A comparison of methods assessing soil compaction on black vertosols.
South-Eastern Queensland, Australia

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Abstract

Mechanical soil compaction is a major problem for cotton production on vertosols in Queensland, Australia. To understand the state and impacts of soil compaction reliable measurements are essential. However an overall comparison of measurement methods does not exist for compaction in black vertosols. This research investigates which traditional and innovative methods are the most adequate to measure soil compaction on cotton grown black vertosols. Three methods were tested in the field and lab: ring sampling, the penetrometer and the EM-38. For varying reasons several other methods could not be tested and were evaluated by means of literature research. The methods were assessed on their costs, time efficiency, user-friendliness, and most importantly their reliability and physical limits. Results indicate that there was not one particular method superior to the other methods. As hypothesized, the traditional ring sampling method provided inconsistent data on soil compaction. In contrast, the penetrometer was found to be significantly correlated to the volumetric water content of the soil and proved to be an adequate device to measure soil compaction in dry conditions. Complementing the penetrometer, the shear vane method was found to be a good alternative method for use in wetter conditions. Major advantages of modern techniques over traditional methods, such as the EM38 and Electric Resistivity Tomography (ERT), were that they are non-destructive to the soil and able to detect soil compaction in a wide range of soil moisture contents. However, ERT should be further investigated for specific use on black vertosols. Compared to traditional methods, the use of the EM38 and ERT as a routine operation for farmers is still unlikely due to the higher costs, specialized equipment and need for advanced analysis. Each method has its clear advantages and disadvantages, making not one clearly superior to the others. Thus, the context and purpose in which each method is used should be carefully considered.

Key words: compaction, cotton, vertosol, methods, penetrometer, EM38.
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1: Introduction

According to the Food and Agriculture Organization (FAO, 2009) the global population will continue to grow to 9 billion people in 2050. The large increase in population and changing consumption patterns mean that there will be a higher demand for agricultural products. To be able to feed the world’s population in 2050 food production has to increase with 70% (FAO, 2009). In addition to the population pressure, the changing consumption patterns have a large impact on how the agricultural sector will look like in 2050. Over the past decades trends are an increasing demand for animal products, energy, water and luxury products. This produces extra pressure on the existing natural resources and available arable land (Godfray et al., 2010).

While the area used as arable land is still increasing globally, the area of arable land in Western countries is decreasing (FAO, 2009). As arable land is finite and already limited in Western countries, there is a need to intensify the agricultural production. In the past century the mechanization of agriculture in Western countries has contributed to the increase of agricultural production by enhancing for example the harvest efficiency and soil bed preparation. In addition, mechanization has increased the time and labour efficiency which in turn decreased the need for human labour. This is an important driver for mechanization in wealthy countries, as labour costs are relatively high. However, in some cases mechanization has led to unsustainable and undesirable side effects such as erosion, pollution and particularly soil compaction (FAO, 2013).

Soil compaction is a problem which can be observed worldwide: 68 million hectares of land are estimated to be compacted due to vehicular traffic alone (Hamza and Anderson, 2005). Due to heavy machinery the soil gets compacted and negative effects may occur depending on the local situation. In the cotton industry in Australia this issue can be clearly exemplified: the introduction of the JD7760, a new round bale cotton picker, has provided many benefits for the farmers which often outweigh the disadvantages such as the high purchase costs, need for skilled labour and mechanical issues. These benefits as perceived by the farmers express themselves directly in improved time, labour and energy efficiencies. In addition, personnel safety is considered a major advantage in the case of the JD7760. However, a key issue which is already recognized by the local farmers, agronomists and scientists is the increased soil compaction caused by the new picker.

Soil compaction has visibly negative effects on root growth and cotton production (Bakker and Barker, 1998). In Australia, the decreased agricultural production due to soil compaction has a price tag of approximately AUD $850 million per year (Walsh 2002). Despite the advantages of the new picker, soil compaction is thus a serious side-effect and a form of land degradation of which the effects may take years to fade away. Sub-soil compaction is especially hard to observe from the surface and may
accumulate over subsequent seasons before critical values are reached and the effects can be observed. Increasing the complexity of the issue, soil compaction affects the agricultural system differently over subsequent cropping seasons. This is especially true taking into the account the shrink and swelling features of vertosols, a dominant soil type in Eastern Australia. Continuous technological innovations, changing biophysical conditions and propagation of the effects over time make soil compaction a dynamic research subject (Hamza and Anderson, 2005).

Even though its underlying processes make compaction a complex issue, it is possible to quantify compaction and its effects (Bouma, 2013). Research on soil compaction helps to better understand the relevant processes and to gain knowledge to prevent or overcome compaction or to minimize its effects. Therefore, it is important to measure the extent and severity of soil compaction to assess the impact of changes in the agricultural production system. These measurements also provide practical knowledge and information on the spatial variability of soil compaction in the field. This knowledge supports precision agriculture and can eventually help to create integrated models which can assist the farmer in his or her decision making process.

The objective of the overarching project of which this thesis research forms a part, is to create such an integrated impact assessment framework which can identify latent problems for cotton farming in Australia, such as compaction, while also analysing the socioeconomic impacts of these issues. Consequently, the framework can assist to enhance production in a sustainable way while undesired effects can be revealed prior to the mass adoption of an innovation. Linking to this project, this Master thesis specifically investigated which methods are appropriate to measure soil compaction on cotton cultivated black vertosols in Queensland. Traditional methods which are used by farmers and scientists to measure soil compaction can be time consuming, laborious and expensive (Bennet, 2013). Therefore, this research investigated and compared methods which can detect soil compaction, namely soil ring sampling, the penetrometer, EM38, Ground Penetrating Radar (GPR), Electric Resistivity Tomography (ERT) and various other methods. From this study, the quality of the local compaction research and advice to farmers may improve. In addition, it helps farmers to monitor their own land and interpret the data. These ways farmers benefit from improved information and can act accordingly to enhance their farm management practices and production.

The different methods are reviewed using literature, while the methods ring sampling, penetrometer and EM38 were also tested in the field. The scope of this thesis is outlined by first presenting the problem statement, objectives and research questions. Secondly, the existing theory on soil compaction is reviewed and explored. After discussing the methodology, the paper continues with the results and discussion in which the methods are analysed and compared using the outcomes from field work and literature study. Finally, the conclusions and recommendations are presented.
2: Problem statement and objectives

Mechanical soil compaction is a major problem for cotton production on vertosols in Queensland, Australia. The severity of soil compaction is such that it is considered to be a yield limiting factor (NSW, 1998). Adaptations to the farming system affect the cultivated soil for the worse or the better, and many different measurements are possible to monitor and understand the state and impacts of soil compaction. Consequently, there is a need to measure soil compaction in a reliable, cheap and quick way. Proximal sensing exists since the start of soil science itself, as scientists started to use their own senses to assess the soil by looking, smelling, tasting and rubbing the soil particles between their fingers. These elementary techniques are still used today by soil scientists to get a basic feeling of the nature of the soil. However, these techniques are obviously subjective to interpretation. Also, including the deeper layers of the soil provides a challenge, and in the past the only viable way was to dig out a representative cross section of the soil.

Soil compaction research on the local vertosols has proven to be difficult with traditional methods. The methods which are used to measure soil compaction can be time consuming, laborious and expensive (Bennet, 2013). In addition, the results may not be trustworthy for various reasons. Technologies have advanced to new levels and non-destructive techniques are now able to detect soil properties from the surface. This makes it possible to map spatial variability of soil properties while not disturbing the soil itself (Rossel et al., 2010). These modern methods have as of yet been little used on black vertosols. Therefore, this research investigates which traditional and innovative methods are the most adequate to measure soil compaction on cotton grown black vertosols. To do this, this research compares a variation of methods including soil ring sampling, the penetrometer, EM38, GPR and ERT.

The objective of this thesis is to analyse the flaws and merits of the various methods to measure compaction. By investigating which methods are the most appropriate at the given location and time, reliable data can be acquired which can be used as a sound basis for ensuing research and adding to the existing knowledge of the vertosols in the study area. In addition, the quality of the local compaction research and consequently the advice given to farmers may improve. Ideally, the farmers are also able to use the methods to monitor the compaction on their land. This way the study offers high societal relevance as farmers benefit from improved information and can act accordingly to enhance their farm management practices and production.
3: Research questions

3.1 Main research question

Resulting from the research objective a main research question can be formulated:

Which methods are most appropriate to detect and measure soil compaction on cotton cultivated black vertosols in South-Eastern Queensland, Australia?

3.2 Sub questions

It is important to explore what the underlying causes and effects of soil compaction are to understand the underlying processes. Biophysical conditions (like soil moisture and cracking) and land management (like tillage, growing and harvesting) go through different phases over the year and compaction is affected accordingly. Also, it is necessary to understand the physical properties, such as porosity, which are used as an indicator of soil compaction. In order to compare the different methods it is necessary to make an inventory of the factors that are important for soil compaction research methods, such as the costs and reliability. This results in the following research questions:

1. What are the general causes and effects of soil compaction?
2. How does the yearly variation of biophysical conditions affect soil compaction?
3. How does the yearly management cycle of cotton affect soil compaction?
4. Which physical properties are used as indicator of soil compaction?
5. Which practical issues are the most important for compaction research methods?
6. How do the methods perform compared to each other?
7. How can the differences between the methods be explained?

Questions one to five will be investigated in the chapter ‘Concepts and Theories’ to get a sound understanding of soil compaction in the study area. Question six forms the bulk of the thesis under the chapters 6 and 7. Finally, all the questions are recapped on and discussed in the ‘Discussion and conclusion’.
4: Theories and concepts

In this chapter the concept soil compaction is defined and explained. Relating to this, the terms porosity, bulk density, and soil strength are explained. Furthermore, the causes and effects of soil compaction are discussed; to not only get a basic understanding of soil compaction, but also to give an overview of the factors which can be measured relating to soil compaction. In addition, there is an explanation on the local soil type in the study area in order to fully understand its dynamics. The use and concepts of specific methods are further discussed in the chapters six and seven.

4.1 Soil compaction

Soil compaction is defined in this paper as presented by the Soil Science Society of America (1996): “the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density”. For example, when someone presses loose soil together the soil will be more consolidated (compressed) as the density of the soil is increased by displacing the air (void space) between the grains of the soil. The definition used for soil compaction uses the terms “void space” and “bulk density”. In this research void space will more often be named as porosity. Thus, because of soil compaction the pore volume will decrease, while the bulk density will increase. In addition, the soil strength will increase because of compaction. These terms are visualized in Figure 1. The next section will further elaborate on the terms porosity, bulk density and soil strength.

