio (ε_R) was greater than 1 when MC4 and MC0.25 were added ($p=0.008$) and was greatest at application rates of 50% and 80% ($p<0.001$).

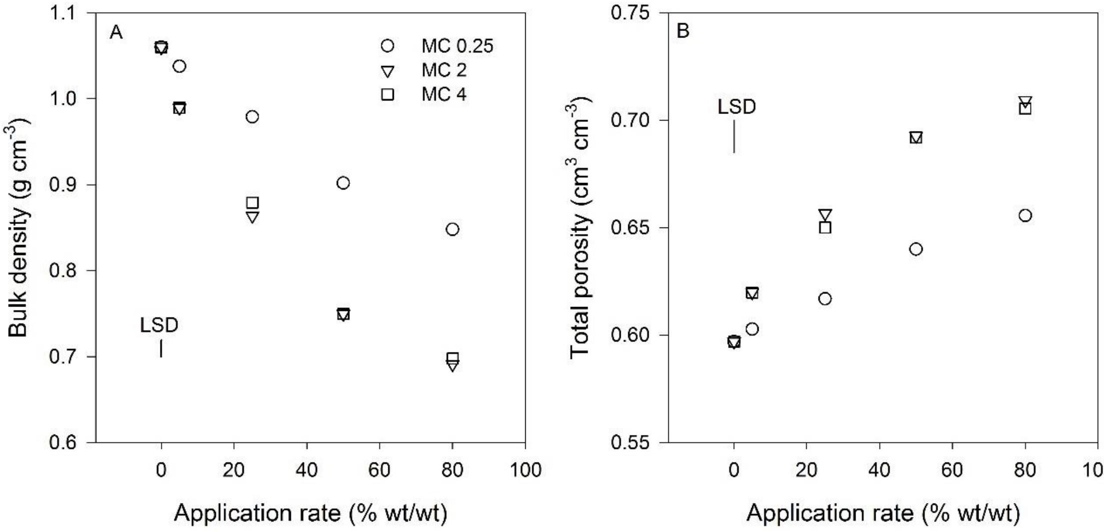


Figure 4.1 Interaction effect of MC application rate and screening size on A) bulk density and B) total porosity

Table 4.2 Effects of compost particle size (MC4 = <4 mm, MC2 = <2 mm and MC0.25 = <0.25 mm) and application rate (*A*) on oven dry bulk density (ρ_b), total porosity (ϕ_t), bulking strain (ε_B), net strain (ε_N), strain ratio (ε_R), and dilution strain (ε_D).

Treatment	A	ρ_b	ϕ_t	ε_B	ε_N	ε_R	ε_D
	g g^{-1}	g cm^{-3}	cm^3 cm^{-3}				
Control	0	1.07	0.59	1	1	1	1
MC4	0.05	0.99	0.62	1.11	1.18	1.07	1.03
MC4	0.25	0.88	0.65	1.54	1.59	1.03	1.13
MC4	0.5	0.75	0.69	2.08	2.32	1.07	1.27
MC4	0.8	0.7	0.71	2.73	2.88	1.05	1.43
MC2	0.05	0.99	0.62	1.11	1.10	0.99	1.03
MC2	0.25	0.86	0.66	1.54	1.50	0.97	1.12
MC2	0.5	0.75	0.69	2.08	2.08	1.00	1.25
MC2	0.8	0.69	0.71	2.73	2.70	0.99	1.40
MC0.25	0.05	1.04	0.60	1.07	1.08	1.01	1.02
MC0.25	0.25	0.98	0.62	1.34	1.36	1.01	1.12
MC0.25	0.5	0.90	0.64	1.67	1.77	1.06	1.24
MC0.25	0.8	0.85	0.66	2.07	2.26	1.09	1.38
Rate LSD (p)		0.022 (<0.001)	0.009 (<0.001)		0.053 (<0.001)	0.029 (0.008)	0.007 (<0.001)
Size LSD (p)		0.017 (<0.001)	0.007 (<0.001)		0.041 (<0.001)	0.022 (<0.001)	0.006 (<0.001)
Rate x Size LSD (p)		0.038 (<0.001)	0.015 (<0.001)		0.092 (<0.001)	0.050 (0.069)	0.012 (<0.001)

4.3.2 Porosity

To understand the effect of MC particle size and application rate on soil pore size distribution the following pore sizes were calculated: A) macroporosity (>30 µm), B) macro-mesoporosity (30 µm – 3 µm), C) mesoporosity (30µm – 0.2 µm diameter) and D) microporosity (<0.2µm) (Figure 4.2). In order to understand the effect of volume change on porosity, the strain corrected porosity ($\varepsilon c\phi_p$), amendment porosity (ϕ_a) and net pore volume factor ($\lambda\phi_p$) are also presented. All data relating to these pore sizes is presented in Table 4.3 and Figure 4.2.

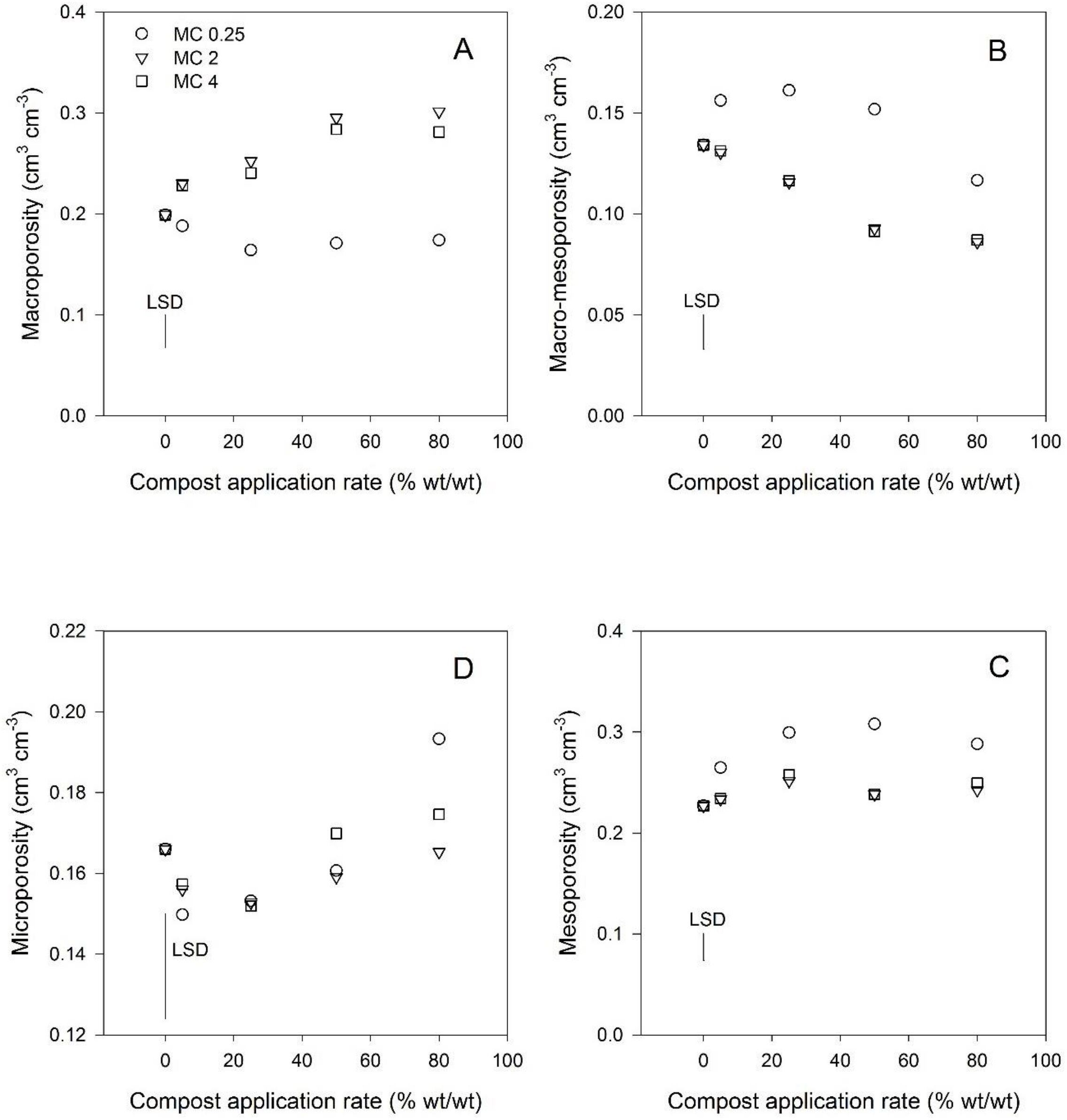


Figure 4.2 Interaction between compost application rate and particle size on porosity, where A) is macroporosity, B) is macro-mesoporosity, C) is mesoporosity and D) is microporosity. LSD is represented on each plot to highlight significance.

Macroporosity increased ($p<0.001$) compared to the control when MC4 and MC2 were incorporated, while the addition of MC0.25 decreased macroporosity compared to the control (Figure 4.2A). Increasing application rate increased macroporosity ($p<0.001$), with application rates of 50% and 80% producing significantly greater macroporosity than 5% and 25% application rates. There was also a significant interaction ($p<0.001$) between the maximum particle size and the application rate. This interaction was that MC4 and MC2 increased macroporosity at all application rates while MC0.25 decreased macroporosity at rates of 25% and greater. Increasing MC application rate decreased the strain corrected soil porosity ($\varepsilon c\phi_{Macro}$) and increased the amendment contribution, ϕ_a. The greatest increase in ϕ_a was produced by MC2 and MC4 at the 80% application rate ($p<0.001$). The net increase in macropore volume factor ($\lambda\phi_{Macro}$) followed the trend of MC4>MC2>MC0.25 for all application rates ($p<0.001$), with the greatest increase occurring when MC4 was applied at the maximum rate of 80% ($p<0.001$).

Macro-mesoporosity decreased ($p<0.001$) compared to the control when MC4 and MC2 were incorporated, while the addition of MC0.25 increased macro-mesoporosity compared to the control. Increasing application rate had varying effects on macro-mesoporosity ($p<0.001$) with 5% increasing, 25% causing no change and 50% and 80% significantly decreasing macro-mesoporosity compared to the control. There was also an interaction between the maximum particle size and the application rate. This interaction was that MC0.25 increased macro-mesoporosity at application rates less than 80% while MC4 and MC2 either produced no change or decreased macro-mesoporosity (Figure 4.2B). The $\varepsilon c\phi_{Mac\text{-}Mes}$ decreased with increasing MC application rate ($p<0.001$) but not compost particle size ($p=0.105$). The amendment contribution to porosity, ϕ_a, was greatest when MC0.25 was applied at all rates and there was no difference between MC2 and MC4. The macro-mesopore volume factor ($\lambda\phi_{Mac\text{-}Mes}$) increased with increasing application rate, with MC0.25 producing a greater increase at all application rates than MC2 and MC4 which were not significantly different; however, $\lambda\phi_{Mac\text{-}Mes}$ decreased at 80% application of MC0.25.

Mesoporosity increased ($p<0.001$) compared to the control when MC was added in the order of MC0.25>MC4>MC2. Increasing application rate increased mesoporosity ($p<0.001$) at application rates of 25% and greater compared to the control. There was also an interaction between the maximum particle size and the application rate ($p<0.001$). This interaction was that MC0.25 produced greater mesoporosity than the control, MC2 and MC4 at all application rates (Figure 4.2C). MC0.25 had the greater ϕ_a at all application rates ($p<0.001$). The mesopore volume ($\lambda\phi_{Meso}$) was increased by increasing application rate ($p<0.001$) and reducing particle size ($p<0.001$) with the relative increase being MC0.25>MC2>MC4, with maximum $\lambda\phi_{Meso}$ for all composts occurring at 80% application rate.

Compost particle size did not affect microporosity ($p=0.176$, Table 4.3). However, there was a significant effect of application rate ($p<0.001$) and an interaction between compost particle size and application rate ($p=0.01$). Microporosity decreased compared to the control when MC was added at 5%, 25% and 50% but increased when added at a rate of 80%. The interaction between application rate and particle size was that microporosity was significantly greater than the control, MC4 and MC2 when MC0.25 was incorporated at a rate of 80% (Figure 4.2D). Incorporation of MC4 produced the greatest increase in ϕ_a when compared to MC2 and MC0.25, with this difference maintained as application rate increased. The micropore volume factor ($\lambda\phi_{Micro}$) was increased by increasing application rate ($p<0.001$). An interaction between application rate and particle size ($p=0.003$) was evident at application rates of 50% and 80%, whereby, MC4 produced significantly greater $\lambda\phi_{Micro}$ than MC2 and MC0.25.

Table 4.3 Changes in porosity following incorporation of MC4, MC2 and MC0.25. Where A is MC application rate, ϕ (pore size) is porosity, $\varepsilon c\phi$ (pore size) is the strain corrected pore size, ϕ_a is the amendment contribution to specific pore size, $\lambda\phi$ (pore size) is the pore volume factor.

