CRANFIELD UNIVERSITY

David Whattoff

A MULTI SENSOR DATA FUSION APPROACH FOR CREATING VARIABLE DEPTH TILLAGE ZONES

School of Energy, Environmental Technology and Agrifood

Masters by Research
Academic Year: 2014-2015

Supervisor: Dr Abdul Mouazen,
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ABSTRACT

Efficiency of tillage depends largely on the nature of the field, soil type, spatial distribution of soil properties, and the correct setting of the tillage implement. However, current tillage practice is often implemented without full understanding of machine design and capability leading to lowered efficiency and further potential damage to the soil structure. By modifying the physical properties of soil only where the tillage is needed for optimum crop growth, variable depth tillage (VDT) has been shown to reduce costs, labour, fuel consumption and energy requirements. To implement VDT it is necessary to determine and map soil physical properties, spatially and with depth through the soil profile. Up until now the measurement of soil compaction for VDT has been soil penetration resistance, expressed as Cone Index (CI).

In this research a multi-sensor and data fusion approach was developed that allowed augmenting data collected with an electromagnetic sensor, a standard penetrometer, and conventional methods for the measurement of bulk density (BD) and moisture content (MC). Packing density values were recorded for eight soil layers of 0-5, 5-10, 10-15, 15-20, 20-25, 25-30 30-35 and 35-40 cm. From the results only 62% of the site required the deepest tillage at 38 cm, 16% required tillage at 33 cm and 22% required no tillage at all. The resultant maps of packing density were shown to be a useful tool to guide VDT operations. The results provided in this study indicate that the new multi-sensor and data fusion approach introduced is a useful approach to map layered soil compaction to guide VDT operations. The economic benefit analysis demonstrated fuel savings of 48% by implementing the proposed system. Further work is needed to implement the packing density map for VDT in larger numbers of field in order to generalise the approach.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

ASABE	American Society of Agricultural and Biological Engineers
ASAE	American Society of Agricultural Engineers
ATV	All-Terrain Vehicle
BD	Bulk Density
BS	British Standard
BSI	British Standards Institute
CC	Clay Content
CI	Cone Index
CT	Conventional Tillage
DGPS	Differential Global Position System
ECa	Apparent Electrical Conductivity
EMI	Electro Magnetic Induction
ER	Electro Resistivity
FEM-MLR	Finite Element Modelling - Multiple Linear Regression
GHG	Green House Gas
GIS	Geographical Information System
GPS	Global Positioning System
HCP	Horizontal Co-Planar
IDW	Inverse Distance Weighted
IQR	Inter Quartile Range
MC	Moisture Content
MF	Multiplication Factor
MLR	Multiple linear Regression
MPa	Mega Pascal
MSDF	Multi Sensor Data Fusion
PD	Packing Density
PDBS	Prototype Bulk Density Sensor
PR	Penetration Resistance
PRP	Perpendicular
PSD	Particle Size Distribution
UK	United Kingdom

USA	United States of America
VDT	Variable Depth Tillage
vis-NIR	Visible Near Infra-Red

INTRODUCTION

Traditional tillage practices use a whole field approach in which the tillage effect is applied uniformly across the whole field. Management decisions on which cultivation machinery to use and how deep to operate it at are usually decided on historical management or occasionally based on information derived from a soil inspection. This universal approach is attractive to growers because it requires little specialist knowledge of the soil, simply relying on cultivator design to achieve a satisfactory result.

There are several disadvantages to this approach. Firstly from an economic perspective, disturbing the soil unnecessarily in areas where the soil structure and condition is not required is wasteful of time and fuel (Keskin et al., 2011). Secondly, incorrect tillage depth can cause damage to the soil structure by smearing wet plastic soil (Gill and Vandenberg 1965). This problem can lead to the formation of an impervious layer, restricting the development of plants roots, negatively impacting on yield. Finally inappropriate tillage may lead the soil to be susceptible to erosion where nutrients are not retained in the soil but are lost to the environment through leaching and runoff (Halcro 2013).

Recently, with increasing economic and environmental pressures, researchers have been looking at methods to improve cultivation efficiency by assessing the physical soil parameters and varying tillage depth according to soil structural need and crop requirements. Growers on the other hand have been using an informal approach to this problem, generally making manual tillage depth adjustments to the cultivator on a field by field basis. Although some with a more advanced knowledge of soil structure, aware of the damage caused by inappropriate tillage, have taken within-field measurements to quantify and understand the cause of variation thereby going some way to avoid the disadvantages already discussed.

With modern GPS technology, soil variability can be managed by delineating areas or management zones with similar properties and yield potential. This management zone approach is now a widely accepted practice for variable rate application of agrochemical and nutritional crop inputs. Recent attempts to implement variable depth tillage however, haven’t been universally accepted because of the time taken to collect the necessary data has been perceived to outweigh the benefits.

This thesis examines the problems associated with variable depth tillage and offers a solution to improve the collection and interpretation of data using a multi sensor data fusion approach.

1 Literature Review

In this chapter a literature review about different aspects related to soil compaction and the need for tillage is provided.

1.1 Soil profile

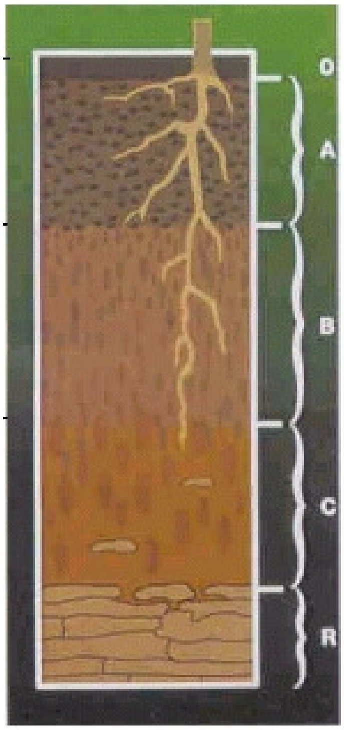

Figure 1-1 Schematic diagram of soil horizons (Mount St Mary's Uni, Maryland, USA. 2015)

As soils develop over time they are each subject to a particular combination of influences causing a different set of layers to form. A vertical exposure of this sequence is termed a soil profile (Brady and Weil 2006). For this work understanding the soil profile is essential for working out the best strategy to follow when varying the tillage depth.

In agricultural soils there are two soil horizons which impact crop production and tillage (Figure 1-1). The A horizon or topsoil is the surface layer, predominately mineral containing partially decomposed organic matter which leads to a dark colour. Most tillage activities take part within this layer with the type of tillage governed by soil texture and other influencing soil physical properties. If this layer is subjected to tillage practices repeated at the same depth over several years or tillage carried at an inappropriate time a plough pan is created. To date the primary method of locating the depth and thickness of hardpans has been achieved with a cone penetrometer (Clark, 1999).

Immediately below the topsoil is the B horizon or subsoil. This layer, which is rarely subjected to annual movement by tillage, can become dense due to the natural settling of the soil particles and or damage from mechanised operations creating a hard pan, preventing roots from penetrating, reducing their volume and their ability to uptake nutrients (Mouazen and Neményi, 1998). This has a significant impact on a soil's productivity potential; hence, hardpan and plough pan should be removed by subsoiling. However, subsoiling is an expensive operation (Mouazen and Neményi, 1999), which necessitates the need to reduce the cost of this operation. One way to do that is by variable depth tillage (VDT).

It is well documented that topsoil compaction is easier to ameliorate by the assistance of the natural processes including swell-shrink of the soil due to wetting-drying cycle or freezing-melting (Brady and Weil 2006). Other biological activities like earth worms may contribute to the amelioration of top soil compaction. However when compaction occurs in the subsoil, it is difficult to ameliorate as natural processes and biological activities are minimal. However an efficient method of mapping the spatial and through profile distribution of soil compaction would enable VDT to become a viable approach in compaction remediation.

1.2 Soil texture

Soil texture obtained by particle size distribution (PSD) test is used to describe the physical composition of soil. Particle sizes are defined precisely into three groups, with the upper limit of 'soil' set at 2mm. The classification of the soil texture is determined using a ternary graph where the apices represent 100 per cent sand, silt and clay fractions respectively (Quarishi, 2013; Marshall et al., 1996). The relationship between soil texture and compaction is of a strong correlation and is affected by moisture content, especially in medium and heavy textured soils (Spivey et al., 1986; Domzal et al., 1991). Soil texture is also highly correlated to moisture content and bulk density (Gupta and Larson, 1979; Spivey et al., 1986). The lighter the soil (towards the sandy type), the smaller is the water holding capacity and moisture content (Mouazen et al., 2015) and the larger is the bulk density (Abramson et al., 2002) and vice versa. Literature showed that heavy soils (e.g. clay soils) when wet are much more susceptible to compaction occurrences than light soils (e.g. sandy soils) (Quarishi, 2013).

Textural assessment is one of the most important tests that can be done on soil as it can give a guide to the retention of soil water, structural stability, erodability and ease of cultivation (Batey, 1988). Soil texture also influences soil compaction. Ellies Sch et al. (2000) reported that in soil with a coarse texture, the dominant stress during soil penetration was in vertical direction, while in a fine texture stress propagation was multidirectional. This demonstrates that soils with different soil textures will compact at different depths and directions, therefore soils of varying texture would benefit from a VDT approach to be investigated in the current work.

1.3 Soil structure

Soil structure is defined by the arrangement of soil particles and the spaces and soil pores between them. (Batey, 1988) The relevance of structure to good soil husbandry is intrinsically linked to the soil pore's ability to allow drainage of water, aeration and passage of roots (Figure 1-2).

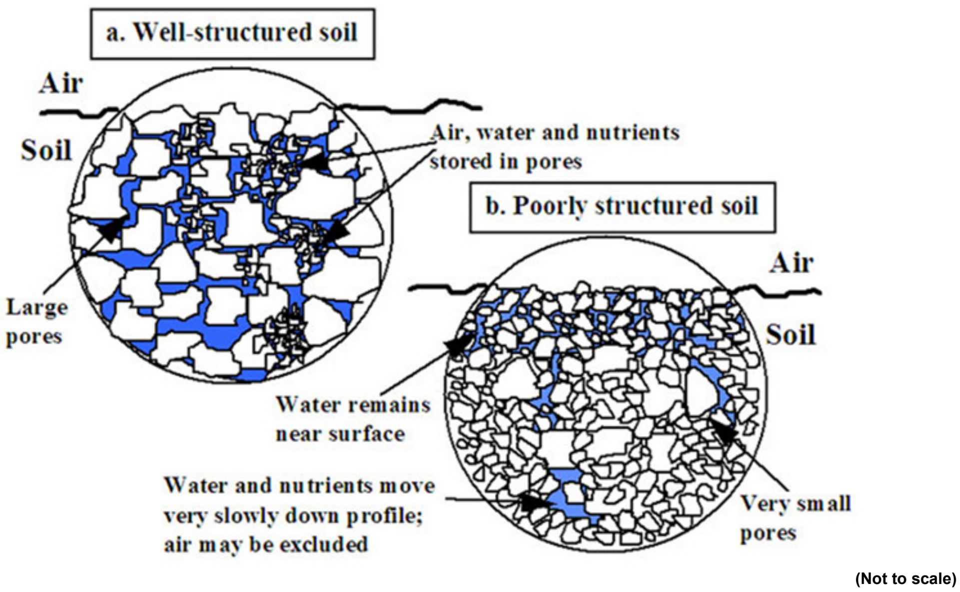

Figure 1-2 Schematic diagram comparing differences between well-structured and poorly structured soil (State Government, Victoria, Australia 2015)

The pore spaces are also home to many living organisms ranging from microscopic bacteria to earthworms and beetles (Batey, 1988). The annual practice of tillage repairs and maintains the soil structure by increasing the number and volume of pores spaces, reducing the soil bulk density and increasing the mass flow of moisture and gasses within the soil profile (Quarishi, 2013). The presence of a hard pan or plough plan will have a huge impact of these soil physical properties, hence it is necessary to eliminate the compacted layers with VDT.

1.4 Soil consistency

Soil consistency is categorised as solid, plastic or liquid (Marshall et al., 1996) (Figure 1-3).The solid category is further sub divided in to hard and friable. Hard soils are more difficult to cultivate than friable ones because the forces required to fracture them are much higher. Plastic soils on the other hand will initially deform rather than fracture as the energy transferred during tillage is absorbed by the soil (Hamza et al., 2005).

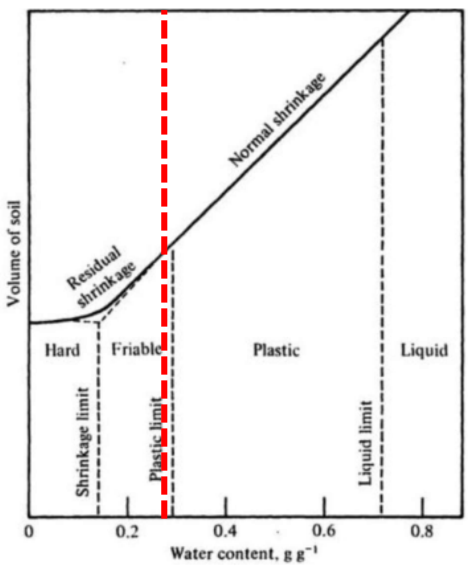

Figure 1-3 Consistency and shrinkage states of remoulded soil illustrated by values appropriate to soil of a high clay content (Marshall et al., 1996) The optimum soil moisture for tillage (Allmaras 1969) is indicated by the red line.

It is important for growers to recognise the different soil textures and soil moisture content as these have a significant impact on the cost and effectiveness of tillage (Ohu et al., 1989). Allmaras et al. (1969) noted that tillage carried out at 95% of the lower plastic limit was the point of optimum workability. This is because cultivating when the soil moisture content is greater than the plastic limit will damage the soil structure by smearing and deformation. Conversely, if soil is below the shrinkage limit, then more energy will be required to fracture the soil. Therefore it is important to till the soil at the right soil moisture if compaction is to be minimised (Gysi et al., 1999).

1.5 Soil compaction

The Soil Science Society of America (1996) defined soil compaction as “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”, as shown in (Figure 1-4). Soil compaction is the spill of air, which is different than soil consolidation, which is defined as the spill of water.

