Land use and tillage effects on soil saturated hydraulic conductivity:

Does infiltration method matter?

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Abstract of a Dissertation submitted in partial fulfilment of the requirements for the Degree of Bachelor of Agricultural Science (Honours).

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The detrimental effects of tillage on soil hydraulic has been a focus of research for many years and is still widely researched globally. Tillage is used to prepare a seedbed to ideal conditions for plant establishment and growth. Intensification and increase in agricultural production has lead to increased concerns around tillage. Understanding how tillage effects the soil hydraulic properties is crucial in determining how to move forward with a sustainable focus. This study focuses on the effects of tillage in different land uses, using four different measurement methods. Land uses include pasture and cropping (oats) before tillage. The methods used include the tension infiltrometer, intact cores using constant head in the laboratory, Beerkan estimation of soil transfer procedure (BEST) and constant head double ring infiltration The purpose of this study is to investigate the interaction between tillage and land use which has not been conducted in previous studies.

For each method investigated there is a significant effect due to tillage and land use effect. The two types of methods that have been used include infiltration data when the soil is unsaturated or saturated. Tension infiltrometer and BEST method are unsaturated methods used to determine K_{sat} whereas the constant head double ring infiltration and intact cores under a constant head are saturated methods. There is no significant difference in K_{sat} within the unsaturated or saturated methods at each land use either before or after tillage. But there is a significant difference between each of the saturated methods and unsaturated methods. The BEST method showed that in the pasture system the K_{sat} increased by 40.7% as a result of tillage compared to the crop system where the K_{sat} increased by 47.9% as a result of tillage. The tension infiltrometer showed that in the pasture system the K_{sat} increased by 88.3% as a result of tillage compared to cropping decreased by 13.4% as a result of tillage. The constant head double ring infiltration showed that in the pasture system the K_{sat} reduced by 44.6% as a result of tillage whereas in the cropping system it increased by 48.6%. The intact core under constant head showed that before tillage occurred, the pasture had a slower log 10

K_{sat} than the cropping system by 22.9% compared to after tillage the pasture was slower than cropping by 33%.

The difference in bulk density, porosity and soils structure before and after tillage influences the results, as saturated flow and unsaturated flow in the field vary. The unsaturated methods result in higher K_{sat} in cropping land use and after tillage compared to the saturated methods that resulted in higher K_{sat} under pasture system and before tillage. The higher the bulk density of the soil (before tillage or pasture land use), the more appropriate the saturated methods used may be. This shows that the pasture and the before tillage systems have similar soil properties and the cropping and after tillage systems are also similar.

Keywords: Soil hydraulic properties, saturated hydraulic conductivity, tillage, land use, constant head double ring infiltration, tension infiltrometer, Beerkan estimation of soil transfer procedure, intact core under constant head.

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Chapter 1

Introduction

The detrimental effects of tillage on soil hydraulic has been a focus of research for many years and is still widely researched (Strudley et al., 2008). Tillage is used to prepare a seedbed to ideal conditions for plant establishment and growth. Intensification and increase in agricultural production has led to increased concerns around tillage. Understanding how tillage effects the soil hydraulic properties is crucial in determining how to move forward with a sustainable focus.

Previous research has compared the effect of tillage under an individual land use with an individual method. There are separate studies that have used different land uses or measurement methods but these cant be directly compared as they occur in varying environments. There is a gap in research where the interaction of land use and tillage has not been investigated. The different land uses may have a different effect from tillage.

Comparison of methods to measure soil hydraulic properties is where there is some unconsistancy in measuring methods and results. There are multiple ways to measure hydraulic conductivity, but each method has different advantages and disadvantages and also differs in principles, cost, time and accuracy (Hu et al., 2017). Tension infiltrometer is a widely used method used to measure the near saturated hydraulic conductivity of soils (Perroux & White, 1988). The results obtained from this method are easy to collect and stable between measurements. This method saves water in comparison to other field methods which can be important if this is to be measured in a remote location. Using this method the distribution of pore sizes can also be obtained which is not possible in most other methods. Intact cores are another method which is easy to collect and doesn't require much time. This can be important when working around the weather, which can be difficult using field measurements. Using one core, the soil water release curve, saturated and unsaturated hydraulic conductivity can be measured. All other parameters can be calculated from this. This is a benefit compared to field measurements, as the multiple methods are required to retrieve the same data. The size of cores collected can be a limiting factor as it may not be representative of the field scenario. Colecting cores also destroys the soil profile in a small area so if repeat measures are required this becomes an issue. BEST-Beerkan estimation of soil transfer procedure is a new field method that has been developed but has not been tested in New Zealand, so the validity of their method needs to be proven. It is the only method to date that can measure both the soil water retention curve and saturated hydraulic conductivity using only infiltration data (Lassabatere et al., 2006). It is important to use this as a comparison to see if the results are similar. This method considers the shape parameters of the soil from particle size analysis data and their scale parameters, which is accounted for through infiltration measurements. Constant head double ring infiltration is the traditional method that is used to measure soil hydraulic conductivity. It has been said to be the method that most represents the field conditions as the measurment site is not disturbed like some other methods. The methods and calculations involved are simple in both falling head and constant head measurements of double ring infiltration.

The objective of this study is to investigate the change in soil saturated hydraulic properties under different land uses after tillage. Methods used to measure soil saturated hydraulic conductivity are also compared to determine the influence of the choice of method has on the results. Our hypotheses are: (1) land use and tillage can significantly affect the saturated hydraulic conductivity; and (2) significant interaction between measurement method and land use/ tillage exist.

Chapter 2

Literature review

2.1 Background

Tillage is the procedure where soil is disturbed through practises carried out by man. The soil is rearranged or overturned to create ideal soil conditions for plant growth (Khan et al., 1999). Tillage is a practise that is essential in the process of crop and pasture establishment prior to sowing. There is known to be negative impacts of tillage on the soil and environment. There are high energy requirements to perform tillage, equipment that is larger is required to pull tillage implements which can have an impact on compaction of soil. Tillage can be used to incorporate residuals and overturn soil to break it up to prepare the seedbed. When tillage occurs the bare soil is exposed for a period of time which means the soil is open to increased temperatures, which can result in moisture loss. The aim of tillage is to optimise crop yield by preparing the seedbed. Most tillage operations change the bulk density and roughness of the soil. This alters the soil structure and hydraulic properties in the soil such as, pore distribution, water holding capacity, infiltration rate, surface runoff, gas exchange and evaporation (Panachuki et al., 2015). It is important to understand how tillage management, biological activity and hydraulic properties interact (Strudley et al., 2008). This can impact how efficiently crops use water, which changes the potential of production. The temporal changes to hydraulic properties of the soil are inconsistent across studies, as the soil type, tillage practises or the amount of irrigation/rainfall. There are several different tillage methods that are used throughout New Zealand and globally. Tillage is the most widely researched management practise that effects soil hydraulic properties and processes (Strudley et al., 2008). Conventional, minimum and no tillage are three main types that describe the intensity of the tillage carried out. Conventional tillage is a popular practise but minimum tillage is becoming more widely used in NZ as farmers are becoming aware of the detrimental effects tillage has on the environment and the soil structure. The variety of tillage methods alter the impacts on soil hydraulic properties. Intensive tillage is expected to have greater effects and be more detrimental to the environment and requires high energy inputs for several passes. The hydraulic properties of the soil convert back to the original state prior to tillage over time. This occurs through wetting and drying cycles (Green et al., 2003). The time taken is effected by several factors and the extent of change is also variable.

This review of current literature focuses on the benefits and concerns around tillage and the effect on soil hydraulic properties over time under different land uses. Methods used to measure changes in hydraulic properties is also reviewed.

2.2 Tillage methods

2.2.1 Benefits of tillage to crop production

Benefits of using tillage in an agricultural system includes the breakdown of soil to a more suitable size for a seed bed (Gill, 2012). It makes the process of establishing a successful crop easier. For seeds to germinate they require moisture and warmth, tillage helps to increase the contact of this requirements. Tillage in a conventional matter can also be used to bury weeds and residues from previous crops. Fertilisers and chemicals can also be incorporated into the soil, so that the use is more effective.

2.2.2 Concerns about tillage

There are increasing concerns about the level of tillage and how it is disturbing the environment. Conventional tillage is disrupting macro pore connectivity that is formed from biological activity in the soil which can be detrimental in the long term. This change in pore characteristics has been seen to have a cumulative impact on infiltration rates (Figure 2-1), the conventional tillage treatment had the highest infiltration (Lipiec et al., 2006).

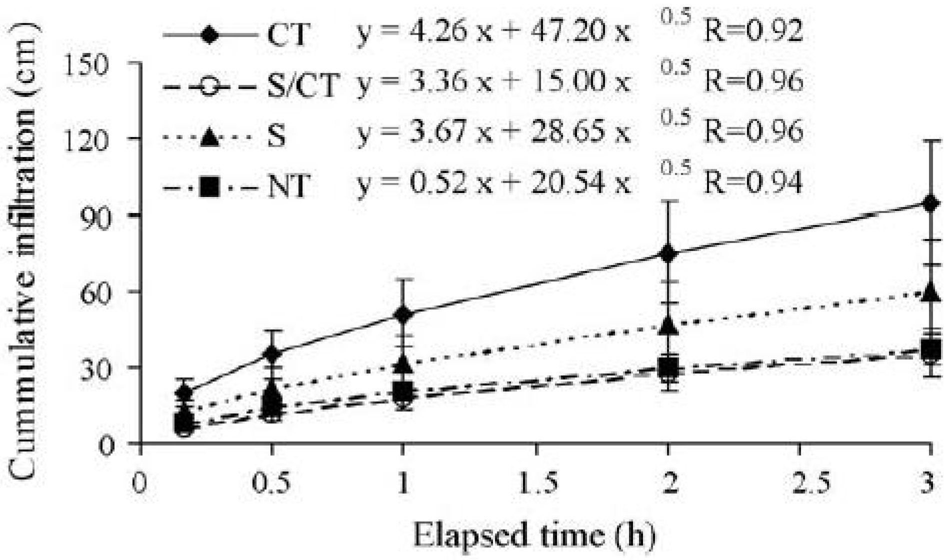

Figure 2-1 Infiltration rate of soil under different tillage treatments (CT- ploughing to 20 cm deep, S/CT- ploughing to 20 cm every 6 years and 5 cm in the remaining years, S – harrowing to 5 cm each year, NT – uncultivated soil) (Lipiec et al., 2006).