		Macropores >30 µm				Macro-Mesopores 30-3 µm				Mesopores 30-0.2 µm				Micropores <0.2 µm			
Treatment	A ($g\ g^{-1}$)	ϕ ($cm^3\ cm^{-3}$)	$\varepsilon c\phi$ ($cm^3\ cm^{-3}$)	ϕ_a ($cm^3\ cm^{-3}$)	$\lambda\phi$	ϕ ($cm^3\ cm^{-3}$)	$\varepsilon c\phi$ ($cm^3\ cm^{-3}$)	ϕ_a ($cm^3\ cm^{-3}$)	$\lambda\phi$	ϕ ($cm^3\ cm^{-3}$)	$\varepsilon c\phi$ ($cm^3\ cm^{-3}$)	ϕ_a ($cm^3\ cm^{-3}$)	$\lambda\phi$	ϕ ($cm^3\ cm^{-3}$)	$\varepsilon c\phi$ ($cm^3\ cm^{-3}$)	ϕ_a ($cm^3\ cm^{-3}$)	$\lambda\phi$
Control	0	0.2	0.2	0	1	0.13	0.13	0	1	0.23	0.23	0	1	0.17	0.17	0	1
MC4	0.05	0.23	0.14	0.08	1.65	0.13	0.12	0.01	1.08	0.23	0.21	0.02	1.10	0.16	0.13	0.03	1.23
MC4	0.25	0.24	0.11	0.13	2.31	0.12	0.09	0.03	1.28	0.26	0.16	0.10	1.62	0.15	0.10	0.05	1.60
MC4	0.5	0.28	0.08	0.21	3.87	0.09	0.06	0.03	1.42	0.24	0.11	0.13	2.11	0.17	0.07	0.10	2.55
MC4	0.8	0.28	0.06	0.22	4.94	0.09	0.05	0.04	1.74	0.25	0.09	0.16	2.85	0.18	0.06	0.12	3.35
MC2	0.05	0.23	0.2	0.03	1.15	0.13	0.12	0.01	1.08	0.23	0.20	0.04	1.20	0.16	0.16	0.01	1.01
MC2	0.25	0.25	0.15	0.10	1.71	0.12	0.09	0.03	1.31	0.25	0.14	0.11	1.76	0.15	0.11	0.05	1.35
MC2	0.5	0.30	0.11	0.19	2.77	0.09	0.06	0.03	1.45	0.24	0.10	0.14	2.30	0.16	0.08	0.08	1.95
MC2	0.8	0.30	0.08	0.22	3.68	0.09	0.05	0.04	1.75	0.24	0.08	0.16	3.05	0.17	0.07	0.10	2.64
MC0.25	0.05	0.19	0.19	0	1	0.16	0.12	0.04	1.36	0.27	0.20	0.07	1.35	0.16	0.16	0	0.92
MC0.25	0.25	0.16	0.15	0.01	1.13	0.16	0.09	0.07	1.77	0.30	0.16	0.14	1.92	0.15	0.13	0.02	1.19
MC0.25	0.5	0.17	0.12	0.05	1.53	0.15	0.07	0.08	2.18	0.31	0.12	0.19	2.58	0.16	0.10	0.06	1.63
MC0.25	0.8	0.17	0.09	0.08	2.02	0.12	0.06	0.06	2.12	0.29	0.09	0.20	3.09	0.19	0.08	0.11	2.50
Rate LSD (p)		0.018 (<.001)	0.018 (<.001)	0.021 (<.001)	0.359 (<.001)	0.01 (<.001)	0.005 (<.001)	0.008 (<.001)	0.113 (<.001)	0.015 (<.001)	0.011 (<.001)	0.011 (<.001)	0.114 (<.001)	0.009 (<.001)	0.007 (<.001)	0.009 (<.001)	0.178 (<.001)
Size LSD (p)		0.014 (<.001)	0.014 (<.001)	0.016 (<.001)	0.278 (<.001)	0.008 (<.001)	0.004 (0.105)	0.006 (<.001)	0.088 (<.001)	0.012 (<.001)	0.008 (<.001)	0.008 (<.001)	0.088 (<.001)	0.007 (0.176)	0.005 (<.001)	0.007 (<.001)	0.138 (<.001)
Rate.Size LSD (p)		0.032 (<.001)	0.032 (0.843)	0.036 (<.001)	0.621 (<.001)	0.017 (<.001)	0.008 (0.002)	0.014 (<.001)	0.196 (<.001)	0.026 (<.001)	0.018 (0.021)	0.018 (0.001)	0.197 (0.131)	0.015 (0.010)	0.012 (0.628)	0.016 (0.003)	0.308 (0.003)

4.3.3 Porosity of compost

Compost fractions exhibited different pore size distribution characteristics (Figure 4.3). The results from pure compost samples reflect those of the mixed samples. Macroporosity increased with increasing maximum particle size, while macro-meso, meso and microporosity all increased with decreasing maximum particle size.

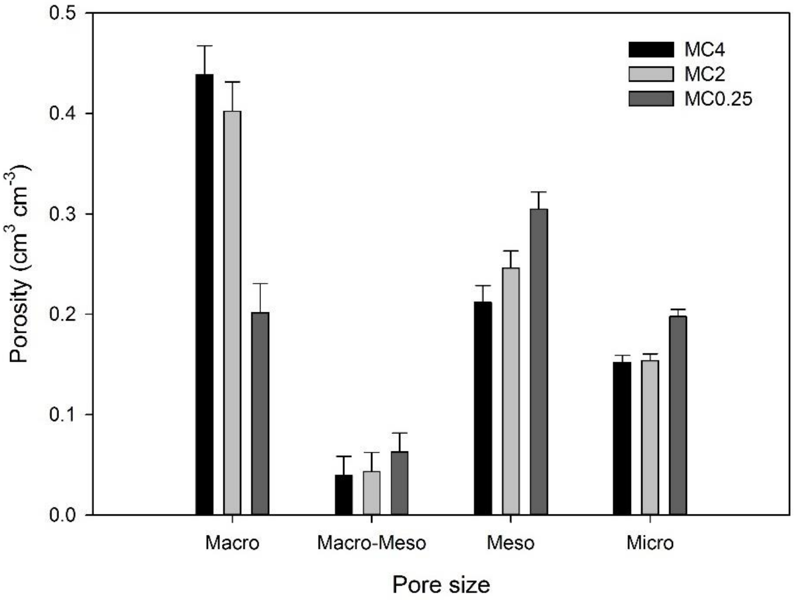


Figure 4.3 Characterisation of MC water desorption for macroporosity, macro-mesoporosity, mesoporosity and microporosity. Error bars are an LSD ($p<0.05$).

4.4 Discussion

The hypothesis of this experiment was that reducing MC particle size and increasing application rate would increase mesopore concentration and volume. Although mesopore concentration (mesoporosity) was not greatly increased, mesopore volume represented by the mesopore volume factor was increased with application rate and reducing particle size which confirmed the original hypothesis. To achieve this, metrics derived from the physical properties of the MC and soil components were applied to predict the potential volume change through the use of the bulking strain, ε_B, and dilution strain, ε_D. The combination of this prediction with the measurement of the physical properties of the resulting amended soil allowed for a better understanding of the mechanisms involved in altering the soil porosity.

This experiment found that net strain (ε_N) cannot be accounted for by the dilution strain (ε_D) alone. Evidence for this is that ε_N was consistently greater than ε_D, with this difference increasing with application rate. This means that pores in the MC are retained and new pores are created with soil MC interaction, and that this pore creation increases with application rate. This finding differs from the conclusions of previous work which suggests that the change in soil density (and therefore volume) following amendment is due to the dilution of dense soil particles with a low density solid (Khaleel et al., 1981). However, these findings agree with studies that have acknowledged that amendments retain intra-particle pore space (Kinney et al., 2012; Novak et al., 2012), and that amendments increase inter-particle pore space through aggregate stabilisation (Pagliai et al., 2004). The calculation of the strain ratio, ε_R, provides further confirmation of this conclusion as ε_R is often greater than one, indicating that the interaction of soil and MC enhances porosity over the porosity of individual components.

The changes in soil volume due to amendment also had significant effects on the pore sizes of interest for improving soil water retention and movement. Macroporosity, which controls water entry and movement through the soil, increased with increasing MC application rate when MC2 and MC4 were incorporated; however, the reverse was found when MC0.25 was incorporated. The addition of MC0.25 increased the total volume of macropores, but this increase was significantly less than that measured from MC2 and MC4. This result agrees with Liu et al. (2017) who reported that larger biochar particle sizes produced greater increases in macroporosity while Reynolds et al. (2003) reported that macroporosity increased with increasing MC application rate. The response from the current experiment suggests that soils impeded by relatively low infiltration could be improved through the addition of MC4 and MC2, whereas soils where rapid infiltration is a limitation (such as shallow stony soils) would benefit from the addition of MC0.25.

Macro-mesoporosity decreased with increasing rates of MC4 and MC2 but increased when MC0.25 was added. This finding is significant as it provides evidence that modifying MC by screening has the potential to increase water-retaining porosity at relatively low application rates. The current study found a total gain in macro-mesopore volume factor ($\lambda\phi_{Mac\text{-}Mes}$) of 36% at a relatively low (5%) application rate of MC0.25. For comparison, an application rate of between 25% and 50% would be required to achieve a similar increase with MC2 or MC4. To further cement this finding the application of MC0.25 at 25% produced a greater increase in macro-mesopore volume than an 80% application rate of MC2 or MC4.

Mesoporosity also responded to compost application rate and particle size. The greatest increase in both mesoporosity and mesopore volume factor ($\lambda\phi_{Meso}$) was produced by MC0.25, followed by MC2 and MC4. Increasing application rate increased $\lambda\phi_{Meso}$, with the greatest volume of mesopores occurring at the highest application rate for all composts. These results contrast with the results of Liu et al. (2017) who found that increasing particle size of biochar increased mesoporosity; Liu et al. (2017) argued that larger particles contributed a greater volume of intra-particle pore spaces from within the biochar itself than smaller particles. Therefore, as the particle size increased so did the contribution from smaller intra-particle pores, leading to greater mesoporosity. The results from pore size analysis of pure compost indicated that macro-mesoporosity, mesoporosity and microporosity all increased with decreasing particle size. This result may be due to either an increased contribution of intra-particle pores from MC or due to the packing of particles and the resultant inter-particle pores, as large particles are likely to create large inter-particle pore spaces, whereas smaller particles will produce the reverse; unfortunately this study was unable to separate these two mechanisms. The knowledge that decreasing MC particle size increases water-retaining porosity in combination with the greater bulk density of MC0.25 suggests that screening MC may improve the practical application of MC as 1) less mass would be required to achieve changes in water retaining porosity and 2) greater bulk density means 60% more product can be transported at once when compared to MC4 and MC2. These factors are likely to combine to reduce the application cost, which may improve adoption of this management practice.

Microporosity was unaffected by MC particle size but was initially reduced by compost application rates of 5% and 25% and increased by application rates of 80%. This result agrees with that of Stewart et al. (1998) who reported that incorporating mushroom substrate in to a Templeton silt loam at a rate of 80 t ha^{-1} reduced microporosity, while rates of 160 t ha^{-1} and 320 t ha^{-1} increased microporosity; however, these changes were not statistically significant. Although particle size did not affect the concentration of micropores, the total volume ($\lambda\phi_{Micro}$) was significantly increased by increasing particle size, with the greatest volume of micropores occurring in MC4 treated soil.

The significant finding from this pore size analysis was that application rate and particle size of MC can influence the water-retaining porosity of a cultivated arable soil. The use of MC0.25 in this study reduced macroporosity and increased both macro-mesoporosity and mesoporosity. These changes would benefit a cultivated soil as mesoporosity would be increased without the potential increase in macroporosity, which could lead to increases in water losses due to rapid infiltration and drainage of irrigation water. To determine if these changes in porosity would effectively increase water-retaining pores in an irrigated system and therefore allow irrigation management to be altered it is recommend that further experiments quantify the effect of MC incorporation on macro-meso and mesoporosity when the soil is managed under spray irrigated field conditions. The aim of these studies should be to determine how amendment would alter both the water retention of a cultivated soil but also the flow of water through the soil, as the increase in macropore concentration and volume noted in this chapter may have detrimental effects in soils that already have rapid permeability.

4.5 Conclusions

This study has found that increasing application rate and reducing maximum particle size of MC results in greater increases in water-retaining pore space with a muted increase in water transport pores at low application rates. This important finding provides evidence that changes in specific pore spaces can be targeted through the modification of a common waste stream, which is likely to benefit a large range of systems and soil types that require the soil to be modified to suit a particular land use. This experiment found that the most effective MC particle size for shallow stony soils, which are limited by poor water retention and rapid drainage, was MC0.25. The use of this product may be an economic solution to increasing the concentration and volume of macro-meso and mesopores in a cultivated soil without the potential risk of increasing water and nutrient movement due to increases in macroporosity. The application of MC0.25 is effective at significantly lower application rates than MC4 and MC2; this finding coupled with the higher bulk density of MC0.25 means that less product would need to be transported and incorporated to reap the same potential water retention benefits as MC4 and MC2. Production of MC0.25 may be difficult on a commercial scale; however, this research has highlighted a trend of increasing macro-mesoporosity and mesoporosity with reducing maximum MC particle size. Therefore, it is recommend that further research uses the smallest practical size of MC. Further field scale measurements are required to confirm these findings under spray irrigation, and determine the potential benefits in terms of production, plant water use and soil water retention.

Chapter 5 Amendments to increase water retention under spray irrigation

This chapter builds on the findings of Chapter 3 and Chapter 4 by determining if the increases in mesoporosity associated with sphagnum moss (SM), polyacrylamide (PM) and municipal compost (MC) incorporation are maintained under spray irrigation and whether these changes engender a functional difference with respect to water storage and plant yield. This chapter also aims to understand whether the increases in macroporosity measured in Chapter 3 and Chapter 4 lead to changes in water movement through the soil profile.

5.1 Introduction

Previous results have identified that the incorporation of PM, SM or MC can increase soil water retention by increasing water-retaining mesopores and potentially increase water movement due to an increase in macroporosity. The challenge that remains is to determine if amending soil: 1) increases water retention of a shallow soil under spray irrigation and 2) increases water infiltration and movement. This understanding is an important step in determining the potential of this practice as spray irrigation is applied to 95% of Canterbury's irrigated area (Brown, 2016). It is likely that spray irrigating amended soil will produce different water retention responses to the gradual capillary-driven wetting applied in Chapters 3 and 4. Determining whether there is an interaction between the selected amendments and irrigation rates is another critical step as recent work has shown that irrigation application rate can have a significant effect on soil wetting (Cichota et al., 2016) and amendments may have the potential to mediate or enhance these effects.

Therefore, the following three hypotheses were set:

- Incorporation of MC, SM and PM will increase mesoporosity and subsequently increase soil water retention under two rates of irrigation.
- The increase in water retention will increase plant growth relative to the control.
- Incorporation of MC, SM and PM will increase macroporosity and therefore increase the rate of water movement through the soil profile.

5.2 Method and Materials

5.2.1 Experimental set up

A lysimeter experiment was established inside a temperature-controlled glass house at Plant & Food Research, Lincoln (Figure 5.1). The experiment tested three amendment treatments and a control irrigated at two different rates over a six week period. Each treatment combination was replicated four times in a randomised complete block design to account for temperature and radiation variability within the glass house.