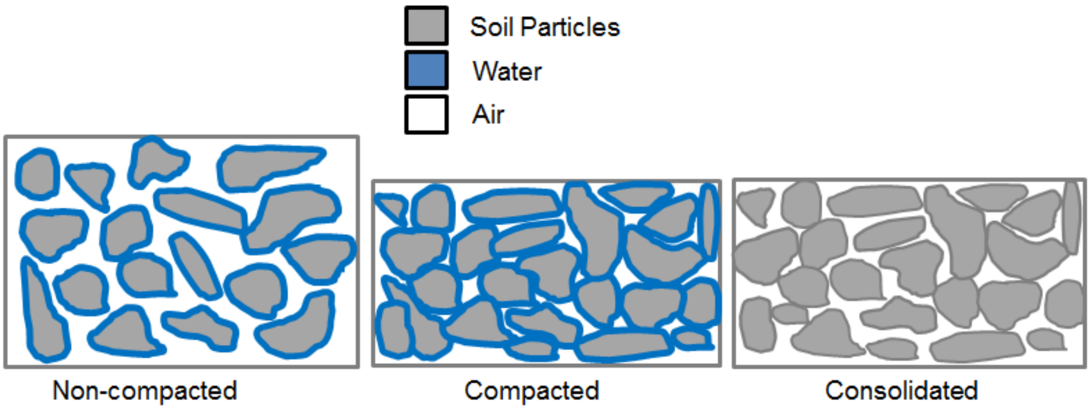

Figure 1-4 Effect of soil compaction on altering soil pore orientation and spacing (Adapted from University of Minnesota, 2001)

This combination of higher bulk density and lower porosity in the compacted layer as opposed to the soil directly above or below it can be as a result of external pressure caused by agricultural machinery (Gorucu, 2006), or natural factors such as hard pans caused by particle settling and cementation (Brady and Weil 2006). Either the naturally occurring or pressure induced soil pans can have a significant impact on the growing crop. If the layer of soil is extremely dense, and the soil penetration resistance value is over 2 MPa (Taylor et al., 1996) roots may not penetrate, decreasing the rooting volume, reducing nutrient uptake and increasing drought susceptibility. Furthermore, the compacted layer may prevent water infiltrating into the subsoil, thus limiting available water for plant growth and increasing surface run off and the potential for soil erosion (Raper, 2005). However if the layer is of a density that does not restrict root development, gas exchange and drainage, it can play an important part in absorbing compaction stresses before they reach deeper sections of the subsoil (Spoor, 2005). This is important to note, as deep soil compaction is difficult to ameliorate.

Soil compaction caused by anthropogenic activities such as heavy farm machinery or result of cyclic tillage is a big concern for farmers as it is directly related to crop growth and potentially to yield. Other factors, such as heavy rainfall and natural cementation can also lead to soil compaction. According to the natural soil susceptibility to compaction, Houšková and Montanarella (2008) divided soils in Europe into four categories of low, medium high and very high susceptibility to compaction. Soil compaction is associated with increase in bulk density and penetration resistance, while significant reduction of porosity and pore space may be expected (Hakansson, 1990). Therefore, soil compaction also affects the hydraulic properties of the soil. The decrease in infiltration rate leads to surface run off, which enhances soil erosion particularly in areas with intensive rainfall (Franzen et al., 1994). This also causes increased risk of flooding, particularly in areas with steep slopes that experience intensive rainfall (Presbitero et al., 2005). The increase of soil resistance to penetration affects not only plant growth but also leads to increase energy requirement for tillage.

Therefore, the occurrence of soil compaction should be avoided otherwise a proper management of tillage should be utilised.

1.6 Causes of soil compaction

1.6.1 Mechanized farm operations

Heavy wheeled machinery with high axle loads exerts a vertical pressure on the soil. This force is localised directly below each wheel, where it increases soil density and reduces porosity. If the force is sufficiently large surface ruts are formed (Hamza and Anderson, 2005). The depth of compaction varies widely from 10 to 60 cm (Flowers and Lal, 1998; Hamza and Anderson 2005). Furthermore multiple layers of compaction can be created by tillage when the soil is too wet. As draught increases and traction is reduced, the wheels on the tractor slip, creating a smeared layer or plough pan. Further soil damage can be caused by the tines of the cultivator which can also smear the soil creating an additional impervious layer inhibiting the natural function of the soil. (Godwin and Spoor 1978; Daniel et al., 1988).

1.6.2 Natural factors

Rainfall on fine, naturally unstable soils can lead to slaking (running together of the surface creating an impenetrable cap of up to 5mm thickness). This can restrict the seedling emergence. Heavy rainfall on compacted soil can cause erosion due to reduce infiltration of water through the soil surface (Houskova et al., 2011). Genetic hard pans also have a significant impact on crop performance. These hard layers form naturally within the soil profile where the soil texture is coarser than the adjacent layers, gradually cementing over time. (Hakansson and Lipiec, 2000).

1.6.3 Animal traffic

Grazing livestock can cause soil compaction (Figure 1-5), (Quarishi 2013; Batey 1998). The areas at most risk are those where the animals congregate namely, gateways, feeders and tracks (Betteridge et al., 1999). This type of soil compaction, known as poaching, often takes years to recover as the fields are rarely cultivated (Quarishi 2013, Warren et al., 1986; Whitmore, 2010)

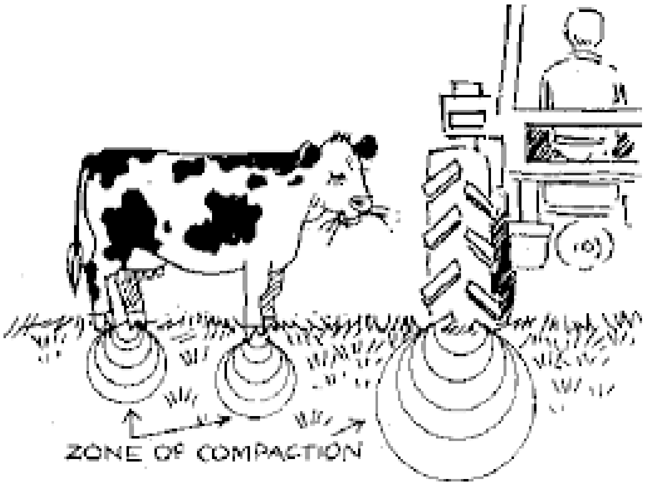

Figure 1-5 Soil compaction caused by grazing livestock can take many years to recover naturally. (Quarishi 2013)

1.6.4 The misuse of tillage tools

Tillage is often implemented without full understanding of machine design and capability. However, this can be put down to a bad choice or a poor design of implement, which leads to lowered efficiency and further potential damage to the soil structure. Tillage tools can also create damage by working below their design depth. In this situation the soil absorbs the lift energy and smears the mass of soil above (Vandenberg, 1965). Naderman (1990) observed that the cultivator should be set below the hardpan layer but above the finer textured B horizon. He suggested that when the clay soil is within reach of the cultivator, the optimum tillage depth must be set at the depth of the B horizon.

1.7 Methods of detecting soil compaction

Soil compaction can be measured by assessing bulk density, porosity, and pore size distribution. Therefore there are direct and indirect methods of measuring soil compaction (Figure 1-6).

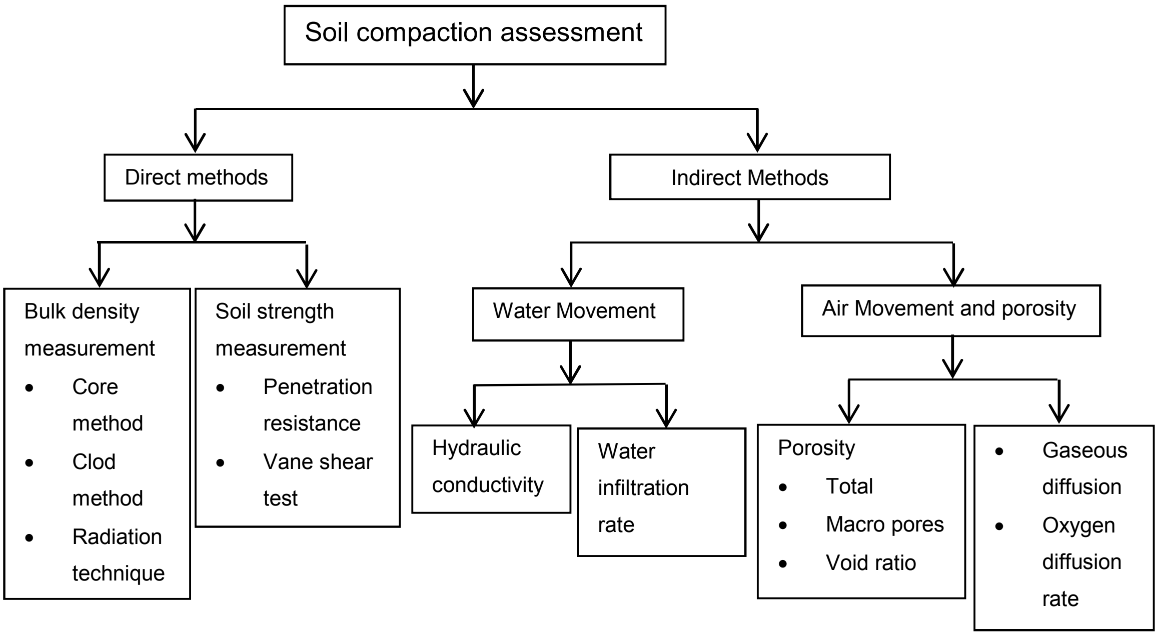

Figure 1-6 Summary of direct and indirect methods of assessing soil compaction (Lal and Shukla, 2004)

In addition to the above conventional methods of measuring soil compaction, there are innovative methods such as those established recently for on-line measurement of topsoil bulk density (Mouazen and Ramon, 2006; Mouazen et al., 2009). Although the system measures topsoil bulk density, it is based on multi-sensor and data fusion approach, which will be considered in this work for fusing vertical penetrometers and a geophysical method (e.g. Electro Magnetic Induction).

1.8 Cone penetrometer for the assessment of soil compaction

A cone penetrometer is a simple tool designed for measuring the soil strength or soil bearing capacity (Figure 1-7). Soil strength is traditionally referred to as the cone index (CI), i.e. penetration force per unit base area of the cone expressed in MPa and is universally accepted as a method to estimate soil compaction caused by field traffic and soil tillage (Domsch et al., 2006). The diameter of the base, top angle and the surface coarseness of the cone are parameters of the penetrometer which affect the measured value (Krajko 2007; Bajla, 1998).

To enable a comparison between obtained readings, dimensions of the cone penetrometer were unified and defined by ASAE Standard 313.3 (ASABE, 2004).

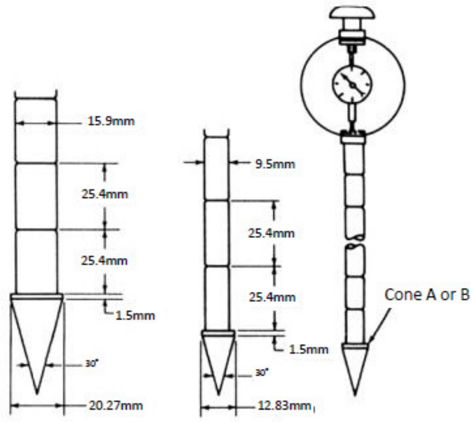

Figure 1-7 Soil cone penetrometer (after ASABE, 2004)

The main advantages of a cone penetrometer are its simplicity of use and cost effectiveness, however even when automated, the stop go nature of the operation makes it very time consuming and the small volume of soil measured mean results can be highly variable (Adamchuk et al 2003). To overcome these limitations a number of horizontal penetrometers have been developed enabling on-the-go sensing of soil strength which have been used to obtain data at specific or multiple depths, Figure (1-8) (Richards, 2000; Sun et al., 2006; Hemmat et al., 2009). Alihamsyah et al. (1990) developed a horizontal cone and wedge penetrometer to measure soil strength at a particular depth. He found encouraging correlation coefficient R^2 of 0.74 and 0.98 between measurements made by a horizontal penetrometer and those from a vertical penetrometer. (Quarishi, 2013)

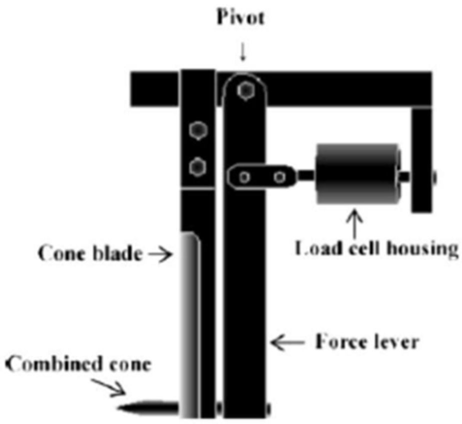

Figure 1-8 Horizontal penetrometer system (after Sun et al., 2006)

Chung et al (2003) developed a horizontal prismatic penetrometer that measured soil strength to 50 cm depth with 10 cm increments. The cutting forces of five prismatic tips in front of the main blade were measured by load cells as the sensor operated through the field. Hall and Raper (2005) developed a mechanical impedance sensor to measure horizontal soil wedge penetration resistance. The authors reported similar results between the wedge index and cone index. A difficulty in translating the sensor data to cone index is caused by the type of soil failure. This is because a vertical penetrometer is always in a bearing capacity failure mode whereas a chisel or knife type sensors act as a simple rigid tines (Hemmat and Adamchuk, 2008).

To determine the extent of compaction across a field using a penetrometer requires a robust and methodical procedure (Domsch 2006). To gain a meaningful understanding of soil variation within a field, not only do multiple tests have to be undertaken but soil moisture content, soil bulk density, organic matter content, soil texture and soil porosity all have to be taken into account when interpreting value of the soil penetration resistance.

One method of minimising the variation is to restrict data collection to conditions of constant moisture states, e.g. at field capacity (Domsch, 2006). This will ensure that when a threshold value is required to decide if to cultivate or not, measurements within a site can be compared. In a study looking at the effect of soil texture, moisture content and bulk density, Kumar et al. (2007) concluded that higher soil cone indexes occurred at the greater soil depth and bulk density. Since penetration resistance of the soil is simultaneously affected by moisture content, bulk density, texture, salinity and organic matter content, cone index alone is not a scientifically accepted option to mapping soil compaction.

1.9 Electro-magnetic Induction (EMI)

EMI is a proximal sensing method which measures a soils ability to transmit electrical current or apparent electrical conductivity (ECa). It is commonly expressed in units of milli-Seimens per meter (mS/m) (Grisso et al, 2009). The proximal nature of the measurement method means that the values recorded define the apparent soil conductivity as a weighted average for a column of soil to a specified depth (Doolittle et al., 1994). The primary factors which affect the measured ECa are the pathways of current flow in the soil. Rhoades et al., (1999) identified these pathways as (i) liquid phase, (ii) solid-liquid, and (iii) a solid pathway. McNeill (1980) and Krajko (2007) listed other physical parameters of the soil which can affect ECa readings, namely soil moisture, cation exchange capacity, salt content of the soil sensing depth and temperature. Furthermore, low conductivity is associated with sandy soils, whereas medium and high conductivities are associated with silt and clay soils, respectively.