![Bulk density, porosity and soil strength](image1.png)

Figure 1: The effect of compaction on bulk density, porosity and soil strength (DAF, 2014)
4.2 Porosity, bulk density and soil strength

Figure 1 illustrates how compaction influences soil volume, pore space, bulk density and soil strength. Traditional sampling mostly uses the factors porosity, bulk density and soil strength as an indicator of soil compaction. As these factors play a major role in soil compaction research, this section will go into more detail on their characteristics. Soil compaction transforms macropores to mesopores or micropores reducing the pore volume effectively. The differentiation between macro-, meso- and micropores is characterised by the pore size, even though the exact boundaries are debated within the soil science field. Following Mitchell and Soga (2005) the pore sizes are characterised in Error! Not a valid bookmark self-reference. as follows:

<table>
<thead>
<tr>
<th>Pore Size</th>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;75 μm</td>
<td>Macropores</td>
<td>Gravitational forces, facilitates pore connectivity</td>
</tr>
<tr>
<td>75 μm–30 μm</td>
<td>Mesopores</td>
<td>Capillary forces, water storage available for plant</td>
</tr>
<tr>
<td>&lt;30 μm</td>
<td>Micropores</td>
<td>Adhesion forces, water storage unavailable for plant</td>
</tr>
</tbody>
</table>

The main functions of macropores are the gravitational drainage of water and pore connectivity. If the soil is saturated, all the pores including the macropores are filled with water. In this stage the soil is at its maximum retentive capacity. After a considerable time the soil will not drain any further and all or most of the water in the macropores will have substituted the air (Mitchell and Soga, 2005). At this specific moment the soil is at field capacity. The destruction of macropores (due to compaction) decreases the pore interconnectedness, which causes both mesopores and micropores to be isolated from each other (Vidrih, 1996).

Mesopores could be considered ideal for crops as an increase of mesopores would increase the water availability for root uptake of a plant. The capillary forces in the mesopores between the soil aggregates are stronger than the gravitational (drainage) forces effectively storing the water in the soil. When there is no additional water supply the soil will eventually dry up through plant uptake and evaporation. The moment the water in the mesopores is emptied and the plants start wilting is called the wilting point. The only water left in the soil will be within the micropores, also called hygroscopic water (Mitchell and Soga, 2005).

As the amount of micropores increases, the amount of surface contact of soil particles with soil water increases. On a molecule level the water is attracted due to adhesion forces to the soil particles (Mitchell and Soga, 2005). The ability of the soil to attract and hold water from the environment is called hygroscopy, hence the name hygroscopic water. Hygroscopic water is held so tightly to the soil particles that it cannot be taken up by plants. Still, the water can evaporate. When the soil is excluded from any water supply the soil moisture level is only depended on the air
moisture. At this moment the soil is air-dried and cannot become any drier in a natural way. The soil is at its residual saturation point.

At this point the soil can still be put in an oven at 105 degrees Celsius up to the moment the weight of the soil does not change anymore. The instant the soil sample is taken from the oven it can be described as oven-dried. The weight of the oven dried soil divided by its volume is called the dry bulk density. Note that after the sample is taken from the oven it will take up moisture from the air again, which can be noticed in a matter of days. A summary of the different soil moisture parameters is visualized in Figure 2. It is important to note that the vertosol in the study area features (heavy) clay soils and a porosity which is literally ‘off the charts’ in this Figure, as during this study volumetric water contents were found higher than 50% for vertosols in field conditions.

![Figure 2: Relation soil moisture parameters with texture class (UCF, 2014)](image)

The soil bulk density (BD) is the weight of oven dry soil divided by the total soil volume. The total soil volume is the sum of the volume of soil solids, water and air. The total volume is measured by taking an intact soil sample. The soil is weighed after the soil is oven-dried in order to calculate the BD. Additionally, the soil moisture can be calculated when the soil has been weighed before it went into the oven. Both bulk density and porosity have proven to be a good indicator for the soil structure (McKenzie et al., 2004).

Soil strength, or the soil shear strength, is the ability of the soil to withstand forces (stresses) without structural failure. So in the case of this specific research, it is the ability of the soil to withstand the pressure caused by the wheels and the load from agricultural trafficking before the soil compacts further. According to Defossez and
Richard (2002) soil strength is influenced by soil properties such as texture, organic matter content, the tillage layer state of the soil, soil structure and soil water status. The ability of the soil to withstand compaction is described by soil cohesion and angle of friction. Soil cohesion of sand describes the cementation between sand grains or electric bonding between clay particles. The angle of friction refers to the resistance of soil particles to slide over each other. The round grains of sand are hereby more likely to slide over each other than platy clay particles. The cohesiveness of soil is affected by the soil water status and influences the soil strength. Under very dry conditions soils feature high cohesion and strong bonding between soil particles, which rapidly decreases with increasing soil moisture. This facilitates movement within the soil, making the soil vulnerable to compaction. However, under wet conditions the effects of compaction may decrease as there will be less air filled pores and the mechanical forces will be partly absorbed by the water within the soil. The water content at which most compaction will occur is called the optimum water content or the optimum moisture content.

4.3 Causes and effects

The causes and effects of soil compaction are now explained more broadly in order to better understand the underlying processes. Liepic et al. (2003) provides a scheme which illustrates the effects of soil compaction, as shown in Figure 3. The scheme of Liepic et al. (2003) illustrates how soil compaction affects soil properties, processes, crop yield and the environment. However in order to maintain the simplicity of the overview, many of the intercausal relations are not included.

Figure 3: Scheme of the effects of soil compaction (Liepic et al., 2003)
In general soil compaction is often caused by mechanical trafficking or animal trampling, mechanical traffic being the case in this research. Mechanical trafficking provides a stress to the soil which is influenced by the load, contact area, inflation pressure of the wheels and velocity of the vehicle. The soil strength reflects the ability of the soil to withstand these stresses, influenced by variables such as clay content, organic carbon content, soil water content and soil structure (Defossez and Richard, 2002). When the stress exceeds the soil strength soil compaction will occur. This results in a combination of effects as visualized in the scheme of Liepic et al. (2003), not all of which are necessarily negative. First of all, compaction increases the (mechanical) strength of the soil which improves the ability of the soil to withstand further stresses. In addition, soil compaction may provide a higher surface contact to seeds and moisture which can improve the germination of seeds. Also, a higher surface contact between the roots and soil may result in a higher uptake of nutrients and water. Furthermore, the ability of the soil to hold water may improve and evaporation is reduced.

However, as in the case of the study area, too much compaction is detrimental for the soil and crop. Root growth can be heavily limited by soil compaction, resulting in a decrease of water and nutrient uptake. Compaction decreases infiltration rates and the total capacity of the soil to store water due to the decrease in pore volume, resulting in visible pools of water on the surface. In addition, more contact with water may facilitate water-born plant diseases. Soil life such as worms may not be able to penetrate the soil when it is heavily compacted, while these organisms help to mix organic matter through the soil profile. Low oxygen levels in the soil due to saturation may aid bacteria in the process of denitrification, resulting in nitrogen losses to the atmosphere. In practical terms, a compacted and wet soil reduces the workability of the land leading to clogged tires and increased fuel use (Zwart et al., 2011).

The pore space and distribution in the soil changes the aggregation distribution (Hamza and Anderson, 2005). The pore volume is directly related to the aeration, water holding capacity and the ability for the roots to penetrate the soil. A high pore volume means that there is more aeration and the soil becomes less quickly saturated by water. In addition it is easier for plants to root in soils which are easier to penetrate, i.e. soils which have high pore volume and low soil strength. The relation between pore volume, penetration resistance, soil water content and the crop root ability is illustrated in Figure 4 (Akker, 2010). Under the influence of soil compaction the structure of the soil is severely altered and its effects propagate through the soil properties and ultimately affect crop growth.

![Figure 4: Root ability, pore volume and soil water suction (Akker, 2010)](image-url)
However, the study of Kulkarni (2003) concludes that a decrease of yield cannot be related to compaction alone but that it depends on a large set of parameters such as soil type, irrigation and nutrient management. In addition, compaction and the management cycle have an interconnected relationship which changes over the year due to for example workability, moisture of the soil, irrigation and drainage. Not to mention that every year will be different, as temperature and rainfall will have their effects on the soil moisture (Droogers, 1996). Due to propagation of effects, seasonal changes and alterations to the farm management, soil compaction is a highly dynamic and complex issue. The different conditions mean that some sensors may also be more appropriate than others to measure compaction.

4.4 Black Vertosols

The soils in the study area is dominated by heavy clay soils originating from the basalt geology and flood plains of old rivers. Using the Australian soil classification system these soils are called black vertosols, or vertisols using the Soil classification system of the United States. These are typically clay soils with cracking and shrinking and swelling features. In dry periods the clay soils will shrink, creating the deep cracks which are typical for this soil type. Under wet conditions the clay will swell again to their original state. The shrinking and swelling processes create a surface which is more crumbly and that consists of fine aggregates. Due to this process, the soils are often referred to as self-mulching. Loose particles from the top soil fall into the deep cracks sometimes, effectively mixing the soil layers. As a result the clay soils are fairly deep and have normally a uniform colour and clay content. Below 40cm large diagonal shear planes, called slickensides may be present (NSW, 1998). Figure 5 shows a clear example of a cotton cultivated vertosol with cracks at the surface going into the subsoil.

The colour of vertosols may differ according to the capacity of the soil to drain water. Most common in the study area are sites with a lot of rainfall up to 1150 mm/year and restricted drainage which result in an often black colour, while well drained soils with rainfall up to 900 mm/year may look more red (Gray and Murphy, 2002). Vertosols often are alkaline and calcareous (NSW, 1998). The soils have a high chemical fertility and a high water holding capacity which offers a lot of potential for agriculture.
However, despite the high water holding capacity, water is not readily available for the crop as the micropores between the clay particles hold the hygroscopic water within the soil. Therefore, soil moisture content should be relatively high to stay above wilting point. Thus, in order to grow crops either a large amount of rain or supplementary irrigation is needed. In addition, plastic clays in wet conditions can be hard to cultivate upon as there is higher risk for compaction (Gray and Murphy, 2002). Compaction of the surface occurs, but the topsoil can recover itself over the year from surface compaction due to the characteristic self-mulching function of the soil which is caused by shrinking and swelling processes. The layering feature of clay, large diagonal shear planes in combination with stress caused by the machinery may cause sub soil compaction in these soils, especially under wet conditions which can occur due to the high water holding capacity of the soil.

Ring sampling of the bulk density and water contents at the study area provided basic information. Figure 6 shows the cumulative proportions of soil water and air. These proportions were calculated using the average of four samples from the surface of a black vertosol, assuming a specific gravity of 2.75 for the solids of the clayey soil. Normally, clayey soils should have a specific gravity between 2.7 and 2.8. Figure 6 clearly shows the large amount of water which can be stored in the soil, even though this water is not fully available for the plant. The description for black vertosols of McKenzie et al. (2004) shows similar proportions of the volume of air, water and soil solids, with a slightly higher volume of soil solids deeper in the soil.

As the topsoil can recover itself from surface compaction due to self-mulching, particularly sub-soil compaction is a cause for concern. As there are no clear horizons in the cultivated vertosols, there is a need to define where and what the subsoil exactly is, for which Van den Akker (2010) offers a rather simple representation. The topsoil is defined as the depth from the surface to the plough pan, which in the case of our study area would be up to 40cm deep. The subsoil could be defined as the layer under the plough pan. SOILpak For Cotton Growers (NSW, 1998) defines the following depths for each layer:
- topsoil: Soil between the depths 0–10 cm.
- sub-surface soil: Soil between the depths 10–30 cm.
- subsoil: Soil between the depths 30–120 cm.
  - subdivided into Upper subsoil (30–60 cm),
  - Mid subsoil (60–90 cm)
  - Lower subsoil (90–120 cm).