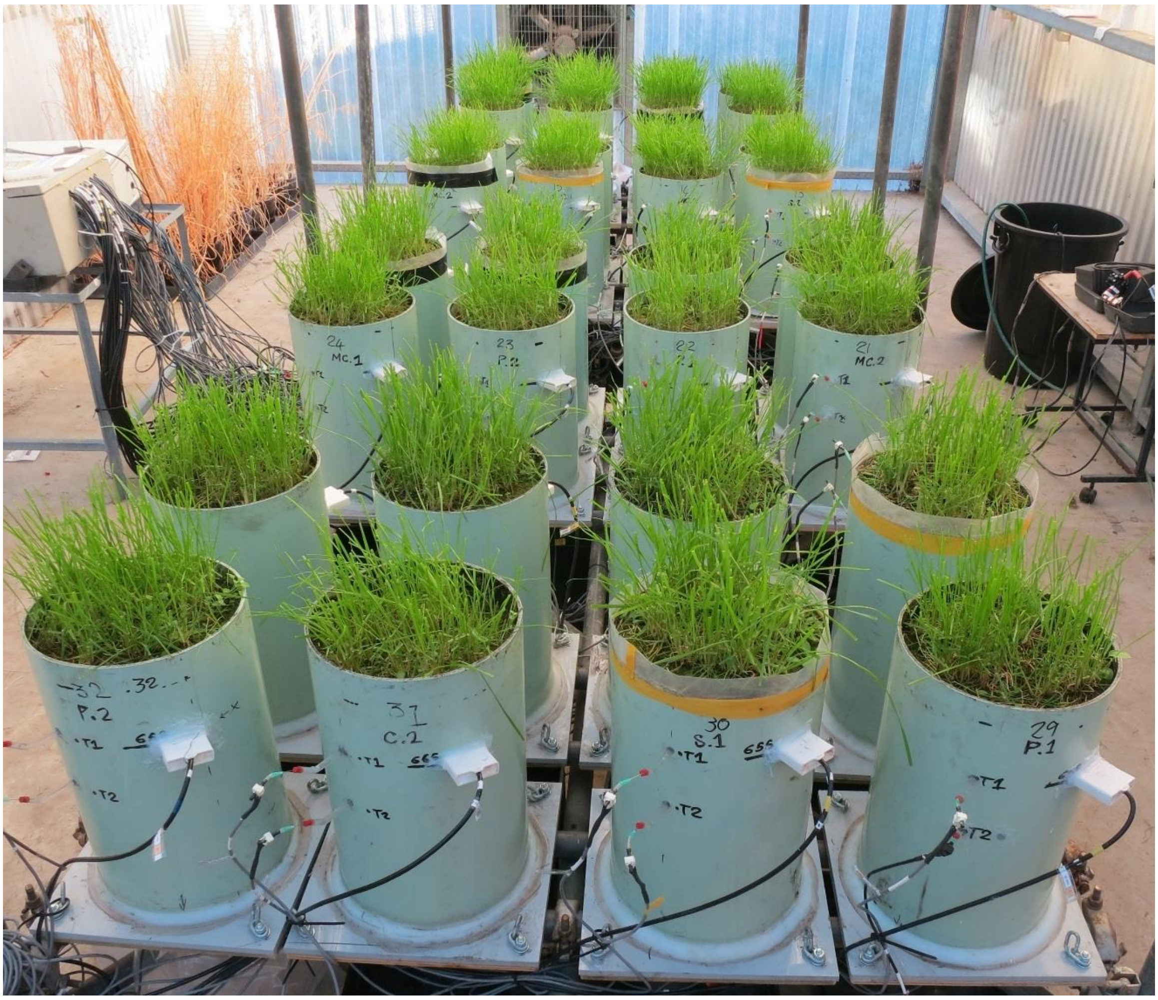


Figure 5.1 Instrumented lysimeter set up in glass house

5.2.2 Soil

The soil used for this experiment was a Templeton silt loam (Typic Immature Pallic Soil, Hewitt, 2010) collected from a Plant and Food Research site situated approximately 2 km south east of Lincoln (43°62’ S, 172°47’E), Canterbury, New Zealand, which had been under long term (>15 years) cropping management. Soil texture was 22% clay, 66.5% silt and 11.5% sand; the soil had a pH of 5.7, total C of 2.9% and total N of 0.24%.

5.2.3 Treatments

Three amendments were selected for incorporation into the soil: MC, SM and PM, which were compared to an un-amended control and irrigated at two rates.

Amendments

Municipal compost (certified organic, aged 21 weeks) was sourced from Living Earth, Christchurch and screened to a particle size of ≤1 mm diameter. This decision was made as Chapter 4 identified that reducing particle size increased the concentration and total volume of mesopores, therefore, the smallest practical screening size was selected for this experiment. Sphagnum moss, originally harvested on the West Coast of New Zealand, was purchased from a landscape supply store, and PM (Broadleaf P4, Broadleaf Industries, USA) was sourced from Transplant Systems New Zealand.

Irrigation rate

Each amendment treatment received irrigation at a rate of 10 mm h^{-1} or 80 mm h^{-1}. These rates were selected to represent the range in water application rates applied along the 800 meter length of a conventional centre pivot irrigator (Powers 2012).

5.2.4 Lysimeter construction

Lysimeters were constructed from polyvinyl cholride (PVC) culvert pipe and had an internal diameter of 30 cm and a depth of 50 cm. Each lysimeter contained two soil layers, a stony subsoil and a cultivated topsoil. Lysimeters were manually packed, which allowed the volume and depth of stones in the subsoil of each lysimeter to be controlled. Prior to packing, a 5 mm thick layer of petroleum jelly was applied to the internal walls of the core to prevent side wall flow.

The subsoil was packed in 5 cm increments to a thickness of 20 cm, the texture of this layer was 80% gravels by mass (60% 10-20mm gravels, 40% 6-8 mm gravels) and 20% sand (50% coarse, 50% fine) to replicate a typical Canterbury gravel layer (Dann et al., 2009). Bulk density of this layer was 2.12 g cm^{-3} and the average volumetric drained upper limit was 8.5%. Bulk density was determined by dividing the mass of oven dry material in the lysimeter by the packing volume. The average volumetric drained upper limit was calculated by saturating the subsoil, calculationg water retention (Section 5.2.6) and dividing by the packed depth.

The topsoil was first screened with an 8 mm sieve to remove aggregates that would be difficult to evenly replicate across lysimeters, and would therefore increase variability. The selected amendments were then thoroughly mixed with soil using a mixing trough and swan neck hoe at rates of 18 t ha^{-1}, 3 t ha^{-1} and 150 t ha^{-1} (equivalent to 0.6%, 0.1% and 5% wt/wt respectively) on an oven dry basis for the SM, PM and MC treatments, respectively, before being packed in to the lysimeters in 5 cm layers. The topsoil of the control lysimeters was packed to a target bulk density of 1.2 g cm^{-3}

and depth of 25 cm, the depth of amended lysimeters was adjusted according to the predicted bulking strain (ε_B) as discussed in Chapter 3, Section 3.36, which resulted in packing depths of 25.5 cm, 27.5 cm and 30 cm for the PM, MC and SM treatments respectively.

5.2.5 Lysimeter management

Planting

Lysimeters were planted with Italian rye-grass (*Lolium multiflorum*) by initially cultivating the surface using a hand rake to 2 cm depth. Seeds were then broad cast over the surface at a rate of 40 kg seed ha^{-1}. Following emergence, populations were thinned to 65 plants per lysimeter.

Irrigation

Irrigation was applied every 14 days over the six week duration of the experiment using a hand-held system consisting of a single pump (Shurflo SLV, Pentair/Shurflo, Dandenong South, Australia) and spray nozzle (Quick TeeJet QJ200 nozzle bodies with FL5VC nozzles, TeeJet Technologies, Illinois, USA). The application volume was calibrated prior to each irrigation event and controlled by an analogue timer relay to apply 0.5 mm of water per 2 second pulse. Prior to starting the experiment, each lysimeter was gradually saturated by applying 10 mm of water per day at an application rate of 10 mm h^{-1}. The target drained upper limit (R_{DUL}) of each lysimeter was then set as the point at which drainage ceased. This drained upper limit was considered 0 mm deficit and was the target refill point. The volume of water applied at each irrigation event varied as each lysimeter was returned to its original drained upper limit, plus an additional 10 mm to ensure drainage was achieved. If a lysimeter was at a 10 mm deficit it would receive a total volume of 20 mm. Two irrigation rate treatments were imposed on this experiment; 10 mm h^{-1} and 80 mm h^{-1}. The 10 mm h^{-1} irrigation rate was applied as a single 0.5 mm application pulse on a three minute return interval whereas the 80 mm h^{-1} treatment was pulsed as eight 0.5 mm applications spaced 0.5 seconds apart on a three minute return interval. This schedule meant that if a 20 mm volume of water was required it would be applied over a period of two hours in the 10 mm h^{-1} treatment and 15 minutes in the 80 mm h^{-1} treatment.

Fertiliser

Fertiliser was applied as a solution of ammonium nitrate (NH_4NO_3), monopotassium phosphate (KH_2PO_4), potassium sulphate (K_2SO_4) and potassium chloride (KCl) to provide the 4.5:0.35:2:0.3 ratio of nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) required to support rye-grass production (Cornforth and Sinclair, 1984). A 20 t ha^{-1} dry matter crop was assumed to ensure nutrient imbalance did not affect yield. The P, K and S were applied post plant-emergence as a base application while the N was applied in four equal applications: an initial base application and following dry matter cuts thereafter. The N fertiliser solution was applied through the irrigation system as a 1 mm application, applied 24 hours after the soil had reached drained upper limit to ensure even distribution through the root zone.

Plant growth

Rye-grass was cut to a height of 5 cm every 14 days, following lysimeter weighing and prior to irrigation. The cut rye-grass was then placed in a paper bag and dried at 65°C for four days to determine dry matter content. Weeds were removed by hand and left in the lysimeters to break down.

5.2.6 Measurements

Automated data

Continuous changes in volumetric water content were measured using Campbell CS655 water content sensors (Campbell Scientific, Logan, UT, USA) installed horizontally at 10 cm below the soil surface. Soil matric potential was measured at 10 cm and 20 cm depth with custom built tensiometers (Soilmoisture Equipment Corporation high flow ceramic cup 28 mm long 9 mm outside diameter, polycarbonate pipe and Honeywell 15 psi differential pressure sensor). Drainage was measured using a tipping spoon mechanism (PCB 9602, Pronamic, Denmark) mounted underneath the lysimeter. All sensors were controlled by a Campbell CR6 logger, which collected measurements on 1 minute and 10 minute intervals; all data were downloaded weekly.

Total water retention

Lysimeter mass was measured twice a week by weighing each lysimeter using a Wedderburn hanging load cell (Wedderburn WS65 Max capacity = 150 kg, accuracy +/- 50 g which translates to an error of +/- 0.7 mm of water content). This measurement allowed the mass of water in each lysimeter (water content - WC) to be measured directly by subtracting the mass of all oven dry components (which were weighed prior to starting the experiment) from the total mass of the lysimeter. A soil water balance approach was used to determine the total soil water retention following irrigation (R_T) of the amended soil in each lysimeter (Equation 5.1). Total water retention was defined as the amount of irrigation water retained in the lysimeter once drainage had ceased. The mass of R_T was converted to a depth of water (mm) by dividing by the lysimeter area.

$$R_T = WC_{T0} + P - D - ET - SS \tag{5.1}$$

where WC_{T0} is water content (mm) measured by lysimeter mass at time zero, which was measured immediately prior to the irrigation being applied. P is the amount of irrigation added (mm), D is the amount of drainage lost (mm), ET is the estimated evapotranspiration over the drainage period (mm) and SS is water retention of the stony subsoil (mm).

To calculate the water loss due to *ET* the change in water content (*ΔWC*) was first calculated using Equation 5.2.

$$\Delta WC = WC_{T0} + P - WC_{T3} \qquad 5.2$$

Where WC_{T3} is the water content measured three days after the experiment started (mm) and drainage had become negligible. The three-day total *ET* (ET_3) was calculated by subtracting the total drainage (*D*) from the *ΔWC* (Equation 5.3).

$$ET_3 = \Delta WC - D \qquad 5.3$$

The *ET* rate ($\dot{ET}$) was then calculated by dividing ET_3 by the three-day time period to get mm day^{-1}. Finally, total *ET* for the calculation of R_T was estimated by multiplying $\dot{ET}$ by the time required for drainage to become negligible (ΔT_D) in days (Equation 5.4).

$$ET = \dot{ET} \times \Delta T_D \qquad 5.4$$

Density and porosity

The soil bulk density, particle density, total porosity and pore size analysis presented here were measured at the conclusion of Experiment 4, which is discussed in Chapter 6. The assumption has been made that the irrigation treatments applied in the current experiment (Chapter 5) and the subsequent experiment (Chapter 6) would have a negligible effect on soil porosity and that the amendment effect would dominate.

To estimate the soil porosity, two soil cores from each lysimeter were removed at the end of the final experiment (Chapter 6). A large core (10 cm diameter x 7.5 cm deep) was removed from the 1 - 8.5 cm soil layer and a smaller core (5.2 cm diameter x 3 cm deep core) was removed from the 3 – 6 cm soil layer. All cores were saturated incrementally from the base, with 1 cm of water added every 24 hours for 72 hours. Large cores were then placed on silica sand tension tables and soil water contents were determined after core mass had equilibrated at a matric potential of -10 kPa (Reynolds and Topp, 2007b). Small cores were placed on ceramic plates in pressure chambers (Soilmoisture Equipment Corporation, USA) and pressures equivalent to a matric potential of -100 kPa and -1500 kPa were applied. Once the final pressure was reached each core was oven dried at 105°C for 48 hours to determine the gravimetric water content at each matric potential. Bulk density was then used to calculate volumetric water content. Particle density (ρ_p) was measured by the pycnometer method (Gradwell and Birrell, 1972), and total porosity (ϕ_t) according to Equation 5.5.

$$\phi_t = 1 - \frac{\rho_b}{\rho_p} \tag{5.5}$$

The drained upper limit (θ_{DUL}), macroporosity (ϕ_{Macro}), mesoporosity (ϕ_{Meso}) and microporosity (ϕ_{Micro}) were calculated using Equation 5.6, 5.7, 5.8 and 5.9, respectively.

$$\theta_{DUL} = \theta_{v10kPa} \tag{5.6}$$

$$\phi_{Macro} = \phi_t - \theta_{v10kPa} \tag{5.7}$$

$$\phi_{Meso} = \theta_{v10kPa} - \theta_{v1500\,kPa} \tag{5.8}$$

$$\phi_{Micro} = \theta_{v1500\,kPa} \tag{5.9}$$

where θ_v is volumetric water content.

5.2.7 Strain and pore volume

As in previous chapters the bulking strain (ε_B) was calculated to determine the target packing depth of the lysimeters (Equation 5.1).

$$\varepsilon_B = 1 + \frac{\rho_{bS}}{\rho_{bA}} A \tag{5.10}$$

where ρ_{bS} is soil bulk density (g cm^{-3}), ρ_{bA} is amendment bulk density (g cm^{-3}) and A is the mass rate of amendment addition (g g^{-1}). The assumption with this calculation is that the voids that are apparent when the bulk density of the amendment is measured are maintained when the soil and amendment are mixed.

Once packed, the net strain (ε_N) was calculated (Equation 5.11).

$$\varepsilon_N = (1 + A)\frac{\rho_{bS}}{\rho_b} \tag{5.11}$$

where A is the amendment application rate (g g^{-1}), ρ_{bS} is the bulk density of the control soil (g cm^{-3}), ρ_b is the bulk density of the amended soil (g cm^{-3}).

The strain ratio (ε_R), which is the ratio between the measured net strain ε_N and the predicted bulking strain (ε_B), was then calculated using Equation 5.12.

$$\varepsilon_R = \frac{\varepsilon_N}{\varepsilon_B} \qquad 5.12$$

The strain ratio provides a metric for exploring the nature of the interaction between the amendment and soil. When the ratio is greater than 1 ($\varepsilon_R>1$) it is assumed that interaction between the amendment and soil has created inter-particle pore spaces; when the strain ratio is less than 1 ($\varepsilon_R<1$) it is assumed the interaction between soil and amendment has infilled pore spaces.

Because amendment involves adding new material to the soil it is necessary to know the absolute change in water retention due to 1) changing pore size distribution relative to the control and 2) the net strain effect. The net pore volume factor $\lambda\phi$ (Equation 5.13), defines the factor by which a volume of pores of size range, p, in a nominal volume of soil increases by the addition of an amendment. For example, if 1 cm^3 of soil had α cm^3 of pores of size range p, after incorporating an amendment the expanded volume would have a volume of pores of size range p given by $\alpha\,\lambda\phi_{p.}$.

$$\lambda\phi_p = \frac{\phi_{As,p}}{\phi_{s,p}}\varepsilon_N \qquad 5.13$$

where $\phi_{As,\,p.}$ is the porosity of the amended soil in size range p ($cm^3\ cm^{-3}$) and $\phi_{s,\,p}$ is the un-amended control soil's porosity in size range p ($cm^3\ cm^{-3}$).