In recent research, it has been seen that the practise of tillage has an impact on soil hydraulic properties (Figure 2-1). Effects can be seen immediately, but can diminish rapidly depending on soil condition and climate, this is the temporal effect of tillage on soil conditions. Tillage is expected to have an impact on soil hydraulic properties including: soil bulk density, porosity, pore geometry and soil structure; water retention; hydraulic conductivity; infiltration capacity; and soil crusting/cracking

(Strudley et al., 2008). These can all be measured using a variety of methodology in the field and lab. Generally, no tillage (NT) has been seen to increase macro pore connectivity, but varied responses in bulk density and porosity measures have been seen compared to conventional tillage practises (CT). It is also seen that increased tension infiltration and saturated hydraulic conductivities under NT. Changing from CT to NT practises has previously thought to have negative impacts on the soil properties. The change in organic C content, reduces as a result of tillage. This is one way to show degradation of soil structure (Figure 2-2). Several studies including Horne et al. (1992); Schwartz et al. (2000); Strudley et al. (2008) have shown inconsistent changes infiltration as result of tillage, due to different methods used for measurement.

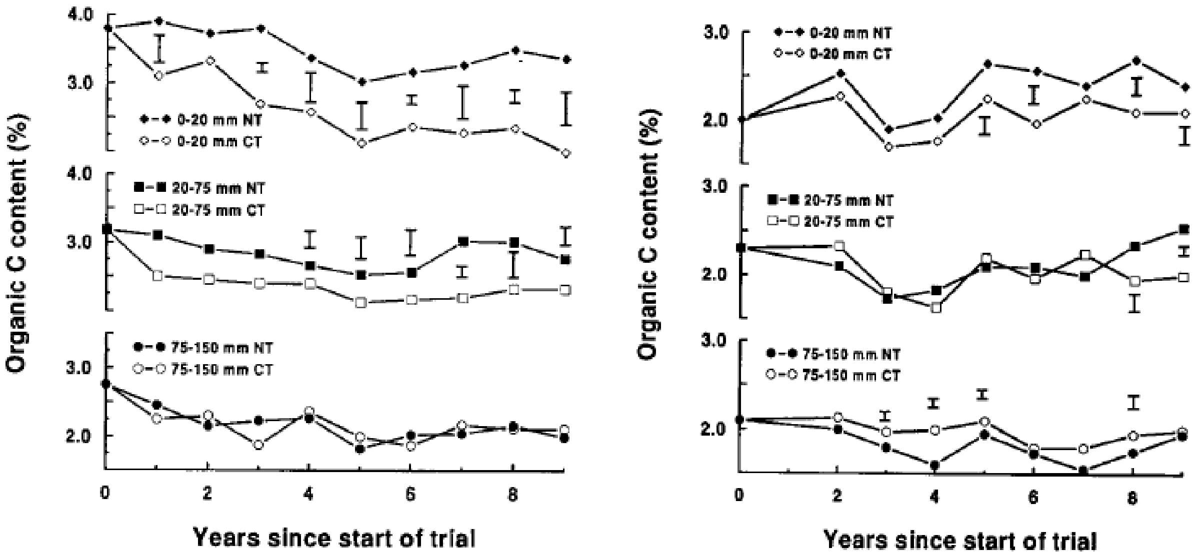

Figure 2-2 Distribution of organic carbon in no tilled (NT) and conventionally tilled (CT) Lismore stony silt loam (Left) and Wakanui silt loam (Right) soil during trial carried out by (Francis & Knight, 1993).

2.2.3 Soil bulk density, porosity, pore geometry and soil structure

Measures of soil structure include bulk density and porosity. These measures can show the level of compaction due to tillage practises or other related agricultural management practises. Soil density and macro porosity can be measured in the laboratory.

Tillage is expected to decrease bulk density. Studies that have focused on minimising tillage or no tillage have meant bulk density is greater, they have found the bulk density was greater in NT treatment than CT in a study carried out over 10 years. This is the same result found in a study carried out in New Zealand by Horne et al. (1992) that also showed an increase in aggregate size and bulk density under NT compared to MT and CT, but lower porosity and infiltration rate in NT and CT.

Soil that has not been tilled has interconnected fine pores. The average pore size is greater in NT than CT due to structure and more earthworm channels in NT compared to CT. Conventional tillage was seen to have no earthworm channels left intact. Derdour et al. (1993) showed no change in total porosity between tillage and not tillage, but NT caused higher bulk density values in the soil surface and reduced macro porosity compared with conventional tillage. This difference may be seen due to different soil types and previous practises.

2.2.4 Water retention characteristics

Water storage in a soil is impacted by several parameters. There is also uncertainty around the impacts that tillage has on water retention characteristics for the same reasons. A soil that was under NT treatment for 10 years in winter wheat showed decreased water holding capacity in 30-60cm zone (Chang & Lindwall, 1992). No other effects were in in zone above or below this level. Another study by Brandt (1992) showed contradictory results that NT resulted in higher soil water content compared to CT. All results showed that it may be beneficial to carry out NT to maximise soil hydraulic properties and water retention characteristics. Soils that have not been tilled and may be in a permanent pasture or crop, would expect to have better soil structure as there is a chance for organic matter to build up.

Water retention curve of a soil is very much dependent on the distribution of particle size. Particle size of a soil determines the texture and the arrangement of particles, which makes up the structure of a soil. Organic matter content also plays an important role in the shape of the water retention curve, due to its ability to absorb and store water (Dane & Hopmans, 2002).

2.2.5 Hydraulic conductivity

Unsaturated values of soil hydraulic conductivity can be highly variable in space and time. The response can be complex as it may depend on other secondary effects of tillage. Climate, plant growth and the soil structure may be a driving factor of the tillage response (Strudley et al., 2008). Wetting and drying cycles, tillage and growth of plants alter the hydraulic conductivity over time. (Murphy et al., 1993) saw the greatest differences between tillage treatments later in the growing season. The lower the tension, the less difference was seen between CT and NT. At 10 mm tension NT resulted in greater hydraulic conductivity. This shows that tillage impacts the larger pores more than the smaller pores. The soil type also impacts that extent of this effect. Saturated hydraulic conductivity is affected by the presence of connected macro pores, which can be from biological activity. Crop rotations is seen to have an impact on K_{sat}. A study by Cresswell et al. (1993) resulted in lower macro-porosity in excess and intermediate tillage compared to minimum tillage. Aeration porosity was also greater in minimum tillage, showing that larger pores are more affected (Table 2-1).

Table 2-1 Mean effect of tillage on macroporosity, aeration porosity and available water holding capacity (Cresswell et al., 1993).

Tillage Treatment	Macropores	Aeration pores	AWHC
	% of total soil volume		
Minimum	42.7 b	37.7 a	13.1 a
Intermediate	37.2 a	32.6 ab	14.8 a
Excess	35.7 a	30.7 b	15.9 a

*Macro pores are pores > 30 µm equivalent spherical diameter (ESD), aeration pores are pores > 300 µm ESD, AWHC refers to pores between 0.2 and 30 µm ESD.
*Means labelled with the same letter are not significantly different art the 0.05 level as determined using Duncan's new multiple-range test.

2.2.6 Infiltration rate and capacity

Measurements of infiltration rate is important for practises including irrigation scheduling. Infiltration can be measured under either ponded or matrix conditions (positive or negative soil water pressure). It is important to have knowledge of the history of the soil, due to cumulative effects. Climate and weather have an impact on temporal variability, it impacts management decisions and the resulting impacts on soil conditions. In previous studies NT has been seen to increase macro pore connectivity but had varied responses in bulk density and total porosity. Horne et al. (1992) showed that NT resulted in lowest infiltration rate compared to MT and CT.

2.3 Land use impact on hydraulic properties

Pastoral farming compared to cropping long term prior to tillage is expected to impact soil structure and hydraulic properties to varying extents over time. Continuous cropping systems is expected to decrease infiltration rates as result of repeated tillage operations causing a reduction in organic carbon in the soil. This reduction is what the expected reduction in infiltration rate is driven by.

A study by Schwartz et al. (2000) showed the effect of land use on the movement of water through the soil is greater than the effect of soil type. Saturated hydraulic conductivity is influenced more by the size, arrangement and distribution of pores rather than total pore space. Native grasslands are seen to be more efficient in water use and movement through the soil as the hydraulic conductivity is high when saturated and low when unsaturated. The saturated hydraulic conductivity measured in a silty soil was 202 mm h^{-1} in cropland (wheat) and grassland was 422 mm h^{-1}. Hu et al. (2009) found that the lower the pressure head, the larger the trend of K_{sat} in different land uses. The near saturated hydraulic conductivity at -15cm pressure head (K15), was the only measure to be significantly different between land uses (figure 2-3). Temporal impact was greater than land use effect.

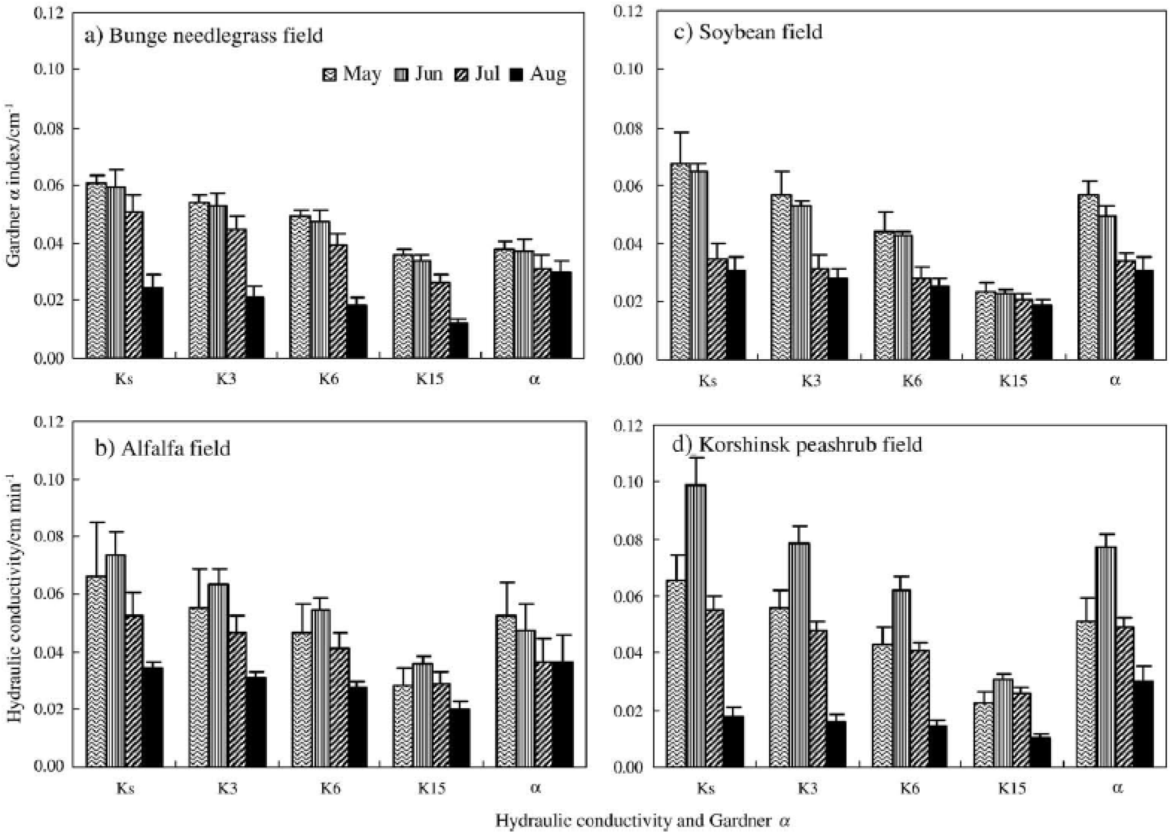

Figure 2-3 Temporal changes of soil hydraulic conductivity and Gardner α under different land uses (vertical bars represent standard error) (Hu et al., 2009).