The basic principle of operation of the EMI instrument is shown schematically in Figure (1-9). A transmitter coil (Tx) located in one end of the instrument induces circular eddy current loops in the soil. The magnitude of these loops is directly proportional to the ECa in the vicinity of that loop. The current loops generate a secondary electromagnetic field that is proportional to the value of the current flowing within the loop. A fraction of the induced electromagnetic field from the loops is intercepted by the receiver coil (Rx), and the signal is amplified and formed into an output voltage which is linearly related to ECa. (Robinson et al., 2004; Corwin and Lesch 2005a; Abdu et al., 2007)

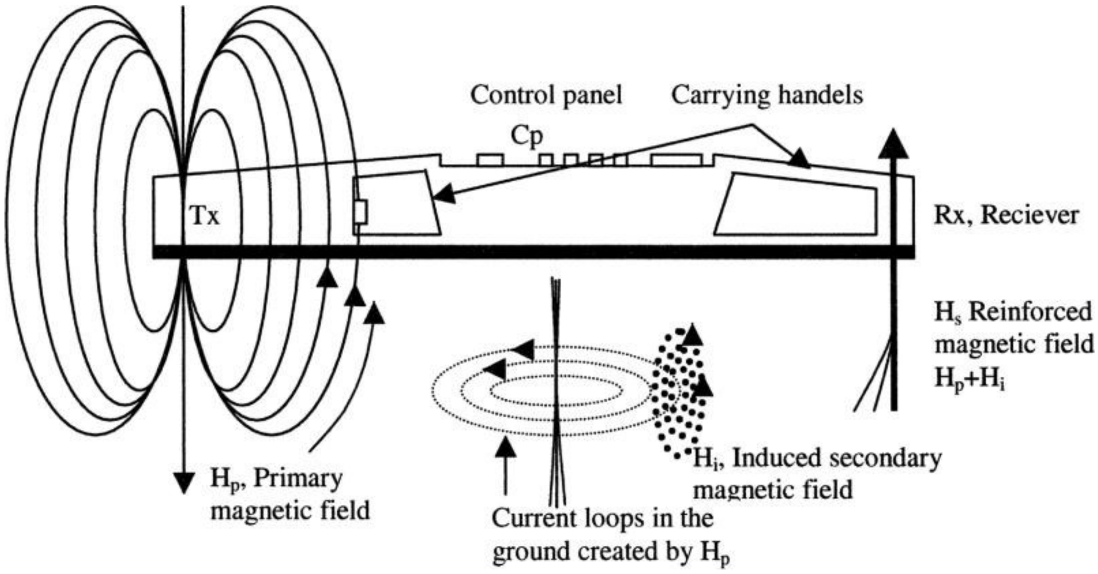

Figure 1-9 Basic principle of operation of EMI meter (Robinson et al., 2004)

ECa of a soil profile can be used as an indirect indicator for a number of soil properties. O'Leary et al. (2003) used an EMI sensor for identifying subsoil properties. They concluded that since electrical conductivity is well correlated with high soil water content, EMI technology coupled with accurate GPS equipment could provide economic opportunities to map out areas of a farm that are affected by subsoil compaction. A study by Rahman (2011) revealed that ECa, which was related to different soil physical properties such as clay content, moisture content, bulk density and salinity can be conveniently used to determine soil variability.

Krajco (2007) investigated using EMI techniques as a cost effective method for the assessment of soil compaction, greatly enhancing the process of soil compaction management. However, because of the EMI sensors sensitivities to other key soil properties as previously discussed he concluded that EMI as one tool in isolation is not sufficient to map soil compaction, although it can offer a possible rapid measurement for soil variability (Kuang et al., 2012). In a similar investigation Al-Gaadi (2012) concluded that whilst ECa measurements could provide a potential for an effective and efficient means of soil compaction assessment, high correlations were only observed between soil compaction and ECa values when the soil moisture content was below 6.94%. At a higher value of 8.0%, low correlations were observed leading him to recommend measurements at low soil moisture content (less than 7% in the case of sand). Abdu et al. (2007) observed that the EMI sensors are most sensitive at the surface and the sensitivity decreases rapidly with depth. Dabbas and Tabbagh (2003) noted that soil profiles are seldom homogeneous and that ECa values measured at the surface represent the same apparent physical characteristics of a homogenous medium therefore many different profiles may produce similar measurements of ECa. Therefore the potential of combining the two methods e.g., penetration resistance and EMI with a proper data fusion approach should be investigated, as to overcome some of the shortcomings of the two methods if they are implemented individually to maps soil compaction horizontally throughout the soil profile.

1.10 On-line measurement systems of soil compaction

Tillage tool draught has often been used to predict and map the spatial variation of soil compaction. Hayhoe at al. (2002) proposed a method of measuring mouldboard plough draught as a surrogate variable for crop limiting properties such as soil compaction. However, Mouazen and Ramon (2003) noted that it is useless to consider draught as a direct indicator of soil compaction whilst ignoring the main important variables such as dry bulk density, moisture content and depth. Therefore it is not recommended to use draught as a measure of soil compaction with on-line mechanical sensors (Quarishi, 2013).

As an alternative method, Mouazen and Ramon (2002) carried out a hybrid finite element model - multiple linear regression (FEM-MLR) simulation to derive a model to predict bulk density as a function of draught, moisture content and depth. They established a linear relationship between draught and moisture content and a nonlinear relationship between draught and bulk density, and draught and depth. The resulting equation (Eq.1-1) can be used to predict dry bulk density if the data on the subsoiler draught, moisture content and depth are provided simultaneously. Mouazen et al. (2009) have updated the original equation to correct further for moisture content and clay content as follows:

$$BD = \left(\sqrt[3]{\frac{D + 21.36\,MC - 73.9313\,d^2}{1.6734}}\right) \times (1.240 - 0.592MC - 0.000792\%clay) \quad \textbf{1-1}$$

where *D* is subsoiler draught [kN], *MC* is gravimetric moisture content [kg kg^{-1}], *d* is cutting depth [m] and *BD* is bulk density [Mg m^{-3}].

The limiting factor of this approach is that the combined measurements are only relevant to the specific depth (e.g. top layer of the soil down to 15 cm) of the instrumented tine making its application limited in a site specific tillage context to topsoil variable tillage. However the method does demonstrate the potential for VDT through the soil profile for eliminating hardpan or plough pan.

1.11 Assessment of the state of compaction

The literature highlights multiple methods for locating and measuring compaction. However, these methods as a measure of soil quality with respect to crop production are unsatisfactory since they lead to crop response curves and optimum values that are different for different soils.

Bulk density values are frequently used as an indicator of soil compaction as it is possible to predict the bulk density value at which root growth and yield are limited. Several researchers have reported a parabolic relationship between bulk density and yield with the maximum value dependant on soil texture, crop and climate (Kaufmann et al., 2008; Pabin et al., Czyz, 2004). A generalised relationship on how changes in bulk density influences crop yield is given in Figure (1-10).

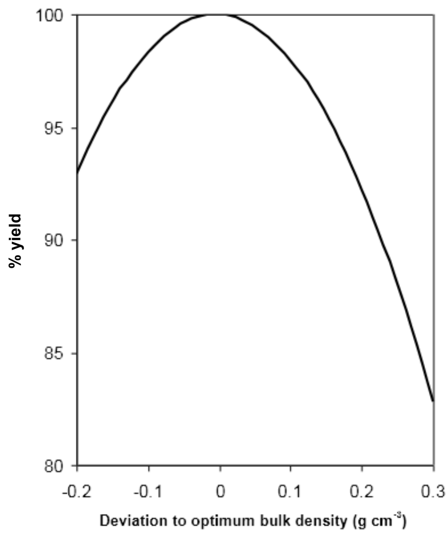

Figure 1-10 Generalised relationship between plant yield and the deviation to the optimum bulk density, after Kaufmann (2008)

However, in a review of methods for assessing the state of compaction, Kaufmann (2008) noted that both the optimum bulk density and yield limiting bulk density values decrease simultaneously with clay and silt content. This is because compacted soil prevents root development due to the soil pores being smaller than the diameter of the growing roots (Daddow and Warrington, 1983). Thus, the sensitivity of bulk density value to the clay fraction renders bulk density a poor indicator of root growth and yield because climatic conditions and soil moisture content will have a large influence on the bulk density value at the time of the measurement. To overcome this limitation, the calculation of packing density (PD) using eq. (1-2) allows for the transformation of bulk density values into a clay independent indicator by adding a correction term given as the product of clay content with the slope of the regression lines (Kaufmann, 2008)

$$PD = BD + 0.009\ CC \tag{1-2}$$

where PD is packing density, BD is bulk density (g/cm3) and 0.009 CC is the correction term given as a product of clay content with the slope of the regression lines (Renger 1970).

Implementation of packing density as an indicator of the state of compaction requires a table of mean values classifying the lower and upper ranges of optimum and limiting values for crop growth (Table 1-1).

Table 1-1 Packing density classifications for crop growth (Kaufmann 2008)

PD value (t/m^3)	Crop growth condition
< 1.40	Below optimum range
1.40-1.55	Lower optimum range
1.55-1.70	Upper optimum range
1.70-1.82	Lower limiting range
> 1.82	Upper limiting range

1.12 Tillage Systems

Tillage is the mechanical disturbance of soil with the intent of reducing strength and bulk density thereby alleviating compaction. Normal tillage operations do not disturb soil deeper than approximately 20-30 cm and in the case of no-till crop production; there is generally no disturbance. When compaction occurs below the normal depth of tillage, deep tillage or subsoiling is required.

The concept of precision tillage was described by Carter and Tavernetti (1968) where the tillage depth was precisely specified to reach and disturb a compacted layer. However, as discussed above there is a great amount of variability in the depth and thickness of hardpan layers because different soils vary in their bearing capacity to support given loads without suffering compaction damage. This ability is very dependent upon the more stable properties of soil type and the packing arrangement of soil particles and aggregates (Spoor et al., 2005). Moreover, in some areas of the field, compaction doesn't exist at all (Clark, 1999; Raper et al., 2001).

Precision deep tillage is attractive from the stand point of eliminating unnecessary effort, thus reducing energy consumed. Raper et al. (2005b) performed an experiment to investigate the benefits of subsoiling at different depths. The results showed slightly higher savings with a 59% and 35% decrease in draught with the 25 cm and 35 cm depths, respectively, compared to the uniform depth tillage at 45 cm. Reductions in power requirements reached 52% with the 25 cm depth compared to deep tillage and 26% less power required at the 35 cm tillage depth. Estimations of fuel savings ranged from 43% with the 25 cm depth and 27% less fuel for the 35 cm tillage depth.

Gorucu et al. (2001) researched variable depth tillage based on geo-referenced soil compaction using data from a cone penetrometer, electrical conductivity and yield maps to assess soil variability of the field. The field was divided into four management zones according to soil electrical conductivity and penetrometer data. According to predicted tillage depths, 75% of the field could be tilled shallower than the conventional tillage depth. Each zone was subjected to five replications of three treatments; no tillage, uniform depth tillage and variable tillage. Variable depth tillage was carried out at 25 cm, 33 cm and 38 cm. Deep tillage was performed at a depth of 41cm. A tractor was implemented with a data acquisition system that collected fuel consumption, engine speed, ground speed, wheel slip and draught forces. Results indicated a 42% energy savings and a 28% fuel savings with variable depth tillage compared to constant depth tillage.

2 Research aim and objectives

2.1 Research gaps

Agricultural soils are susceptible to soil compaction which restricts root growth and plant development. Compaction also increases the soil bulk density and soil strength which increases the cost of remediation through tillage.

Soil textures containing fine soil particles and a higher portion of soil pores are assumed to compact more easily. Therefore clayey soils can be compacted more easily than sandy soils (Krajco 2007). Recognising and mapping these variations within field using direct and indirect sensors has been demonstrated to be an acceptable method of implementing site specific tillage. However, the limitations of this approach are twofold. Firstly, using sensors in isolation means that their operating constraints are always factored into the tillage plan. Secondly, the readings are of physical soil parameters e.g. soil resistance and ECa, which don’t translate well across varying soil types and moisture content, unlike a relative compaction approach which can indicate an optimum growing environment across different soils. Furthermore, existing on-line soil sensors to measure bulk density are useful for mapping topsoil soil compaction, while no information about soil compaction profile can be obtained.

This research will propose a method of the fusing multi sensor data to delineate management zones using relative compaction (e.g. packing density), as a trigger for whether to apply tillage or not.

2.2 Research aim

To develop a new approach and measurement system of soil compaction through the soil profile based on a multi-sensor and data fusion approach. The final output will be a 2-D packing density maps for each of the eight soil layers used as input for variable depth tillage.

2.3 Research objectives

1. To collect geo-referenced data on soil penetration resistance, ECa and bulk density and moisture content using an electromagnetic induction (EMI) sensor, hydraulic cone penetrometer and a Kopecky ring, respectively.
2. To fuse the multi-soil data, using geo-statistical methods to delineate by layer management zones for site specific tillage.
3. To establish models to derive bulk density as a function of PR, ECa and MC using multivariate statistical methods.
4. To calculate the mean and maximum packing density of each management zone through different soil layers thereby determining the depth of tillage site specifically.
5. To develop a 2-D packing density map for each soil layer to be used as input for variable depth tillage.

3 Materials and Methods

3.1 Experimental site

A 2.43 ha arable site near Bourne, South Lincolnshire, England (520 44’ N, 00 19’ W) was selected (Figure 3-1).

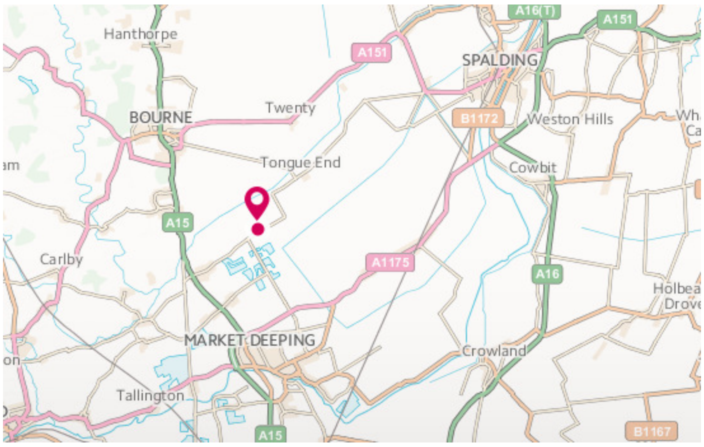

Figure 3-1 Site location of the field experiment

Located on the edge of the clay fens, the organic clay site (Table 3-1) is described as being part of the Badsey 2 Association, relatively stone-free loam material overlying sands and gravels between 30 and 80 cm (Soil Survey of England and Wales).

Table 3-1 Soil textural assessment from the experimental site

Sand % w/w	Silt % w/w	Clay % w/w	O.M. % w/w
31.75	35.25	33	9.6

Wheat, potatoes and sugar beet are the main crops of cultivation, which is typical for the area. At the time of the experiment the site was fallow and had not been cultivated. To conduct the experiment a 90 x 270 m, area was divided into 243, 10 x 10 m grid squares. After identifying the experimental site, field measurements were carried out successively by EMI sensor to measure ECa, a mobile penetrometer to measure soil penetration resistance and a Kopecky ring kit to measure bulk density and moisture content, as described below.

3.2 Apparent electrical conductivity (ECa) survey

The ECa data collection was obtained with a mobilised DUALEM-1S sensor (Dualem, Inc., Milton, ON, Canada) working on the principle of electromagnetic induction. The DUALEM-1S instrument maintains a spacing of 1 m between the transmitting coil at one end of the instrument and the receiver coils at the other. Although no infield calibration is required as the working parameters are pre-set by Dualem Inc. during manufacture, the sensor automatically compensates for temperature during operation. An analogue output is provided to allow data to be recorded on a data logger or computer. Two working depths are measured simultaneously by the instrument. This was achieved by the geometry of the transmitting and receiving coils (Figure 3-2).

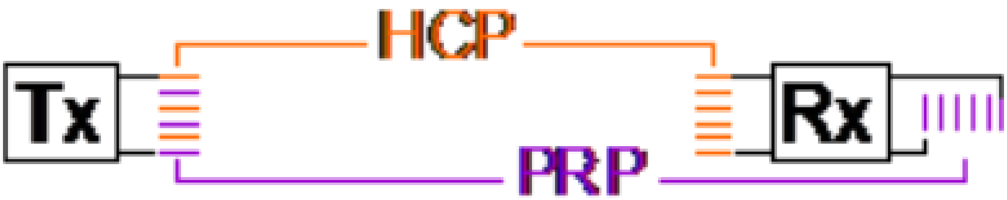

Figure 3-2 Schematic diagram of the DUALEM 1S transmitting (Tx) and receiving (Rx) coil orientation, enabling simultaneous measurements of two soil depths

The vertical coil (HCP) provides an effective measurement depth of approximately 1.2 m. The horizontal coil (PRP) provides an effective measurement depth of 0.75 m. The ECa measurements from the DUALEM sensor are averaged over a lateral area approximately equal to the measurement of depth.