5.2.8 Water movement

Drainage

To quantify differences in drainage, a drainage to irrigation ratio (*D:P*) was calculated (Equation 5.14).

$$D:P = \frac{D}{P_D} \qquad 5.14$$

where D is drainage in mm and P_D is the amount of excess irrigation applied to trigger drainage (10 mm). The ratio approach accounts for the variability in antecedent soil water content at the time of irrigation that would influence other possible measures, such as time to drainage, and allows all lysimeters to be compared.

Effective infiltration

To calculate the effective rate of water infiltration (I_E) through the soil the assumptions of the Green and Ampt infiltration model (Green and Ampt, 1911) have been applied. Based on this model, it is assumed that the wetting front during irrigation was rectangular and that at the depth of the soil moisture sensor z_f, the soil was saturated (θ_s) and beyond that, the soil remained at its initial water content (θ_n). The mass balance integral of the power series solution was applied (Equation 5.15), as originally proposed by Philip (1957), to define the rate of infiltration in to the soil (Clothier, 2000).

$$I_E = \frac{d(z_f(\theta_s - \theta_n))}{dt} = \frac{dz_f}{dt}.(\theta_s - \theta_n) \tag{5.15}$$

where z_f is the depth of the wetting front (mm) at time, t (hours). θ_s is volumetric water content at saturation ($cm^3\ cm^{-3}$) and θ_n is initial volumetric water content ($cm^3\ cm^{-3}$). θ_s and θ_n values were measured with the Campbell CS655 water content sensor.

Wetting efficiency

The wetting efficiency (*WE*) of each irrigation event was calculated (Equation 5.16) to determine if either amendment or irrigation rate could improve soil wetting.

$$WE = \frac{R_T}{R_{DUL}} \tag{5.16}$$

where R_T is the measured soil water retention following irrigation (mm) and R_{DUL} is the amount of water retained at the target drained upper limit (mm).

5.2.9 Statistical analysis

Repeated measures analysis of variance was used to determine if there were significant differences in water retention (R_T), effective infiltration (I_E), drainage to irrigation ratio (*D:P*) and wetting efficiency (*WE)*. These factors were calculated three times during the experiment. General analysis of variance was used to determine if there were significant differences between variables that were measured once, such as soil physical properties, cumulative plant yield and growth rate. A result was considered to be significant when $p<0.05$.

5.3 Results

5.3.1 Bulk density, total porosity and strain

All amendments significantly reduced bulk density (ρ_b) ($p<0.001$) and increased total porosity (ϕ_t) ($p<0.001$) compared to the control; the order of change was SM>MC>PM (Table 5.1). Particle density (ρ_p) decreased with incorporation of MC and SM. This physical change resulted in an increase in soil volume represented by the net strain (ε_N), which increased ($p<0.001$) in the order of MC, SM and PM (Table 5.1).The predicted bulking strain (ε_B) increased in the order of SM>MC>PM with the ratio of ε_B and ε_N being represented by the strain ratio (ε_R). The strain ratio indicated that PM caused an increase in soil volume over and above the volume transferred by the soil and amendment ($\varepsilon_R>1$), whereas the SM soil interaction led to a loss in volume relative to the sum of bulk soil and amendment volume ($\varepsilon_R<1$).

Table 5.1 Bulk density (ρ_b), particle density (ρ_p), total porosity (ϕ_t), bulking strain (ε_B), net strain (ε_N) and strain ratio (ε_R) when municipal compost (MC), polyacrylamide (PM) and sphagnum moss (SM) were incorporated. Bold indicates a significant difference from the control.

Treatment	ε_B	ε_N	ε_R	ρ_b (g cm^{-3})	ρ_p (g cm^{-3})	ϕ_t (cm^3 cm^{-3})
Control	1.000	1.000	1.000	1.16	2.61	0.55
MC	1.097	**1.108**	1.010	**1.11**	**2.58**	**0.57**
PM	1.002	**1.046**	**1.044**	**1.12**	2.61	**0.57**
SM	1.196	**1.106**	**0.925**	**1.06**	**2.60**	**0.59**
LSD (p)		0.0291 (<.001)	0.0249 (<0.001)	0.029 (<0.001)	0.005 (<0.001)	0.011 (<0.001)

5.3.2 Porosity

To explore effects on porosity as they relate to water retention and movement, results of soil macroporosity, mesoporosity and microporosity are presented in Table 5.2.

Macroporosity

Macroporosity increased significantly ($p<0.001$) compared to the control (0.22 $cm^3\ cm^{-3}$) through incorporation of SM, PM and MC with the greatest increase being produced by SM. When these changes in macroporosity were considered alongside the net strain, ε_N, the macropore volume factor ($\lambda\phi_{Macro}$) increased according to the same trend as macroporosity.

Mesoporosity

Mesoporosity increased compared to the control (0.17 $cm^3\ cm^{-3}$) when SM, PM and MC were incorporated, although this increase was not significant ($p=0.06$). However, the mesopore volume factor ($\lambda\phi_{Meso}$) was increased significantly ($p<0.001$) compared to the control in the order of SM>MC>PM.

Microporosity

Microporosity decreased compared to the control (0.17 $cm^3\ cm^{-3}$) through incorporation of MC, PM and SM, although this decrease was not significant ($p=0.165$). Amendment also had no effect ($p=0.479$) on the micropore volume factor ($\lambda\phi_{Micro} \approx 1$).

Table 5.2 Changes in drained upper limit (θ_{DUL}), macroporosity (ϕ_{Macro}), mesoporosity (ϕ_{Meso}), microporosity (ϕ_{Micro}), net macro ($\lambda\phi_{Macro}$), meso ($\lambda\phi_{Meso}$) and micro ($\lambda\phi_{Micro}$) pore volume factor. Bold denotes the value is significantly different from the control.

Treatment	θ_{DUL} ($cm^3\ cm^{-3}$)	ϕ_{Macro} ($cm^3\ cm^{-3}$)	ϕ_{Meso} ($cm^3\ cm^{-3}$)	ϕ_{Micro} ($cm^3\ cm^{-3}$)	$\lambda\phi_{Macro}$	$\lambda\phi_{Meso}$	$\lambda\phi_{Micro}$
Control	0.34	0.22	0.17	0.17	1.0	1.0	1.0
MC	0.34	**0.23**	0.18	0.16	**1.21**	**1.21**	1.049
PM	0.34	**0.23**	0.18	0.15	**1.15**	**1.14**	0.978
SM	0.34	**0.25**	0.20	0.14	**1.29**	**1.30**	0.970
LSD (p)	0.0093 (0.541)	0.01 (<0.001)	0.019 (0.06)	0.019 (0.165)	0.1330 (0.001)	0.135 (0.001)	0.113 (0.479)

5.3.3 Soil water retention

The average soil water retention (R_T) following irrigation of the control topsoil was 86.3 mm, which increased significantly ($p<0.001$) by 12.9 mm, 11.5 mm and 7 mm with incorporation of SM, MC and PM, respectively (Table 5.3). Irrigation application rate had no significant effect on R_T and there was no interaction between amendment type and irrigation rate.

5.3.4 Drainage and infiltration rate

The drainage to irrigation ratio ($D:P$) increased significantly ($p<0.001$) when the irrigation application rate was 80 mm h^{-1} compared to 10 mm h^{-1} (Table 5.3) although there was no significant effect of amendment on this ratio ($p=0.265$).

Wetting efficiency (WE) reduced ($p=0.005$) due to amendment incorporation compared to the control with the lowermost WE resulting from the addition of PM followed by MC and SM. There was no effect of irrigation application rate on WE.

The other descriptor of water movement, effective infiltration (I_E), increased significantly ($p<0.001$) by both amendment and irrigation rate and there was also a significant interaction ($p<0.001$) between these two main effects (Table 5.3). Incorporating PM produced the greatest increase in I_E followed by MC, while I_E in the SM lysimeters was not significantly different to the control. The irrigation application rate significantly increased I_E from 2.9 mm h^{-1} at an irrigation application rate of 10 mm h^{-1} to 16.4 mm h^{-1} when irrigation was applied at 80 mm h^{-1} ($p<0.001$), which is the equivalent of a 5.6-fold increase. The interaction between these two main treatment effects determined that I_E was significantly greater in PM and MC lysimeters than in SM or control lysimeters when irrigation was applied at 80 mm h^{-1}.

Table 5.3 Average water retention (R_T), drainage to irrigation ratio (*D:P*), wetting efficiency (*WE*) and effective infiltration (I_E) when municipal compost (MC), polyacrylamide (PM) and sphagnum moss (SM) were incorporated and irrigated at 10 mm h^{-1} or 80 mm h^{-1}.

Treatment	Irrigation rate (mm h^{-1})	R_T (mm)	*D:P*	*WE*	I_E (mm h^{-1})
Control	10	86.7	0.55	0.949	2.42
MC	10	101.1	0.62	0.933	3.14
PM	10	93.3	0.60	0.909	3.03
SM	10	99.4	0.55	0.921	2.86
Control	80	86.0	0.73	0.973	10.44
MC	80	94.4	0.75	0.918	16.10
PM	80	93.3	0.79	0.927	25.23
SM	80	98.9	0.69	0.945	10.50
Treatment LSD (p)		5.26 (<.001)	0.09 (0.265)	0.024 (0.005)	1.20 (<.001)
Irrigation rate LSD (p)		3.72 (0.290)	0.06 (<.001)	0.017 (0.150)	1.14 (<.001)
Treatment x Irrigation rate LSD (p)		7.43 (0.535)	0.13 (0.847)	0.034 (0.329)	1.30 (<.001)

5.3.5 Plant yield

There was no significant difference in yield either as a daily growth rate or as a cumulative yield (Table 5.4). There was, however, a significant interaction between amendment treatment and irrigation rate. The rate and cumulative yield of the control was significantly greater when the control was irrigated at 10 mm h^{-1} compared to 80 mm h^{-1}.

Table 5.4 Average growth rate of rye grass and total cumulative yield following incorporation of municipal compost (MC), polyacrylamide (PM) and sphagnum moss (SM).

Treatment	Irrigation rate (mm h^{-1})	Growth rate (g DM day^{-1})	Cumulative yield (g DM)
Control	10	0.338	4.725
MC	10	0.324	4.531
PM	10	0.292	4.083
SM	10	0.331	4.628
Control	80	0.272	3.812
MC	80	0.320	4.476
PM	80	0.310	4.346
SM	80	0.333	4.657
Treatment LSD (p)		0.0287 (0.124)	0.402 (0.124)
Irrigation Rate LSD (p)		0.0203 (0.240)	0.284 (0.240)
Treatment x Irrigation Rate LSD (p)		0.0406 (0.027)	0.569 (0.027)

5.4 Discussion

This experiment found clear evidence that incorporation of SM, MC and PM had a significant effect on the soil's structure and porosity. There was a similar response from amendment incorporation to that measured in the previous chapters of this thesis, with a decrease in bulk density and a subsequent increase in total porosity compared to the control, which is supported by previous studies (Aggelides and Londra, 2000; Celik et al., 2004). These physical changes resulted in a significant increase in net strain (ε_N) and an increase in the concentration and volume of water-retaining pores compared to the control. Mesoporosity was increased by all amendments in the order of SM>MC>PM which confirmed the initial hypothesis; however, this increase was only statistically significant once the contribution of the net strain (ε_N) was considered and the mesopore volume factor ($\lambda\phi_{Meso}$) was calculated. The increase in $\lambda\phi_{Meso}$ was reflected in changes in water retention (R_T), which increased in the order SM>MC>PM; however, no significant change in concentration of water retention pores (θ_{DUL}) was measured. Although R_T includes the water retained in micropores the comparison between $\lambda\phi_{Meso}$ and R_T is valid as there was no effect of amendment on either microporosity (ϕ_{Micro}) or the micropore volume factor ($\lambda\phi_{Micro}$). This contrast of significance produced by pore volume (R_T and $\lambda\phi_{Meso}$) and pore concentration (θ_{DUL} and ϕ_{Meso}) provides further evidence of the importance of volumetric changes when amendments are incorporated, and that if experiments persist in only considering pore concentrations, the full water retention benefit of the soil amendment is unlikely to be fully quantified.

Previous studies have identified comparable changes in bulk density and mesoporosity following incorporation of sphagnum peat (Li et al., 2004), municipal compost (Reynolds et al., 2015) and polyacrylamide gel (Akhter et al., 2004) into various soils. Unfortunately, there is a lack of studies which have estimated the resultant change in mesopore volume when bulk density is decreased and mesopore concentration is increased, which makes comparison the results from the current study difficult. There is also a lack of research on the use of SM such as that used in the current study. Li et al. (2004) reported that sphagnum peat incorporation into a podzol was able to increase soil water retention (at -33 kPa) and total porosity while reducing bulk density, and the degree of these changes was positively correlated with amendment application rate. The authors concluded that the increase in soil water content was due to the high water-retaining capacity of the peat and the decrease in bulk density, which allowed a greater portion of the soil to be occupied by water. The relevance of this comparison is somewhat questionable as sphagnum peat is the decomposed and compressed version of fresh sphagnum moss, which has been shown to have differing hydraulic properties compared to sphagnum moss (Boelter, 1964).

Compost incorporation has received a greater level of interest and has been reported to both increase (Aggelides and Londra, 2000; Reynolds et al., 2015) and decrease (Mandal et al., 2013) soil water retention. The difference in reported results has been suggested to be due to interactions among climate, compost type, compost addition rate and a range of soil physical-chemical-biological processes (Reynolds et al., 2015). Water retention of the Templeton silt loam used in the current study increased with an MC application rate of 150 t ha^{-1}, which agrees with the findings of Aggelides and Londra (2000) and Reynolds et al. (2015) who applied a similar rate of compost to a loam and a clay loam.

The increase in water retention following PM incorporation is supported by Akhter et al. (2004) who found that incorporation of 0.1% PM into small pots increased water retention by 23%. This increase is greater than the proportional increase measured in this study; however, the contrast is likely due to a difference in experimental design as Akhter et al. (2004) used a loam soil that was 45% sand and saturated each pot over a 24 hour period, allowing for greater proportional change in water retention.

The changes measured in water-retaining mesopores are likely to be driven by pores that are either inherited from the amendment (intra-particle pores) or physically created by soil-amendment interaction (inter-particle pores). The influence of intra-particle pore space is likely to be greater in SM and PM as these products have been reported to absorb a volume of water equivalent to 25 times (Taskila et al., 2016) and 160 times (Abedi-Koupai et al., 2008) their dry weight, respectively. Chapter 4 provides evidence that fine compost (particle size <0.25 mm) reduced macroporosity and increased mesoporosity, therefore, the contribution of this MC (max. particle size ≤1 mm) is likely to have a similar effect in the current experiment.

Adding organic carbon in the form of organic amendments to soil has been previously discussed as a means of increasing mesoporosity (Rawls et al., 2003). The importance of C for increasing water retention has been disputed by Minasny and McBratney (2017) who reported that adding 10 g C kg^{-1} soil or 1% wt./wt. increased available water capacity (mesoporosity) by between 0.7% and 2% which led to the conclusion that the addition of C produces a negligible effect. For comparison, in the current study 12.5, 2.7 and 0.4 g C kg^{-1} soil were added in the MC, SM and PM treatments, while the proportional increases in mesoporosity were 7%, 16% and 8% respectively. These increases in mesoporosity greatly exceed those reported by Minasny and McBratney (2017) and are poorly correlated with the amount of C added, which provides evidence that factors other than C content (i.e. amendment size, shape, intra-particle pores, etc.) may be more important for modifying soil porosity.