2.4 Methods to measure saturated hydraulic conductivity

Infiltration rates can be measured either under positive pressure (ponded infiltration) or negative pressure (tension conditions) (Strudley et al., 2008) in both the field and the laboratory. These methods can be useful when compared to determine hydraulic conductivity and porosity of the soil. A fundamental part of the characterisation of soil is the relationship between soil water content and matric potential in terms of water retention and storage properties (Dane & Hopmans, 2002). There are several methods available to measure the hydraulic properties and in particular the saturated hydraulic conductivity in soil. Mohanty et al. (1994) compared fours methods to determine K_{sat} and found that the constant head permeameter resulted in the least variability but the highest K_{sat} values. The main reason is due to the sample size in the laboratory compared to the field. If the cores used in the laboratory were larger it is expected that the result may be more accurate but field methods are still the preferred method to measure K_{sat} rather than laboratories due to the inaccuracies of estimated values. The reason that laboratory methods are used is due to the lower cost and there is greater flexibility of conducting these methods. Field methods also require a lot of labour and are dependent on weather effects as to when methods can be performed (Ibrahim &

Aliyu, 2016). Figure 2-4 shows that laboratory estimates of K_{sat} are generally greater than field estimates.

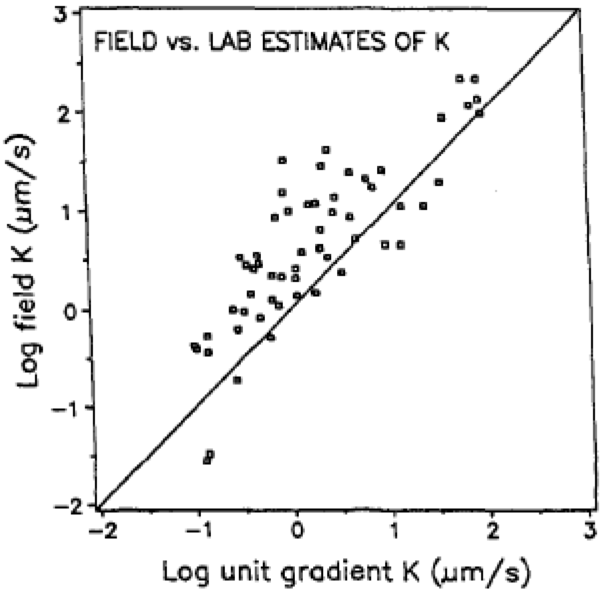

Figure 2-4 Estimates of hydraulic conductivity using field vs laboratory experiments at tensions of 0, 30, 60 and 150mm (Ankeny et al., 1991).

2.4.1 Field measurements

The accuracy of field measures can be more reliable and a greater representation of the soil structure and hydraulic properties. On a field scale soil water movement is a dynamic process, where alterations of wetting and drying cycles occur (Dane & Hopmans, 2002).

Field methods for measuring soil hydraulic properties have several advantages: 1) require less time and less expensive, 2) are more accurate and precise than laboratory measurements as soil cores usually are not representative of the soil in entire field site, 3) laboratory equipment are badly adapted for revealing the hydraulic behaviour of watersheds at field scale (Lassabatere et al., 2006). In the field, there are several soil water zones. The first is the transmission zone where the top section of the soil has a relatively uniform water content. This zone is affected by several factors including evaporation and plant water uptake. The wetting zone is next, below the transmission zone. Throughout this zone the water content rapidly decreases as depth increases (Dane & Hopmans, 2002). Measurements in the field and in the laboratory, can be highly variable in both space and time. The variability can be as large as coefficient of variance of 400%.

Beerkan estimation of soil transfer procedure (BEST method)

The Beerkan estimation of soil transfer procedure (BEST) method was developed as a new method to determine water retention characteristics and hydraulic conductivity curve. These can be calculated from estimations of sorptivity and from steady state infiltration rate. Other methods have failed to accurately provide data that is representative of the soil and the physical principles of water infiltration (Lassabatere et al., 2006). Other methods that are generally used in the field involve using simple rings or disc infiltrometer and a given pressure head on the surface. The BEST method can be used to measure infiltration. It usually consists of one metal ring that is pushed into the soil to approximately 20mm in depth. This method allows water to move in all directions in the soil not just vertically (Lassabatere et al., 2006). To measure the infiltration data, a known volume of water is added in the ring and when it is infiltrated completely the time is recorded and the next amount of the same volume is added and repeat. This is repeated for a total of 8 to 15 series of known volumes. This method can measure both hydraulic conductivity and soil water retention curve; using particle size distribution, bulk density, soil water content for shape parameters and infiltration data for scale parameters.

Single ring infiltration

Using single ring infiltration to measure hydraulic properties of soil can be more variable than double ring infiltration, as the direction of infiltration is three dimensional. The water can flow through the ring and into the soil profile in any direction (Figure 2-5). There can be several errors in measurement using single ring infiltration. Depending on the amount of other information required, various methods have been used to analyse the single ring infiltration data for K_{sat} calculations.

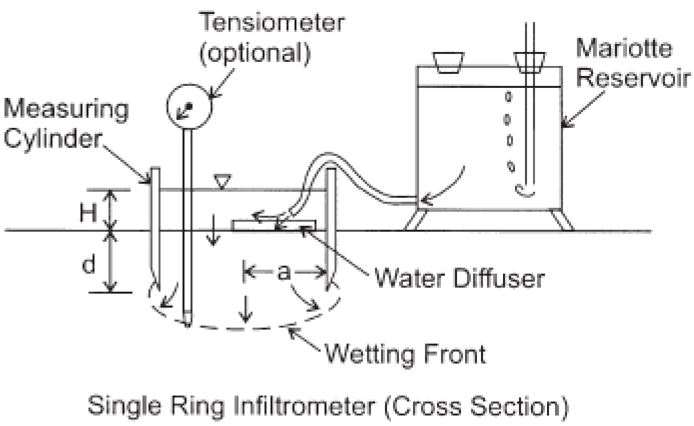

Figure 2-5 Cross section of one method using a single ring infiltrometer in the field (Reynolds et al., 2002).

Double ring infiltration

Rings used to measure infiltration are usually 10-50 cm in diameter and 5 -20 cm long. The rings are driven into the soil at 3-10 cm in depth. Double ring infiltration is a method used to determine the hydraulic conductivity and volumetric water content of a soil. Double ring infiltration method is similar to that of the single except there is a larger buffer ring surrounding the inner measuring ring which ensures water movement from the inner ring is only one dimensional, as the water flow from the buffer ring is physically preventing flow divergence (Reynolds et al., 2002) (Figure 2-6). The outer ring should be at least 4 times the area of the inner. Measurement of constant head infiltration is where the water head is maintained at 5cm of water in the inner ring as Infiltration is measured as a function of time. To maintain a constant water head, a mariotte bottle can be inverted on the rings and the rate of fall measured on the bottle. The K_{sat} isn't calculated in this method as it is approximately the steady state infiltration rate.

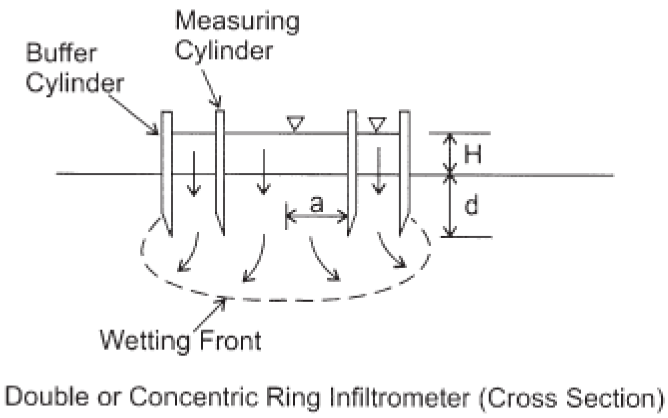

Figure 2-6 Cross section of a double ring infiltrometer being used in the field (Reynolds et al., 2002).

The greater depth that the rings are inserted into the soil, the greater the accuracy of the measurements, but the limitations of inserting the rings in too far is the time taken for equilibrium to be met is greater and there is more risk of causing excessive damage to the soil.

There can be error in measurement from using either single or double ring infiltration methods due to potential compaction of soil when rings are inserted into the ground. This can cause flow along the cylinder walls, but this can be reduced by cutting along the edge of the ring before installation if the surface it too hard (Reynolds et al., 2002). Error can also occur in these measurements when there is a change in soil permeability with depth. This may be due to the presence of a soil crust or shallow water table which causes interference of infiltration.

Tension infiltrometer

Tension infiltrometer data can be used to determine K_{sat} based on the relationship between steady state infiltration and matrix potential at the soil surface. Tension infiltrometer are a widely-used method for measuring the saturated hydraulic conductivity of soils. This device also has the ability to quantify paths of infiltration that are impacted by preferential flow and macropores (Hopmans et al., 2002; Hu et al., 2009). To accurately estimate infiltration parameters either two disc diameters are required or using a single disc at multiple tensions. The flow of water from the disc is not confined to one dimension but it is 3 dimensional and occurs on an axial symmetry (Clothier & Scotter, 2002).

Good hydraulic contact between the porous disc surface and the soil surface are essential, so a thin layer of sand is generally applied on the soil surface to ensure this. The K_{sat} value of sand is expected to be large enough to prevent extensive flow impedance effects. Initially water is supplied at the greatest suction to fill the macropores first, then as infiltration reaches steady state the suction is decreased consecutively until the soil is saturated.

This method may provide adequate information without having to perform other methods such as additional tensiometer and Time-Domain Reflectometry (TDR) measurements. Tension infiltrometer method can accurately approximate both unsaturated hydraulic conductivity and soil retention properties that may be required.