To mobilise the DUALEM-1S sensor the unit is mounted on a 3 m long trolley (Figure. 3-3). Manufactured from a composite frame the trolley is supported at the rear by two pneumatic tyres, which was pulled by a quad bike. Use of a composite material is necessary because the DUALEM-1S will respond strongly in the presence of metallic object within ~1 m, which is avoided by the composite material used.

Figure 3-3 Composite field trolley for the DUALEM sensor (SOYL, 2015)

The length of the trolley is also an important consideration as this extends the distance between the sensor and prime mover eliminating the effects of engine noise from the quad bike on the instrument readings. Using this configuration the instrument is suspended 20 cm above the ground surface during data collection. Analogue ECa data from the DUALEM 1S was read into a differential global positioning system (DGPS) data logger (NOMAD, Trimble, USA) mounted in front of the quad bike operator using Star Pal GPS Mapping software (Star Pal, CO, USA). The DGPS data were integrated with the DUALEM 1S data to provide the coordinates of each measurement point. Data were collected on 10 m transects spaced evenly over the study area (Figure 3-4). Data was recorded at a 1 second interval, corresponding to a measurement every 2–3 m along the measurement transects. In total 2569 ECa measurements were recorded at each ECa depth, namely 0-40 cm and 0 – 120 cm.

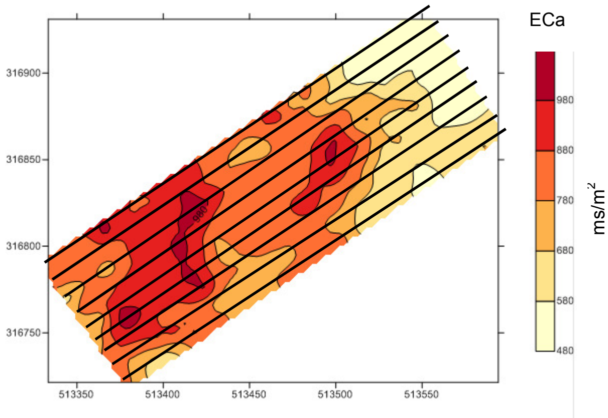

Figure 3-4 Simulation of an on-the-go sensor platform was achieved by ensuring the DUALEM 1S and the Amity soil penetrometer followed the same transects

3.3 Soil penetration resistance

3.3.1 Penetrometer survey

Spatial and with depth soil resistance data was collected every 10m along each transect followed during the ECa measurement. The Amity mobile penetrometer (Amity Technology, ND, USA) used was a self-contained, trailer mounted penetrometer designed to be pulled along by a quad bike (Figure 3-5). An on board power unit and hydraulic cylinder are used to insert the penetrometer measurement probe to a maximum depth of approximately 50 cm. Actual insertion depth relative to the ground surface may vary by several cm due to uneven ground. Maximum insertion force is limited to approximately 1 kN, or 5 MPa to prevent overloading the mechanical components.

Figure 3-5 Mobilised Amity penetrometer in work

Insertion depth is detected by a proximity switch that senses a slotted bar attached vertically to the sensing probe. Data collection is triggered every 1.8 cm as the slotted bar moves past the proximity switch. Insertion force is measured by a pressure transducer mounted in the hydraulic circuit. The insertion force is reported as cone index (CI), or the insertion force per unit cone base area. Data are location-tagged by a DGPS and read on a mobile computer (NOMAD, Trimble, USA) using Amity Compaction Mapping Software.

3.3.2 Amity penetrometer calibration

To translate the insertion force (measured as hydraulic pressure) into cone index the Amity penetrometer requires a multiplication factor (MF) to be calculated and entered into the compaction mapping software. As it was not safe or practical to physically measure the force exerted by the cone, an investigation to determine the MF was carried out at the soil bin facility at Cranfield University using a Eijkelkamp Penetrologger (Giesbeek, Holland) (Figure. 3-6)

Figure 3-6 Eijkelkamp Penetrologger

The Eijkelkamp penetrometer is able to record measurements up to a depth of 0.8m with a 10mm depth resolution. During the penetration, soil depth is measured by an internal ultrasonic sensor using the depth reference plate. All the logged data is saved in the internal memory of the penetrologger.

Figure 3-7 Amity penetrometer during calibration at the Cranfield soil bin

The soil bin was prepared prior to the investigation by splitting the soil bin into two zones of equal density using the soil compactor. The first was 1.4 kg/cm^3 and the second was 1.6 kg/cm^3. These densities were confirmed from random samples taken from the soil bin using the Kopecky ring method**.** A benchmark soil resistance data set was created using the calibrated Eijkelkamp instrument by logging ten penetrations, 30 cm apart along the soil pit. The Amity instrument (Figure 3-7) was then operated at alternate locations to those taken with the Eijkelkamp instrument.

This procedure was repeated in the denser soil, previously prepared in the second half of the soil bin. The resulting values of penetration resistance as a function of depth from both data sets were averaged to determine a single mean value for each instrument. These single values were then combined to determine a multiplication factor for the Amity instrument, explained as follows. (Eq. 3-1)

$$\text{(Eijkelkamp mean value)/ (Amity mean value) = Multiplication factor.} \qquad \textbf{3-1}$$

3.4 Collection of soil samples

It was not economic to take soil samples from each of the 243 penetrometer sample points. Therefore the number of samples and their location was determined from management zones derived from the ECa data collected by the DUALEM sensor (Figure 3-8). To develop the management zones a data set was created by averaging and squaring the two depth ECa data, thus ensuring that all of the sensor data was included, and each zone had a wide value range because of the squaring. This new data was then interpolated with an inverse distance weighted algorithm in SURFER 10 (Golden Software, CO, USA). Using a GPS device (NOMAD, Trimble, USA), pre-loaded with the management zones, four sample sites were randomly selected within each of the four ECa^2 ranges for BD and MC. To minimise the cost of the particle size distribution test for clay content analysis, three samples were taken randomly from management zones using a wider ECa^2 range (Table 3-2).

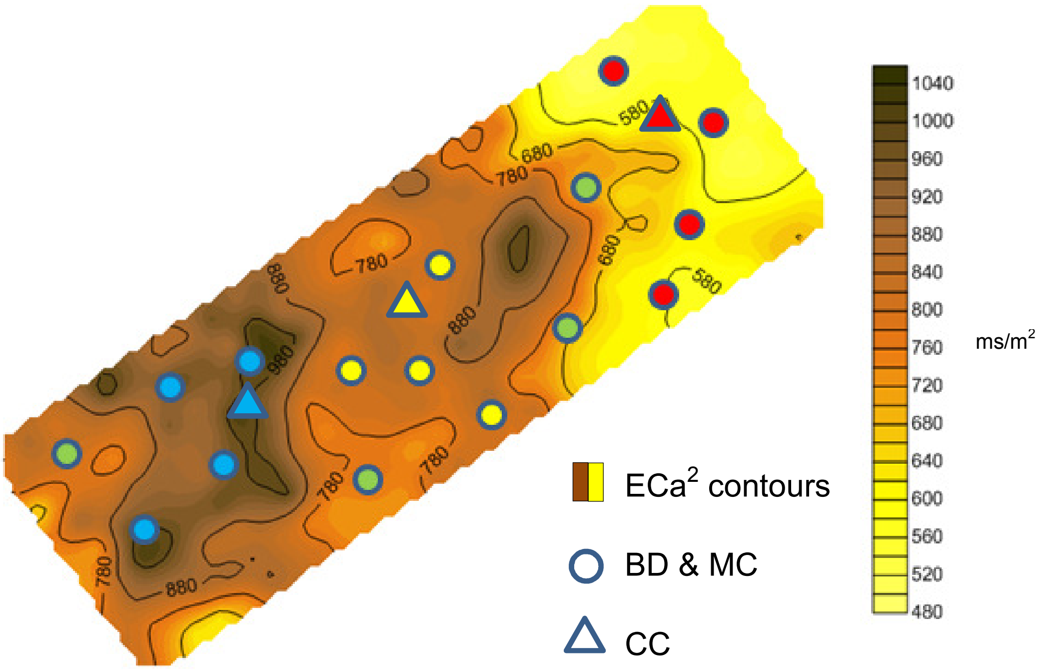

Figure 3-8 Soil sample location for bulk density (BD), moisture content (MC) and clay content (CC)

Table 3-2 Summary table of ECa^2 values used to create the sample zones

Sample	Classification	ECa^2 Range	Sample #
BD & MC		480 – 630	12, 14, 15, 16
		631 – 780	1, 6, 11, 12
		781 – 930	7, 8, 9, 10
		930 - 1080	2, 3, 4, 5
Clay content		480 – 680	3
		681 – 880	2
		881 – 1040	1

3.4.1 Samples for moisture content and bulk density

To collect the samples for bulk density and soil moisture by depth, a Kopecky ring method was used. For each sample a 5 cm deep ring was hammered into the ground collecting 100 cc of soil per sample. In total 8 x 5 cm undisturbed soil samples were taken sequentially down the profile. The resultant soil was sealed in a polythene bag, to prevent weight loss by evaporation, and labelled with GPS location and profile position.

3.4.2 Samples for clay content

At each clay content sample location, a soil pit (50 cm x 50 cm x 50 cm) was manually excavated using a spade. From one side of each of the three soil pits, 4 x 10 cm samples of soil were carefully removed sequentially down the profile using a trowel, after which they were placed into a plastic bag labelled with GPS location and profile position.

3.5 Laboratory experiments

Overall 140 soil samples were collected from the experimental site (128 samples for BD, MC and 12 samples for CC) and analysed in the laboratory (APPENDIX A). The methods used for the measurements are described below.

3.5.1 Moisture content analysis

Moisture content of the soil was determined by drying the soil samples in an oven at 105℃ for a minimum of 24 hours (BS 7755, 1994). The moisture content measurement was deduced by calculating the difference between the mass of the wet samples and the samples after drying.

3.5.2 Bulk density analysis

Bulk density of the soil was determined by subtracting the dry weight values from the moisture content analysis and dividing them by the volume (100 cm^3) of the soil core. (Eq.3-2)

$$\text{Bulk density} = (\text{Dry weight of bulk sample (g)})/(\text{volume of soil core } (cm^3)) \quad \textbf{3-2}$$

3.5.3 Particle size distribution (PSD) analysis

Soil texture was determined using a sieve and sedimentation method according to BS 7755 section 5.4 (BSI, 1998). This method has four successive processes, each of which further separates the soil particles.

1. Organic matter removal
2. Dispersal and wet sieving
3. Dry sieving the sand fraction
4. Determination of silt and clay by pipette extraction

Having reduced the soil sample to individual particles their distribution is calculated using the following equations

$$D = d/20 \tag{3-3}$$

$$F = S + [(Z - D) * 20] \tag{3-4}$$

$$\%sand = (\text{mass of particles of sand fraction})/F * 100 \tag{3-5}$$

$$\%\ 0.002 \text{ to } 0.063mm = ((Z - C)*20)/F * 100 \tag{3-6}$$

$$\% < 0.002mm = ((C - D)*20)/F * 100 \tag{3-7}$$

Where, D = Dispersant factor

F factor = (mass all sand sample) + (mass of all silt sample – D) x 20

d = oven dry mass of sodium hexametaphosphate solution (g)

Z = mass of 0.002 – 0.063mm pipetted sample (silt + clay) (g)

C= mass of < 0.002mm pipetted sample (clay) (g)

3.5.4 Soil texture classification

The textural class of a soil was defined on the relative proportions of sand, silt and clay. The UK uses a system of classification developed by the former soil survey of England and Wales, which is different from others in use around the world such as the United States Department of Agriculture (USDA.) The particle size classes are based on particle size grades of the British Standards Institute (BSI). (Table 3-3)

Table 3-3 Particle size classes based on particle size grades of the British Standards Institute

Particle Class	Particle subclass	Particle size (mm)
Clay		<0.002
Silt		0.002-0.06
Sand	Fine	0.06-2.0
Sand	Fine	0.06-0.2
	Medium	0.2-0.6
	Coarse	0.6-2.0

To determine the soil textural classification the calculated percentages of sand, silt and clay were plotted on a UK soil texture classification triangle.

3.6 Data processing, mapping and tillage zone delineation.

3.6.1 Penetration resistance data

The Amity penetrometer records 22 soil resistance measurements throughout the soil profile, the depth interval between each sample is 1.8 cm. To fit these 22 measurements into eight, equal depth soil layers the data to be modified by averaging values of neighbouring points within the soil profile. The allocation of each measurement is defined in Table 3-12.

Table 3-4 Allocation of penetration resistance measurements to experimental depth layers

Measurement	1,2,3	4,5,6	7,8	9,10,11	12,13,14	15,16	17,18,19	20,21,22
Soil layer	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm

A further benefit of combining adjacent penetration resistance measurements is data smoothing. Domsch (2006) had noted that by calculating the means of consecutive 50 mm depth layers within penetrometer data, irregularities were largely removed and the character of the function became obvious. The penetration resistance measurements for each layer were then interpolated using the inverse distance weighting algorithm to develop maps for each of the eight soil layer using SURFER 10 (Golden Software, CO, USA)

3.6.2 EMI data

The ECa data was not manipulated because the ECa survey track precisely followed the transect centre line of the penetrometer survey ensuring that the same soil profile was measured. To aid with interpretation of the experiment results and to determine the location of clay content samples the ECa shallow and ECa deep data were visualised by IDW interpolation using SURFER 10 (Golden Software, CO, USA)

3.6.3 Bulk Density and Moisture content data

Using the IDW interpolation method the 16 x 8 bulk density and moisture content samples were interpolated by layer and plotted as contour maps using SURFER 10 (Golden Software, CO, USA).

3.6.4 Clay content data

To extend the clay content results across the experimental site, each grid node located within the ECa^2 zones defined in Table 3-2 was allocated with the clay content sample result taken from that zone (Figure 3-9).