Although amendments had a significant effect on R_T, there was no effect of irrigation application rate on R_T and also no interaction between amendment and irrigation rate. This result may be due to a combination of having a largely unstructured soil and selecting irrigation rates that, although realistic, may have both promoted preferential flow through the soil. Recent local research by Cichota et al. (2016) concluded that irrigation intensity had a significant effect on preferential flow, with greater water matrix interaction through a Lismore stony soil when the irrigation application rate was 5 mm h^{-1} (85% interaction) rather than 20 mm h^{-1} (58% interaction). This difference in water-matrix interaction suggests that the minimum application rate of 10 mm h^{-1} applied in the current study may have been too great to produce a significant difference in soil wetting and therefore R_T.

The second part of the hypothesis was that increases in macroporosity following amendment incorporation would increase water movement through the soil profile under two irrigation rates. The experiment confirmed that amendments significantly increased macroporosity (ϕ_{Macro}) and macropore volume factor($\lambda\phi_{Macro}$), with the greatest increase resulting from the addition of SM. Increasing the concentration of connected macropores in soil is known to increase water movement (Beven and Germann, 1982) and infiltration (Clothier and Green, 1994) which would likely limit adoption of this practice on shallow soils. To determine whether or not the new macropores measured in this experiment contributed to increased water conduction, effective infiltration (I_E) following each irrigation event was calculated. The main effect on I_E was the irrigation application rate; I_E was 5.6 times greater when the irrigation application rate increased from 10 mm h^{-1} to 80 mm h^{-1}. This result makes sense as the latter application rate is eight times greater than that of the former and suggests that at 80 mm h^{-1} the soil becomes limited by hydraulic conductivity; however, at no point was significant surface ponding observed. This result is supported by the findings of Cichota et al. (2016) who found that the time to drainage (a proxy for I_E) of lysimeters irrigated at 20 mm h^{-1} was significantly less than those irrigated at 5 mm h^{-1}. A significant interaction between amendment and irrigation rate was also observed with the maximum I_E occurring when PM was irrigated at 80 mm h^{-1} which is likely due to the slow response time of intra-particle PM pores. PM may be unable to swell rapidly enough to plug macropores created by the shrink swell action of PM; these empty pore spaces (Figure 5.2), if connected, would therefore allow a greater I_E. Incorporating MC also increased I_E when irrigation was applied at 80 mm h^{-1}. This result is likely due to an increase in $\lambda\phi_{Macro}$ and macropore connectivity which would combine to produce greater I_E than that measured in the control. Interestingly, SM had no significant effect on I_E even though it produced the greatest increase in macropore concentration and volume. This finding is in contrast to the established relationship that increasing macroporosity increases infiltration (Clothier and Green, 1994). This result is likely due to differences in pore shape and connectivity as SM has been previously reported to produce low infiltration rates in sphagnum peat bogs (Taskila et al., 2016) and the incorporation of long chains of fibrous material in to soil is likely to produce a less connected pore structure than granular particles such as MC and PM.

Along with modifying the rate of water movement through the soil (I_E), it is important that the movement of irrigation water into the water-retaining pores is also understood. In an attempt to quantify this, the drainage to irrigation (*D:P*) ratio and the wetting efficiency (*WE*) were calculated. The *D:P* ratio suggests that increasing irrigation rate significantly increased drainage, there was a significant effect of amendment and no interaction between amendment and irrigation rate. This result indicates that although amendments modify pore size distribution, the change does not necessarily result in more drainage, and irrigation management is likely to play a vital role in reducing the amount of drainage from shallow soils. Amendments decreased *WE* compared to the control in the order of Control>SM>MC>PM. This result is likely due to the target drained upper limit (R_{DUL}) of the amended lysimeters being greater than that of the control, which may have been brought about by the slow wetting conditions that preceded the measurement of the target R_{DUL}. Future research with these amendments should aim to measure pore architecture through the use of thin section or computed tomography scanning techniques to determine pore size, shape and connectivity. These results have demonstrated that macroporosity alone may be a poor indicator of potential water movement and that increasing mesoporosity does not necessarily equate to more effective soil wetting under spray irrigation.

Figure 5.2 Example of pore space remaining (circled) when PM particle has released majority of water, and core has reached equilibrium at -1500 kPa.

The final component of the initial hypothesis was that plant growth would increase due to an increase in R_T. The results from this experiment contradict this hypothesis as the increase in R_T did not translate to a significant increase in yield over the six week measurement period. However, there was a significant interaction whereby the yield from the control was significantly greater when irrigated at 10 mm h^{-1} than when irrigated at 80 mm h^{-1}. This result agrees with observations from Gray et al. (2016) who reported that dry matter yield from pasture decreased as irrigation application rate increased; however, this result was not significant. The lack of plant response suggests that although R_T was increased due to amendment, this water was not required as the plants did not become water stressed with the 14 day irrigation return interval. Further work is required to determine if the measured increase in water retention is beneficial to production when plant water stress is imposed.

5.5 Conclusion

This experiment identified that under spray irrigation management, total water retention (R_T) of a cultivated Templeton silt loam was increased by the incorporation of SM, MC and PM. This increase in R_T was produced by an increase in the concentration and volume of mesopores. The change in macroporosity resulted in an increase in infiltration when irrigation was applied at 80 mm h^{-1}; however, in general the relationship between macroporosity and infiltration was poor. This finding suggests that understanding pore size, shape and connectivity will be important in future amendment studies to predict the response of a specific soil to a specific amendment. Irrigation rate dominated water movement, suggesting that appropriate irrigation management is vital to reduce drainage losses. Interestingly, the addition of SM produced the greatest increase in R_T without causing any significant increase in I_E, suggesting that further research with products such as this may provide a solution to the limiting hydraulic characteristics of shallow stony soils. Questions remain about how these changes can benefit plant growth, as the plants in this experiment failed to reach a state of water stress. Understanding the effects of amendment incorporation on plant water use under water limited conditions is required to determine the viability of this practice to improve the irrigation suitability of Canterbury’s shallow soils.

Chapter 6 Effect of amendment incorporation on the relationship between cumulative yield and cumulative water use.

6.1 Introduction

This thesis has demonstrated that incorporation of sphagnum moss (SM), municipal compost (MC) and polyacrylamide (PM) can successfully increase soil water retention, however, this change has not been correlated with increased plant growth. Compost incorporation has been reported to either increase plant yield (Horrocks et al., 2014; Stewart et al., 1998) or have no effect (Reynolds et al., 2015). Likewise, incorporation of PM has been reported to both increase plant yield in sandy soils (Agaba et al., 2011; Silberbush et al., 1993; Sivapalan, 2006) and have no effect (Green et al., 2004). Increases in plant yield have been reported following incorporation of sphagnum peat (Li et al., 2004); however, there is a lack of data relating to sphagnum moss. Due to the variability of results in these previous studies and to address whether amendment incorporation is agronomically viable, an experiment was designed to test the following hypothesis: incorporation of SM, MC and PM will prolong plant water use and increase yield by increasing macro-meso and mesopore volume.

6.2 Methods

For a full description of the lysimeter experimental design refer to Chapter 5, Section 5.2. Briefly, treatments were an un-amended control, SM incorporated at 18 t ha^{-1}, MC incorporated at 150 t ha^{-1} and PM incorporated at 3 t ha^{-1}. Lysimeters were split into two irrigation treatments: irrigated, which were returned to the target drained upper limit every 10 days; and non-irrigated, which received no irrigation for the duration of the experiment. Each treatment combination was replicated four times in a full factorial design. The experiment was initiated by returning each lysimeter to drained upper limit (R_{DUL}) with the spray irrigation system at an application rate of 10 mm h^{-1}. The experiment then ran for 50 days and was concluded when full senescence of plants in the non-irrigated lysimeters was achieved and water use had become negligible. This experiment focuses on results from the non-irrigated lysimeters in order to test the initial hypothesis.

6.2.1 Dry matter

Dry matter of Italian rye grass (*Lolium perenne*) was measured every 10 days by cutting grass to 5 cm height and drying at 65°C. Total yield was calculated as cumulative growth over the experimental period.

6.2.2 Water use

Water use (WU) was calculated over the course of the experiment through the measurement of lysimeter mass using a Wedderburn hanging load cell (Wedderburn WS65 Max capacity = 150 kg, accuracy +/- 50 g which translates to an error of +/- 0.7 mm of water retention). This measurement allowed the mass of water in each lysimeter (water content - *WC*) to be measured directly by subtracting the mass of all oven dry components (which were weighed prior to starting the experiment) from the total mass of the lysimeter. A soil water balance approach was used (Equation 6.1) to determine the total water retention following initial irrigation (R_T). Water retention was converted to a depth of water (mm) by dividing R_T (mm^3) by the lysimeter area (mm^2).

$$R_T = WC_{T0} + P - D - ET - SS \qquad 6.1$$

where WC_{T0} is water content (mm) measured through lysimeter mass at time zero, which was immediately prior to irrigation being applied, *P* is the amount of irrigation added (mm), *D* is the amount of drainage lost (mm), *ET* is the estimated evapotranspiration over the drainage period (mm) and *SS* is the amount of water retention in the stony subsoil (mm). Water use was then calculated using Equation 6.2.

$$WU = R_T - WC_{Tx} \qquad 6.2$$

Where R_T is initial water retention (mm) and WC_{Tx} is water content (mm) at *x* days after drainage had ceased.

6.2.3 Water use and yield relationship

To test the initial hypothesis, cumulative water use in mm (Section 6.2.2) was plotted against cumulative yield in g DM m^{-2} (Section 6.2.1). Split line regression allowed a break point in the water use relationship to be identified, which has been used to determine if water use was prolonged by amendments compared to the control. To convert the water use break point in to an estimate of volumetric water content ($\theta_{WU\,BP}$), Equation 6.3 was applied.

$$\theta_{WU\,BP} = \frac{WU\,BP}{D_H} \qquad 6.3$$

where *WU BP* is the water use break point (mm) and D_H is the depth of the soil horizon (mm). The slope of the relationship prior to the break point has been termed the growth slope and allows differences in water use efficiency to be determined, while the slope following the break point has been termed the stress slope which indicates whether equivalent stress was reached by all treatments.

6.2.4 Density and porosity

To determine bulk density (ρ_b), total porosity (ϕ_t) and volumetric water content at a matric potential of -10 kPa, -100 kPa and -1500 kPa two soil cores from each lysimeter at the conclusion of the experiment. A large core (10 cm diameter x 7.5 cm deep) for ρ_b, ϕ_t and -10 kPa was removed from the 1 - 8.5 cm layer and a smaller core (5.2 cm diameter x 3 cm deep core) was removed from the 3 – 6 cm layer to measure volumetric water content at -100 kPa and -1500 kPa. Once the required matric potentials were reached each core was oven dried for 48 hours to determine ρ_b. Particle density (ρ_p) was measured using the pycnometer method (Gradwell and Birrell, 1972), and the total porosity was calculated according to Equation 6.4.

$$\phi_t = 1 - \frac{\rho_b}{\rho_p} \tag{6.4}$$

Macroporosity was calculated as the difference between ϕ_t and volumetric water content at -10 kPa. Macro-mesoporosity was calculated as the difference in volumetric water content between -10 kPa and -100 kPa. Mesoporosity was calculated as the difference in volumetric water content between -10 kPa and -1500 kPa and microporosity was reported as volumetric water content at -1500 kPa.

6.2.5 Strain and pore volume

Net strain

To determine the net pore volume of water-retaining pores, the net strain (ε_N) was first calculated (Equation 6.5).

$$\varepsilon_N = (1 + A)\,\frac{\rho_{bS}}{\rho_b} \tag{6.5}$$

where A is the amendment application rate (g g^{-1}), ρ_b is the bulk density of the amended soil (g cm^{-3}) and ρ_{bS} is the bulk density of the control soil (g cm^{-3}).

Net pore volume factor

The net pore volume factor ($\lambda\phi_p$) was then calculated to quantify the volume of pores of size range *p* relative to the un-amended soil. This is achieved by accounting for the change in pore concentration (cm^3 cm^{-3}) and the change in net volume (ε_N) due to amendment incorporation.

The net pore volume factor can then be applied in the following way: if 1 cm^3 of soil has α cm^3 of pores of size range, *p*, then after amendment the expanded volume would have a volume (cm^3) of pores of size range, *p,* given by $\alpha\lambda\phi_p$. Accordingly, the net pore volume factor is calculated using Equation 6.6.

$$\lambda\phi_p = \frac{\phi_{As,p}}{\phi_{s,p}}\varepsilon_N \tag{6.6}$$

where $\phi_{As,,p}$ is the porosity (cm^3 cm^{-3}) of pore size range *p,* in the amended soil and $\phi_{s,p}$ is the porosity (cm^3 cm^{-3}) of pore size range p, in the control soil.Net pore volume

To convert the $\lambda\phi_p$ in to the net volume pores in mm (λ_p), Equation 6.7 was applied.

$$\lambda_p = (\phi_{s,p} \times D_I)\lambda\phi_p \tag{6.7}$$

where D_I is the depth of amendment incorporation (250 mm). The approach of using λ_p as a measure of the pore volume is novel as it does not require measurement of the resulting soil depth following amendment incorporation. Traditionally, horizon available water (HAW) has been used to calculate the volume of plant available water in a specific soil horizon (McQueen, 1993) which is calculated using Equation 6.8.

$$HAW = AWC \times D_H \tag{6.8}$$

where D_H is the depth of the soil horizon (D_H) in mm and AWC is the available water capacity of the soil in cm^3 cm^{-3} which is equivalent to mesoporosity (ϕ_{Meso}). Although measurement of mesoporosity is relatively simple, the measurement of the depth of amendment can be difficult. This experiment allowed both λ_p and HAW to be calculated, the two approaches have been compared using linear regression (Figure 6.3).

6.2.6 Statistical analysis

Statistical analysis was performed using GenStat 17 (GenStat, 2016). Split line regression was used to determine the break point at which the relationship between cumulative yield and cumulative water use changed. The explanatory variate used in the split line regression was cumulative water use with the response variate being cumulative yield. All variables were analysed using general ANOVA (amendment treatment by replicate) and statistical significance was considered to occur where $p \leq 0.05$. All linear regression was performed in SigmaPlot version 12.5 (Systat Software Inc, 2013).

6.3 Results

6.3.1 Water retention and yield

SM and MC both increased water retention (R_T) compared to the control by 13.1 mm and 11.3 mm respectively (Table 6.2), however, this increase was not significant (p=0.104). Total yield was significantly increased (p=0.014) by 15.9% and 11% by the addition of MC and SM compared to the control (Table 6.1). PM had no significant effect on either water retention or total yield.