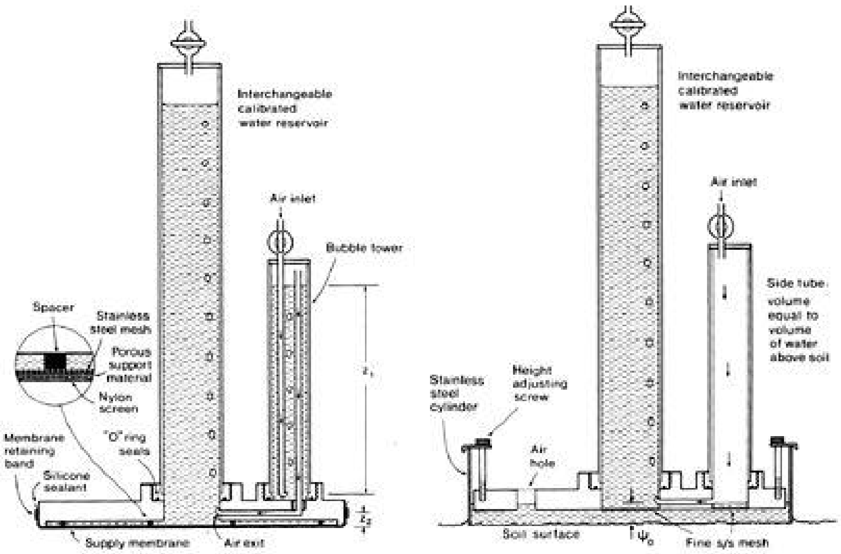

Figure 2-7 Diagram of a tension infiltrometer showing the various components.

Tension infiltrometers allow measurements of infiltration with a constant negative pressure head at the soil surface. A porous plate and membrane that is atached to the base disk of the device allows the suction to be maintained. As the tension of at the soil surface increases the infiltration rates decreased. (Ankeny et al., 1991). Hydraulic conductivity using tension infiltrometer were approximately three times greater in the field compared to laboratory experiments. Neither is more accurate than the other as there are errors that can occur in both scenarios. A diagram of the components of a tension infiltrometer can be seen in Figure 2-7. Depending on the disc size and number of tensions used. A variety of methods are available to analyse the tension infiltrometer data. Among which, the multi-pressure with non-linear fitting method has been formed due to the fast and stable results. They also do not give any negative results, which other methods do (Hu et al., 2009).

2.4.2 Laboratory measurements

Core samples that are collected to measure hydraulic properties in the lab usually range from 5–8 cm in diameter and 1-6 cm in height for undisturbed samples (Dane & Hopmans, 2002). The main issue with using a small core to measure soil hydraulic properties is the effect of the walls. Wall effects mean the sample is not a realistic representative of the sample area or field. Disturbed/repacked samples can also be collected but more accurate measurements of water retention will be collected in an undisturbed core as soil structure impacts the retention curve.

Constant head

Measuring saturated hydraulic conductivity using soil cores collected from the field can be highly variable due to biological activity in the soil such as algal growth and earthworm burrows after the cores are collected. This can have a substantial time dependent impact on the measurement of K_{sat} (Reynolds et al., 2002). Earthworms burrowing through the core can significantly increase the measured K_{sat}, which may not be an accurate representation of the field scale in time and space.

The method through the cores are collected and how much care is taken can have an influence on the measurements collected. Cores must be fully saturated before the measurement process can begin. It may take 4 days to slowly saturate cores. Water is then allowed to flow through the soil at a steady state under a constant hydraulic gradient. The range of K_{sat} that can be measured using constant head on soil cores is 10 to 10^{-5} cms^{-1} (Reynolds et al., 2002). This method is suited for high volume projects, as it is simple to have up to 60 cores set up at once with a large tank containing several outflow assemblies and the data can be easily collected in the same time period it would take from a smaller number of cores. The saturated hydraulic conductivity can be calculated using Darcy's law.

Falling head

The range of K_{sat} values that can be measured using the falling head soil core method in the laboratory is 10^{-4} to 10^{-7} cms^{-1}. As with the constant head method, the soil cores must be saturated before starting measurements. This is designed to complement the constant head method where flow of water through the soil is slow, the falling head can be used.

2.5 Future research areas

Temporal variability of soil hydraulic properties as a result of tillage have not been studied in great depth in New Zealand or overseas. Of the studies that have been carried out, the results are variable. Some studies result in increase in saturated hydraulic conductivity, others decrease and others do not change. This makes it very difficult to predict or have an understanding of the effect of tillage in soil. This difference in response may be due to several factors including the method used to measure soil hydraulic properties or the management of the soil (e.g. land use) prior to tillage.

- The interaction of different land uses as a result of tillage have not been studied. The effect of tillage is expected to change when the land use prior to tillage is different.

- The Beerkan Estimation of soil transfer parameters (BEST) method has not been used in New Zealand. A comparison of this method with other estalished viable methods is essential before it can be used as a viable measurement method.

- The effect of tillage and land use may be influenced by the methods. A lot of studies have been conducted to compare different methods but usually with a single land use or tillage treatment. This may prevent us from identifying the possible effect of methods on treatment effect.

Chapter 3
Materials and methods

3.1 Background and experimental design

Location of the study is Lincoln University Arable farm paddock U2.4. The soil type is Templeton silt loam. Prior to comencement of this experiement the site was used for a Plant and Food Research tillage and treading field trial (ex TnT). Treatments of this study included different tillage practises, no tillage and intensive tillage. The intensive till treatment was ploughed in Autumn 2016 and no tillage occurred for the no till treatment. Oats was planted in both of these tillage treatments. Both were then surface tilled in spring 2016. The perimeter of these sites was permanent pastures.

Tillage began on 8 September 2017 where the paddock was ploughed using a mouldboard plough to the depth of 20cm. The second pass involved harrow and cambridge roll on 11 September 2017 and finally Maxitill grubber crumbler on 13 September 2017. The crop was then treated with the agrichemical Adama Trifluralin 480 at 1.7 L ha^{-1} and incorperated with Maxitill on 19 September 2017. The garden pea crop (*Pisum sativum)* was sown and rolled post sowing on 3 October 2017.

For this study, measurements are taken at two different time points at this site. One immediately prior to the paddock being ploughed and one after the peas were sown. The treatments of this experiment include the effect of tillage; two land uses: permanent pasture and oats; four methods to measure soil hydraulic properties: tension infiltrometer, constant head constant head double ring infiltration, BEST method, and intact core under constant head measurements in the laboratory. A layout of where each replicate was measure can be seen in Figure 3-1. Each measurement set was completed within 3 days. The first set began on 28 August 2017 and final set began on 5 October 2017.

Figure 3-1 Overview of paddock where the experimentation took place. The row on the left represents cropping before tillage and the right is pasture before tillage. The distance between each replicate is 2 meters.

3.2 Field measurements

The moisture content was measured using TDR probe (Cable tester) and HydroSense for initial surface soil moisture content, before any measurements commenced. These measurements used 13.5 cm and 12 cm rods respectively to measure surface moisture.

3.2.1 Tension infiltrometer

For each measurement set and land use, five replicates in each land use were conducted. The tension infiltrometer used are similar to those described by (Ankeny et al., 1988), the radius of the disc was 150 mm and the radius of the reservoir tube was 22.5 mm. This was used to determine the steady infiltration under five pressure heads applied in the ascending order (-11.3, 8.3, 5.3, 2.3 and 0.3 cm). Preparation of the soil surface is prepared using scissors and a putty knife, any excess plant material is removed to ensure surface is flat. Contact sand is spread over the prepared area and a membrane is attached to the base of the disc to ensure good contact with the soil. The initial water content is measured using HydroSense and TDR probe. The infiltrometer (bubble tower and reservoir) are filled with water and attached to the disc. Appropriate tension is set on the bubble tower. Initial water level is recorded. A stopwatch was used to record time and water level at set intervals until the change in water infiltration per unit time is constant (steady state) as seen in Figure 3-2. In the same location, the tension is adjusted repeated until steady state is reached for all five tensions that are run. Repeat this in 5 locations for each land use.

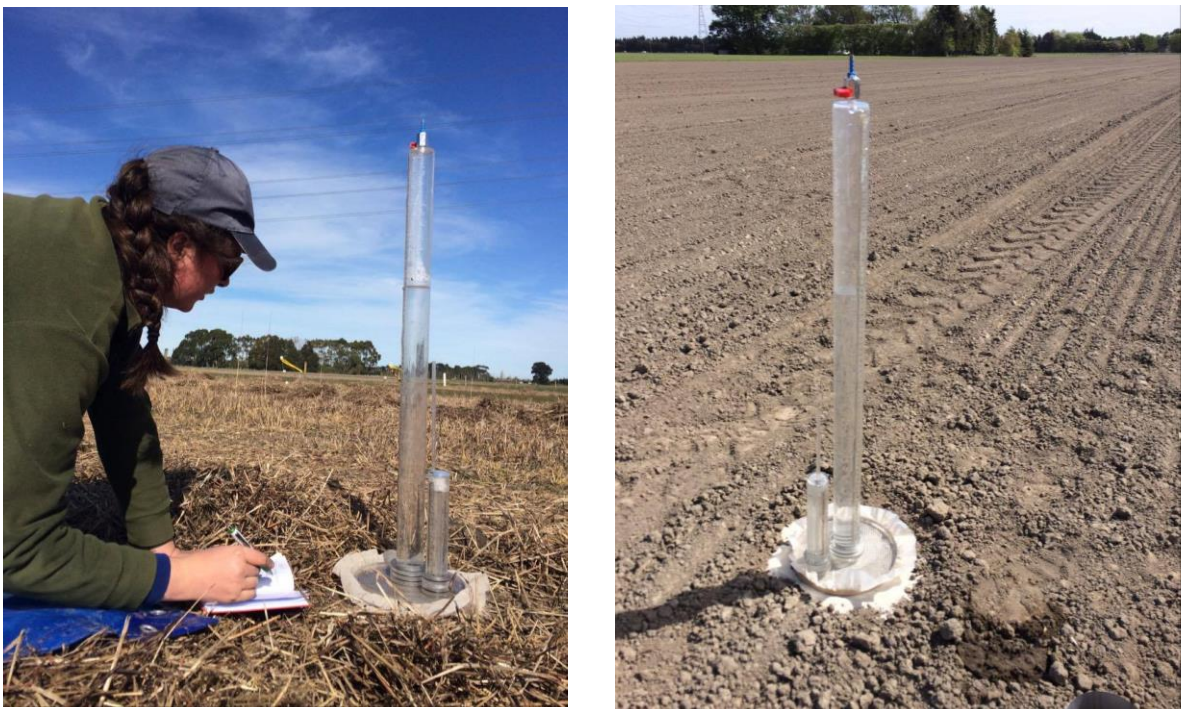

Figure 3-2 Measuring the water level on the tension infiltrometer under the land use -cropping before and after tillage.