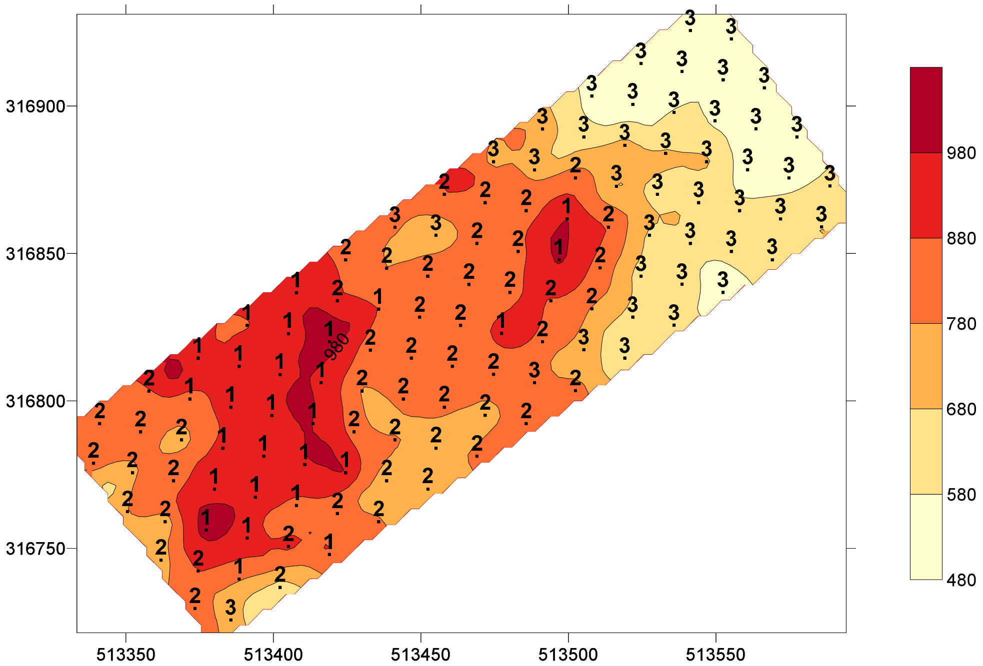

Figure 3-9 Classification key of the extrapolated clay content analysis at the 10 cm layer

To create the by depth clay content data for each of the eight soil layers the four 10 cm samples were extended into 5 cm layers (Table 3-5)

Table 3-5 Allocation of by depth clay content results to experimental soil layers

Sample Depth	10 cm		20 cm		30 cm		40 cm	
Allocated Depth	5 cm	10 cm	15 cm	20 cm	25 cm	30 cm	35 cm	40 cm

3.6.5 Data fusion by raster analysis

As an initial step towards data fusion, data for each measured soil property was IDW interpolated and then transformed into a common 10 m raster using Manifold GIS (Manifold Software Ltd, Wanchai, HK). The raster squares of the soil property layers were then converted into a grid of common points by spatially joining the mid-point of each raster square. The output from this process was a 10m grid of point values which would allow the application of the k-means clustering algorithm. Halcro (2013) and Khosla et al., (2008) used this method to delineate management zones from a range of soil properties, measured at different resolutions. The 10 m grid in this work provided a practical balance between characterising the spatial variation and being able to control a VDT cultivator in the field.

3.6.6 Management zone delineation

To achieve the research objective of creating a site specific tillage plan it was necessary to create management zones by identifying sub regions within the field which have internally similar characteristics. This was achieved by applying the k-means clustering to the ECa, penetration resistance, bulk density and moisture content measurements of each depth layer. The k-means clustering process transforms the measurements into normalised numerical values associated with each variable in the analysis. As an iterative process the normalised values were grouped and re grouped into classes until the within group variation is minimised and the between group variation is maximised (Taylor et al. 2003). A feature of k-means clustering, which is of benefit to precision farming applications, is the option to preselect the total number of clusters prior to processing, thereby managing the size and number of the clusters. (Taylor et al. 2003). For this work three clusters were selected because of the relatively small size of the experimental site. The cluster analysis was performed using STATISTICA 12 (Statsoft. Inc. OK, USA).

3.6.7 Cluster Analysis

Graphs of normalised continuous means of each soil depth were produced using STATISTICA 10 (StatSoft Inc., USA). The graphs were examined to understand the characteristics of each cluster. The differences in mean levels of individual soil properties defined the cluster characteristics for each depth, which would then be used to delineate management zones.

3.6.8 Multi linear regression analysis (MLR)

The real time calculation of bulk density as opposed to the time consuming laboratory methods would be an important development for VDT, enabling the state on soil compaction to be determined in real time. This can be obtained by means of a penetrometer equipped with multi-sensors, which was developed at Cranfield University (Quraishi and Mouazen, 2013). This multi-sensor platform consists of a load cell to measure penetration resistance and a visible and near infrared spectroscopy sensor to measure clay content and moisture content (Figure 3-10).

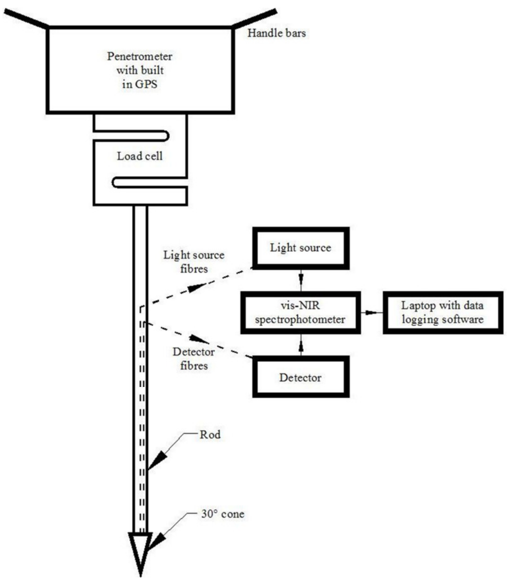

Figure 3-10. A prototype bulk density sensor (PBDS) with built-in load cell, GPS, and vis-NIR spectrophotometer. This sensor was validated to predict topsoil bulk density in three fields in Silsoe farm in Bedfordshire the UK (After: Quraishi and Mouazen, 2013).

Using this instrumented penetrometer to measure penetration resistance and moisture content and a commercially available EMI sensor to measure ECa, the key factors affecting bulk density, namely ECa, penetration resistance and moisture content could be measured and used to predict bulk density using an empirical model to be developed with multi-linear regression (MLR) analysis. Therefore, a MLR analysis was carried out with bulk density being the dependent parameter and ECa, penetration resistance and moisture content are the independent parameters as follows:

$$\text{BD (g/cm}^3\text{)} = f(\text{ECa, PR and MC}) \qquad \textbf{3-8}$$

3.6.9 The MLR analysis was carried out using STATISTICA 12 (Statsoft, USA) for each of the eight soil layers. Packing Density (PD)

Bulk density measurements are sensitive to changes in soil texture making it unsuitable as a measure of compaction for VDT where soil texture is expected to change significantly in a short distance across the field and through the soil profile. Overcoming this limitation is therefore important and can be achieved by adopting the packing density of the soil instead of the bulk density. By taking account of the clay content and transforming the bulk density value into a clay independent indicator by adding a correction term given as the product of clay content with the slope of the regression lines, the packing density can be derived (Kaufmann 2008). Taking the interpolated by layer bulk density and the assigned clay content values from the data, the mean packing density for each cluster was calculated using (eq. 3-9)

$$\text{Packing density} = \text{BD} + (0.009 \times \text{CC}) \qquad \textbf{3-9}$$

where PD is packing density, bulk density is bulk density (g/cm3) and 0.009 CC is the correction term given as a product of clay content clay content with the slope of the regression lines (Renger 1970).

The need for tillage and more precisely variable depth tillage was decided based on the effect of packing density values on crop growth (Table 3-6). As can be observed the need for tillage can start from any packing density values in the upper optimum range (1.55-1.70 t/m^3), but will be definitely needed for any packing density value larger than 1.70 t/m^3. This was the guideline adopted in this work to calculate the need for variable depth tillage.

Table 3-6 Packing density range for crop growth (Kaufmann 2008)

PD value (t/m^3)	Crop growth condition
< 1.40	Below optimum range
1.40-1.55	Lower optimum range
1.55-1.70	Upper optimum range
1.70-1.82	Lower limiting range
> 1.82	Upper limiting range

3.6.10 A holistic approach

Figure (3-11) describes the holistic approach for the derivation of variable depth tillage recommendation maps. After a management zone for a soil layer is derived, average bulk density and clay content are calculated per cluster and substituted into equation (3-9) to calculate the packing density per cluster, hence the need for tillage or not can be established based on the packing density classes of described above (Table 3-6). However, **for future application**, a modelling approach to derive bulk density and packing density in real time is needed. This should be combined with multi-sensor and data fusion approach. The established per layer models of Equation 3-8 will be utilised to calculate bulk density based on input data on ECa obtained with an EMI sensor and moisture content and penetration resistance data obtained with the multi-sensor platform (Figure 3-10). By substituting the calculated values of bulk density and measured values of clay content with the multi-sensor platform (e.g. NIR penetrometer sensor), into Equation 3-9, packing density can be calculated. Finally, the decision on variable depth tillage is obtained by comparing the calculated packing density values with those in Table 3-6. When any packing density value at a point is larger than 1.7 t/m^3, this should be considered as critical to crop growth and yield and tillage should be implemented.

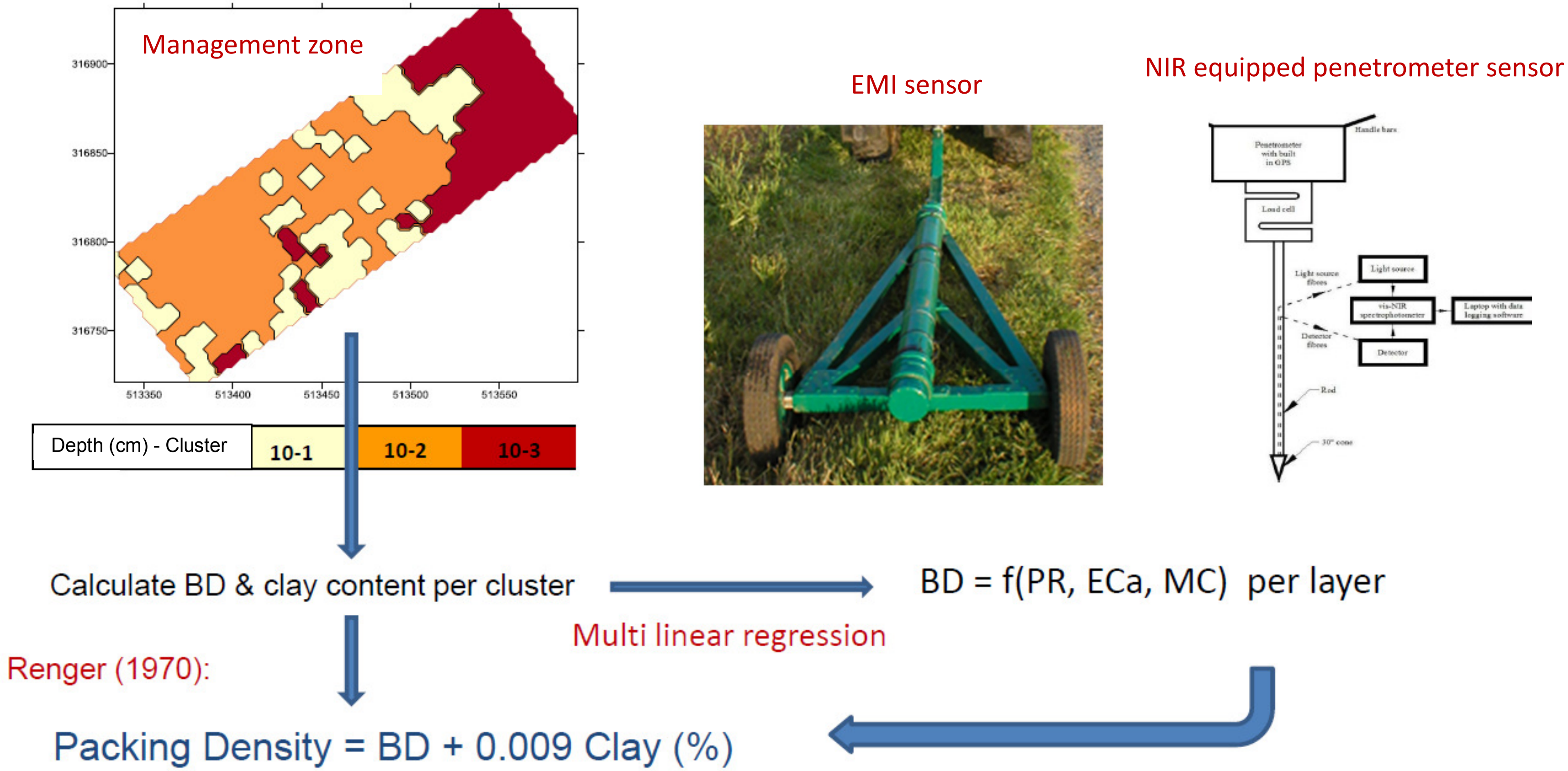

Figure 3-10 A holistic approach for the derivation of variable depth tillage prescription maps. Bulk Density (BD) is calculated from the combined inputs of soil ECa, penetration resistance and moisture content measurements.

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3.7 Assessment of tillage cost

To calculate the potential financial benefit of VDT a test was performed to calculate the total cost of tillage at a universal depth. A four wheel drive CLAAS Arion 630 cis agricultural tractor was the prime mover for this experiment. A Tim Howard, three legged, 2.7 m wide subsoiler (Figure 3-11) was used as the tillage implement. The data acquisition system for the experiment was the CLAAS Cebis terminal fitted as standard equipment to the tractor. Cebis combines signals from the linkage load cells, ground speed radar and the engine with implement width to calculate total and spot work rate and fuel usage. The parameters for the test were a universal tillage depth of 40 cm, with the tractor operated at a commercially acceptable speed of 7 kph and 1700 rpm engine speed. Tillage depth describes the measure of distance from the point tip of the cultivator in the soil to the soil surface. The depth of the implement was controlled by the packer roller behind the tines. The depth was measured by inserting a measurement probe into the ground and hydraulically adjusting the position of the roller until the correct depth was achieved.

Figure 3-11 Tim Howard three legged subsoiler being operated during the tillage cost assessment

4 Results and Discussion

4.1 Soil Characteristics

The planned start date of the experiment was the beginning of March 2014. This had to be postponed for three weeks due to 211mm of rain falling since the beginning of January in that year, waterlogging part of the site, making physical measurement and vehicular access impossible. During the postponement it was necessary to monitor field moisture content to ensure that the planned penetrometer values would be taken at field capacity and therefore would not be adversely affected by soil moisture.

4.1.1 Particle size distribution (PSD)

To determine the soil texture horizontally and with depth a PSD analysis was carried out with soil from three locations comprising four 10 cm samples taken sequentially down through the soil profile. (Figure 4-1)

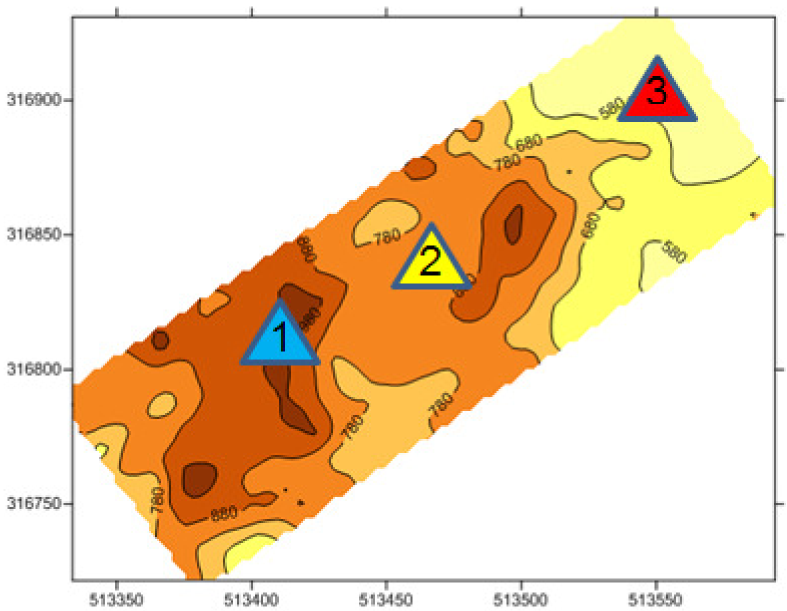

Figure 4-1 Sample location for the particle size distribution analysis

The PSD results presented in Table 4-1 and Figure 4-2 indicate a predominately clay soil which changes to a clay loam as the sand fraction increases. At and below 40 cm the soil organic matter content declines significantly and the sand fraction increases. This is typical of the area and has a significant impact on the productivity of the site. In dry years, moisture in the free draining soil quickly becomes exhausted and if it isn't replenished severely limits the crop yield potential. Therefore cultivating only the areas of the field where the soil structure is poor will ensure that the naturally occurring capillary channels within the clay layer are not destroyed, allowing good root penetration and moisture utilisation within the soil profile. The notable rise in the sand fraction within the third sample group has the effect of moving the 40 cm sample from clay into clay loam. At the 40 cm depth, the sand and gravel horizon becomes more evident from the significant reduction in organic matter values across all the samples.