6.3.2 Water use break point

The water use break point was significantly greater (p=0.046) in the SM treated lysimeters compared to the control, with MC and PM producing no significant difference (Table 6.1 and Figure 6.1). Although not significant, the incorporation of MC allowed for an additional 5.9 mm of water use, while SM provided an additional 13.4 mm and PM reduced water use by 5.9 mm compared to the control. Although the yield break point was increased by incorporation of SM and MC, this increase was not significant (p=0.186). The volumetric water content at the water use break point ($\theta_{WU\ BP}$) was not significantly different between treatments (p=0.979), with an average water content of 0.12 cm^3 cm^{-3} at the break point (Table 6.1). Neither the slope during growth (growth slope) nor the slope once evapotranspiration ceased (stress slope) were significantly changed by amendment compared to the control.

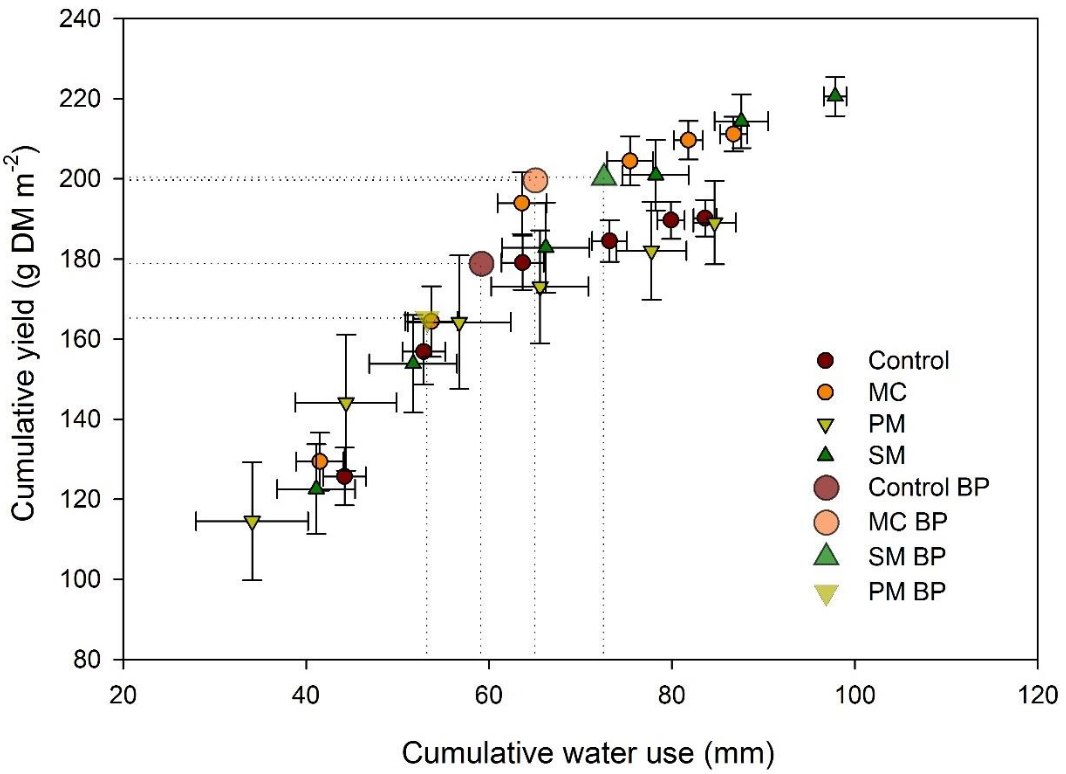


Figure 6.1 The relationship between cumulative yield and cumulative water use for each amendment treatment, where MC is municipal compost, PM is polyacrylamide and SM is sphagnum moss. BP is the break point. Error bars represent 1 standard error (n=4).

Table 6.1 Results from split line regression analysis to determine the water use break point (WU BP) and yield break point (Yield BP) when municipal compost (MC), polyacrylamide (PM) and sphagnum moss (SM) were incorporated. The volumetric water content at the water use break point is $\theta_{WU\ BP}$ Bold represents values significantly different to the control.

Treatment	WU BP (mm)	$\theta_{WU\ BP}$ ($cm^3\ cm^{-3}$)	Yield BP (g DM m^{-2})	Total yield (g DM m^{-2})	Growth slope (g DM m^{-2} mm^{-1} WU)	Stress slope (g DM m^{-2} mm^{-1} WU)
Control	59.1	0.113	178.9	190.2	3.86	0.60
MC	65.0	0.122	199.7	**211.2**	3.10	0.66
PM	53.2	0.136	165.3	189.1	2.92	0.70
SM	**72.5**	0.093	200.40	**220.6**	2.50	0.76
LSD (p)	13.21 (0.046)	0.060 (0.460)	35.34 (0.136)	19.95 (0.014)	1.295 (0.186)	0.776 (0.998)

6.3.3 Soil bulk density, strain, porosity and pore volume

The effects of amendments on soil bulk density and porosity are shown in Table 6.2. Amendments reduced bulk density (p=0.001) and increased total porosity (p=0.001) in the order of SM, MC, PM, Control. These changes resulted in a significant net strain (ε_N) (p<0.001) when MC, SM and PM were incorporated.

Table 6.2 Changes in soil physical properties following incorporation of municipal compost (MC), polyacrylamide (PM) and sphagnum moss (SM). Where bulk density is ρ_b, total porosity is ϕ_t, soil water retention is R_T, macro-mesoporosity is $\phi_{Macro\text{-}meso}$, mesoporosity is ϕ_{Meso}, microporosity is ϕ_{Micro}, macro-mesopore volume is $\lambda_{Macro\text{-}meso}$, mesopore volume is λ_{Meso}, horizon available water is HAW. Bold figures represent a significant difference from the control.

Treatment	ρ_b (g cm^{-3})	ϕ_t (cm^3 cm^{-3})	ε_N	R_T (mm)	$\phi_{Macro\text{-}Meso}$ (cm^3 cm^{-3})	ϕ_{Meso} (cm^3 cm^{-3})	ϕ_{Micro} (cm^3 cm^{-3})	$\lambda_{Macro\text{-}meso}$ (mm)	λ_{Meso} (mm)	HAW (mm)
Control	1.17	0.553	1.00	87.3	0.084	0.166	0.168	21.03	41.6	41.6
MC	**1.09**	**0.577**	**1.12**	98.6	0.078	0.187	0.144	21.86	**52.4**	**51.4**
PM	**1.11**	**0.573**	**1.05**	87.9	0.085	0.181	0.151	22.29	47.4	46.2
SM	**1.06**	**0.589**	**1.11**	100.4	**0.100**	0.189	0.144	**27.75**	**52.3**	**56.6**
LSD (p)	0.04 (0.001)	0.013 (0.001)	0.04 (<.001)	13.3 (0.104)	0.01 (0.003)	0.031 (0.393)	0.032 (0.310)	2.73 (0.001)	8.51 (0.054)	8.05 (0.012)

The addition of SM increased macro-mesoporosity (p=0.003), although none of the amendments significantly increased mesoporosity (p=0.393) or microporosity (p=0.310). Macro-mesopore volume was increased by the addition of SM (p=0.001) compared to the control, while both SM and MC increased the volume of mesopores (p=0.05) and horizon available water (p=0.012).

The strongest correlations with water use break point (Figure 6.2) were produced by the volume of macro-mesopores (R^2=0.586) and mesopores (R^2=0.424), which were both stronger than the correlations with macro-mesoporosity (R^2=0.463) and mesoporosity (R^2=0.059), respectively. Bulk density (R^2=0.269) and total water retention (R^2=0.249) were both similarly correlated to water use break point.

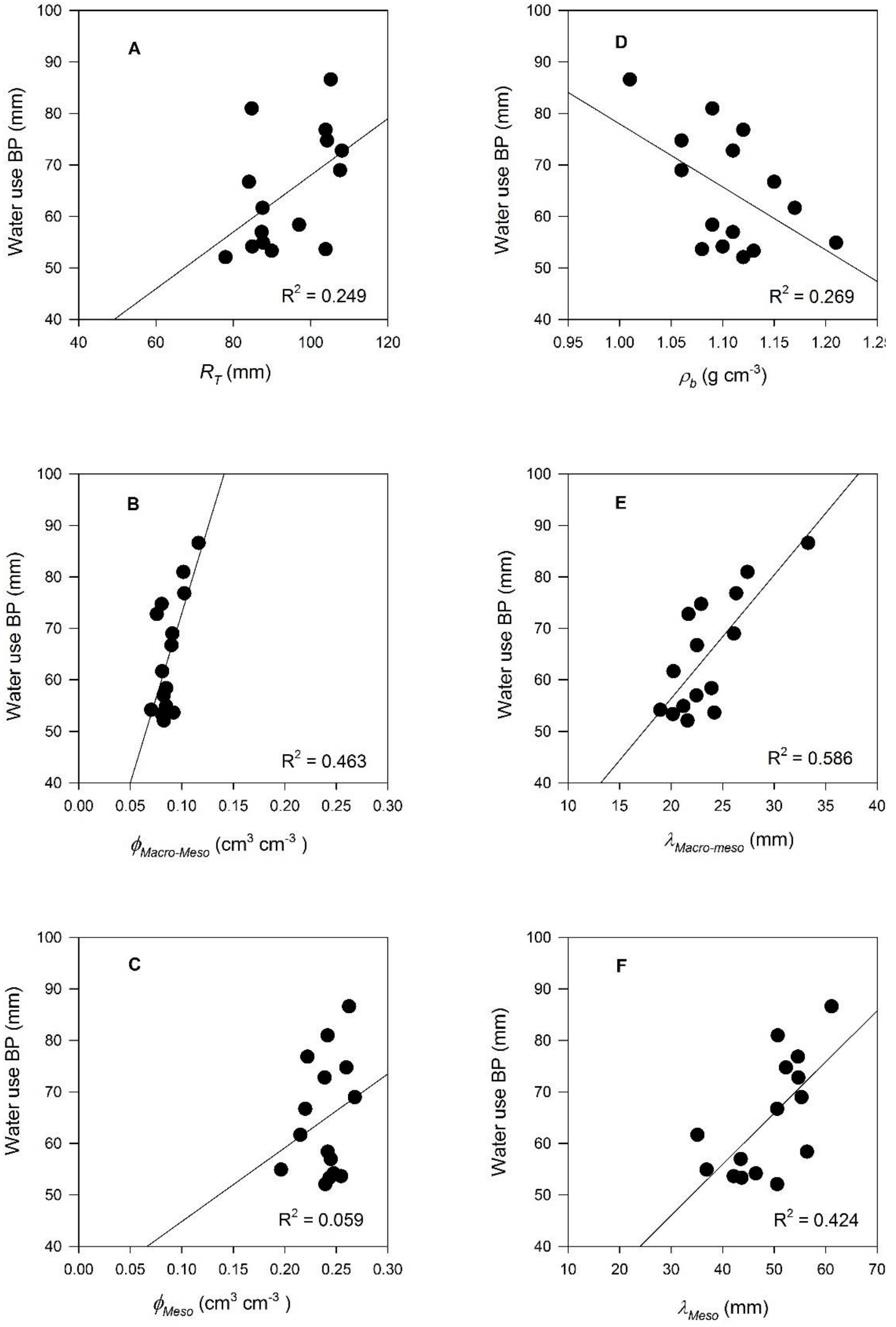


Figure 6.2 Correlations between water use break point (BP) from all amendment treatments and A) water retention (R_T), B) Macro-mesoporosity ($\phi_{Macro\text{-}Meso}$), C) Mesoporosity (ϕ_{Meso}), D) bulk density (ρ_b), E) macro-mesopore volume ($\lambda_{Macro\text{-}meso}$) and F) mesopore volume (λ_{Meso}).

The volume of mesopores (λ_{Meso}) was strongly correlated (R^2=0.89) with horizon available water (HAW) (see Figure 6.3). The correlation between water use break point and total yield (R^2=0.372) was not as strong and is shown in Figure 6.4 .

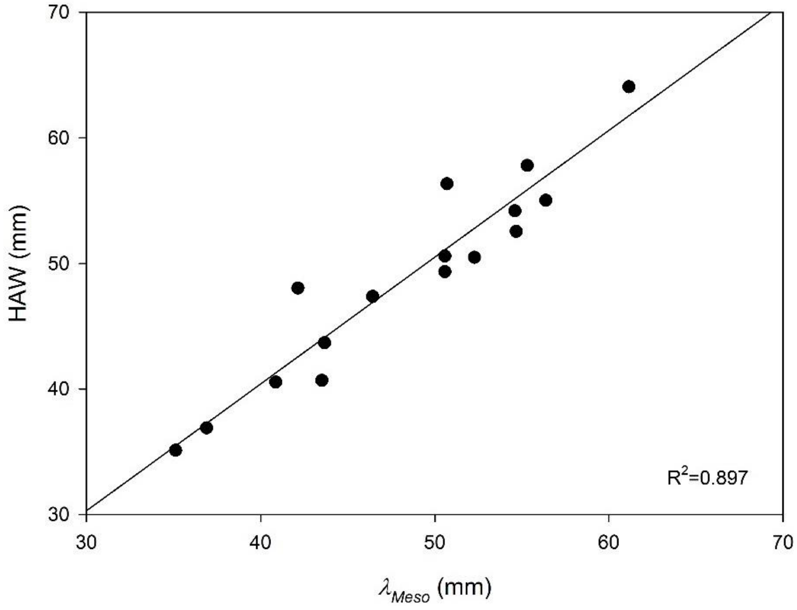


Figure 6.3 Relationship between horizon available water (HAW) and mesopore volume (λ_{Meso}) of all non-irrigated lysimeters.

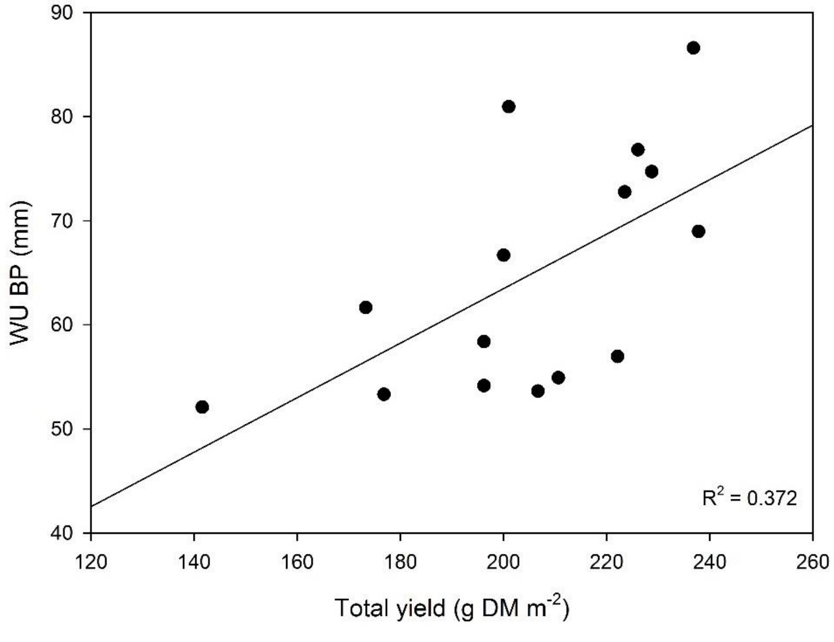


Figure 6.4 Relationship between water use break point (WU BP) and total yield of all non-irrigated lysimeters.