The non-linear regression method used to calculate the soil hydraulic conductivity and Gardner α was determined by Logsdon and Jaynes (1993), which is based on the theoretical analysis of the 3D quasi-steady-state water flux under a tension infiltrometer (Wooding, 1968).

$$\frac{Q_s(h)}{\pi R^2} = K_{\text{sat}}\exp(\alpha h) + \frac{4K_{sat}\exp(\alpha h)}{\pi R\alpha} \qquad \textbf{Equation 3-1}$$

Where $Q_x(h_f)$ is the steady infiltration rate (L^3T^{-1}) under head pressure of h_f (-cm), the radius of the disc infiltrometer is R (L), α is the Gardner constant which characterizes soil pore size distribution (L^{-1}), and K_s is the saturated hydraulic conductivity ($L\ T^{-1}$).

3.2.2 Constant head double ring infiltration

Figure 3-3 One replicate of the constant head double ring infiltrometer in the pasture before tillage (left) and after tillage (right).

In three different areas, the large guard rings are carefully and evenly hammer into the soil. The 15 cm diameter rings are added inside these larger ones (30 cm diameter) ensuring they are concentric with the larger rings. While inserting these rings it was made sure there was no damage to the soil, this sometimes require pre-wetting the soil surface when the soil is dry. All inner rings were inserted 7.5 cm into the soil and the outer ring 5 cm.

Water is poured into the outer ring to a depth of approximately 5 cm. This level maintained throughout the entire measurement period (Figure 3-3). The centre ring was kept filled with water until steady state condition occur. A head reading was taken on the centre ring and the time was started (t = 0). Readings were taken for approximately two hours, at 30 minute intervals, as the head begins to drop, while maintaining approximately 5 cm in the outer ring at all times (figure 3-4). The K_{sat} is calculated from all readings obtained.

Figure 3-4 Measuring the drop in head height on the constant head double ring infiltrometer.

3.2.3 Beerkan estimation of soil transfer procedure (BEST method)

On a level area of soil, grass is cut down to soil surface and dead grass is removed using a paint brush. This is repeated in five locations for each land use. A 15 cm diameter ring is placed on the surface and carefully cut with a box cutter, 5mm deep around the outside of the ring. The ring was gently pressed into the soil using a piece of wood and using the hammer to knock it down to 10mm depth marked on the side of the ring.

Bulk samples were collected using the soil core to collect samples to a depth of 5 cm. A sample was collected from beside the infiltration ring. These were weighed immediately and placed in labelled sample bags. These were used to calculate the initial water content. The first volume of 150 mL or 100 mL of water was added to the ring and the start time was recorded (Figure 3-5). Once all the water was infiltrated into the soil, the second volume was added and start time was recorded. This is repeated until steady state is reached. This was carried out for five infiltration rings. Then when completed the ring was carefully removed and another bulk sample was collected to 2 cm depth within the infiltration ring. The samples were then placed in a labelled sealed plastic bag and weigh immediately.

Figure 3-5 Beerkan estimation of soil transfer procedure (BEST) being carried out using single rings in the cropping land use after tillage.

Particle size distribution analysis

Two methods of particle size distribution are used as a comparison. These methods were the standard pipette method and MasterSizer 2000 laser particle size analysis.

To prepare the samples for analysis the organic matter needs was removed. To achieve this approximately 10 g of dry soil was weighed and the exact amount noted. 15 mL of hydrogen peroxide (30% v/v) was added to 10 g of dry soil sample and left overnight to break down any organic matter. Na-HMP 50 g L^{-1} solution was then added to the samples to disperse particles. This was left overnight again. The samples are then ready to be analysed.

The pipette method: the samples were added to a 1 L measuring cylinder and filled to 1 L with distilled water. These needed to be mixed well so the samples were inverted for 60 seconds continuously. After 45 second's a pipette was used to extract 25 mL from 10 cm below the surface, this allows for the sand fraction of the sample to be calculated. This was put in a ceramic weigh boat (which the weight had previously been recorded and labelled) and dried in the oven. The samples were left to settle for eight hours, then another 25 mL was extracted to calculate the silt and clay fraction of the soil. When samples had been in the oven drying for 24 hours the samples are weighed.

The sand fraction represents particles that are 0.06 mm to 2 mm, silt is 0.002 mm to 0.06 mm and clay particles are smaller than 0.002 mm.

Figure 3-6 Measuring cylinders fill with dispersed soil sample and topped up to 1 L with water. These are used for the pipette method for particle size analysis.

$$\%\,clay = \frac{Actual\ wt\ of\ sample\ at\ 8hrs}{total\ soil\ weight} \times 100$$

$$\%\,silt = \frac{Actual\ wt\ of\ sample\ at\ 45s - Actual\ wt\ of\ sample\ at\ 8hrs}{total\ soil\ weight} \times 100$$

$$\%\,\boldsymbol{sand} = \mathbf{100} - (\%\boldsymbol{clay} + \%\boldsymbol{silt})$$ **Equation 3-2**

MasterSizer 2000 laser method: a representation of the prepared samples was placed into small vials and placed on a roller mixer to remove any bubbles. Once bubbles were removed a small amount was placed into the MasterSizer 2000 and the analysis begins. Results were produced using the MasterSizer 2000 analysis software.

Saturated hydraulic conductivity calculation

$$\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} = \left[1 + \left(\frac{h}{h_g}\right)^n\right]^{-m}$$

$$m = 1 - \frac{k_m}{n}$$

$$\frac{\boldsymbol{K}(\Theta)}{\boldsymbol{K_s}} = \left(\frac{\Theta - \Theta_{\boldsymbol{r}}}{\Theta_{\boldsymbol{s}} - \Theta_{\boldsymbol{r}}}\right)^{\eta}$$

Equation 3-3

Where *n, m* and η are shape parameters and h_g, θ_s, θ_r and K_s are scale parameters. These relations between parameters are proven to be accurate and reliable for describing the hydraulic properties if most soils (Lassabatere et al., 2006).

$$I_s(t) = (A \cdot S^2 + K_s)t + C\frac{S^2}{K_s}$$

$$\text{Slope, } i_s^{exp} \approx A \cdot S^2 + K_s$$

$$\text{Intercept, } \boldsymbol{b_s^{exp}} \approx \boldsymbol{C\frac{S^2}{K_s}}$$

Equation 3-4

Where, $I_s(t)$ is the steady state cumulative infiltration, A and C are parameters that are obtained from water content, bulk density and pore size distribution. These shape and scale parameters (particle size distribution and infiltration rates) are used to determine the value of K_{sat} for a particular soil.

3.2.4 Collection of cores

The process to collect cores from the field is simple. The area where the cores were taken needs to be level. A block on top of the core casing was used slowly and pressure was evenly applied to push the core into the ground. Once it was in the soil by approximately 3 cm, the soil was cut from around the outside of the casing. As the soil from the outside is removed the core is continued to be pushed into the soil until the top of the soil is flush with the top of the core casing (another core will need to be placed on top to achieve this). Each side around the core needed to be dug out using a spade, and then dug underneath the core to carefully lift out of the ground. Some of the excess soil was trimmed off from around the core. Once the cores were collected they were immediately placed in plastic bags to reduce the amount of evaporation. The number was the recorded on the outside of the core which corresponds to what treatment it is. Once they were all collected, they were taken back to the laboratory and stored in the cool store until measurements of K_{sat} measurement using the intact core under constant head took place.

3.3 Laboratory measurements

3.3.1 Soil cores

Preparation of cores

Figure 3-7 Preparation of soil cores, before deworming. The bottom of the core is trimmed level (left) and then picked with sharp tool to remove smearing and expose pores.

Cores were prepared for laboratory measurements. The bottom of the cores were trimmed until the soil is flush with the core casing. Using a tool that is pointy, the bottom surface of the core was picked to remove the smeared layer caused from the knife (Figure 3-7). This exposes the pores that may have been covered during the trimming process. When picking the surface, a small amount of soil is removed so the volume of soil was not largely changed. A vacuum cleaner was used to remove the loose dirt.

Cores were weighed and weights recorded. Silica sand was added to the base of the core to ensure there is good contact when the cores were added to the tension table, and weight recorded (Figure 3-8). The bottom of the cores were covered with a 17cm^2 piece of voile cloth (Shearline 100% acetate from Frost textiles) and secured with a rubber band (no. 83 from Waugh Rubber bands).

Figure 3-8 Silica sand is added to the base of the core to ensure good surface contact while on the tension tables.

Earthworm removal from cores

A metal tray was placed on top of a panel heater, and filled to a depth of 5mm of water. Once the cores have been trimmed the cores are placed in the centre of the tray. The metal lid was placed on top of the tray and heater turned on. After the cores were left to heat for 1.5 hours, the lid was removed and worms that emerged were removed from the top of the core. The lid was replaced after the worms were removed and this was repeated every 30 minutes for three hours. Cores were removed from this tray and placed on wetting up trays overnight in preparation for K_{sat} and tension table measurements. Cores were then placed in wetting up trays on the metal gauze. Distilled water was added so the water level was at the top of the core.

3.3.2 Intact cores under constant head

The cores were removed the wetting up trays, and the saturated cores were brought into the laboratory. The height of the soil in the cores was checked and if the height is more than 2 mm below the core, three readings were taken around the core. Rubber collars were added to the top of the cores about 15mm above the core. Making sure the collar was level with the core and the hose clip tightened. Each core was placed over the funnels. The core number that is in each funnel was recorded. Filter paper was put on top of each core, to ensure the soil surface was not disturbed when water was applied. Taps were opened to ensure there was no air in the system, then was closed once water is flowing out. Water was poured onto the top of each core with a jug, to above the water inlet. Smaller taps were now turned on to allow water from supply container to maintain a constant head above the cores. Large containers were put under the funnels to catch the leachate material. The head of water was measured on all cores to make sure it remained constant and there was no air in the system (head measure should be approximately 40 mm). Making sure none of the cores were not running too fast. If this was the case, the inlet tube was clamped off and run this core separately later. The start time was noted on the data sheet and the cores were checked to see if they were level in both directions. Water in the drainage containers was checked approximately every 30 minutes to ensure they were not too full. The supply tank was topped up with distilled water if it was getting low. The system was left running for around 4 hours until the flow had reached equilibrium. After they have reached equilibrium, four readings of the water head were taken from around each core. The temperature of the water head was measured with the thermometer on each core (Figure 3-9).

To take the infiltration readings, the large containers were removed from under the funnels. The 300 mL measuring jars were used to collect leachate material, weigh and record the weight of each empty jar. The jars were lined up beside each filter. Each jar was placed under the filter and leachate was collected for 8 minutes. Samples were weighed and recorded. This was repeated three times per core or until constant measurements are taken.