Table 4-1 Clay content results from the particle size distribution analysis by sample location and depth interval

Sample location	Sample depth (cm)	Sand %	Silt %	Clay %	Organic Matter (LOI) %
1	10	20	38	42	13.5
	20	20	44	36	11.7
	30	19	42	39	11.4
	40	19	43	38	8.5
2	10	22	38	40	14.2
	20	21	40	39	14
	30	22	37	41	13.9
	40	20	46	34	8.1
3	10	28	36	36	12.2
	20	29	36	35	11.7
	30	31	32	37	10.9
	40	39	37	24	3.6

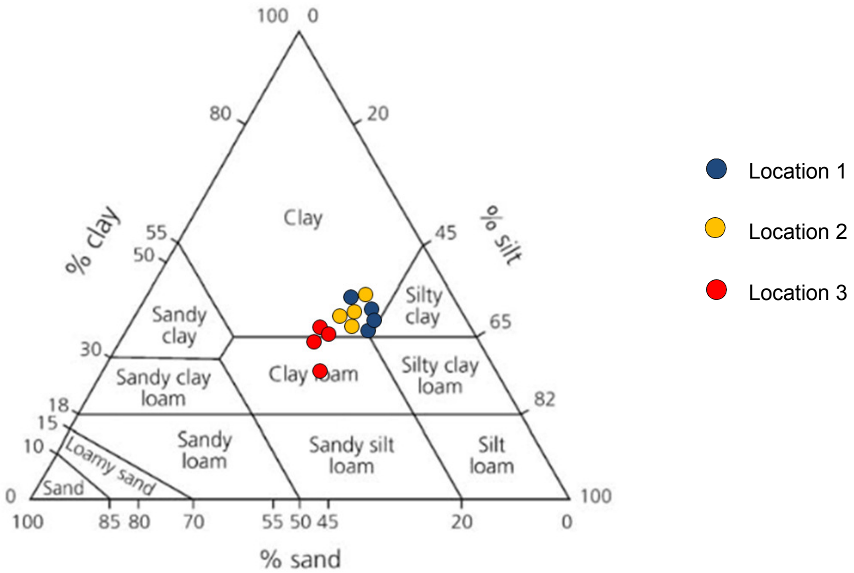

Figure 4-2 Soil texture classification according to the UK Soil Classification Scheme

4.1.2 Bulk density and moisture content analysis

The bulk density results from the laboratory analysis are shown in APPENDIX A. Boxplot analysis of the bulk density by depth has been displayed in Figure (4-3). The general trend of bulk density is to that it increases with depth. This can be attributed to the root crop rotation previously practiced in this field where soil preparation would involve deep tillage, loosening the soil profile, making it very susceptible to compaction. During the root harvest the vertical forces exerted by heavy agricultural machinery compact the deep subsoil. Individual distributions are all relatively even with the exception of the 30 cm layer. At this depth the large interquartile range indicates a transient layer of less dense to more dense soil at 25 to 30 cm. In terms of range, which can be inferred as spatial variation, the 20 and 35 cm depths are the most significant. At 20 cm the bulk density value ranges from 0.85 to 1.45 mg/m^3 indicating that there are areas at that depth that are not compacted (0.85 mg/m^3) and those that are relatively compacted (1.45 mg/m^3). The layer at 20 cm is also typically the maximum depth at which most surface cultivations are carried out therefore this range could be indicative of an implement induce compaction layer. The 35 cm on the other hand is immediately above the sand and gravel horizon at 40 cm, which is likely to have had an effect on the bulk density values.

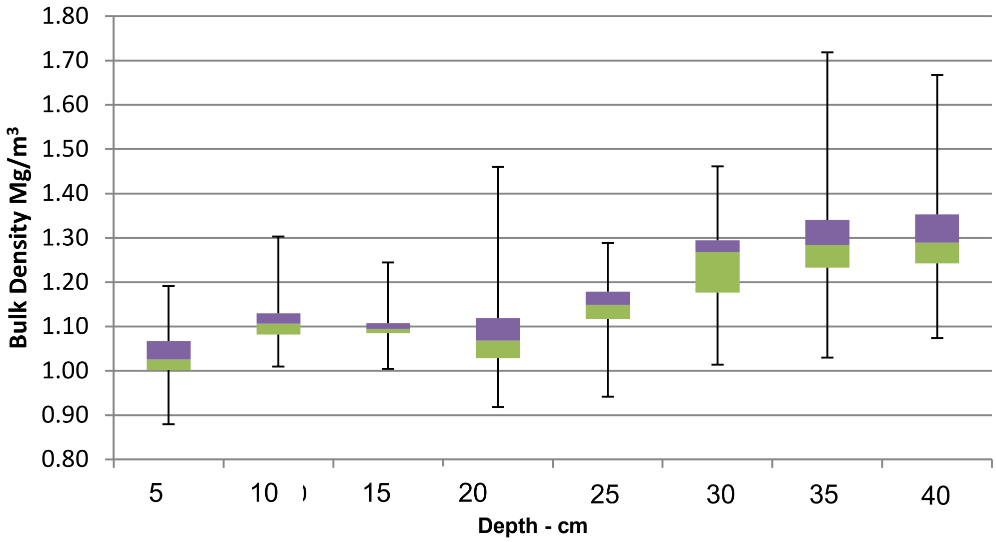

Figure 4-3 Bulk density analysis by depth (cm). The measurement range is illustrated by the plot whiskers. The interquartile range, mean and distribution are represented by the coloured box. n=243

4.1.3 Moisture content analysis

The individual moisture content results from the laboratory analysis are shown in APPENDIX A. The general trend of the moisture content, shown by the boxplot analysis in Figure (4-4), is that moisture content decreases with depth. Individual distributions are mainly even with the exception of the 30 cm depth where the large interquartile range illustrates a wide range of moisture content values. The respective inter quartile ranges (IQR) at 20 and 25 cm are the smallest of the sample, indicating there is very little variation of moisture at that depth. This information taken in conjunction with the results found from the bulk density could be further evidence of a plough pan at 200 mm where that the natural soil pores have been damaged preventing the movement of water through the profile.

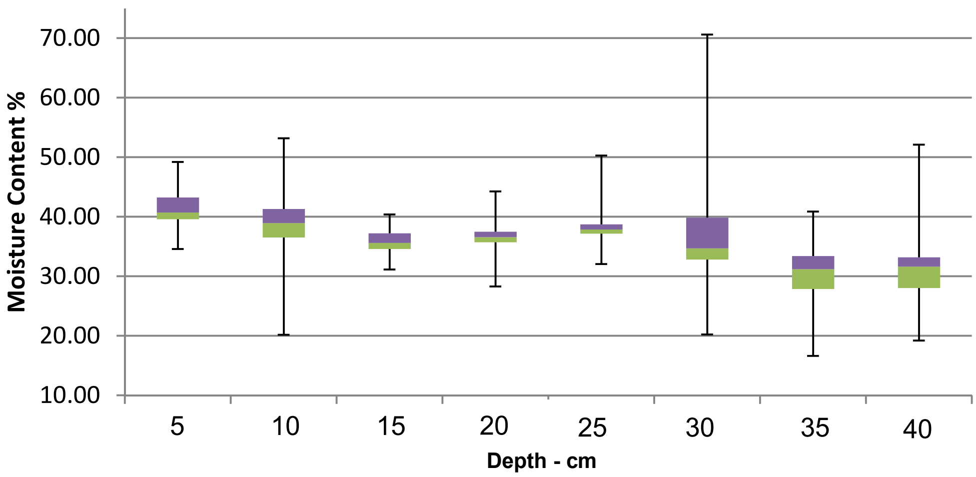

Figure 4-4 Moisture content analysis by depth (cm). The measurement range is illustrated by the plot whiskers. The interquartile range, mean and distribution are represented by the coloured box. n=243

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4.1.4 Penetration resistance

Soil penetration resistance measurements were completed in 243 locations using the 10x10 m sampling grid. At each sample point 22 individual soil resistance measurements were recorded at 1.8 cm intervals. These measurements were then modified to 8x5 cm depths, to coincide with the previously recorded bulk density and moisture content measurements, by averaging recorded values immediately adjacent to a 5 cm interval.

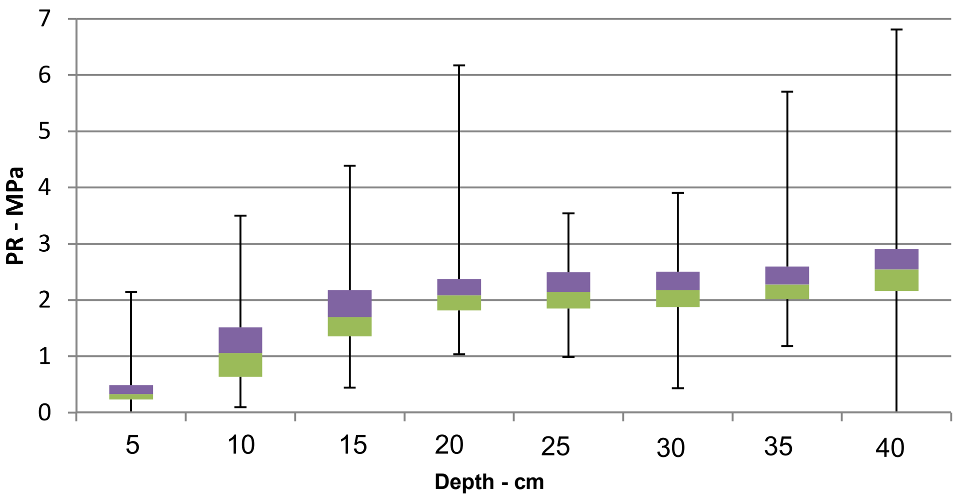

Figure 4-5 Penetration resistance (PR) analysis by depth (cm). The measurement range is illustrated by the plot whiskers. The interquartile range, mean and distribution are represented by the coloured box. n=243

Figure (4-5) shows the variability of the penetration resistance between individual layers. The underlying trend of the data is for the penetration resistance to increase with depth which is in line with other research (Domsch et al. 2006; Chamen, 2011). The whiskers on the box plot show the range of values increasing from 5 cm to 20 cm which illustrates large penetration resistance variability within this region of the soil profile, but then the range becomes much smaller, almost stable, at 25 and 35 cm suggesting a tillage induced compacted layer where the repeated use of cultivation equipment pulled by heavy machinery has formed a dense layer immediately below the plough pan e.g. > 35 cm. However, the trend of variation of bulk density with depth does not match that of bulk density confirming the penetration resistance measurement to be of less use to indicate soil compaction, since penetration resistance is simultaneously affected by moisture content, bulk density, organic matter content and soil texture (Kuang et al., 2013). This is the reason why this project attempts to establish a new approach to quantify and map soil compaction through the soil profile.

The Spearman correlation test of the penetration resistance data (Table 4-2) demonstrates that the soil layers were significantly and positively correlated at the 0.01 level. Adjoining layers show the closest relationship, however as the distance between the layers increased the correlation decreased. The closest agreement was found between 25 and 30 cm (R = 0.68). On the other hand the correlation between the 35 and 40 cm was the weakest (R= 0.34). This was probably caused by the distinct change of soil texture at that level.

Table 4-2 Spearman correlation coefficients between the cone index data series of the soil layers. Significant values are shown in red.

Depth (cm)	5	10	15	20	25	30	35	40
5								
10	0.44							
15	0.26	0.66						
20	0.18	0.42	0.67					
25	0.17	0.27	0.35	0.59				
30	0.22	0.25	0.30	0.44	0.68			
35	0.08	0.11	0.16	0.28	0.30	0.43		
40	0.15	0.15	0.19	0.20	0.18	0.15	0.34	

4.1.5 Apparent electrical conductivity

Soil ECa varied across the site depending not only on soil texture and moisture content, but bulk density and perhaps organic matter content. Table (4-3) shows the measured ECa (mS/m) values at two depths. The narrow range of the measured data at both depths is indicative of a consistent soil texture and is in agreement with the PSD analysis previously discussed.

Table 4-3 Descriptive statistics of the Electrical Conductivity survey

	Shallow ECa (mS/m)	Deep ECa (mS/m)
Minimum	10.98	33.50
Maximum	19.46	46.23
Mean	15.32	40.13
Range	8.48	12.73

Figure (4-6) illustrates the ECa spatial variation across the site with ECa values reducing from west to east, which indicates the increasing sand fraction and reducing clay fraction within the soil across that direction. This effect was not surprising because the influence of soil texture on the measured ECa values has been highlighted in previous research (Corwin and Lesch, 2005) where, soil with higher clay contents are expected to result in a higher measured value compared to soils with a higher content of sand fraction, due to the increased grain size of the sand. However it should also be noted that the absolute ECa values cannot be used for successful quantitative analysis of texture as they are simultaneously affected by soil texture, compaction, moisture content and organic matter (Sudduth et al., 2005; Hezarjaribi and Sourell, 2007; Kuang et al., 2011).