This research will use the description and definitions for the soil layers as used by SOILpak for Cotton Growers, as the self-mulching layer of the vertosol at the top layer is well represented by the definitions as used by SOILpak For Cotton Growers. However, due to the limitations of the methods used the lower subsoil will extend to 150 cm. It should be noted that the subsoil is fairly uniform in terms of texture and chemical properties.
5. Research Methodology

5.1 Study area

The study area selected for this research is located on a farm situated near the villages Macalister and Jimbour, -26° 58' 33.91"S, +151° 7' 47.65"E. These towns are located in the region of Darling Downs and a two hour drive from Toowoomba. This area was selected as the farmer was growing cotton on a vertosol and willing to cooperate, while the area was relatively close by Toowoomba. The mechanical trafficking on this specific farm is highly controlled. Noteworthy, this expressed itself in the modifications the farmer made to his cotton picker JD7760 in order to practice controlled traffic. This is very unusual for a cotton farmer to do, as the modifications forfeit the warranty on the JD7760. For this research it offered a perfect opportunity to measure the differences in compaction levels between permanent traffic lanes versus non trafficked lanes. For comparison and verification of the results, two “sub-sites” were selected in the study area which will be referred to as “site 1” and “site 2”. Both sites are located along Kents road but on different agricultural fields as shown in Figure 7.

Figure 7: Study sites 1 and 2 (Google maps, 2014)
The soil of the agricultural fields in the study area is characterized by black vertosol, a heavy clay soil with crack and swell features as described in section 4.4. The land is rain fed and grown with cotton in rotation with sorghum or barley depending on the available soil water. In dry conditions the soil is left bare so that water can accumulate in the soil rather than be taken up by a crop. In extreme conditions, when a failed harvest is unavoidable, standing crops are killed to save soil water. Site 1 of the study area was left bare for over a year. Site 2 was also bare, but with recent stubble of presumably barley, used as soil cover. The sites were purposely chosen to be bare for practical reasons such as accessibility and minimization of possible crop damage. Also, these sites would only be disturbed by minimal farm management practices during the time of the research.

Annual climate statistics from the closest weather station are provided in Figure 8. While typically most rainfall in Queensland is in the Australian summer months from November to January, this year (2014) severe droughts occurred. On the first of March 2014 around 80% of Queensland was declared to be in drought, and it was consequently recorded to be the most extensive drought ever recorded in Queensland. The drought was specifically troubling for the cotton farmers, as most cotton fields are not irrigated. However, after the summer an uncharacteristic major rainfall event occurred in Queensland. This particular rainfall event recorded 99.4 mm within 24 hours on the 28th of March in Darling Downs, while the three days previous to the rainfall event recorded a cumulative rainfall of 62.4 mm (Weatherzone, 2014). Compared with the monthly rainfall in March in Figure 8, the rainfall amount of this event alone was more than twice (!) the monthly rainfall. Because of this rainfall event the soil went from relative dry conditions to beyond field capacity even flooding particular areas outside of the study area during a few days. As will be explained in section 5.3, this major event also impacted the experimental design of the research.

![Figure 8: Monthly climate data for Dalby (Weatherzone, 2014)](image-url)
5.2 Indicators

Before discussing the different methods to measure soil compaction it is important to set certain indicators that define what an ‘appropriate’ method is. According to Adamchuck and Viscarra (2010) a perfect soil sensor should be cheap, simple and time-efficient. In addition it should work in a wide range of conditions while providing reliable results. Based on these general attributes, a list of five criteria has been developed for this research. Each criterion was divided in sub-criteria which were used for guidance for the evaluation of the methods. It should be noted that this study will mostly look at methods usable at the field scale.

1. **Financial Costs**: The overall financial costs of the sampling methods should be cost effective. The costs of using the device should be in proportion to the other criteria such as reliability and user friendliness. The financial costs can be divided in purchase costs, operational costs and costs for analysing the data. These include the use of additional instruments, lab operation costs, etcetera. It should be noted that the (economical) lifetime of a technological device and the costs for repairing the device are not included.

2. **Time Efficiency**: The time costs of a method should be low and relate to the areal coverage. This enables to make more measurements and cover a larger area, but also minimizes the financial labour costs. In addition, the spatial resolution is related to the time efficiency, as more measurements are needed for better resolutions. The preparation and the analysis of the results also cost time. This category is subdivided in the calibration time, covered area per time, and the analysis time.

3. **User friendliness**: Ideally, the method should be easy to understand, have a small learning process and have an easy procedure in order that as few mistakes are made as possible. This makes it possible for the methods to be operated by multiple users, for example both scientists and farmers. In addition, the method should be easy to use in the field in terms of the strain to the body. Concluding, a method should be accessible and easy to understand, master, and use.

4. **Reliability**: Obviously, the main purpose of the method is to provide good results which can be reliably used for research. The results should be close to the true values (accurate) and have little variation between its measurements (precise). Relating to this, ideally the sensor measures a single soil attribute which is directly related to soil compaction. However, it should be noted that this is in reality almost never the case and separation of the influences of each soil attribute is demanding or even unfeasible. Also the spatial resolution and scale are important factors, as high spatial resolution helps to measure and explain differences within the field, even though it also affects the scale and areal coverage. Relating to this, the method should be able to differentiate between compacted and non-compacted soil.
5. **Limits**: Finally, the limits for each method should be investigated. In order to measure over the whole year and for a wide range of biophysical conditions, the method should be very versatile. This study specifically looks at the range of soil water contents in which a method works, as these vary a lot over the year for black vertosols. Relating to this, the method should work in every season. In addition, it should be able to measure the values for little compaction to extreme compaction, and be able to measure over depth.

5.3 **Assessment**

This section discusses how the different methods were assessed, while a detailed methodology for the soil coring and ring sampling, penetrometer and the EM38, and their results, are presented in sections 6.1, 6.2 and 6.3, respectively. It was this research’s aim to test four different methods in the field, including the electric resistivity tomography (ERT) method. However, this proved not possible as the instruments still had to be sent from Canada to Australia by the time of the field work. Hence two methods were tested in the field and one in the lab. For the remaining methods a literature study was done to examine the suitability of the methods to black vertosols. Using existing literature the selected methods were evaluated based on the selected criteria defined in section 5.2. Table 2 provides a quick overview of the methods and how they were assessed.

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Method(s)</th>
<th>Assessment</th>
<th>Reason not field tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Soil coring and ring sampling</td>
<td>Field</td>
<td>-</td>
</tr>
<tr>
<td>6.2</td>
<td>Penetrometer</td>
<td>Lab</td>
<td>Field conditions too wet</td>
</tr>
<tr>
<td>6.3</td>
<td>EM-38</td>
<td>Field</td>
<td>-</td>
</tr>
<tr>
<td>6.4</td>
<td>Electric Resistivity Tomography (ERT)</td>
<td>Literature research</td>
<td>Not available (at the time)</td>
</tr>
<tr>
<td>6.5</td>
<td>Ground penetrating Radar (GPR)</td>
<td>Literature research</td>
<td>Not available</td>
</tr>
<tr>
<td>6.6</td>
<td>Thermal methods</td>
<td>Literature research</td>
<td>Not available</td>
</tr>
<tr>
<td>6.7</td>
<td>Other alternatives</td>
<td>Literature research</td>
<td>Various, mainly restricted by availability and time limitations</td>
</tr>
</tbody>
</table>

The initial plan was basically to select random points within a plot where measurements would be made using each method. Unfortunately, due to the wet field conditions it was not feasible to use the penetrometer. Field work was always executed in dry weather and in daylight due to safety reasons, as the EM38 works as a large lightning rod in case of thunderstorms.
6. Methods tested in the field

This chapter will test the application of three methods for measuring soil compaction on vertosols. In addition, these methods will be discussed using several indicators, such as the costs, time consumption, user friendliness, reliability and the limits of the method. The three methods which will be discussed are consecutively ring sampling and coring (6.1), penetrometer (6.2) and the EM-38 (6.3). Other methods which were reviewed with literature but not tested in the field are discussed in chapter 7.

6.1 Ring sampling and soil coring

This section discusses the more traditional method for measuring soil compaction, which is taking soil samples with (a) small rings, (b) large rings and (c) soil coring. These basic methods are normally used to measure bulk density, volumetric water content and/or gravimetric water content for a specific point. First the general concepts and use of the methods are introduced. After this, results of the fieldwork are presented and finally discussed using the guidelines provided in section 5.2.

General concepts and methodology of ring samples and soil coring

The dry bulk density is probably the most widely used guide for measuring soil compaction. The methods used in this section specifically measure the dry bulk density of a sample, in addition to the water content. Especially ring sampling is a popular choice for standard soil research due to its simplicity. Basically, a metal ring is inserted into the soil. This metal ring is carefully taken out with its contents (the soil) and sealed to ensure that there are no water losses and to keep the soil sample intact. Due to time limitations this research focused on taking samples on just a few locations, but in depth. In addition, to verify the ability to measure differences between compacted and uncompacted soil the points were located on both permanent traffic lanes and normal rows. Before the samples were taken, the electric conductivity (EC) was measured with the EM-38 so that the results of the EM38 and the soil coring and ring sampling could be correlated. The EM38 is a non-destructive technique, contrary to soil coring and ring sampling, and thus did not influence the results of the soil coring and ring sampling. In the laboratory the ring and soil inside are weighed and put in an oven at 105 degrees Celcius for 48 hours to evaporate all the soil water. The rings and dry oven weight of the soil are weighed again in order to calculate the bulk density, gravimetric water content and volumetric water content of the soil (eqs. 1, 2, 3).

\[
BD = \frac{\text{Weight of dry soil}}{\text{Volume of ring}}
\]

\[
SM_g = \frac{\text{Weight of water}}{\text{Weight of dry soil}} \ast 100\%
\]

\[
SM_{vol} = SM_g \ast BD
\]
Where BD = Bulk Density in g/cm$^3$, SMg = gravimetric Soil Moisture in percentages and SMvol = volumetric Soil Moisture in percentages. It should be noted that for the bulk density the weight of the rings needs to be taken into account. The weight of the water is calculated by subtracting the weight of oven dry soil sample from the wet weight of the soil sample.

The rig uses a motor to press a metal pipe into the soil (Figure 9). The soil in the pipe is pressed out, and the length of the samples is measured to know the soil depth at which it is taken. This way the use of the rig circumvents the need to dig pits. After each sample is sealed and tagged with a label the same procedure applies as for the soil rings. As the rig saved the effort and time of digging pits, it was used whenever it was available. The rig was used three times, but only provided usable data once. When the rig was not available, the rings were used to measure the soil compaction.

The small rings were 4.7 cm in diameter and 5.5 cm in length. The large rings were homemade and therefore varied slightly in diameter and length, all being around 7.3cm in diameter and 10.4cm in length. In the case of the small ring methods (a) pits were dug up to 75cm by hand in order to get samples at depth. As the availability of the small standardized rings was limited, larger, handmade, rings were used at the upper subsoil (between 30-60cm depth) to at least have an estimation of the dry bulk density. In these cases the gravimetric water content was still measured over depth, by bagging small samples of soil each 10 cm up to a depth of 75 centimetres.

The maximum bulk density of a soil is different for each soil type. Therefore, compaction characterized by bulk density should be seen relative to the maximum bulk density of that specific soil type. Using the ASTM D698 methodology for the proctor test, the maximum bulk density and the optimal water content for soil compaction of the vertosol in the study area was estimated. In the proctor test, soil is compacted in a known volume at an estimated soil moisture content. The weight is measured, and the gravimetric water content is confirmed by taking and analysing representative samples from the soil. The bulk density and water content are calculated using equations 1, 2 and 3.
Results

First the results of the proctor test are presented in order that the results of the rig, small rings and large rings method can be associated to the maximum bulk density. As visualized by Figure 10, most compaction takes place at gravimetric soil moisture content around 30%, compacting the soil up to a dry bulk density of 1.44 g/cm³. This bulk density is considered to be the maximum of how compacted this specific soil can get. The blue lines indicate where there should be no more air in the soil assuming a specific gravity of 2.6, 2.7 or 2.8.