Figure 3-9 Apparatus used to run the constant head K_{sat} measurements in the laboratory. Leachate is collected for a set time period (left) and the head on top of the core remains constant (right).

$$K_{\mathrm{sat}} = \frac{QL}{ATH}$$

Equation 3-5

Where Q is the volume of steady state infiltration (L^3 T^{-1}), L is the length of the soil core (L), A is the cross-sectional area of the core (L^2), T is the time corresponding to the discharge water volume Q and H is the difference of hydraulic head (L). K_{sat} values were then adjusted for differences in water temperature between cores.

3.4 Statistical analysis

All data was analysed using Genstat 18. The hydraulic conductivity data was transformed using Log10 transformation so the data was normally distributed. For all data sets a general analysis of variance (ANOVA) was carried out to determine the effects of the different treatments. If a significant result was found a 5% least significance difference test (LSD) was conducted to determine which means the values are significantly different where there are more than two levels.

Chapter 4

Results

The structure and infiltration data is presented first for tension infiltrometer and BEST method. These parameters are required to calculate the final K_{sat} of the soil. There is no extra data provided for the constant head double ring infiltration and intact core under constant head as the only data required to calculate the K_{sat} of the soil is the steady infiltration rate.

4.1 Infiltration rate for tension infiltrometer method

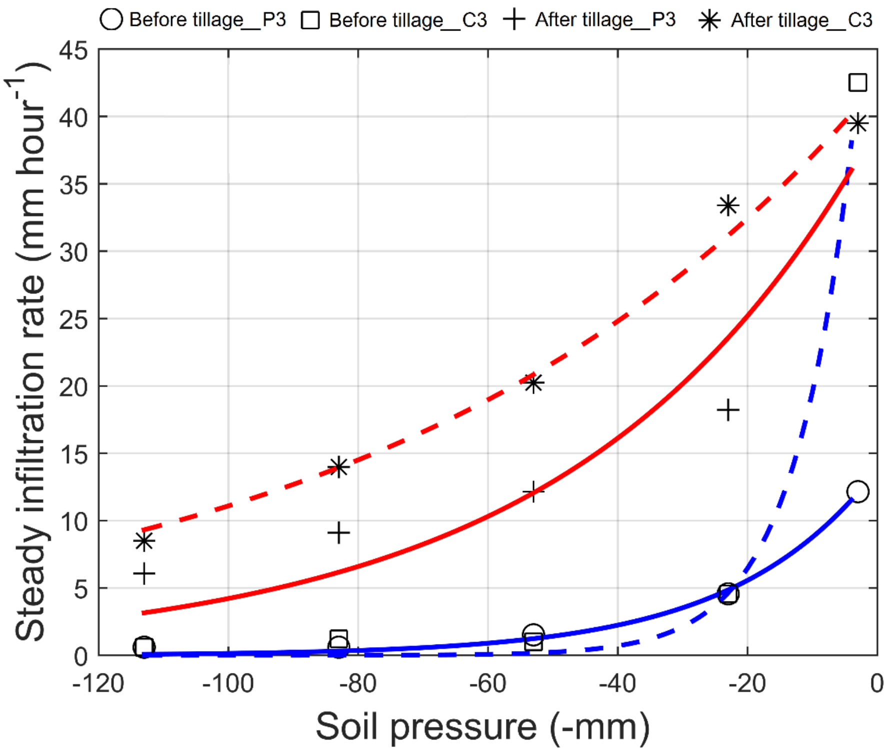

Figure 4-1 Infiltration rate measured using the tension infiltrometer a five different soil pressures.

The steady infiltration rate that was measured using a tension infiltrometer is seen to differ between land uses and before and after tillage (Figure 4-1). After tillage in both land uses the steady infiltration rate was consistently greater under all soil pressures than the same land use before tillage.

4.2 Particle size distribution and infiltration process for BEST method

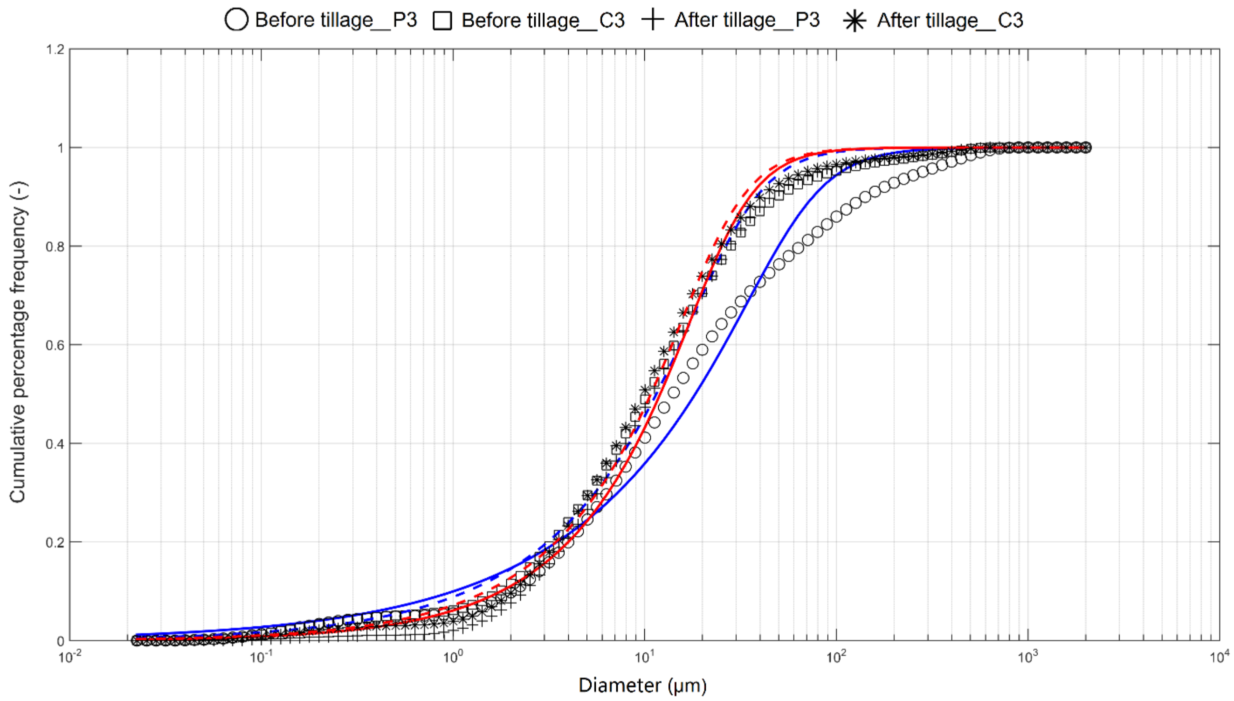

Figure 4-2 Particle size distribution parameters of the soil under the different land uses and before and after tillage occurred. These parameters are used in calculation of the BEST method.

Particle size distribution is calculated using theoretical distribution described by Lassabatere et al. (2006). There are two methods that are used to determine the particle distribution of the soil. The MasterSizer 2000 laser method and traditional pipette method. There was not much difference in terms of shape parameters (n, m and η). Figure 4-2 shows the distribution of particle sizes in the sample.

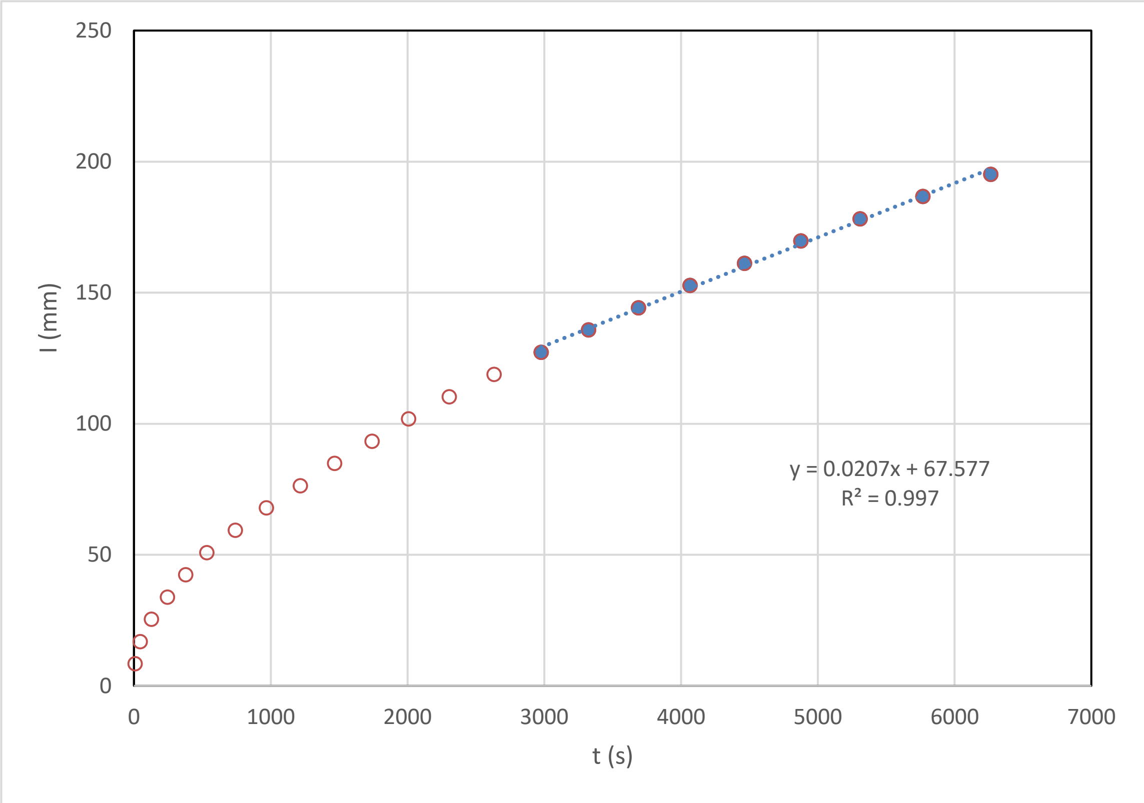

Figure 4-3 An example of the curve produced to estimate the slope and intercept of steady state cumulative infiltration over time for the BEST method.

The slope and intercept data is one requirement for calculating K_{sat} using the BEST method. Figure 4-3 is example of the cropping replicate 1 after tillage, which is used to determine the slope and intercept parameters. For after tillage replicate C1 the slope is 0.0207 mms^{-1} and the intercept is estimated to be 67.577 mm. Initially the infiltration rate is very fast then plateaus as time increases when steady state is reached.