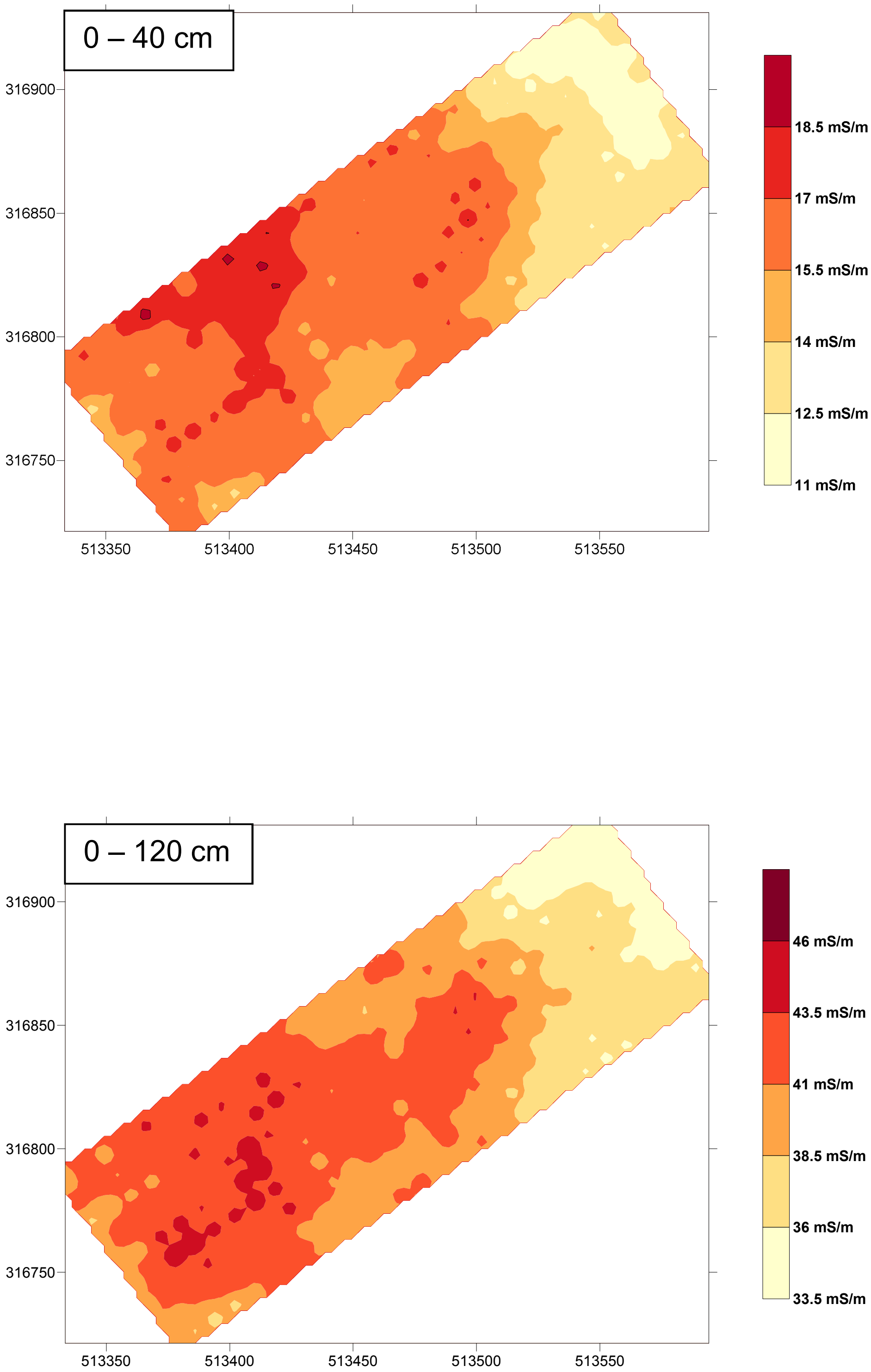

Figure 4-6 Spatial variation of apparent Electrical Conductivity (ECa) at 0 – 40 cm and 0 – 120 cm depths.

In addition to the above mentioned influence of soil texture, the ECa readings collected by the DUALEM 1S are also affected by bulk density. In a study identifying compaction using EMI techniques, Krajco (2007) found that the ECa values increased in the areas of the field which had been regularly trafficked by agricultural machinery. To test this hypothesis the Spearman correlation test was applied to both ECa measurements and the mean bulk density values of individual soil layers, with results shown in Table (4-4).

Table 4-4 Spearman correlation coefficients between the bulk density (BD) values and the electrical conductivity (ECa) by depth.

BD cm	ECa 0 – 40 cm	ECa 0 – 120 cm
5	-0.09	-0.02
10	-0.27	-0.25
15	0.12	0.15
20	0.20	0.28
25	0.01	0.05
30	0.01	0.12
35	0.30	0.36
40	-0.46	-0.47

It was found that although the r^2 values were universally low the ECa deep values correlated more consistently with a significance of $p<.0500$ than the ECa shallow values. This was surprising as the two depths of measurements available from the DUALEM 1S are 0 – 40 cm and 0 – 120 cm where it stands to reason that the shallow values would be more applicable to a multi-sensor data fusion (MSDF) approach. Therefore, it can be concluded that it not possible to correlate ECa with bulk density, and there are no robust correlations could be reported so far. Also, EMI is very limited to map soil variability through depth, and only two depths can be scanned compared to the 8 soil layers considered in the current project. Again this is the reason why a new approach to quantify and map soil compaction through the soil profile is needed.

4.2 Variable depth tillage management zones

4.2.1 Data processing

Multivariate k-means clustering was used for the creation of per layer management zones for the eight soil layers (Table 4-5). The selected variables were ECa at 40 cm (ECa $_{40}$) and 120 cm, (ECa $_{120}$), penetration resistance (PR), bulk density (BD) and moisture content (MC) with depth. Analysis parameters were set to maximise the initial Euclidean distance of the cluster separation whilst the cluster number was limited to three in order to minimise the amount of management zones created.

For analysis the normalised mean of each physical soil property was plotted at each depth (soil layer) (Figure 4-7, a-h). A consistent feature of all the analysis is the high ECa value of cluster 2 and the low ECa value of cluster 3. The co-variables for these clusters also follow convention where a low penetrometer measurement is a function of a high moisture value and vice versa irrespective of the bulk density value. This is in line with findings of others where low soil resistance to penetration or soil cutting associated with high moisture content and vice versa (e.g. Mouazen et al., 2002). Cluster 1, on the other hand, has no consistency of ECa values being both high and low whilst the respective co-variables have no discernible pattern. The 20 cm depth is unique within the analysis as penetration resistance, bulk density and moisture content values of all three clusters converge irrespective of ECa value. This is indicative of a compacted layer and concurs with the soil physical property analysis discussed earlier.

Regarding soil compaction indicated as bulk density, cluster 1 seems to have the highest bulk density in the top soil layers down to 30 cm depth. Cluster 3 was the second cluster as associated with the highest bulk density, which became of the largest bulk density in the soil layer between 30 and 35 cm, whereas cluster 3 has the highest bulk density for the soil layer of 35-40 cm.

Table 4-5 Descriptive statistics of k-means clustering for eight soil layers. Where ECa 40 and ECa 120 are ECa measurements at 40 cm and 120 cm, PR is penetration resistance, BD is bulk density and MC is moisture content.

Depth	Variable	Units	Mean	Minimum	Maximum	Std. Dev.
0-5 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	0.42	-0.07	2.14	0.33
	BD	g/cm^3	1.03	0.88	1.19	0.05
	MC	g/g	41.08	34.60	49.19	2.73
5-10 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	1.16	0.09	3.50	0.67
	BD	g/cm^3	1.11	1.01	1.30	0.04
	MC	g/g	38.95	20.15	53.19	4.05
10-15 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	1.79	0.45	4.39	0.64
	BD	g/cm^3	1.10	1.00	1.24	0.03
	MC	g/g	35.81	31.17	40.39	1.94
15-20 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	2.14	1.04	6.17	0.55
	BD	g/cm^3	1.08	0.92	1.46	0.07
	MC	g/g	36.57	28.28	44.27	1.85
20-25 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	2.18	0.99	3.54	0.49
	BD	g/cm^3	1.14	0.94	1.29	0.06
	MC	g/g	38.21	32.09	50.31	2.42
25-30 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	2.19	0.43	3.91	0.51
	BD	g/cm^3	1.24	1.01	1.46	0.09
	MC	g/g	36.78	20.25	70.59	7.31
30-35 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	2.38	1.19	5.70	0.61
	BD	g/cm^3	1.29	1.03	1.72	0.10
	MC	g/g	30.48	16.60	40.88	4.34
35-40 cm	ECa 40	mS/m	15.32	10.98	19.46	2.03
	ECa 120	mS/m	40.13	33.50	46.23	3.00
	PR	MPa	2.70	0.00	6.81	0.91
	BD	g/cm^3	1.31	1.07	1.67	0.10
	MC	g/g	30.78	19.23	52.09	4.85

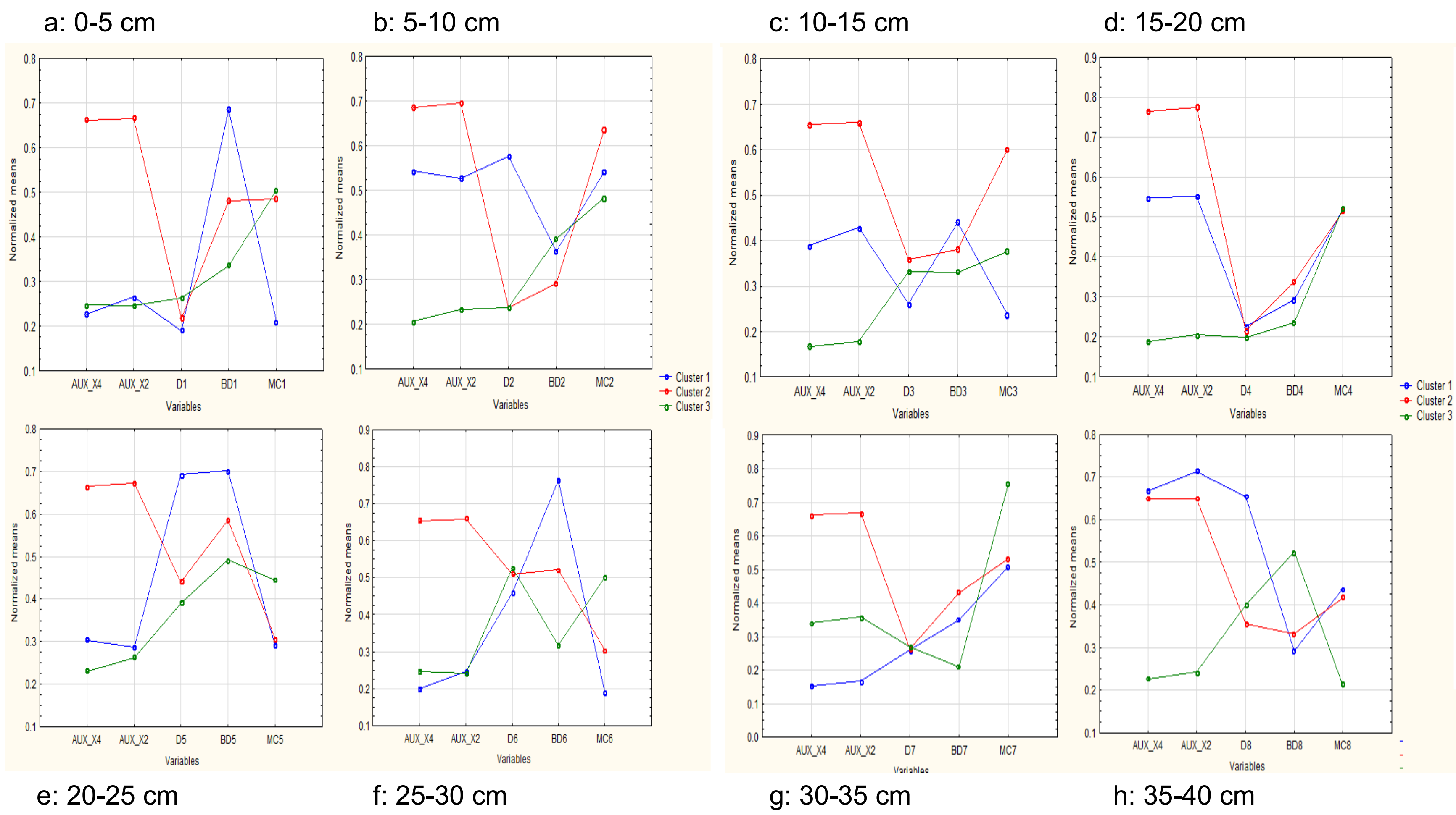

Figure 4-7 Plots illustrating the normalised physical soil property value of each cluster by depth.

Where AUX_X4 is ECa 40 cm, AUX_X2 is ECa120 cm, D is soil penetration resistance. Cluster 1 is blue, cluster 2 is red and cluster 3 is green.

4.2.2 Management Zone (MZ) maps by cluster analysis

The newly delineated clusters were plotted for the 8 individual soil layers using a Nearest Neighbour interpolation (Figure 4-8, a-h). The clustering process affords an a priori selection of cluster number which was set to three for this experiment. Using only three clusters, the pattern of variation is very distinct. Underlying trends of soil type are evident. Cluster 1 on the eastern side of the site, has an increased sand fraction when compared to the higher clay content soil on the western side which visually compares very well with the ECa results (Figure 4-6). Further evidence that these clusters process were closely related to soil texture can be drawn from box plot analysis that confirmed high bulk density values resulted in high penetrometer values thus indicating a natural clustering parameter and in line with what was expected. Cluster 3 demonstrated the most spatial variation across all depths. In the 0-5 cm and 5-10 cm there was a distinct change in cluster location from the small triangular area at the eastern extent 0-5 cm manifesting itself in a more general way at 5-10 cm. This was caused by the reducing bulk density values between a shallow layer of surface compaction and the looser soil just below. Cluster 3 has the most significant change in spatial extent occurring at 20 cm which was a result of the close alignment of normalised means of penetration resistance, bulk density and moisture content variables (Figure 4-7). Initially the map looked like a layer of compaction but this was discounted by the low bulk density means. A possible reason behind the spatial extent is the wide range of bulk density and penetration resistance values (Figures 4-3, 4-5) indicated a transient layer between the regularly cultivated surface and the less frequently cultivated subsoil. Below the 20 cm layer the clusters are spatially more stable, adding further evidence that 20 cm is a transient layer.

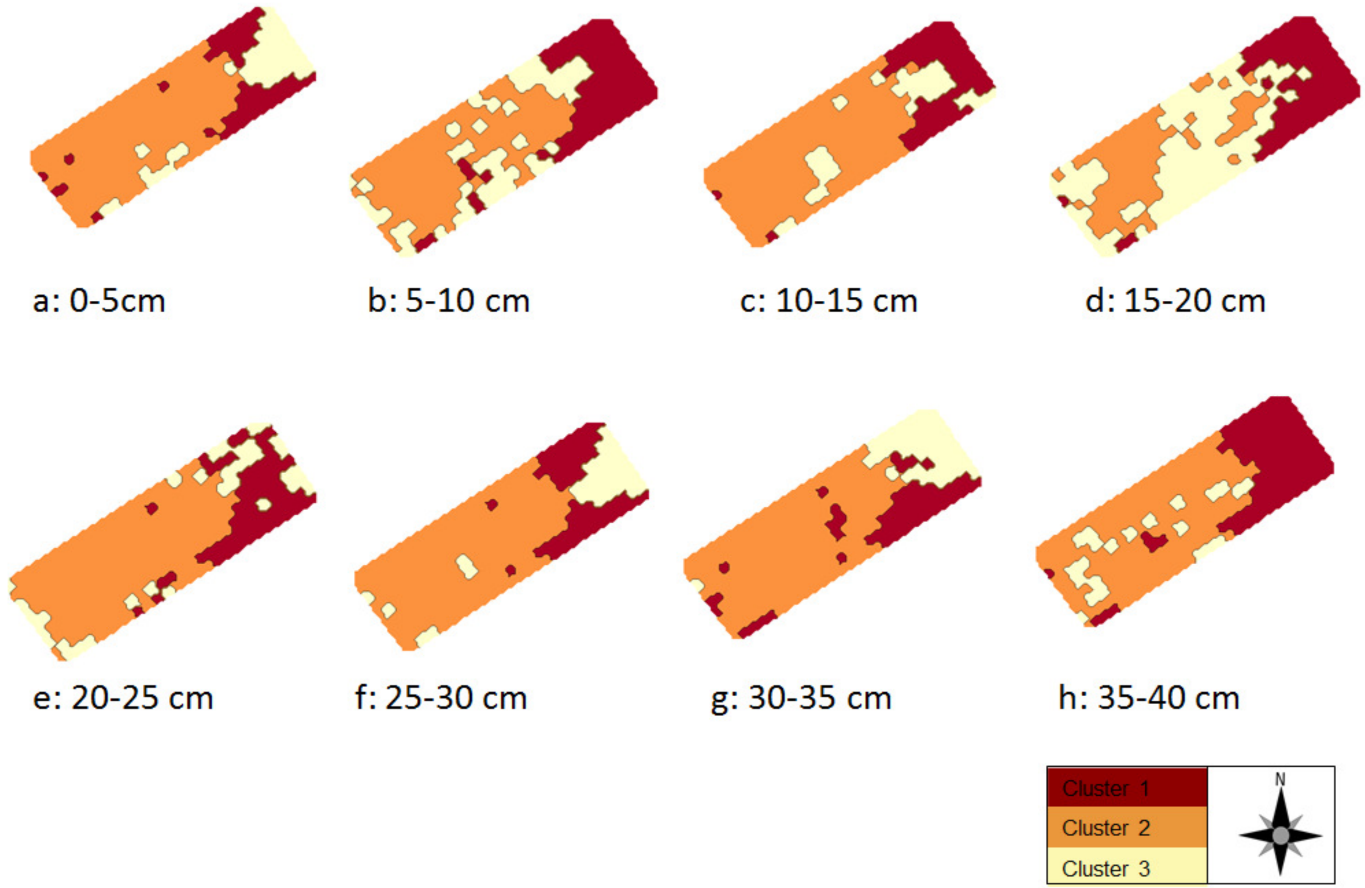

Figure 4-8 Visualisations of the spatial extent of each cultivation management zone cluster, created using a nearest neighbour interpolation.