![Figure 10: Results of Proctor test](image)

The results are presented for the rig in Figure 11, the small rings in Figure 12 and the large rings in Table 3. As there were only a few large rings available it was not possible to do the measurements over depth for these points.
Figure 11: Bulk density plotted against depth; results from rig measurement. Study site 1. N=36.

Figure 12: Bulk density plotted against depth; results from sampling with the small rings. Study site 1 (line 1 and 2) and site 2 (line 3 and 4). N=26.
In Figure 11 it can be seen that the bulk density varies mostly from 1.3 to 1.4 g/cm³, which is close to the maximum bulk density as measured in the proctor test (see section 4.4: vertosols). This might mean that the soil has been compacted by the rig itself, as the rings provide lower bulk densities, suggesting that the results from the rig are unreliable and can not be used. Samples 1a and 1b, taken on the same wheel track, vary from each other but show a similar profile. However, there is no clear difference between trafficked (compacted) and non trafficked (uncompacted) rows. For the small and large rings however, there is a difference showing that trafficked rows have a higher bulk density. However, there is quite a variation through the soil profile for the small rings, while not enough samples have been taken with the large rings to draw any more conclusions. The variation of the soil samples may have different causes, such as cracks in the soil. Also, compaction may have occurred when taking the soil samples, as in a few cases the metal rings had to be slammed into the surface in order to penetrate the plastic clay. In addition, in most cases the rings did not have a flat bottom and top surface. To compensate this, the extra volume at the top surface was measured with the addition of dry sand. Before putting the samples in the oven, a sample was weighed. The extra volume was covered with extra sand to make a smooth surface and the sample weighed again. Before this, the sand weight per volume was measured. Although this made it possible to calculate the extra volume at the top surface of the ring, the bottom surface was not accounted for.

<table>
<thead>
<tr>
<th>Field</th>
<th>Wheeltrack</th>
<th>Depth (cm)</th>
<th>BD (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>25-35</td>
<td>1.12</td>
</tr>
<tr>
<td>1</td>
<td>Yes</td>
<td>25-35</td>
<td>1.18</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>25-35</td>
<td>1.01</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>25-35</td>
<td>1.18</td>
</tr>
<tr>
<td>3*</td>
<td>No</td>
<td>10-20</td>
<td>1.23</td>
</tr>
<tr>
<td>3*</td>
<td>No</td>
<td>30-40</td>
<td>1.21</td>
</tr>
<tr>
<td>3*</td>
<td>Yes</td>
<td>10-20</td>
<td>1.23</td>
</tr>
<tr>
<td>3*</td>
<td>Yes</td>
<td>30-40</td>
<td>1.30</td>
</tr>
</tbody>
</table>

* : Located on a field of a neighbour of J. Grant (also vertosol)
Discussion
This simple method is fairly cheap, consisting mainly of the purchase costs of the rings or soil coring rig. Energy costs could be considered such as fuel for the rig and electricity for the oven. However, the main cost is probably the man labour involved in this method. Most of the time is consumed by the field work itself. Especially the digging of pits for the rings is time consuming and a strain for the body. Due to this, soil sampling with rings is more feasible for taking measurements at the surface. Alternatively, the soil coring rig is easier and faster as pits are not needed. Still, in the case of vertosols it is a slow process as the wetness and plasticity of the clay result in the need to take samples in small increments to make it possible to retrieve the soil from the pipe. In addition, when large increments are taken the soil could be extra compacted by the pressure of the machine and the soil already in the pipe. Due to this, some experience with the rig is necessary to use it effectively.

Even though the simplicity of takings soil samples with rings makes it possible to be done by anyone, experience still helps to choose representative samples and ensuring flat surfaces at the bottom and top of the rings. The method involving the rig involves some tricks, mainly the use of small increments but also the help of tools such as paperclips and lubricant. While paperclips ensure that the soil sample does not fall out immediately when lifting the rig, the lubricant helps to push the soil out (using a stick). The lubrication and the appliance of a paperclip should be repeated for every increment.

The size of an increment varied during the field work between 10 to 30 centimetres, depending on the plasticity of the soil. Even so, under wet field conditions it might turn out to be impossible to remove the increment gently if the clay is too plastic. In between increments it should be noted that loose soil from the surface can fall down in the gap, which should be removed and not taken into account for the measurements. The length of the increment is noted down, which makes it possible to calculate the volume and ultimately bulk density of the soil using the known internal diameter of the pipe. The spatial resolution and scale depend largely on the number of point measurements. Because of this, the scale can vary from square metres to hectares depending on the number of measurements and chosen resolution.

All in all, it can be concluded that ring sampling and soil coring are cheap, but time consuming and provide varying results, influencing negatively the reliability of the measurements. The effective depth is limited to the depth of the pit, or to the length of the pipe in the case of the rig. In very wet conditions compaction by hand or rig may influence the measurements and it may not be possible to use the rig at all if the soil will stick in the pipe. Under very dry conditions, the cracking of the soil makes it harder to get a representative soil sample. However, when using the rings it is possible to see differences in bulk density between wheel tracks and non trafficked rows to some extent.
6.2 Penetrometer

This section discusses the use of the penetrometer in compaction research. First, literature is used to explain the concepts and use of the penetrometer. In the second part the penetrometer experiment performed during this research is discussed. The penetrometer is a classical method to indicate soil compaction in an easy way at field scale. This method is widely used among soil researchers and farmers, as it is relatively easy to use, cheap and easy to transport. A penetrometer is basically a shaft with a cone tip which is driven in the soil by the operator or a hydraulic system. A force sensor in the cone tip measures the resistance of the soil to the applied force, called the penetration resistance.

General concepts and methodology of the penetrometer

The penetration resistance is defined as "the penetration force divided by a standard cone base area during the penetration of the soil with a standard soil cone penetrometer at a constant penetration rate" (Tekin et al., 2008). A low penetration resistance of the soil makes it easier for the roots of a plant to penetrate and develop through the soil. Logically, smaller cone sizes provide a better representation of roots. In addition, smaller cones are related to intra-aggregate strength, while larger cones are related to inter-aggregate strength (Lowery and Morrison, 2002). The penetration resistance depends on the size, shape of the cone, and the penetration rate of the penetrometer (Perfect et al., 1990). Beside this, the penetration resistance is influenced by the soil strength. The soil strength is the ability to withstand stresses from the surface, for example the stresses generated by heavy machinery (Defossez and Richard, 2002). While there are several variables which influence soil strength, soil water content is considered the most important. Soil strength is reduced in a non-linear way with increased soil moisture up to field capacity of the soil. Thus soil strength and penetration resistance are strongly influenced by soil moisture levels of the soil (Tekin et al., 2008). Consequently, the outcomes of the measurements have to be calibrated to the characteristics of the device, and the soil moisture and the bulk density of the soil. Calibration to these factors in the lab can be labour intensive, but if this is not done the measurements should be treated as comparative to themselves. In other words, the measurements would give an estimate of the penetration resistance, but little knowledge is acquired whether this is due to bulk density or soil moisture levels. In addition, both spatial and temporal variation of soil moisture and bulk density may give a distorted view making correct interpretation of the results difficult.

In the case of vertosols, it has been recommended to use the penetrometer below the plastic limit of the soil (McKenzie, 2001). The plastic limit is the moment when the soil is moist enough to go from a semisolid to plastic state. One can determine if the soil has reached the plastic state by rolling soil in the hand; when the soil crumbles the soil moisture levels are still below the plastic limit. If the soil does not crumble it is in the plastic state. This method is normally used by farmers to quickly identify when the
soil is too wet to work on. Coughlan and Mckenzie (2002) suggest that the plastic limit of vertosols is only just above permanent wilting point. Work of McKenzie and McBratney (2001) suggest a value of 0.28 g/g for grey vertosols. Weaver and Hulugalle (2007) measured a range between 0.15g/g to 0.30g/g for vertosols using the traditional thread method, with the plastic limit increasing with clay content. This seems to match with the optimal gravimetric water content for maximum compaction found using the proctor test, which was around 30%. In wetter conditions the soil around the cone of the penetrometer clogs up influencing the measurements severely (McKenzie and McBratney, 2001). McKenzie and McBratney (2001) discuss that a rotating tip and a sharper point may mitigate this effect.

According to the definition of penetration resistance, the penetrometer should be operated with a constant penetration rate. In practice, it is very difficult to maintain a constant velocity with a hand driven penetrometer (Tekin et al., 2008). Soil layers and air gaps may force the operator to use more force or suddenly slide through an air gap, the latter certainly being the case in dry vertosols. Different operators would also increase the variability between measurements. Therefore, often hydraulically driven penetrometers are used to ensure that the penetrometer is driven into the soil with a constant penetration rate. These devices are more expensive and less accessible, but the amount of labour is decreased while the accuracy of the measurements is improved (Tekin et al., 2008). Measurements are normally recorded electronically. Statistical methods can be used to interpolate the data and create 3D maps of the soil combined with GPS data. To produce reliable 3D maps it is important to collect a large number of data points with high accuracy. This can however cost a lot of time and effort (Tekin et al., 2008). Especially in loose soils there may be more spatial variation, which stresses the importance of taking many measurements and replications.

Penetrometers which are designed to drive the penetrometer into the soil with a constant velocity are called static cone penetrometers. Alternatively, dynamic cone penetrometers can be used. Dynamic cone penetrometers drop weights from a known height to measure the penetration resistance to a known energy force. For every method it is important that the device is driven into the soil vertically, therefore a machine driven penetrometer often use stands to ensure that there is no angle. The depth to which measurements can be taken is the effective length of the rod. However, depth may be further limited when there are layers at which the penetration resistance is so high that either not enough force can be produced to drive the penetrometer further or the rod may bend under the force. In the latter situation the measurement should be stopped to prevent the rod from breaking.
Due to the unexpected rainfall in March it was not possible to use the penetrometer in the field. Therefore, measurements were taken in a controlled situation in the lab. Soil of vertosol was collected from the field and brought to the lab where it was air dried, crushed and sieved with a 4.7mm sieve over a period of months. Ultimately, around 100kg of sieved soil was redistributed over seven cylinders of 10 Litres each. Beforehand, the soil was wetted and mixed with a known volume of water to reach the target water content. The soil was stored in a dark environment in sealed plastic bags for two weeks so that the water was distributed equally over the volume of soil. After this, the seven cylinders of 10 Litres each were filled with the pre-wetted soil and compacted to a layer of 5cm depth with a hammer as used in the standard proctor test. Following this procedure multiple layers were made of 5cm, with a known bulk density and water content, up to the moment the cylinder was completely full. This procedure is illustrated in Figure 13. As this process took several days, the cylinders were wrapped up in plastic to prevent evaporation losses. Using this procedure, the tubes were compacted and wetted as uniformly as possible to the values as provided in Table 4.

**Table 4: The bulk density and gravimetric soil moisture content for each cylinder**

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>BD</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>SMg</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>20%</td>
<td>25%</td>
<td>30%</td>
<td>30%</td>
</tr>
</tbody>
</table>

Using a motorized penetrometer with a constant velocity, each cylinder was inserted with the rod three times for replication, with the exception of cylinder 1 which had four insertions. The motorized penetrometer was placed on top of a small platform as shown in Figure 14. As the tip had to go through several centimetres of air, the electronic computer had to be slightly calibrated. The cone tip had a size of 100mm, which was the smallest available. Experimentation with larger tips created too much resistance, due to which the electronic computer was unable to record the measurements. The experiment resulted in 22 insertion with each insertion recorded the penetration resistance 21 times (interval 1cm).