4.3 Saturated hydraulic conductivity

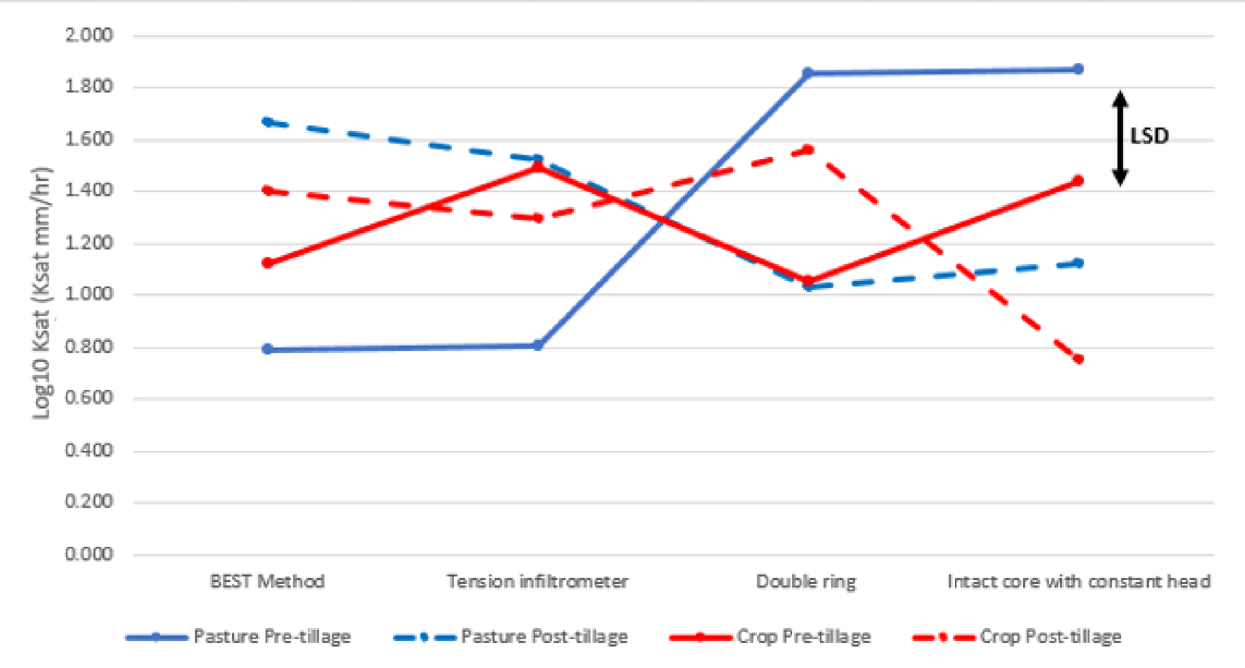

Figure 4-4 Average log10 K_{sat} (K_{sat} mm/hr) before and after tillage using methods as comparison in the two land uses (pasture and cropping). LSD = 0.3823.

The average change in K_{sat} due to tillage ($P = 0.885$) across all methods ($P = 0.583$) and land uses was not significantly different ($P = 0.318$). Some methods showed an increase in saturated hydraulic conductivity and others decreased (Figure 4-4). This large variability across methods used to measure saturated hydraulic conductivity caused no significant result to be found. There was a significant interaction effect found between the method and tillage treatments ($P < 0.001$), method and land use ($P = 0.013$). For each method there is a significant effect on tillage i.e. for the BEST method the average K_{sat} increased by 37.6% as a result of tillage. For each method there was also a land use effect i.e. for the tension infiltrometer there was an increase in K_{sat} in cropping compared to pasture by 16.4%. The change is not a significant or consistent change across methods in each land use or tillage (Table 4-2). There is not a significant interaction effect between land use and tillage ($P = 0.848$). This means that each land use responds the same on average before tillage compared to after tillage. The Log 10 K_{sat} was not significantly affected by the methods used ($P = 0.318$) as the variability is large between methods. The two types of methods that have been used include infiltration data when the soil is unsaturated or saturated. Tension infiltrometer and BEST method are unsaturated methods used to determine K_{sat} whereas the constant head double ring infiltration and intact cores under constant head are saturated methods. There is no significant difference in K_{sat} between the tension infiltrometer and BEST method (unsaturated methods) at each land use either before or after tillage ($P = 0.594$). The crop system had the highest K_{sat} before tillage and the pasture had the greatest K_{sat} after tillage when measured using both the tension infiltrometer method and BEST method. There is also no significant between the constant head double ring infiltration and the intact core under constant head (saturated methods) at each land use either before or after tillage (P =

0.519). But there is a significant difference between each of the saturated methods and unsaturated methods.

Table 4-1 Analysis of Variance (ANOVA) of Log10 K_{sat} values, for all methods, land uses and tillage treatments (d.f = degrees of freedom, m.v = missed values, s.s = sum of squares, m.s = mean squares, v.r = variance ratio, F pr = P value showing significance).

Source of Variation	d.f	(m.v)	s.s	m.s	v.r	F pr.
Method	3		0.17946	0.05982	0.65	0.583
Land_use	1		0.09270	0.09270	1.01	0.318
Tillage	1		0.00193	0.00193	0.02	0.885
Method.Land_use	3		1.06546	0.35515	3.88	0.013
Method.Tillage	3		4.69234	1.56411	17.10	<.001
Land_use.Tillage	1		0.00340	0.0340	0.04	0.848
Method.Land_use.Tillage	3		3.71161	1.23720	13.52	<.001
Residual	63	(1)	5.76318	0.09148		
Total	78	(1)	15.47734			

Table 4-2 Average log10 K_{sat} before tillage to after tillage and in each land use (pasture and crop) in each method (mean ± S.E). Letters in superscript represent significant differences according to LSD = 0.382.

		K_{sat} Log10 (K_{sat} mm/hr)				
		BEST method	**Tension infiltrometer**	**Constant head double ring infiltration**	**Intact core under constant head**	**Average**
Land use	**Pasture**	1.227 ± 0.165	1.164 ± 0.124	1.442 ± 0.196	1.496 ± 0.157	1.332
	Crop	1.261 ± 0.072	1.393 ± 0.075	1.305 ± 0.091	1.096 ± 0.182	1.275
		↑ crop	↑ * crop	↑ pasture	↑ * pasture	↑pasture
Tillage	**Before**	0.955 ± 0.105	1.150 ± 0.132	1.453 ± 0.183	1.654 ± 0.146	1.303
	After	1.534 ± 0.063	1.407 ± 0.054	1.294 ± 0.113	0.938 ± 0.131	1.293
Tillage		↑ * after	↑ * after	↓ after	↓ *after	↓ after

		Before tillage	**After tillage**	
Land use	**Pasture**	1.330 ± 0.148	1.334 ± 0.080	↑ after
	Crop	1.275 ± 0.080	1.253 ± 0.088	↓ after
		↑ pasture	↑ pasture	

(Note: ↑ = increased K_{sat}, ↓ = decreased K_{sat} and * = significant change in K_{sat}).

4.4 Methods used to determine the saturated hydraulic conductivity

The greatest average K_{sat} measurements were in the pasture system before tillage when using the constant head double ring infiltration (1.86 ± 0.26) and intact core under constant head in the laboratory (1.89 ± 0.14). The lowest K_{sat} measurements were in the pasture system before tillage when using the BEST method (0.79 ± 0.15), tension infiltrometer (0.81 ± 0.06) and using the intact core under constant head after tillage in the cropping system (0.75 ± 0.19).

4.4.1 Beerkan estimation of soil transfer procedure (BEST method)

The BEST method showed a significant increase (Table 4-5; P < 0.001) in K_{sat} due to tillage under both land uses (pasture and cropping). In the pasture system, the K_{sat} increased by 40.7% as a result of tillage compared to the crop system where the K_{sat} increased by 47.9% as a result of tillage. The effect of the different land uses was not significantly different between before and after tillage (P = 0.737). There was also a significant interaction effect between land use and tillage (P = 0.010). The K_{sat} before tillage is significantly greater in the cropping system compared to pasture and the K_{sat} after tillage is not significantly different in the pasture and cropping system.

Table 4-3 Analysis of Variance (ANOVA) of Log 10 K_{sat} values for the BEST method comparing land uses and tillage treatments (d.f = degrees of freedom, m.v = missed values, s.s = sum of squares, m.s = mean squares, v.r = variance ratio, F pr = P value showing significance).

Source of Variation	d.f	s.s	m.s	v.r	F pr.
Tillage	1	1.67595	1.67595	33.65	<.001
Land_use	1	0.00581	0.00581	0.12	0.737
Tillage.Land_use	1	0.42956	0.42956	8.62	0.010
Residual	16	0.74708	0.04981		
Total	19	2.84172			

4.4.2 Tension infiltrometer

There is a significant difference in Log10 K_{sat} as a result of tillage (Table 4-4; P = 0.006) and land use (P = 0.011). There was also a significant interaction effect between tillage and land use (P < 0.001). In the pasture system the K_{sat} increased by 88.3% as a result of tillage compared to crop decreased by 13.4% as a result of tillage.

Table 4-4 Analysis of Variance (ANOVA) of Log10 K_{sat} values for the tension infiltrometer method comparing land uses and tillage treatments (d.f = degrees of freedom, m.v = missed values, s.s = sum of squares, m.s = mean squares, v.r = variance ratio, F pr = P value showing significance).

Source of Variation	d.f	s.s	m.s	v.r	F pr.
Tillage	1	0.32886	0.32886	10.21	0.006
Land_use	1	0.26274	0.26274	8.15	0.011
Tillage.Land_use	1	1.04182	1.04182	32.33	<.001
Residual	16	0.51554	0.03222		
Total	19	2.14896			

4.4.3 Constant head double ring infiltration

The data points where no change occurred during infiltration were removed for calculations and data analysis. This method is a traditional method that is used globally to measure changes in hydraulic conductivity. There was no significant difference of Log10 K_{sat} as a result of tillage or land use, but there is an interaction effect between tillage and land use (Table 4-3; $P < 0.001$). In the pasture system the K_{sat} reduced by 44.6% as a result of tillage whereas in the crop system it increased by 48.6%.

Table 4-5 Analysis of Variance (ANOVA) of Log10 K_{sat} values for the constant head double ring infiltration method comparing land uses and tillage treatments (d.f = degrees of freedom, m.v = missed values, s.s = sum of squares, m.s = mean squares, v.r = variance ratio, F pr = P value showing significance).

Source of Variation	d.f	s.s	m.s	v.r	F pr.
Tillage	1	0.1258	0.1258	1.09	0311
Land_use	1	0.0932	0.0932	0.81	0.381
Tillage.Land_use	1	2.2397	2.2397	19.46	<.001
Residual	16	1.8412	0.1151		
Total	19	4.2999			

4.4.4 Intact core under constant head

The effect of tillage on log10 K_{sat} was consistent in both land uses when using the intact core under constant head method. In the pasture system, the log10 K_{sat} decreased by 39.8% as a result of tillage compared to the cropping system where it also decreased by 47.8% ($P = 0.001$). There was a significant difference between land uses ($P = 0.044$). Before tillage occurred, the pasture had a slower log 10 K_{sat} than the cropping system by 22.9% compared to after tillage the pasture was slower by 33% compared to cropping. There was no significant interaction effect ($P = 0.879$) as the effect of tillage is consistent across land uses.