6.4 Discussion

The initial hypothesis of this experiment was that the incorporation of SM, MC and PM would prolong plant water use and increase yield under non-irrigated conditions by increasing macro-meso and mesopore volume. The experiment confirmed this hypothesis, as amendment with SM prolonged water use and increased total yield compared to the control. Amendment with MC also prolonged water use (although non-significantly) and increased total yield; however, amendment with PM had no effect on water use or total DM yield compared to the control.

The results from MC and SM-treated lysimeters agree with those of previous studies. Horrocks et al. (2014) reported that the addition of 25 t ha^{-1} of MC (from the same source as that used in this thesis) improved maize yields when combined with conventional fertiliser; however, this study was unable to report the mechanism for this response. The use of SM in irrigated arable systems is novel and as such there few comparative studies available. However, the study of Li et al. (2004) incorporated sphagnum peat at rates of up to 68 t ha^{-1} in to sandy cropping soil and reported that potato yields were increased by up to 30% relative to the control. This increase in yield was correlated with decreasing bulk density, increasing drained upper limit and increasing soil organic matter.

Although the hypothesis was confirmed with the use of MC and SM, this was not the case for soil treated with PM. The use of PM decreased the water use break point; however, this decrease was not significant and did not translate to any significant change in yield compared to the control. This result contrasts that of Silberbush et al. (1993) who applied PM at rates of 0.15%, 0.3% and 0.45% but reported increases in corn cob yield of 3%, 5.7% and 18.5%, respectively. However, previous work with PM in agricultural systems has failed to find a yield response. Green et al. (2004) incorporated PM at a rate of 1 t ha^{-1}, which is comparable to the 3 t ha^{-1} applied in the current study, and found no yield response of an irrigated bean crop which agrees with the result of the current study. The contrast between the results from the current study and the study of Silberbush et al. (1993) are likely due to differences in the soil component and PM product. Unfortunately, there is a lack of studies that have incorporated PM in to silt loams that are comparable to the Templeton silt loam used in the current study. Interestingly, PM did not significantly increase R_T as it did in Chapter 5. This result may be due to the amendment reducing in effectiveness over numerous wetting and drying cycles. Reductions in effectiveness have previously been reported in the literature, with Akhter et al. (2004) reporting significant declines in water absorption of PM over three wetting and drying cycles in a similar controlled study.

The initial hypothesis proposed that the increase in water use would be driven by an increase in the volume of water-retaining macro-meso and mesopores. This hypothesis was confirmed as water use break point was strongly correlated with mesopore volume (R^2=0.424) and macro-mesopore volume (R^2=0.586). The correlation with pore volumes was stronger than that with pore concentrations which highlights the importance of accounting for volume change when incorporating soil amendments. Importantly, this experiment has provided a novel approach which simplifies the estimation of pore volume. The traditional approach has been to calculate HAW (McQueen, 1993), which requires measurement of mesoporosity, bulk density and specific knowledge of the amended horizon depth. The method applied in the current study simply requires knowledge of the amendment application rate, incorporation depth, bulk density and mesoporosity; factors that are all commonly recorded in amendment studies. As such, the calculation of pore volume using this method is encouraged in future studies. Along with pore changes, the correlation with water retention and bulk density was also calculated. Bulk density (R^2=0.269) provided a slightly stronger correlation with water use than water retention (R^2=0.249). The relationship between bulk density and water use agrees with Stewart et al. (1998) who incorporated spent mushroom substrate, and Li et al. (2004) who incorporated sphagnum peat. Both of these studies reported that reducing bulk density was correlated with increased potato yields; however, neither study was able to report the total water retention of the amended layer.

The correlation between water use break point and total yield indicates that yield differences may be produced not only by increased water-retaining pore volume but also by improved soil physical conditions. Nguyen et al. (2012) measured increased root development when bulk density decreased through the addition of MC. This indicates that reducing the physical density of the soil may have positive effects not only for increasing the volume and concentration of water-retaining pores but also for increasing plant root density. The combination of these changes may be the driver of improved yield following amendment incorporation due to increased water availability and improved growing conditions.

The water use break point identified in this experiment has the strongest correlation with the volume of macro-mesopores. The strength of this correlation indicates that the majority of the difference in water use is likely to be occurring in the macro-mesopore range. However, it is likely that the break point represents a higher degree of plant stress than that experienced within the macro-mesopore range. The established water use break point for grasses is typically reached in grass plants when soil pores 3 µm in diameter are emptied of water (Lacey, 2017; McQueen, 1993) and this represents the lower limit of macro-mesoporosity. However, the results from the current study suggest that the break point occurred at or near the lower limit of mesoporosity. Evidence for this is that the break point is close to the measured total water retention, and the estimate of volumetric water content at the break point is less than the measured microporosity, which is the lower limit of mesoporosity. This result means that the water use break point can be used as an indicator of the total volume of water available for plant growth and should therefore be proportional to the volume of mesopores. Although the correlation between these two measures is relatively good (R^2=0.424), the result reinforces that improvements can still be made in the understanding of the relationship between soil pore size distribution and plant water use. The discrepancy between the volume of plant available water measured in the field and in the lab has recently been discussed by Horne and Scotter (2016). Their study identified that pasture is capable of drying out the top 300 mm of a Tokomaru silt loam to 0.07 cm^3 cm^{-3} less than the lower limit of mesoporosity measured in the lab. The results from the current study agree with the findings of Horne and Scotter (2016), as the average water use break point was 0.04 cm^3 cm^{-3} less than the lower limit of mesoporosity.

The water use break point results from this experiment indicate that SM and MC have the potential to reduce irrigation frequency. Compared to the control, the water use break point is not reached until a further 13.4 mm and 5.9 mm of additional water use in the respective SM and MC treatments. If this finding is valid in a field situation, this difference in water use could have a significant impact on total water use and power costs over a typical irrigation season. In order to estimate the potential irrigation savings, an irrigation calculator has been developed (see irrigation calculator excel file in digital appendix) following the approach of Hedley (2009). Inputs to the calculator are: 10 years of rainfall and potential evapotranspiration data (2008-2018) for Lincoln from 1 October to 1 March (NIWA, 2018). Water use break point for each treatment which was used as a measure of plant available water. An irrigation schedule was then set which applied 10 mm of water when soil water was 29.5 mm or less. The irrigation trigger was set as half of the control soil's available water, which is consistent with industry practice (Irrigation New Zealand, 2017). Over the 10 year period tested, average irrigation requirement between 1 October and 1 March was 361 mm, 350 mm, 380 mm and 340 mm for the control, MC, PM and SM treatments respectively. Although these differences seem insignificant as an annual average, on a seasonal scale the importance of increased water use break point is emphasized. SM was able to reduce irrigation by up to 30 mm (2008/2009 and 2015/2016 irrigation seasons), while MC reduced irrigation by up to 20 mm compared to the control. In the scenario where 10 mm of water is applied at each irrigation event this would equate to three fewer irrigation events if SM was incorporated and two fewer if MC was incorporated. It is recommended that future work applies a more powerful system model to determine the potential of amendment incorporation under different crop types, climate conditions and irrigation management scenarios.

6.5 Conclusion

This experiment determined that treating soil with SM and MC increased water use and subsequently increased cumulative yield. Macro-mesopore volume was the best predictor of increased water use, indicating that the majority of water extraction occurs in this pore range, however, water use continued beyond this point with the break point occuring past the lower limit of mesoporosity. This finding suggests pore volume is superior to pore concentration as a predictor of plant water use in amended soils. Importantly, a novel method to calculate pore volume was provided and it is recommended that future amendment field studies adopt this approach. Data from this experiment suggests that improved water use is likely to result in between 20 mm (MC) and 30 mm (SM) less irrigation input over an irrigation season following amendment incorporation. It is recommended that the data generated from this experiment be applied in a more powerful agricultural system model to determine which irrigation and crop management scencarios would most benefit from this soil management practice and what the potential environmental and economic benefits would be. The use of such a model would allow for targeted field experiments which could answer more practical questions around amendment incorporation as a soil management practice.

Chapter 7 Synthesis of findings and recommendations

7.1 Introduction

New Zealand has followed global trends of water use, with over 50% of the country's allocatable fresh water being used for irrigation (Ministry for Environment & Stats NZ, 2017). A significant proportion of this irrigation being applied to vulnerable shallow soils in Canterbury (Carrick et al., 2013). These soils present a challenge for irrigators as they are characterised by low soil water retention and rapid permeability (Carrick et al., 2013), two factors that are strongly correlated with increased nutrient leaching (Wheeler et al., 2011) and inefficient water use (Hatfield et al., 2001; Howell, 2001). This thesis aimed to address the limitation of low water retention of these soils by determining the potential benefits and limitations of amendment incorporation.

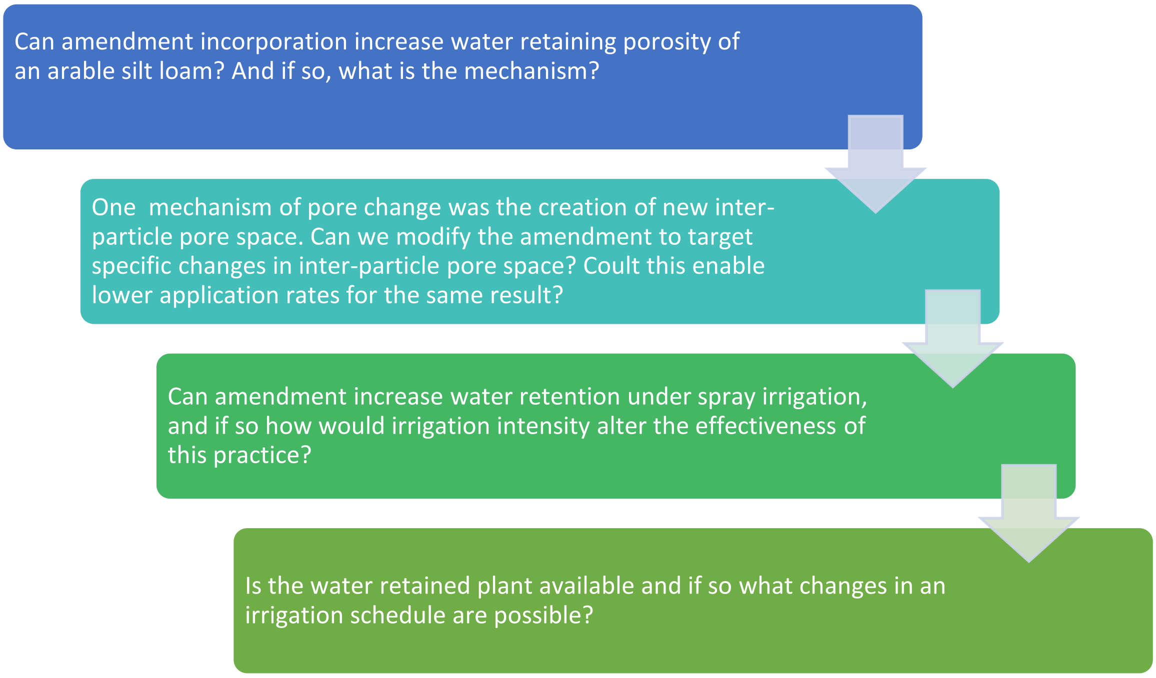
In order to increase water retention, a change in soil pore size distribution towards an increase in macro-meso and mesopores was targeted. Initially, the benefits and limitations of a range of organic and synthetic amendments (Chapter 3) were evaluated which led to the conclusion that amendments were likely to modify pore size distribution by creating new inter and intra-particle pore space. This was followed by an experiment that demonstrated that inter and intra-particle pore spaces can be modified through the modification of the amendment itself (Chapter 4), which will allow for future opportunities to create targeted water-retention amendments from common waste streams. In addition, Chapter 3 and Chapter 4 derived metrics of net strain, strain corrected porosity and the net pore volume factor, which were previously undefined in this research area. These metrics allow changes in pore concentration and pore volume to be compared following amendment and the mechanisms behind any changes to be better understood. These findings were then expanded, by applying the most successful water retention amendments to a system that closely replicated a spray irrigated shallow stony soil (Chapters 5 and 6). The resulting lysimeter study confirmed that the increases in water retention measured in Chapter 3 and Chapter 4 were also possible under two contrasting irrigation regimes. Furthermore, addition of agrichemicals, nutrients and plant/soil interaction did not reduce the effectiveness of this practice and a single amendment in particular, SM, was able to increase soil water retention without increasing water losses via macropore flow (Chapter 5). The thesis concluded that addition of MC and SM were both able to prolong plant water use, increase total plant yield (Chapter 6) and potentially reduce irrigation requirement due to an increase in the volume of water-retaining pores.

The specific objectives of this thesis are defined below;

- To evaluate how a range of organic and synthetic amendments can modify soil porosity for increased soil water retention, and also if these products have limitations that would restrict their adoption in irrigated agriculture.
- To determine if a commonly available waste stream (municipal compost) can be modified to increase soil water retention and quantify the relationship between application rate and changes in soil physical properties.
- To assess how amendment incorporation modifies soil water retention and movement under spray irrigation.
- To quantify whether the increase in water retention associated with amendment incorporation can be utilised to prolong plant water use.

7.2 Thought progression

The thesis objectives were set by following the thought progression outlined in Figure 7.1.



Can amendment incorporation increase water retaining porosity of an arable silt loam? And if so, what is the mechanism?

One mechanism of pore change was the creation of new inter-particle pore space. Can we modify the amendment to target specific changes in inter-particle pore space? Coult this enable lower application rates for the same result?

Can amendment increase water retention under spray irrigation, and if so how would irrigation intensity alter the effectiveness of this practice?

Is the water retained plant available and if so what changes in an irrigation schedule are possible?

Figure 7.1 Thesis thought progression

Initially, I assesed the potential of a range of commonly available amendments for increasing water retaining porosity of a cultivated silt loam and what the mechanisms for change were. Rather than focussing on a limited group of amendments and a diverse range of soils, I decided to focus on a single soil type which closely matched the topsoil condition of a typical arable shallow stony soil and asses a more diverse range of amendments. To compare multiple amendments I developed a method and metrics which were able to be used to understand the mechanims for changes in water retention.

One of the key mechanisms highlighted from this experiment was the formation of new inter-particle pore space. This finding lead me to hypothesise that by introducing smaller particles of a commonly available product (municipal compost) at different rates, the pore size distribution could be preferentially modified towards increasing both the concentration and volume of water-retaining pores. In order to assess a significant range of application rates and particle sizes I chose to maintain a single soil type as used in the initial experiment.