Figure 13: The soil is in the process of being compacted in the cylinder. The space between two black lines is an increment of 5cm.

Figure 14: The penetrometer is put on a platform. One of the cylinders stands ready.
**Results**
The raw data of the experiment can be found in appendix A. The average of the penetration resistance for each insertion was calculated and plotted against bulk density, gravimetric soil moisture and volumetric soil moisture as presented in Figure 15. The averages were calculated after the removal of the first two intervals of the first 10 insertions, as these were substantially lower than the other measurements. From the graphs it can be seen that the penetration resistance (PR) is more related to the gravimetric soil moisture than to the bulk density of the soil. However, visually, the penetration resistance is related most closely to the volumetric water content, which can be calculated as the product of bulk density and gravimetric soil moisture, as:

\[ SM_{vol} = SM_{g} \times BD \]

![Graphs showing BD vs PR, SMg vs PR, SMvol vs PR](image)

Figure 15: The penetration resistance in kPa plotted against respectively BD (A), SMg (B) and SMvol (C)

The values obtained from the Pearson correlation of bulk density, gravimetric soil moisture content, and volumetric soil moisture content versus the PR are -0.269, -0.924 and -0.854 respectively. The lower value for volumetric soil moisture reflects the hyperbolic trend with PR, as the PR increases again around a SMvol of 40%. This results in a lower value, as the Pearson correlation is limited to linear trends. The removal of cylinder seven (BD=1.4) from the data results in a more linear relation and higher correlation values as presented in Table 5.
The upward trend at the end of the graph of the volumetric soil moisture versus PR, can be explained by the clogging of soil around the cone tip as illustrated in Figure 16. From the raw data in Appendix A can be retrieved that there is increasingly more variation with depth in PR between the three insertions. This results in higher values for the PR for the insertions in cylinder 7. This confirms the hypothesis that the results of the penetrometer are only reliable for vertosols with very low soil moisture contents, well below the wilting point of plants.

Discussion

Especially the operational and analysis costs of the penetrometer are fairly low. The purchase costs vary with the configuration, as a motorized or hydraulically driven penetrometer is more expensive but provides more reliable data. With some instruction, the method is easy to use and one can make many point measurements in limited time. However, the relation between bulk density and the penetration resistance is empirical and dependent on the soil moisture content in the soil. As done in this research, the empirical relation can be established in the lab. Still, field conditions are different from the lab, as for example in the field cracks in the soil will make it more difficult to get representative samples. This could be compensated for to some extent by making multiple insertions. The reliability of the results decreases rapidly with volumetric soil moisture contents above 35-40%. A rotating tip and a sharper point may increase the range for which the penetrometer can be used, as there would be less clogging (McKenzie and McBratney, 2001). In wet conditions it might also be harder to access the fields due to accumulation of soil around the wheels of the specific penetrometer used in this research, even though common penetrometers are hand driven.
6.3 EM38 Ground Conductivity Meter

In this section the method of the EM38 ground conductivity meter is described using literature, followed by the description and results from the field experiences. It should be noted that there are several types of the EM38 device. Even though the basic concepts for each type of EM38 are similar, the exact ‘how to’ will differ as certain aspects like the calibration procedures may differ between types. In this study, the EM38-MK2 was used for field measurements. The EM38-MK2 has two receiving coils rather than the standard one receiving coil, which makes it possible to measure over two different depths at the same time. This section first explains how an EM38 device works in general. After this, the experimental design is presented and the results are discussed.

General concepts and methodology of the EM38
The EM38 is a device which uses electromagnetic waves and reads the ability of the waves to propagate through the soil. This ability is called the electric conductivity (EC) of the soil. More specifically the EM38 actually gives readings for the apparent electric conductivity (ECa), a weighted average of EC over a certain depth range and volume (Foley, 2014). The ECa of a soil depends on a range of variables, including soil salinity, clay content, clay mineralogy, organic matter content, cation exchange capacity, pore size and distribution, bulk density, soil moisture and temperature (Corwin and Lesch, 2005). While EC has been used initially to assess soil salinity, it is now also used for a range of agronomic purposes as diverse as the variables which are depended on ECa. The variables are categorized according to the research’ purposes (Corwin and Lesch, 2005):

1. soil salinity, clay content, clay mineralogy, organic matter, cation exchange capacity
2. pore size and distribution, bulk density
3. soil moisture, temperature

The vertosol in the study area can be considered homogeneous except for the porosity due to cracking under dry conditions. The variables under (1) will therefore have fairly little influence on the results of the EM38. The variables under (2) are indicators of soil compaction. This leaves the variables under (3) as the variables which should be taken into account when we want to measure the differences under (2). For the purpose of this thesis, the seasonal differences for the soil and air temperature are not accounted for. Robinson (2004) shows in his paper that the air temperature affect the EM38 readings above 40 degrees Celsius, as the readings will deviate up to 20% from the readings made under air temperature less than 40 degrees Celsius. The extent to which the readings of the EM38 deviate is different for each device. This effect should thus be considered on hot days. However, it was not taken into account as the readings in this research have been made under air temperatures below 40 degrees Celsius. Therefore, soil moisture will be the main variable we will be looking at in the experimental design.
Electrical currents flow through the soil over three possible pathways as visualized in Figure 17 (Corwin and Lesch, 2005):

A) The solid soil aggregates  
B) The water retained in the soil  
C) A combination of (A) and (B).

The air has an infinite resistance, which results in the fact that there is no EC through air and thus it is not considered a pathway. A dry soil will therefore have low electric conductivity as there is a relative high volume of air. Consequently the electromagnetic waves can only propagate through the solid soil and the water which is attached to the soil particles by adhesion forces.

An EM38 has generally one transmitting coil with an alternating current, which sends electromagnetic waves through the soil and induces a magnetic field (Figure 18). From the alternating current from a transmitter coil at Tx a primary magnetic field (Hp) is induced. The magnetic field may create new currents in the soil called Eddy currents, in turn creating a second magnetic field. The receiver coil (Rx) thus measures the results of the primary and second magnetic fields. This effect can also be seen in Figure 19. In Figure 19A the primary magnetic field is created by the transmitter. Eddy currents are induced in the conducting medium (in the case of Figure 19 a body of ore) which creates a secondary magnetic field as shown in Figure 19B. The receiver measures the ratio between the magnetic fields, which is expressed as apparent electric conductivity (ECa) in mS/m using equation 5 (Guo et al., 2008):

\[
EC_a = \frac{4}{2\pi \times f \times \mu \times \tau^2} \times \frac{H_s}{H_p}
\]
Where $EC_a$ is the apparent electric conductivity, $2n*f$ is the angular frequency, $\mu_0$ the magnetic permeability of free space, $r$ the spacing between the coils and $H_s/H_p$ the ratio between the secondary magnetic field and primary magnetic field (Guo et al., 2008).

As shown in equation 5, the readings for $EC_a$ are depended on the spacing $r$ between the coils. The EM-MK2 has two receiving coils rather than one, subsequently the device provides two readings at the same time for two specific depths. In addition, an EM38 device can be put in two different positions which have different response functions: the horizontal dipole position and the vertical dipole position. In Figure 18 the device is in the vertical dipole position. When the device is turned flat on its side it is in its horizontal dipole position. The response of the readings of the horizontal dipole position is more affected by the surface EC, while in the vertical dipole position the EM38 can measure over larger depth. Effectively, when put to the surface the EM-MK2 can deliver four readings as provided in Table 6. In literature it is usually assumed that the H0.5, H1.0, V0.5 and V1.0 positions are limited to respectively 0.375, 0.75, 0.75 and 1.5 meter depths. The EM38 can be lifted from the ground to measure at other depths. For example, when lifted 20 cm off the ground in vertical dipole position it measures at 0.55 m (0.75-0.20) and 1.30 m (1.50-0.20) depths. This makes it possible to have more increments over depth, though it has to be made sure that the lifted height is constant.

Table 6: effective depth of the EM38-MK2 for different positions

<table>
<thead>
<tr>
<th>Position</th>
<th>Depth at $r = 0.5$ m</th>
<th>Depth at $r = 0.5$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal dipole</td>
<td>0.375 m</td>
<td>0.750 m</td>
</tr>
<tr>
<td>Vertical dipole</td>
<td>0.750 m</td>
<td>1.500 m</td>
</tr>
</tbody>
</table>

Figure 19: Eddy currents, adapted after terraGIS (2014)
For the calibration procedure the EM38 also has to be lifted at or above its maximum effective depth (1.50 m). First the EM38 has to acclimatize to the air temperature for about 15 minutes. After this the EM38 has to be calibrated to read 0 mS/m at both the vertical and horizontal position at a height above 1.50 metres. It is important that during calibration and during the actual fieldwork there are no metallic objects in the vicinity such as watches, belts, mobile phones and laptops which may interfere with the readings. The high sensitivity of the device to metals makes it difficult or even impossible to get reliable data (for agricultural purposes) on ferric soils or other soils with high contents of metals. When another device is used to record the data automatically this device should already be linked up during calibration.

The initial planning was to measure the apparent electric conductivity and penetration resistance before wetting, during wetting and during drying. This would enable the testing of the hypotheses that preferential flowpaths, slower infiltration rates and higher adhesion forces in compacted areas would influence how wet the soil would be and thus would influence the EM readings and penetration resistance. The wetting up of the soil would be done with a gravimetric drip irrigation system fed with rain water. Unfortunately, during the span of this thesis research the drip system was not used because of the uncharacteristic major rainfall event discussed in section 5.1.

Because of this rainfall event the soil went from relative dry conditions to beyond field capacity. This made the initial plan to make measurements in a dry situation and while wetting up impossible. Consequently, EM-38 measurements were made after the rainfall event in (very) wet conditions and during the drying phase. The use of two different sites in the study area still helped to some extent to make EM-38 measurements at different soil moisture and compaction levels.

At both sites a grid of 10 by 5 metres was made and measurements were made for every interval of 50 cm. A grid of ropes was brought to the field to ensure even spacing between the point measurements. The values for the horizontal position with 0.5m spacing (H0.5), 1m spacing (H1.0), and the vertical position with 0.5m spacing (V0.5) and 1m spacing (V1.0) were noted down by hand, as the electronic recording device was not available. These measurements were repeated after a few weeks and after a few months of drying to see if the device works at different soil moisture levels. In addition, the ECa was measured on points before ring and core sampling were executed to determine the empirical relation between BD, SM and ECa as measured by the EM38. The point measurements were visualized using the “Simple Kriging” function of the GIS program ILWIS.
Results
The fieldwork with the EM38 resulted in 24 maps: 2 different sites * 4 different positions * 3 different dates. The maps made for the V0.5 position are presented in Figure 20, while the other maps can be found in Appendix B. Comparing the maps of Figure 20, it can be concluded that over time as the soil dried out, lower ECa values were measured. This reflects the importance of soil moisture as a factor influencing ECa. Within the maps linear horizontal features with higher ECa values can be distinguished, correlating to the wheel tracks (WT) as observed on the surface. Noteworthy, between map A and B there was a single pass from agricultural traffic, resulting in a clear feature at the top of maps B and C. Similarly, a linear feature is found at the bottom of map F at site 2. The other maps as presented in appendix B show similar features. However, in the maps for the 25th of July made from the measurements in the horizontal dipole position at site 1, the single pass is less visible. As the EM38 is more sensitive to lower depths in the horizontal dipole position, possible reasons for the reduced visibility of the single pass include the evaporation of water at the topsoil and/or a looser soil due to crumbling.