Table 4-6 Analysis of Variance (ANOVA) of Log10 K_{sat} values for the intact core under constant head method comparing land uses and tillage treatments (d.f = degrees of freedom, m.v = missed values, s.s = sum of squares, m.s = mean squares, v.r = variance ratio, F pr = P value showing significance).

Source of Variation	d.f	s.s	m.s	v.r	F pr.
Tillage	1	2.5637	2.5637	15.42	0.001
Land_use	1	0.7964	0.7964	4.79	0.044
Tillage.Land_use	1	0.0040	0.0040	0.02	0.879
Residual	16	2.6594	0.1662		
Total	19	6.0233			

Chapter 5

Discussion

5.1 Cumulative infiltration – tillage and land use effect

Tillage causes a change in pore characteristics, which has a substantial effect on the infiltration rate through the soil profile. The steady infiltration rate of the cropping system was greater than pasture both before and after tillage. For both land uses the infiltration rate increased as a result of tillage. Lipiec et al. (2006) found that when water was applied on the soil, the fastest infiltration rates occurred after conventional tillage was carried out. This is due to the change in bulk density of the soil. The bulk density of pasture was greater before tillage compared to after tillage. After tillage there was no difference in bulk density between the crop and pasture land use.

5.2 Particle size distribution

The pipette method is the traditional method used to determine the particle size analysis. This method can be time consuming to carry out as one of the samples taken needs to be taken after the soil has been left to settle for 8 hours in solution. On the other hand, the MasterSizer 2000 is the other method that is used to determine particle size. This method is very fast (approximately 10 seconds per sample), but it is questioned to measure accurately as laser diffraction is known to underestimate finer fractions. In addition, this method is not published to determine particle size distribution for the BEST method. Comparison of these two methods has proven no significant difference between K_{sat} values for each land use and tillage treatment. This indicates that the laser method may outperform the traditional pipette method for calculating the shape parameters for the BEST method.

5.3 Methods used to measure saturated hydraulic conductivity – effects of land use and tillage

Saturated hydraulic conductivity is the amount of water that will infiltrate into a certain area of soil per unit time under a unit gradient. It is affected by the presence of connected macro pores which is developed from the biological activity in the soil. Tillage has been seen to disrupt the connectivity of macro-pores, the distribution of pore size is also being altered. Previous studies have found the dynamic changes occur mainly in the larger pore fractions, so the saturated end of the water retention curve is effected more (Strudley et al., 2008). The pore size distribution was not directly measured in this study as the main objective is comparing the saturated hydraulic conductivity.

There was not seen to be any significant difference between methods used in this experiment due to the large variability in trends between methods – two methods showed no difference between land uses, one showed a greater K_{sat} in cropping and the other showed greater K_{sat} in the pasture system. The effect of tillage was also variable – one method showed no difference between tillage, two had a greater K_{sat} after tillage and the last one had a smaller K_{sat} after tillage compared to before tillage. This similar effect has been seen in other studies by Ross and Hughes (1985); Schwartz et al. (2000); Strudley et al. (2008) but they were only using one method to measure K_{sat}.

It is expected that the general trends in soil hydraulic conductivity is initially very pronounced immediately after tillage but the effects will diminish quickly (Strudley et al., 2008). In this study only one measurement after tillage has been carried out so this principle cannot be demonstrated. Generally well-structured soils will drain more freely than a poorly structured soil (Hu et al., 2009). This means that as a result of tillage, it would be expected to have a greater change in K_{sat} in good structured soil i.e. pasture compared to cropping.

Literature has reported various changes in saturated hydraulic conductivity between land uses. Schwartz et al. (2000) investigated the effect of land use on saturated hydraulic conductivity. They found a higher saturated hydraulic conductivity in the pasture than the crop system (422 and 202 mm h^{-1} or Log10 K_{sat} of 2.63 and 2.31 respectively) using a tension infiltrometer. The relative difference between the land use shows a similar result as this study overall (Log 10 K_{sat} 1.330 ± 0.0956 in pasture and 1.275 ± 0.0956 in crop respectively) but opposite to the results when only considering the tension infiltrometer data (pasture = 0.81 ± 0.14 and crop = 1.44 ± 0.23). This is due to differences in the texture of soils measured Hu et al. (2009) also investigated the effect of land use on the saturated hydraulic conductivity but not under traditional pasture and cropping systems, there was no significant difference seen between the land uses.

5.3.1 Saturated methods

Saturated methods used to measure saturated hydraulic conductivity include constant head double ring infiltration and intact cores under constant head in the laboratory. These types of methods are expected to be more suitable when under soils that have good structure. This includes soils that are in a pasture system or before tillage as the structure is expected to better. These types of methods are also ideal, when trying to measure the saturated hydraulic conductivity in a border dyke irrigation system, as the soil is saturated. The percentage of water stable aggregates is expected to be greater in pasture and before tillage compared to cropping and after tillage respectively. Beare et al. (1994) found that the percentage of macro aggregates (>2000 μm) made up the largest proportion of water stable aggregates in the whole soil. There were nearly 1.5 times more in soil that was not tilled compared to conventional tillage. If there is a low proportion of water stable aggregates in a soil the structure will likely collapse when the soil becomes saturated.

Constant head double ring infiltration

Although there was no significant difference seen between the tillage and land use treatments in the constant head double ring infiltration method, there was an interaction effect between land use and tillage. This is due to the K_{sat} decreasing in the pasture system as a result of tillage and increasing in the crop system as a result of tillage. The average K_{sat} reduced by 44.7% in the pasture system as a result of tillage and increased by 48.6% in the cropping system. The initial water content does not have an impact on these results as the method requires the soil to be saturated prior to measurements starting. The difference between land uses may be due to change in physical properties of the soil, such as structure.

Azooz and Arshad (1996) compared the saturated hydraulic conductivity over a two year period under conventional tillage and no till practises in a silt loam soil. The effect of tillage caused a reduction in average K_{sat} by 32.1% in the system that is cultivated annually i.e. a cropping system, compared to this study an increase of 48.6% was seen in the cropping system as a result of tillage. The no tillage system at the same time reduced by 43.6%. In the pasture system in this study, tillage caused a reduction by 43.0%.

Intact core under constant head

Measurements of saturated hydraulic conductivity in intact cores under constant in the laboratory are sensitive to factors including sample size, collection procedures, physical and hydraulic characteristics of the soil. The issue with using cores is that the core may not represent the field site accurately as it is only a small sample. But this method is simple and inexpensive in comparison to other field methods. This method is often used for benchmarking against other methods (Reynolds et al., 2000).

The average K_{sat} that was calculated by Reynolds et al. (2000) using intact core under constant head for Guelph loam (USA), which is a soil with good structure and has similar particle size distribution of the soil in this experiment. In a soil that is tilled annually using intact soil cores the log10 K_{sat} was 1.61 which is the same as this study where the before tillage average log10 K_{sat} was 1.65 ± 0.18 in a system that is not tilled annually the average log10 K_{sat} was 2.09 whereas this study after tillage average log10 K_{sat} was 0.94 ± 0.18. This change between before and after tillage system showed the opposite result to what was seen in this study (an increase of 29.8% in this study compared to 43.0% decrease in the study by Reynolds et al. (2000) and the current study respectively).

5.3.2 Unsaturated methods

These methods are both driven by the initial water content. The initial water content before tillage was 18.5% greater in the pasture system compared to the crop. The BEST method and tension infiltrometer resulted in a greater log10 K_{sat} by 41.7% and 83.9%, cropping and pasture system respectively. As the water is lower after tillage this can lead to an increased K_{sat} calculated. These types of measurements would be suitable to measure the K_{sat} of a soil, that was under spray or drip irrigation. The soil is not always saturated in these types of management systems so, unsaturated methods would be more suitable. If a soil has a weaker soil structure these types of methods may also be more suitable as the soil will likely collapse when saturated so will give different measurements.

BEST method

One replicate resulted in a negative K_{sat} value so had to be removed from the analysis of results. This has occurred in previous studies using the BEST method, which results in the scale parameters not being able to be determined (Lassabatere et al., 2006). The increase in K_{sat} that was calculated after tillage is expected due to the reduced water content after tillage by average of 64.6%. These factors both impact the infiltration rate of the soil, it was much faster after tillage compared to before tillage.

The results of average log10 K_{sat} using the BEST method in a range of soil types result in a range of 1.57 - 2.36. This cannot be directly compared to this study due to these not being in different land uses or a result of tillage. This method has not been used in New Zealand now and is only a relatively new method in general. There is limited data collected around this method.

Tension infiltrometer

The average log10 K_{sat} that was calculated by Reynolds et al. (2000) as the result of annual tillage was 1.75 using a tension infiltrometer compared to this study, the log10 K_{sat} after tillage was 1.41 ± 0.08. In a system where no tillage occurs the average log10 K_{sat} was 2.17 compared to 1.15 ± 0.08 in this study. This changes as a result of tillage is also contradictory to the result of this study. This may be due to the measurements being taken at the same time and the tillage annually or no tillage were under different treatments. In this study the comparative measurements were taken over time in the same location, where the initial water content of the soil varied.

The cost and skill level required to carry out the tension infiltrometer methods is greater than the BEST method. The time taken for each is similar but based on this the variability of the results between studies; the BEST method would be recommended over the tension infiltrometer.

Chapter 6

Conclusions and implications for further research

The objective of this study was to determine the effect of tillage and different land uses on saturated hydraulic conductivity, using four different measurement methods. Out of the four methods – the BEST method and tension infiltrometer both showed an increase in K_{sat} after tillage, intact core under constant head showed a reduction after tillage and no change in the constant head double ring infiltration. Comparison of the land uses also showed a variety of trends between methods – BEST method and constant head double ring infiltration showed no difference between pasture and cropping, tension infiltrometer showed a greater K_{sat} in the cropping system and the intact core under constant head showed a greater K_{sat} in the pasture system.

The trends shown within the saturated and unsaturated methods are consistent, but between the groups there is a large difference. The difference in bulk density, porosity and soils structure before and after tillage has an influence on this as the results, as saturated flow and unsaturated flow in the field vary. The unsaturated methods (the BEST method and tension infiltrometer) resulted in higher K_{sat} in cropping land use and after tillage compared to the saturated methods (constant head double ring infiltration and intact core under constant head) that resulted in higher K_{sat} under pasture system and before tillage. The higher the bulk density of the soil (before tillage or pasture land use), the more appropriate the saturated methods used may be. This shows that the pasture and the before tillage systems are similar in properties and the cropping and after tillage systems are also similar.

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