By summarising the findings of these two small scale experiments I concluded that the addition of pore volume may be more important for increasing water retention than specifically increasing pore concentration. Originally, I had proposed that laboratory experiments would be followed by a field study, however I decided a greater contribution could be made by pursuing the mechanism and process by which water retention had changed rather than focussing on field validation. Understanding any potential negative effects of increases in drainage due to changes in porosity is also important prior to conducting any field validation. To answer these questions I constructed a fully instrumented weighing lysimeter facility, where the effect of spray irrigation management on water retention and movement could be assessed. A single soil type was used to allow irrigation intensity treatments to be applied, as these were hypothesised to have a significant effect on the amount of water retained by the soil following irrigation. The initial lysimeter experiment defined that water retention did increase, however, this did not result in an increase in yield. The initial thinking was that the ryegrass planted in the lysimeters would become stressed at -100 Kpa (lower limit of readily available water). The two week irrigation schedule would have achieved this stress point in the control, whereas the amended lysimeters would remain in an unstressed condition, resulting in greater dry matter production. However, experiment implementation was delayed which reduced daily water use and resulted in no significant water stress for any of the treatments.

The decision was then made to measure dry matter production and water use from the lysimeters under non-irrigated conditions with the expectation that increases in water retention measured in the previous experiment would manifest as prolonged growth and increased yield, allowing the plant to dictate its stress point. Split line regression was then used to determine the plants water use break point which allowed a more complete understanding of how amendment incorporation could alter irrigation schedules and reduce irrigation requirement. This data was then used to estimate how irrigation schedules could be altered following amendment incorporation to conserve irrigation water.

7.3 Evaluation of thesis objectives

7.3.1 Chapter 3: Modifying soil porosity for enhanced water storage using organic and synthetic amendments

The central hypothesis of this initial experiment was that the amendments selected would increase the mesoporosity of a cultivated silt loam and that water repellence and carbon mineralisation would not be increased relative to the control by this soil management practice.

Mesoporosity results for SM, PM, DSM and BC support the original hypothesis in that mesoporosity was increased compared to the control; however, the remainder of the amendments failed to produce a significant increase. Along with changes in mesoporosity, changes in other pore sizes were also noted; SM, PM, DSM and ST all significantly increased macroporosity, while water-retaining macro-mesoporosity increased by PM, SM, DSM and BC incorporation. Microporosity decreased compared to the control when SM, PM, DSM and BC were incorporated. These changes in pore size distribution were the result of the creation of new inter-particle pore spaces, which increased the concentration of larger macropores and increased the volume of the soil cores. A novel approach was applied to calculate this increase in soil volume by calculating the net strain (ε_N), which allowed the net pore volume factor of a certain size range to be calculated. This approach is important in the case of amendment incorporation as it allows a more balanced comparison between amended soil and un-amended soil than simply considering differences in pore concentration. An example of this is that by considering the volume change represented by ε_N, the conclusion was able to be drawn that the measured decrease in microporosity was due to the volume of these pores being spread across a larger volume of amended soil. To further understand the changes in this inter-particle pore space it is recommend the application of scanning techniques such as computerised tomography (CT) to measure the changes in pore shape, size and connectivity. The use of CT scanning was investigated to determine changes in pore shape and connectivity, but the costs involved were outside the budget of this project.

The second part of the hypothesis was not rejected. In general, water repellence increased as matric potential increased, which agrees with the results of Karunarathna et al. (2010) and Wijewardana et al. (2016) with the only significant increase in water repellence occurring at -100 kPa in the DSM treated soil. However, both the control and the DSM treated soil remained in the weakly hydrophobic category as defined by Dekker and Jungerius (1990). Incorporating DSM significantly increased carbon mineralisation compared to the control, which agrees with the findings of Ajwa and Tabatabai (1994) and Bernal et al. (1998) who both concluded that the less mature the organic amendment, the faster the decomposition rate in soil. The rate of carbon mineralisation was still relatively low and suggests that all amendments are likely to persist for the length of an irrigation season, however, this would require field validation. The increase of both water repellence and carbon mineralisation after incorporating DSM requires further assessment before recommendations on its use are made.

Although the original hypothesis was confirmed, there are two main limitations to this experiment that warrant discussion: 1) the decision to use relatively low application rates, and 2) the use of sieved and repacked soil cores. Amendment application rate was a potential limitation as the experiment applied rates that would be advised for field scale application. This potentially limited the effectiveness of amendments such as MC, which subsequently found required a higher application rate to produce a response. The use of mass application rate for organic and synthetic amendments meant that those amendments with a low particle density and large surface area, such as SM and DSM, were likely to have a greater volumetric dilution effect than amendments with a greater particle density such as MC. To alleviate this effect it is recommended that future studies apply multiple application rates of each amendment in order to determine the point at which changes in mesoporosity occur, if at all. Repacking soil cores from sieved soil has also received criticism as the soil structure, pore shape and size distribution are a product of the packing process and therefore results may not apply to the field (Hardie et al., 2014). Although this criticism is valid, the use of repacked soils in this thesis allowed the relative effect of amendments on pore size ranges of a cultivated soil to be compared. The application of the bulking strain aimed to minimise the potential for over-packing soil cores and is recommended as a method to minimise pore destruction in future core and lysimeter studies.

7.3.2 Chapter 4: Reducing compost particle size and increasing application rate increases soil water retention

The initial small core experiment (Chapter 3) found that changes in pore space were likely due to the creation of new inter-particle pore spaces due to re-arrangement of soil aggregates and amendment particles. It follows that adjusting the size of the amendment particle is likely to affect the resulting inter-particle pore space if all other factors remain constant. Therefore, the focus of this small core experiment was to understand if modifying maximum particle size and application rate of a commonly available amendment, MC, could influence mesoporosity. The central hypothesis was that mesoporosity of amended soil will be positively correlated with increasing MC application rate and reducing maximum MC particle size. The modification of particle size is novel as few studies have investigated the modification of MC particle size to target an increase in mesoporosity, although a recent study by Liu et al. (2017) has highlighted the importance of biochar particle size on soil pore size distribution.

The results from this experiment confirmed the original hypothesis. The greatest increase in both mesoporosity and mesopore volume factor was produced by incorporation of the smallest particle size, MC0.25 (MC particles less than 0.25 mm in diameter), followed by MC2 (MC particles less than 2 mm in diameter) and MC4 (MC particles less than 4 mm in diameter). Increasing application rate increased the net mesopore volume factor, with the greatest volume of mesopores occurring at the highest application rate for all composts. The dominance of MC0.25 in improving mesoporosity is driven by the creation of inter-particle pore spaces and inherent intra-particle pores within MC0.25 particles. Analysis of pure MC0.25 confirmed this conclusion as mesoporosity in the MC0.25 was found to be significantly greater than that of MC2, MC4 and the control soil. The key message from this experiment is that modifying the maximum particle size of MC can target specific changes in soil pore concentration and volume. The modification of MC particles may offer an alternative to simply increasing application rate to generate a change in soil porosity. This finding is likely to have positive outcomes for field application as this study determined the same water retention response could be obtained with MC0.25 at much lower application rates than with MC2 or MC4. If this finding is valid under spray irrigated conditions, the incorporation of MC may be an economical solution to increase water retention.

7.3.3 Chapter 5: Amendments to increase water retention under spray irrigation

This chapter builds on the findings of Chapter 3 and Chapter 4 by determining if the increases in mesoporosity associated with sphagnum moss (SM), polyacrylamide (PM) and municipal compost (MC) incorporation are functional under spray irrigation and whether these changes engender a difference with respect to water retention, water movement and plant yield. To address this question a weighing lysimeter facility was constructed which consisted of 32 instrumented weighing lysimeters (30 cm diameter by 50 cm deep) planted in rye-grass (*Lolium perenne)* and managed to standard local practice. SM, PM and MC were incorporated at rates of 18 t ha^{-1}, 3 t ha^{-1} or 150 t ha^{-1}, respectively. Along with amendment treatments, two irrigation application rate treatments of 10 mm h^{-1} and 80 mm h^{-1} were also applied to determine if any interactions existed between amendment incorporation, water retention and spray irrigation intensity. The hypothesis of this experiment was that the incorporation of MC, SM and PM would increase mesoporosity and subsequently increase soil water retention under two rates of spray irrigation, and the increase in water retention would increase plant growth relative to the control. A second hypotheses was that the incorporation of MC, SM and PM would increase macroporosity and therefore increase the rate of water movement through the soil profile.

The results of this experiment confirmed the initial hypothesis with mesoporosity increasing in the order of SM>MC>PM, however, this increase was only statistically significant when the net mesopore volume factor ($\lambda\phi_{Meso}$) was considered. Water retention (R_T) was increased in order of SM>MC>PM; however, no significant change in concentration of water retention pores (θ_{DUL}) was measured. The contrast of significance produced by pore volume (R_T and $\lambda\phi_{Meso}$) and pore concentration (θ_{DUL} and ϕ_{Meso}) provides evidence of the importance of volumetric changes when amendments are incorporated. The results from Chapter 3 and Chapter 4 defined that at a small scale there was an increase in mesoporosity and mesopore volume factor when SM (Chapter 3), PM (Chapter 3), and MC sieved to less than 0.25 mm (MC0.25, Chapter 4) were incorporated in to a similar Templeton silt loam. This experiment has defined that at a larger scale the increase the volume of water retained is more significant than the increase in pore concentration, which is the property typically measured in amendment studies. If experiments persist to only consider pore concentrations, the water retention benefit of soil amendment incorporation is unlikely to be fully quantified. For this reason it is recommended that future studies validate results at the weighing lysimeter scale in order to understand the net benefit of amendment incorporation on water retention.

No interaction between amendment incorporation and irrigation application rate on water retention was found in this experiment. This result may be due to a combination of having a largely unstructured, repacked soil and selecting irrigation application rates that, although realistic, may have promoted preferential flow through the soil.

The changes measured in water-retaining mesopores are likely to be driven by pores that are either inherited from the amendment (intra-particle pores) or physically created by soil-amendment interaction (inter-particle pores). Addition of carbon in amendments has also been proposed to be a driving mechanism for increases in water retention (Rawls et al., 2003). The results from Chapter 5 contrast this notion as there was a poor correlation between the mass of carbon added and the mass of water retained, which is in agreement with the recent meta-analysis of Minasny and McBratney (2017). This finding provides evidence that factors other than carbon content (i.e. amendment size, shape, density, intra-particle pores, etc.) may be more important for modifying soil water retention than carbon content.

The experiment confirmed the second hypothesis in that macroporosity (ϕ_{Macro}) and macropore volume factor ($\lambda\phi_{Macro}$) were significantly increased compared to the control due to the addition of all amendments, with the greatest increase resulting from the addition of SM. This result agrees with those from Chapter 3 and builds on the findings of Chapter 4. Chapter 4 reported that incorporation of MC0.25 at 5% application rate (which matches the current study) resulted in no significant increase in macroporosity compared to the control, whereas the application of MC screened to <1 mm in the current study did increase macroporosity. This suggests that either inter-particle pores created by MC particles between 0.25 mm and 1 mm in diameter are contributing to macroporosity or the interaction of soil, MC, plant roots and biological activity combine to strengthen pore walls and maintain a greater proportion of macropores. This increase in macropore concentration and volume influenced the effective infiltration (I_E) and drove an interaction between amendment and irrigation rate, whereby PM and MC significantly increased I_E at an irrigation rate of 80 mm h^{-1}. Interestingly, SM had no significant effect on I_E even though it produced the greatest increase in macropore concentration and volume. This result is likely due to differences in pore connectivity as SM consists of long chains of fibrous material which may reduce pore connectivity compared to the consistent granular shape of MC and PM particles. This is an important finding as one of the limitations raised in Chapter 3 and Chapter 4 was that the increase in macroporosity may increase water movement through the profile. This result proves that macropore connectivity is of greater importance than concentration for understanding water movement under spray irrigation. Unsurprisingly, the most significant effect on I_E was the irrigation application rate. Effective infiltration increased 5.6 fold when irrigation application rate increased from 10 mm h^{-1} to 80 mm h^{-1}. This result highlights that irrigation management is highly important for controlling the movement of water through soil shallow soils. It is recommended that future studies continue to address the interaction between changes in pore size and irrigation intensity, with the aim of understanding how porosity can be adjusted to maximise the benefit of irrigation under high and low intensities.

The final component of the initial hypothesis was that plant growth would increase due to an increase in water retention (R_T). No difference in dry matter yield was measured, as the plants did not become stressed. In order to answer this component of the hypothesis a second experiment was conducted in the lysimeter facility.

7.3.4 Chapter 6: Effect of amendment incorporation on the relationship between cumulative yield and cumulative water use.

This experiment used the same experimental set up as Chapter 5 and was designed to test the following hypothesis: incorporation of SM, MC and PM will prolong plant water use and increase yield under non-irrigated conditions by increasing macro-meso and mesopore volume. To test this hypothesis, water use and dry matter were measured every 10 days for 50 days and then cumulative water use was plotted against cumulative yield. Split plot regression was applied to find the point at which plant stress occurred and the relationship between water use and dry matter production changed. This analysis found that the break point was lower than the lower limit of mesoporosity. Although this finding was not part of the original hypothesis, it supports the work of Horne and Scotter (2016) who have reported similar discrepancies between field measured stress points and the lower limit of mesoporosity. This result provides further evidence that the -1500 kPa standard for the lower limit of mesoporosity needs revision if irrigation management is to maximise the volume of water available for plant growth.

This experiment confirmed the original hypothesis as amendment with SM prolonged water use and increased total yield compared to the control. Amendment with MC also prolonged water use (although non-significant) and increased total yield, however, amendment with PM had no effect on water use or total DM yield compared to the control. The water use break point was strongly correlated with macro-meso and mesopore volume which were calculated through the use of a novel method. Importantly, the method applied to calculate pore volume in this chapter is well correlated with the traditional approach of the calculation horizon available water. The application of this new pore volume method is recommended to simplify the calculation of pore volume in future amendment studies, as it does not require measurement of the amended horizon depth.

Through the application of an irrigation calculator it was determined that the increase in water use break point measured in this experiment could equate to an irrigation saving of 30 mm (SM) or 20 mm (MC) over an irrigation season in Lincoln, Canterbury. This saving could have significant economic and environmental benefits and rounds out the findings from Chapters 3, 4 and 5 by highlighting the potential of amendment incorporation at the catchment scale. It is recommended that further modelling work utilises the findings from this thesis to define scenarios where amendment incorporation would offer maximum benefit.

7.4 Recommendations for future research

- Subsequent studies should aim to quantify changes in pore architecture, shape and connectivity following amendment incorporation. Understanding the resulting changes in the physical pore space and how these would potentially affect water movement and wetting processes are needed in order to provide a targeted solution that addresses the hydraulic limitations of shallow stony soils.

- Continued development of the net pore volume method is recommended as this thesis has demonstrated that the net volume of water-retaining pores in an amended soil can be of more importance to plant growth than the concentration of those pores. The application of the pore volume approach provided in this thesis is likely to be applicable in a range of similar soil management practices which are likely to alter soil volume or introduce new particles such as tillage, effluent disposal, mulching or cover crop incorporation.

- It is recommended that prior to field application, an agricultural systems model is applied to estimate the economic and environmental outcomes this soil management practice would have. Where would amendment incorporation offer the greatest benefit and under what climatic conditions?

- The final test of this research would be the application of this soil management practice at a paddock scale. This test would quickly identify practical issues and would offer a final proof of concept.

- Ultimately, the use of pore scale modelling would allow changes in both pore architecture and volume due to amendment incorporation to be predicted. Admittedly this an ambitious recommendation; however, the ability to engineer a suboptimal soil in to a productive one may become increasingly important in the future.

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