The empirical relations as found in this study between the ECa, BD and soil moisture for H0.5, H1.0 and V0.5 positions are visualised in Figure 21. As there was not enough data up to a depth of 1.5m, it was not possible to determine an empirical relation for the V1.0 position. The average values of the BD and SMg over depth were plotted against the ECa. It should be noted that the sensitivity of the EM38 to the soil properties changes with depth in a non-linear way, while in this study this was not taken into account for the purpose of establishing the empirical relations. This could explain some of the variance of the ECa readings in Figure 21. Most of the measurements have been made after the rainfall event of the 26th of March, but the coring of samples took place at the beginning of March. This resulted in values for the soil in both a dry and wet state. The bulk density seems to have a slight negative relation with the ECa, which does not correspond to the theory and the results of the maps. However, it is likely that due to self-inflicted compaction the results from the coring are not correct, as explained in section 6.1. This may explain why there are high values for BD, even though the ECa is low. Another explanation is that the ECa is far more dependent on the soil moisture than on the bulk density.
Figure 20: Maps of ECa (mS/m) as measured by the EM38 in the V0.5 position. Numbers above each map indicate date of measurement.
Figure 21: Graphs of the empirical relationships between ECa (EM-38), BD, SMg and SMvol (ring samples)
Discussion

The purchase costs of an EM38 depend on the specific type and the secondary tools. The device used in this research costs around $20,000 AUD, or up to a few $100 AUD a day when rented. The operational and analysis costs are practically zero, even though labour hours should be taken into account. Measurements can be taken fairly quickly, as in this research over 200 measurement points were recorded, times four different positions, in around 2 hours. It should be taken into account that the measurements were recorded by hand, and that an electronic logger would have increased the speed significantly. Broader spacing between the measurement points would obviously have decreased the time needed to cover a certain area, at the loss of a decreased resolution. Calibration procedures should be done every time before fieldwork commences, for which some experience is needed. A single calibration takes around 15 minutes, and should be repeated every few hours. Even though some experience is needed to properly calibrate the device, it is easy to use in the field. However, the theory behind the values is quite technical, and GIS skills are needed to analyse the data and produce the maps illustrated in Figure 20 and appendix B. Still, already by ‘playing around’ in the field a user can get a good feeling of where high or low values occur. Although a range of variables influence the ECa, soil moisture is the most important factor.

The above explains why the EM38 records higher values on the wheel tracks than outside the wheel tracks. Compaction reduces the pore volume of the soil which is filled with air and water. Water is an uncompressible fluid and will stay in the soil, while air is compressed in the soil or pressed out of the soil. As there is a lower amount of the resistant medium, and more pathways in the soil, the ECa is higher for compacted soil than for uncompacted soil. In addition, the increased amount of micro and mesopores will increase the water holding capacity of the soil. Also, as the traffic compacts the soil a few centimetres (see also the front page), the wheel tracks may act as artificial drainage ways of superficial run-off from rainfall. The accuracy of the ECa measurements is difficult to determine. The apparent electric conductivity (ECa) is an average over depth of the EC. However, the EM38 is sensitive to the soil depth in a non-linear way, which is the reason why it is the apparent EC rather than just the average EC of the soil. However, the precision of the EC measurements are very high. Repeated measurements on the exact same location within the same hour will provide exactly the same values. As visualized in Figure 20, it is possible to detect soil compaction with ECa. This ability could however not be related to bulk density, as the results for bulk density are dubious. The linear features from the wheel tracks can be detected from the produced maps at every moisture level. Also, the linear features are visible for all the different positions, even though it is visually less clear for the H0.5 position. This might be due to more variation in the influencing variables on the surface. Thus, even though the empirical relation between compaction and ECa could be further investigated, the EM38 provides qualitatively good results in a wide range of conditions.
7. Reviewed methods

This chapter will review the application of several methods for measuring soil compaction on vertosol. The respective methods which are discussed are the ground penetrating radar (7.1), electric resistivity tomography (7.2) and thermal methods (7.3). Finally, a variation of other methods which were unavailable or unfeasible due to time limitations are discussed in section 7.4.

7.1 Ground Penetrating Radar (GPR)

This section investigates the use of the ground penetrating radar technique (GPR) in soil compaction research. Ground penetrating radar is a non-invasive technique which pulses electromagnetic radiation in the subsurface while a sensor records the reflected waves (Figure 22), similar to the EM38 method described in chapter 6.3. GPR uses low frequencies of electromagnetic waves also called radio waves as shown in Figure 23. The changes in the wave reflectance is mostly depended on the electric conductivity of the soil and can identify a range of both chemical as well as physical soil properties such as the water table, wetting front movement, hydraulic parameters, soil water content, soil salinity, contaminants, soil layers and soil compaction (Adamchuk and Viscarra Rossel, 2010; Conyers and Goodman, 1997; Grandjean et al., 2010; Huisman et al., 2002). The spatial coverage is larger than most point measurements and smaller compared to remote sensing techniques (Huisman et al., 2002). An experienced user can record data for around a hectare in the timeframe of a week assuming a distance of 50cm profile separation (Conyers and Goodman, 1997). The data of the GPR can be visualized in 2D or 3D with high spatial resolution (Conyers and Goodman, 1997; Grandjean et al., 2010). This can produce large amounts of data which has to be interpreted and processed by the user. This presents a challenging task especially for users who are unfamiliar with the GPR (Conyers and Goodman, 1997). However, nowadays a computer with adequate programming can process the data almost straightaway if the data is recorded digitally (Conyers and Goodman, 1997). Still, the GPR is specialized equipment for which some training and experience is needed. The purchase of a GPR system can cost around $20,000 USD or $200 USD/day when rented (Conyers and Goodman, 1997).
The effective depth of the GPR depends on the operating frequency range, the soil’s electromagnetic properties, and on the dynamic range of the radar itself (Lambot et al., 2010). When the waves penetrate the soil the energy of the waves are dispersed and attenuated over depth, making less energy of the waves being reflected and picked up by the sensor (Conyers and Goodman, 1997). Penetration and reflection also depend on the mineralogy, clay content, ground moisture, surface topography, and vegetation (Conyers and Goodman, 1997). While ground penetrating radar has the potential to measure differences in bulk density to several meters in depth in perfect conditions, the high electric conductivity of a wet and clayey soil limits the GPR strongly in depth to a few decimetres (Lambot et al., 2010). Surprisingly, there still have been some cases where measurements were made in clayey soils successfully, and preliminary work suggests that in these cases the clay soil had a relatively low cation exchange capacity due to deviating mineralogy (Weaver, 2006). When waves are used with larger amplitude (lower frequencies) the effective depth of the GPR is increased, but the resolution deteriorates as the spatial interval increases (Lambot et al., 2010). Figure 23 illustrates how the interval between waves changes when the frequency is altered.
There are several limitations to the GPR; one in particular is the simplification of how the electromagnetic wave propagates through the soil. For example, usually only the reflection time (or velocity of the waves) is measured while the amplitude of a wave can also be used to measure changes for soil properties (Grandjean et al., 2010). Air gaps can create changes in the velocity of the waves (Conyers and Goodman, 1997), which may occur specifically in vertosols due to the cracking nature in dry state. Another assumption is that the metal of the radar and antennas do not affect the ground penetrating radar, while it is known that it does affect the propagation pattern (Grandjean et al., 2010). Because of this, many significant errors are often found and only parts of the recorded data are used (Grandjean et al., 2010). Infield more practical problems may occur; for example in the case of furrows, as the transmission of waves can be at an angle and/or the radar is moving irregularly over the surface (Weaver, 2006). Also, wet soil may clog up on the wheels of the GPR during transportation on the field.
7.2 Electric Resistivity Tomography (ERT)

This section discusses how electric resistivity tomography (ERT) can identify soil compaction in the field. While electric conductivity is defined as the ability of the soil to let through an electric current, in contrast electric resistivity is defined as the degree in which the soil limits the electric current flowing through the soil. Hence, when electric resistivity is high the electric conductivity is low and vice versa. Electrodes pulse an artificial electric current through the soil and the potential difference between electrodes is measured. Through this, the electric resistivity of the soil can be calculated (Besson et al., 2004). For ERT multiple (dozens) of probes are inserted into the soil acting as electrodes. A different lay out of probes will affect the sensitiveness of the system to, for example, depth.

When the soil has heterogeneities the apparent electric resistivity is measured, whereas in a homogeneous soil it is just called electric resistivity (Samouelian, 2004). The data has to be calibrated, processed and can be ultimately visualized in 2D or 3D maps (Samouelian et al., 2005). The electric resistivity of a soil depends on several soil properties such as mineralogy, porosity, water content, clay content, salinity and temperature (Besson et al., 2004; Samouelian, 2004). In addition, the climate and in particular temperature affect the recorded values. The values can be corrected for temperature to a standard of 25 degrees Celsius (Campbell et al., 1948). Electric resistivity tomography (ERT) is a non-invasive technique which can be used over time and at different scales. ERT is thus a viable method to measure soil compaction, detect soil horizons and assessing the hydrological properties of a soil (Freeland et al., 1998; Besson et al., 2004). However, the purchase costs vary between $20.000 for a very basic configuration up to $60.000 for advanced equipment, also depending on the number of electrodes/probes used.

It is possible with ERT to measure over a longer time period which makes it possible to account for seasonal changes. As over time many replications are made, the ERT method is less likely to make systematic errors (Samouelian et al., 2005). An example of a systematic error is that there is not enough contact between the soil and the probe (Samouelian et al., 2005). Samouelian et al. (2003) observed cracking patterns which are over time affected by climatic variables such as rainfall, temperature and fluctuating ground water tables. In general the ERT seems to work best for soil moisture levels within a range of 10 to 25% depending on the degree of saturation specific for the soil type, clay content and compaction level. However, for vertosols this can be considered below wilting point and ERT will probably work better in vertosols under a higher soil moisture range (Seladji et al., 2010).

ERT offers flexibility in spatial scale by adjusting the configuration of the electric probes. The outlay of the electric probes is of fundamental importance in the experimental design. By increasing the distance between the probes the effective depth is also increased (Samouelian et al., 2005). According to Seaton and Burbey (2002) the configuration of the electric probes affects the resolution, sensitivity and
depth of investigation. In Table 7 the pros and cons of different set-ups are summarized. The configuration should be carefully chosen according to the context. More exact information on the different configurations can be found in amongst others the papers of Seaton and Burbey (2002) and Samouelian et al. (2005). It should be taken into consideration that at larger scales heterogeneities at smaller levels may come undetected and important information might be overlooked (Samouelian et al., 2005).

Table 7: Qualitative summary for the characteristics of different ERT configurations (Seaton and Burbey, 2002)

<table>
<thead>
<tr>
<th>Characteristics of different 2D arrays configurations types</th>
<th>Wenner</th>
<th>Wenner-Schlumberger</th>
<th>Dipole–dipole</th>
<th>Pole-pole</th>
<th>Pole-dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity of the array horizontal structures</td>
<td>++++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Sensitivity of the array vertical structures</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Depth of Investigation</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Horizontal data coverage</td>
<td>+++</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Signal Strength</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>++</td>
</tr>
</tbody>
</table>

The labels are classified from (−) to (+++), equivalent at poor sensitivity to high sensitivity for the different array configurations.

Besson et al. (2004) provides a good example of what the output will look like after processing the results. In their research the authors used ERT to measure differences in soil compaction and structural heterogeneity in both a laboratory set-up as well as on experimental fields dominated by highly active clay layers. He found in his study that the apparent resistivity values were significantly larger in porous soil than compacted soil as shown in Figure 24. Both the porous soil and compacted soil were corrected for temperature (T1-25, T2-25). Figure 24 shows that the variability of the values found for electric conductivity were higher for the porous soil due to a higher heterogeneity of the soil structure (Besson et al., 2004). The found values were used for 2D mapping as illustrated in Figure 25; in which the ploughing depth of 30cm and the soil compaction in the wheel tracks are clearly visible (Besson et al., 2004).

![Figure 24: Apparent electric resistivity for porous and compacted soil (Besson et al., 2004)](image-url)
As with the ground penetrating radar (GPR) technique the advances in computer technology have improved ERT development. Improved processing techniques and increased computer power have made it possible to analyse large data sets. Still, it can cost a lot of time and effort as at first preliminary laboratory studies are needed to calibrate the values for electric resistivity to the specific soil properties, for which basic knowledge of the soil and its processes is required (Shaaban and Shaaban, 2001; Samouelian et al., 2005). More often than not the results from the calibration cannot be used for different soil types. In addition, to take into account seasonal effects or for example the soil hydraulic, repeated measurements are needed over the year (Samouelian et al., 2005). Advanced knowledge is needed on the different set-ups for the ERT as each set-up will affect what is measured differently. For this number of reasons the use of ERT as a routine operation for farmers appears to be unlikely (Besson et al., 2004, Samouelian et al., 2005).
7.3 Thermal methods

This chapter will discuss how thermal (temperature) differences can be an indicator for soil compaction. First, an indirect relation between the cotton canopy temperature and the soil compaction is explored. Secondly, the relation of the soil thermal properties and soil compaction is investigated.

A plant utilizes water for photosynthesis in order to grow, but most water is used for transpiration in order to transport minerals (1), to make sure that the plant stems remain stiff and upwards (2), and for cooling (3). Under influence of water stress, the canopy temperature will rise as the plant has little water available for transpiration. Roth’s research (2002) discusses this effect and shows that soil compaction can be measured by the canopy temperature. This is illustrated in Figure 26 which shows that the canopy temperature in the afternoon for a trafficked (compacted) wheel track is higher than the two other rows, while the surface temperature of the bare soil steeply rises as it does not have protection from canopy.

The canopy temperature can be measured by thermal infrared sensors. Thermal infrared sensors can measure the temperature of the soil also directly; this is however limited to a depth up to 5 cm (Idso et al., 1981). In his research Roth (1994) uses airborne imagery techniques to measure, among others, the canopy temperature. Major advantages are the areal coverage, high resolution and the use of non-destructive techniques. The costs to operate airborne imaging are fairly high even though a large area can be covered. Alternatively in-field measurements can be taken with thermal infrared devices, however these devices lack areal coverage. The high resolution (2 to 4 metres) makes it possible to distinguish canopy temperature between rows and to reveal soil compaction in rows under permanent trafficking. Distortion effects such as the sun angle, solar radiations and air temperature have to be taken into account. The thermal infrared measurements of the canopy made early in the cropping season were too much affected by the background temperature of the soil to be used (Roth, 1994).

Canopy temperature and transpiration is highly affected by a number of factors which should be taken into account. These include the time of day, weather, state of the plant (canopy coverage and height), soil and other factors. As demonstrated by Idso et al. (1981), it is therefore not possible to find an unique relationship between plant temperature and soil moisture or soil compaction. In addition, the data generated by thermal infrared measurements are difficult to compare with data generated by traditional methods, which use bulk density, penetration resistance and soil strength.

The volumetric heat capacity and heat conductivity of a soil can also indicate soil compaction. The volumetric heat capacity of a soil provides the amount of heat energy that can be stored in a certain volume of soil undergoing a temperature change. Heat conductivity is the ability to transport thermal energy through a certain medium (soil) from A to B. It was found in several studies that the volumetric heat capacity and thermal conductivity increased with the soil moisture content and soil bulk density,
the latter indicating soil compaction (Abu-Hamdeh, 2000; Abu-Hamdeh and Reeder, 2000; Liepic and Hantano, 2003; Usowicz et al., 1996). The increase in the volumetric heat capacity and conductivity can be explained by a higher contact level between soil particles which improves the conductance of the soil (Liepic and Hantano, 2003). In addition, heat convection and diffusion is further enhanced by soil moisture content (Horn, 1994). The relation between volumetric heat capacity, soil moisture, and bulk density for a clay soil is illustrated in Figure 27.

When the relation between volumetric heat capacity, soil moisture and bulk density is investigated in a controlled experiment for a specific soil, as in Figure 27, one could try to estimate the bulk density by the volumetric heat capacity. Using an example after Figure 27; if the soil moisture is determined to be 0.25 kg/kg and the volumetric heat capacity is 2.9 MJ/m$^3$, it is possible to estimate the soil bulk density to be around 1200 kg/m$^3$. To do so, both the volumetric heat capacity and the soil moisture have to be measured to get an estimation of bulk density. To measure volumetric heat capacity soil samples have to be taken. In essence, these samples are heated up and the temperature change and the amount of energy absorbed by the volume of soil are measured using a calorimeter (Abu-Hamdeh, 2003). The method thus includes soil sampling, a ‘sub-method’ which can also be used to measure the bulk density directly. In conclusion, the needed initial experiments and the collection of both the volumetric heat capacity and soil moisture will probably take more effort than the standard compaction measurements such as the determination of bulk density by soil samples, while it is probably less accurate.
Finally, to determine heat conductivity one could use the dual probe heat-pulse technique, a technique which is normally used to indirectly measure the volumetric water content of the soil (Campbell et al., 1991; Bristow et al., 2001). However, this technique can also (either directly or indirectly) measure a range of soil properties such as soil temperature, soil thermal diffusivity, volumetric heat capacity, thermal conductivity, volumetric water content and bulk soil electrical conductivity (Bristow et al., 2001). One of the probes consists of a heater while the other probe at a distance $r$ measures the temperature. The moment the heater is turned on the response time of the thermometer, and the heat conductivity of the soil, is measured (Ochsner et al., 2003). The soil is assumed to be uniform over the distance $r$. While wet vertosols are uniform, the shrinking and swelling processes of a vertisol may create deep cracks which may induce that the probes do not have good contact with the soil due to air gaps. To avoid air gaps and to be sure of the depth and distance $r$, care has to be taken that the probes are not inserted at an angle (Bristow et al., 2001). With the dual probe heat-pulse technique it is possible to take automated non-destructive measurements over time (Ochsner et al., 2003). It is more common to take measurements close to the surface, but depending on the type it is possible to insert the probes up to a depth of 1.5m (Bristow et al., 2001). The probes can be considered relatively cheap and have a small sample size which provides good resolution, but also prompts the need of multiple probes and sensors to cover a larger area (Bristow et al., 2001).
7.4 Alternative methods

As can be seen in the previous sections there is a wide range of methods to measure soil compaction. This final section will provide a summary of methods which were found during the literature review but were not thoroughly investigated due to the destructive nature, limitations of the methods, time restrictions and/or unavailability and inaccessibility of these methods. It should be noted that there probably are even more methods to identify soil compaction which are not discussed, even though this report tried to give a comprehensive overview of the available methods. First the time domain reflectancy device (TDR) and X-ray computed tomography are discussed. Hereafter, other methods based on respectively aggregate size, soil hydraulics and the crop response are briefly summarized. Finally, the shear vane, a possible alternative to the cone penetrometer is discussed.

The TDR device uses electromagnetic (EM) waves to determine the soil moisture, like other methods discussed earlier. The EM waves distort the electrons of the molecules and the medium becomes polarized, meaning the medium (soil) acts like a battery with a negative and positive charged pole through which the EM waves propagate. The extent to which a medium can get polarized is measured as relative permeability or (in older terms) dielectric constant. In practice, electromagnetic waves are pulsed into the soil through one probe and the propagation (delay) time is measured by the other probe (Gong et al., 2003). From the known velocity of the EM wave, the length of the transmission lines and the measured propagation time the (apparent) relative permeability written as $K(a)$ is calculated (Gong et al., 2003). TDR is a low cost technique and easy to use; the probes are inserted into the soil and the value is immediately shown. The data can be either recorded by hand or automatically. This can be done in a fairly quick fashion through which it is possible to take measurements at field scale. However, the use of the TDR is depth limited and depending on the type of TDR will only be able to measure at the soil surface. More specialized TDR’s may measure up to a depth of 3m (van Walt, 2012). Alternatively, a TDR can be inserted horizontally in a dug pit or in soil cores taken in the field.

Water can be considered a very polar molecule, which makes volumetric water content the main variable which determines the relative permeability. Subsequently, Topp et al. (1980) created an empirical formula to convert apparent relative permeability to volumetric water content which was validated in a wide range of soil types by many papers. However, as technology has advanced the resolution and accuracy of the propagation time increased (Song et al., 2003). This induced that several studies started to find deviations from the empirical formula of Topp et al. (1980) in soils with a high clay content and/or salinity, and small differences for different bulk densities (Song et al., 2003; Yu and Drnevich, 2004). Yu and Drnevich (2004) created an empirical formula to calibrate for dry density and gravimetric water content (instead of volumetric water content). The method of Yu et al. (2004) provided fairly precise and accurate results (within a +/- 3% range) for dry density as
shown in Figure 28. However, results were disappointing for soils with high clay and water contents as there was no clear reflection from the probe end.

![Figure 28: Comparison of TDR-measured dry density with dry density determined from total density direct measurements and water contents by oven drying on 14 different sands, two silts, seven clays, one lime-stabilized soil, and one low density mixed waste (Yu and Drnevich, 2004)](image)

The spectrometer is a name which can be used for several devices measuring the reflectance of electromagnetic waves in the form of light, like the ground penetrating radar, electric resistivity tomography and GPR methods discussed previously. Each spectrometer uses a certain range of wavelengths of which the different types can be seen in Figure 22 in section 7.1 (GPR). These ranges of wavelengths are distinguished as radio, microwave, infrared, visible, ultraviolet, X-ray or gamma ray wavelength bands. The GPR, ERT and EM38 methods are found in the radio wavelength band, but it is also possible to analyse soils with for example X-ray computed tomography (CT). Bakker and Barker (1998) used an X-ray CT scanner to demonstrate the structural degradation in the wheel tracks compared to non-trafficked rows in cotton cultivated vertosol. They took large monoliths from the field and used X-ray CT to visualize in 3D the cracking patterns and porosity of the monoliths. Even though they found this non-destructive and high resolution method useful to analyse the soil structure in a fast and convenient way, Bakker and Barker (1998) acknowledged that the maximum diameter (20cm), limited strength of commercial scanners, high (purchase) costs, and limited availability and accessibility are restrictions which make it difficult to use X-ray CT scanner on a routine basis. In addition, it is not possible to take the measurements in the field, making this method less suitable to identify and quantify soil compaction at field scale.
The aggregation size distribution of a soil can be an indicator of the soil structure. Coarse aggregates mean that there is relatively little soil compaction (Zwart et al., 2011). By sieving the soil with different sieve sizes the aggregate distribution can be measured, but this is a labour intensive method. Campbell (1979) used high resolution airborne imaging on bare soils to show shadows cast from the aggregates providing an idea of the aggregate sizes at the surface. In his research in 1979 the computer processing power was a big limitation but this should not be an issue in present days. However, this technique only gives an image of the surface, which in practice is also often covered by stubble. More modern techniques such as laser scanning to determine aggregate size distribution at the surface as used by Sandri et al (1998) are also depth limited.

Hydraulic conductivity of a soil provides an impression on the compaction level of the soil. A heavily compacted soil will have lower infiltration rates and lower hydraulic conductivity. This can be measured with the double ring infiltration meter and/or a tension disc permeameter. These methods are able to estimate the macro porosity of a soil rather well, but the continuous macropores created by shrinking and swelling processes generate a lot of variability of hydraulic conductivity and thus a lot of replications are needed (McKenzie, 2001). Especially in the case of the double ring infiltration meter this will be time consuming. Similar problems arise for air permeameters, which can indirectly measure the porosity of the soil by measuring air permeability (McKenzie, 2001). Tensiometry which measures the soil water potential of a soil is also related to soil pores, as smaller pores (micropores) will have high adhesion forces and increase the matrix potential of the soil. However, in the analysis of the results of tensiometry it is assumed that the pores have cylindrical round shapes. This is not the case for vertosol as the clays in the study area have a platy structure and irregular pore shapes (McKenzie, 2001). Zwart et al. (2011) offer the option of observing the size and amount of pools after irrigation or rain by remote sensing or naked eye. However, in the vertosols in Australia pools are not often found as the cracks in dry soils enable very quick and deep drainage of water into the soil. In addition, the soil is not quickly saturated as these heavy clay soils can contain soil moisture levels of 50% and higher.

The crop development and yield can give an indication of the soil compaction level. Crop development can be monitored by using airborne or satellite systems with sensors which measure the light reflectance band of the plants from infrared waves (Zwart et al., 2011). The yield can give an indication of the average compaction on the field but this does not show the variability within the field. Both crop development and yield are depended on a lot of factors, making it difficult to account for every factor and to relate crop yield decline directly to soil compaction. Another method is to observe the root development of the crop through the soil by digging a large pit or taking undisturbed soil samples. SOILpak, a series of handbooks on the best management practices for cotton growers in Australia, uses a cheap hands-on approach which includes visual observations on root growth, clod structure and features of fraction phases to assess the soil structure (McKenzie, 1998). The quality of this assessment mostly depends on the experience and observation skills of the
user. The assessment method involves the digging of pits, a technique which is labour intensive and destructive to the soil.

An alternative method to the penetrometer is the shear vane. A shear vane is inserted and turned around in the soil. The torque that is needed to turn the shear vane is measured and can be related to the soil strength, just like the penetration resistance of the penetrometer. A shear vane with several options and extension rods is illustrated in Figure 29. This method was however not available for testing.

The shear vane is designed specifically for wet and clayey soils, fitting the description of vertosols. McKenzie and McBratney (2001) investigated the use of soil strength and water content data to model the limiting water ranges on a grey vertosol and sodic haplустert. In their research they measured the soil strength with both a penetrometer and a shear vane. Sampling was repeated over time after irrigation periods, at five different gravimetric water contents ranging from 0.17 g/g to 0.36 g/g. They found that the shear vane provided superior results over a broader range of soil water contents, while the penetrometer delivered less reliable results in moist conditions. However, it should be noted that several measurements, mainly from the shear vane, were recorded as missing observations because they were off-scale. Also, McKenzie and McBratney (2001) observed that the required time to take an individual reading took a lot longer (30 seconds) with the shear vane than the penetrometer (2 seconds). This was mainly caused by the cleaning time of the shear vane, as more soil was attached to the shear vane after insertion. The range of the gravimetric water content of the soil in the paper of McKenzie and McBratney (2001) varied from 0.17 g/g to 0.36 g/g, and was described as respectively ‘very dry’ and ‘very moist’. However, this research found higher gravimetric water contents for the black vertosol in the study area, varying from around 0.30 to 0.45 and even higher. Therefore, the application of the shear vane should be tested to verify the hypothesized superior results of the shear vane to the penetrometer in moist conditions on black vertosol.
8. Summary and conclusions

Larger agricultural machines have not only led to increased time efficiencies and improved personnel safety, but also provide a higher stress to the soil due to higher wheel loads. The resulting soil compaction is a yield limiting factor for cotton production on vertosols and is considered to be a major issue by farmers and agronomists. To some extent, soil compaction can be beneficial for the soil in terms of the ability to withstand higher stresses, improved germination of seeds and root uptake of nutrients and moisture. However, too much compaction is detrimental for the soil and crop as root growth, infiltration rates and water storage of the soil are decreased. Additionally the crop is more prone to water-born plant diseases and soil fauna may decrease, while the lower aeration aids bacteria in the process of denitrification, resulting in nitrogen losses to the atmosphere. In practical terms, soil compaction reduces the workability of the land and increases fuel use. Due to propagation of effects, seasonal changes and alterations to the farm management, soil compaction is a highly dynamic and complex issue. This research investigated which traditional and innovative methods are the most adequate to measure soil compaction on cotton grown black vertosols. In chapter 3 the purpose of this research was formulated in the main research question as:

**Which methods are most appropriate to detect and measure soil compaction on cotton cultivated black vertosols in South-Eastern Queensland, Australia?**

Resulting from the causes and factors of soil compaction a broad list can be included as indicators of soil compaction. However, in soil compaction research most often the soil properties bulk density, porosity and soil strength are used to quantitatively indicate the level of compaction. In this study, electrical indicators such as electric conductivity and electric resistivity are also discussed. These indicators were measured in this study using the ring method, rig coring, penetrometer and EM38. In addition, the ERT, GPR, thermal methods, shear vane and various other methods were discussed. These methods were assessed by their financial costs (1), time cost (2), user-friendliness (3), reliability (4) and the physical limitations (5).

In table 8 the resultsof the methods for each criterion are summarized. It should be noted that this table only provides a simplified overview. Every method which was discussed in depth was included, with the addition of the shear vane which was considered to be noteworthy for further research.
Table 8: Assessment of methods measuring soil compaction. The labels are classified from (+) to (+++) equivalent to how well they were judged to be suitable techniques for the corresponding indicators.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Rings</th>
<th>Rig</th>
<th>Penetrometer</th>
<th>EM38</th>
<th>ERT</th>
<th>GPR</th>
<th>Thermal</th>
<th>Shear vane</th>
</tr>
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<tbody>
<tr>
<td>Costs</td>
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<td>++?</td>
<td>++?</td>
<td>+</td>
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<tr>
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<td>++</td>
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Ring sampling and rig coring are considered to be very cheap, while especially the purchase costs make the EM38, ERT and GPR methods expensive. The shear vane method also could be considered cheap, but it was assumed that a motorized version would be used like the penetrometer. The time costs to take measurements with the EM38, ERT and GPR can be considered very low. The rig, penetrometer and shear vane need to be cleaned before every insertion, of which the cleaning of the shear vane takes significantly more time. The time costs of the thermal measurements are difficult to assess, as it should be taken into account that measurements probably need to be taken over the whole day to take into account the diurnal variation of temperature. Still, the ring sampling is most time consuming as pits have to be dug in the clayey soils before the samples can be taken.

The digging of pits also makes the ring sampling less user-friendly, even though the method is easy to understand and the user can relate very well to these measurements. The rig coring takes away the need to dig pits, but some experience and tricks are needed in order to get a representative and complete sample. The penetrometer seems to work very well and is easy to relate to for the user. However, it should be considered that field experiences attest otherwise. For example, if the soil is wet the soil may clog up the wheels of the penetrometer which would make it more difficult to transport the device over the field. In contrast, the EM38 is very easy to transport and use in the field, however background knowledge to fully understand which soil properties are measured is needed. This is similar to the GPR and ERT, even though the different available set-ups of the ERT make it highly specialized equipment. Basic background knowledge is needed for the use of thermal measurements, while the effort to clean the shear vane impacts both the time costs and the user friendliness.

Remarkable for the reliability indicator of the methods, is that none of the methods can be considered ideal. The results for the ring and rig provided much variation between the measurements, while the core itself may have compacted the sample even further. The penetrometer worked well in the lab under dry conditions, but cracking of dry vertosols in field conditions makes the soil less uniform and makes it difficult to take representative samples. Also, additional samples need to be taken to measure the gravimetric water content in order to indicate the bulk density of the soil. The EM38, ERT and GPR seem to be able to distinguish differences between compacted and uncompacted soil. However, there are several soil properties which
influence the readings for these measurements. The same applies for thermal measurements, although it is considered even more difficult to find an unique relationship between soil compaction and plant or soil temperature than soil compaction and electric properties. The shear vane provided adequate results for grey vertosols, but further research should conclude if this is also true for black vertosols.

Concerning the limitations of ring sampling it is difficult to take representative samples on very dry soils due to the cracks which appear when there is a moisture deficit. In very wet conditions it is also challenging to take good samples due to the plasticity of the clay. The rig is influenced even more by the soil water, as the wet soil might stick in the tube. The penetrometer works only well in (very) dry conditions in the lab, for which in the field the cracking of the soil should be considered. The EM38 proved to work well in a wide range of conditions up to a depth of 1.5m. Literature suggests that the ERT also will work well in a wide range of conditions on vertosols, even though the set-up of the ERT system will influence for example the effective depth. The GPR can only measure up to a few centimetres depth in clayey soils, making the GPR practically useless for soil compaction research on vertosols. Thermal measurements are normally limited to the surface, while probes eventually can also be inserted deeper into the soil. Literature suggests that the shear vane works in a wider range of soil moisture conditions than the penetrometer, but research on black vertosols should be done to determine what the limitations of the shear vane are.

In conclusion, traditional ring sampling proved to be time consuming and untrustworthy. The penetrometer provided adequate results in the lab in dry conditions, but should be tested on field conditions. The shear vane could be a good alternative, but more research needs to be done specifically on black vertosols to verify this. The EM38 can detect soil compaction in a wider range of water content and provide much potential for future research. Literature suggests that the ERT also would provide good results in a wide range of conditions. Future research should prove if this is true and test the different set-ups which are possible for the ERT method. However, compared to traditional methods the use of the EM38 and ERT as a routine operation for farmers is unlikely due to the higher costs, specialized equipment and advanced analysis. Each method that was discussed had its clear advantages and disadvantages, making not one clearly superior to the others. Thus, the context and purpose for which each method is used should be carefully considered.
References


Walsh, P 2002, 'New method yields a worm's eye view', Farming Ahead, no. 132, pp. 16-8


Appendix A: Penetrometer data
Appendix B: EM38 maps

The maps of ECa (mS/m) as measured by the EM38. Numbers above each map indicate date of measurement. ‘WT’ indicates where the wheel tracks are located.

**B1: H0.5 position**

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<th>21/04</th>
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</table>
B2: H1.0 position

Site 1

07/04
21/04
25/07

Site 2

09/04
21/04
25/07

ECa

| 60 | 80 | 100 | 120 | 140 | 160 | 180 |
B3: V0.5 position

Site 1

08/04
21/04
25/07

Site 2

09/04
21/04
25/07

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</table>
B4: V1.0 position

Site 1

08/04  21/04  25/07
WT  WT

Site 2

09/04  21/04  25/07
WT  WT

<table>
<thead>
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<th>ECa</th>
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