4.3 Average cluster packing density, moisture content, bulk density and clay content

The mean values for packing density, moisture content, and bulk density are shown along with the layer clay content in Table 4-6. There are no descriptive statistics for the clay content because of the limited data set collected therefore the clay content value used for the packing density calculation has been reported. From this it can be seen that the clay content range is very narrow in the top 30 cm, averaging 38% in comparison to 32% in the lowest 10 cm. This variation is caused by the distinct horizon at 30-40 cm where the clay percentage reduces by approximately 10%. With this narrow textural range the main effect of the packing density calculation is coming from the bulk density value, which as the bulk density increases with depth the packing density is reflected accordingly. One of the reasons Kaufmann (2008) stated as a benefit of packing density over bulk density for soil compaction identification was the greater range between the yield limiting and non-yield limiting areas of the field, simplifying identification. With such a narrow clay range this effect is less evident in this experiment. Cluster 3 at 20 cm has highest range of packing density values which extends from 1.25 to 1.8 with a mean value of 1.36. This suggests that the distribution is skewed towards the lower values indicating the majority of this cluster is not yield limiting. This observation backs up the earlier cluster analysis discussion where it was considered that the 20 cm layer is a transient layer between densities as opposed to a compacted layer. The mean moisture content values reduce with depth falling from 41.97% at 5 cm to 26.2% at 40 cm. On closer analysis however the most noticeable change in soil moisture occurs at the 25-30 cm mark where there is a drop of 12% in cluster 2. This drier soil is most in the heaviest textured part of the field is indicative of a denser layer.

Table 4-6 Descriptive statistics of packing density, bulk density, moisture content and clay content by depth and cluster

		Packing density				Bulk density g/cm^3				Moisture content g/g				Clay Content
Depth	**Clus.**	**Mean**	**Min**	**Max**	**Std. D.**	**Mean**	**Min**	**Max**	**Std. D.**	**Mean**	**Min**	**Max**	**Std. D.**	**w/w %**
0-5 cm	1	1.43	1.35	1.53	0.05	1.09	1.03	1.19	0.05	37.68	34.60	40.30	1.64	36
	2	1.39	1.24	1.49	0.05	1.03	0.88	1.13	0.04	41.68	35.72	49.19	2.48	40
	3	1.31	1.20	1.39	0.04	0.98	0.88	1.06	0.04	41.97	39.25	46.04	1.92	36
5-10 cm	1	1.47	1.37	1.63	0.05	1.12	1.02	1.27	0.04	38.04	20.15	43.81	3.55	36
	2	1.46	1.46	1.60	0.03	1.10	1.01	1.24	0.03	41.11	24.67	53.19	3.69	40
	3	1.45	1.36	1.66	0.05	1.12	1.04	1.30	0.04	36.13	23.55	40.91	2.73	36
10-15 cm	1	1.44	1.39	1.60	0.05	1.11	1.07	1.24	0.03	33.37	31.17	35.89	1.36	36
	2	1.43	1.32	1.52	0.03	1.10	1.00	1.24	0.02	36.70	33.48	40.39	1.55	39
	3	1.40	1.34	1.47	0.03	1.08	1.02	1.16	0.03	34.64	32.74	39.23	1.59	35
15-20 cm	1	1.42	1.23	1.71	0.07	1.08	0.92	1.36	0.07	36.59	30.96	40.06	1.57	36
	2	1.43	1.30	1.63	0.06	1.10	0.99	1.30	0.06	36.51	32.98	44.27	2.09	39
	3	1.36	1.25	1.81	0.08	1.05	0.94	1.46	0.08	36.61	28.28	38.95	1.96	35
20-25 cm	1	1.53	1.44	1.66	0.05	1.19	1.11	1.29	0.04	37.38	32.09	43.89	2.28	39
	2	1.50	1.29	1.62	0.06	1.14	1.49	1.56	0.06	37.68	32.18	44.35	1.80	41
	3	1.45	1.31	1.54	0.05	1.11	0.94	1.20	0.05	40.19	35.15	50.31	3.11	37
25-30 cm	1	1.69	1.56	1.79	0.06	1.35	1.22	1.79	0.06	29.82	20.25	38.05	5.25	39
	2	1.61	1.43	1.81	0.07	1.25	1.06	1.44	0.07	35.54	25.90	45.69	4.26	41
	3	1.49	1.35	1.58	0.05	1.16	1.01	1.25	0.06	45.44	34.36	50.59	8.60	37
30-35 cm	1	1.49	1.42	1.64	0.03	1.27	1.21	1.33	1.33	28.92	20.38	32.63	3.23	38
	2	1.64	1.41	2.02	0.11	1.33	1.11	1.72	0.10	29.48	16.60	36.84	4.19	34
	3	1.42	1.25	1.65	0.10	1.17	1.03	1.35	0.08	34.87	30.02	40.88	2.26	24
35-40 cm	1	1.57	1.47	1.73	0.07	1.25	1.17	1.43	0.07	33.61	28.23	43.91	3.46	38
	2	1.58	1.32	1.89	0.08	1.27	1.07	1.58	0.07	32.94	23.11	52.09	3.82	34
	3	1.61	1.43	1.97	0.11	1.39	1.22	1.67	0.10	26.20	19.23	33.43	3.30	24

4.4 Bulk Density prediction with multiple linear regression

To establish algorithms to predict bulk density as a function of penetration resistance, ECa at 40 cm and moisture content, multiple linear regressions were performed for each depth layer and the results obtained from the MLR analysis is presented in Table 4-7. The MLR analysis was carried out with a confidence level of 95%.

Table 4-7 Summary statistics of MLR analysis performed for the eight soil layers

Depth	Variables	Units	t-value	p-value	F-test	R^2
5 cm	Intercept		45.04	0.00	96.5	0.54
	ECa 40	mS/m	3.35	0.00		
	PR	MPa	-1.27	0.21		
	MC	kg/kg		0.00		
10 cm	Depth					
	Intercept		80.07	0.00	118.91	0.59
	ECa 40	mS/m	2.54	0.01		
	PR	MPa	-1.09	0.28		
	MC	kg/kg	-17.66	0.00		
15 cm	Intercept		44.02	0.00	18.49	0.17
	ECa 40	mS/m	4.76	0.00		
	PR	MPa	1.94	0.05		
	MC	kg/kg	-7.01	0.00		
20 cm	Intercept		24.56	0.00	69.63	0.45
	ECa 40	mS/m	4.73	0.00		
	PR	MPa	2.62	0.01		
	MC	kg/kg	-13.30	0.00		
25 cm	Intercept		19.16	0.00	8.92	0.09
	ECa 40	mS/m	-0.65	0.52		
	PR	MPa	2.17	0.03		
	MC	kg/kg	-4.54	0.00		
30 cm	Intercept		53.15	0.00	198.95	0.71
	ECa 40	mS/m	-3.79	0.00		
	PR	MPa	1.74	0.08		
	MC	kg/kg	-24.39	0.00		
35 cm	Intercept		24.28	0.00	172.76	0.68
	ECa 40	mS/m	6.81	0.00		
	PR	MPa	2.79	0.01		
	MC	kg/kg	-21.30	0.00		
40 cm	Intercept		53.96	0.00	140.73	0.63
	ECa 40	mS/m	-2.45	0.02		
	PR	MPa	0.46	0.65		
	MC	kg/kg	-16.81	0.00		

The statistical analysis shows that the ECas and moisture content variables were found to be significant in most cases, particularly moisture content. The penetration resistance variable on the other hand was only found to be significant at the 15-20 cm and 30-35 cm soil layers, due to the low t-value and high p-value. The highest coefficient of multiple determination (R^2) of 0.71 was observed at the 25-30 cm layer, which is probably due to the lack of regular tillage disturbance at this depth leaving the soil in a relatively uniform state of compaction. The 5 and 10 cm layer, which have been subjected to regular uniform tillage, had smaller R^2 values (0.54 and 0.59 respectively) than the deeper layers found at and beyond 30 cm. These results are further evidence of the root crop rotation, historically practiced in this field, which was discussed early. The weakest R^2 values (0.18 and 0.09) were found at 15 cm and 25 cm demonstrating negligible correlation. However it is their location within the profile, immediately before a compacted layer, which makes these values interesting. Domsch et al. (2006) also noticed a weak correlation where a loosened soil layer met a compacted layer. He suggested that the data recorded by the penetrometer at these transitional layers were more strongly affected by random fluctuations thereby adversely affecting the result. The author believes the same reason could apply in the current work.

The following models were derived from the MLR analysis.

$$5\ \text{cm BD} = 1.339 + 0.154ECa_{40} - 0.6PR - 0.77MC \quad \textbf{4-1}$$

$$10\ \text{cm BD} = 1.399 + 0.119ECa_{40} - 0.05PR - 0.82MC \quad \textbf{4-2}$$

$$15\ \text{cm BD} = 1.246 + 0.310ECa_{40} + 0.114PR - 0.46MC \quad \textbf{4-3}$$

$$20\ \text{cm BD} = 1.839 + 0.225ECa_{40} + 0.125PR - 0.63MC \quad \textbf{4-4}$$

$$25\ \text{cm BD} = 1.391 - 0.04ECa_{40} + 0.134PR - 0.28MC \quad \textbf{4-5}$$

$$30\ \text{cm BD} = 1.686 - 0.13ECa_{40} + 0.061PR - 0.86MC \quad \textbf{4-6}$$

$$35\ \text{cm BD} = 1.656 + 0.207ECa_{40} + 0.093PR - 0.78MC \quad \textbf{4-7}$$

$$40\ \text{cm BD} = 1.847 - 0.11ECa_{40} + 0.18PR - 0.74MC \quad \textbf{4-8}$$

Where BD is bulk density Mg m^{-3}, ECas is electrical conductivity (shallow) mS/m^{-2}, PR is penetration resistance in MPa, MC is moisture content in kg kg^{-1}.

Having high R^2 values for six multiple linear functions out of eight is encouraging to recommend them in the future for the prediction of bulk density as a function of ECas, penetration resistance, and moisture content. This would require input data about penetration resistance and moisture content measured with the multi-sensor kit shown in Figure. (3-10) (Quraishi and Mouazen, 2013), consisting of a penetrometer and a NIR sensor in addition to input data on ECas measured with a commercial EMI (e.g. DUALEM 1S, SOYL, UK). However, the multivariate models for the 15 cm and 25 cm layers have to be improved, by using nonlinear methods e.g. multiple nonlinear regression, artificial neural network and alternative test sites.

4.5 Derivation of packing density

The literature highlighted that packing density is a better parameter to indicate soil compaction than bulk density because it transforms the bulk density value into a clay independent indicator by adding a correction term given as the product of clay content with the slope of the regression lines (Kaufmann 2008). Using the equation developed by Renger (1970), the packing density values for the site were calculated.

For this work and according to the packing density classes in Table (3-4), values of packing density ≥ 1.7 t/m^3 were deemed to be yield and root growth limiting and tillage should be carried out. Results show the overall packing density range across the soil profile extends from 1.20 to 2.02 (Table 4-8). However, this range can be further sub-divided between the top 25 cm mean packing density of 1.45 - 1.53 t/m^3 and the lower 30 cm mean packing density range of 1.49 – 1.69 t/m^3. The reason for this stepped increase in packing density between the these two observed layers can be attributed to historical tillage practices where ploughing for root crops would often extend down to 25 cm, regularly disturbing the upper soil and potentially compacting the deeper sub soil with large vertical and shear forces.

Typically if a grower had identified a compacted layer like this he would look to remediate it with homogeneous deep tillage, which is an expensive and time consuming operation (Mouazen and Neményi, 1999). However with this approach of packing density cluster analysis it is possible to identify areas below 30 cm that do not require deep tillage offering the potential to reduce tillage depth saving money and resources. Examining the maximum packing density calculated per cluster in Table (4-8) reveals that values exceeding 1.6 t/m^3 already appear on the top layer of 5-10 cm deep, indicating the presence of surface compaction, and suggesting a gentle surface tillage to be considered down to 10 cm in the entire field. After this layer another layer but with critical values on crop growth can be observed at 15-20 cm layer in cluster 1 & 3, suggesting tillage of these two clusters only, whereas no tillage is needed for cluster 2. Going further down in the profile, one can observe the presence of hard pan at cluster 1 and 2 at 30 cm layer, and that expand into cluster 2 at 35 cm layer, where the highest packing density of 2.02 t/m^3 is observed. This may suggest the need for subsoiling down to 35 cm in cluster 2 in particular. At depth of 40 cm another compacted layer can be observed in the entire field with the three clusters.

Table 4-8 Descriptive statistics of the packing density (PD) by cluster and for individual layers.

Depth	Cluster	PD Mean	PD Min	PD Max	PD Std D
5 cm	1	1.43	1.35	1.53	0.05
	2	1.39	1.24	1.49	0.05
	3	1.31	1.20	1.39	0.04
10 cm	1	1.47	1.37	1.63	0.05
	2	1.46	1.46	1.60	0.03
	3	1.45	1.36	1.66	0.05
15 cm	1	1.44	1.39	1.60	0.05
	2	1.43	1.32	1.52	0.03
	3	1.40	1.34	1.47	0.03
20 cm	1	1.42	1.23	1.71	0.07
	2	1.43	1.30	1.63	0.06
	3	1.36	1.25	1.81	0.08
25 cm	1	1.53	1.44	1.66	0.05
	2	1.50	1.29	1.62	0.06
	3	1.45	1.31	1.54	0.05
30 cm	1	1.69	1.56	1.79	0.06
	2	1.61	1.43	1.81	0.07
	3	1.49	1.35	1.58	0.05
35 cm	1	1.49	1.42	1.64	0.03
	2	1.64	1.41	2.02	0.11
	3	1.42	1.25	1.65	0.10
40 cm	1	1.57	1.47	1.73	0.07
	2	1.58	1.32	1.89	0.08
	3	1.61	1.43	1.97	0.11

Green values indicates packing density values ≥ 1.6 (tillage may be required) and red values indicate packing density ≥ 1.7, where tillage should be carried out. Values highlighted in yellow indicate the final depths of tillage used for the VDT plan.

4.6 Variable depth tillage (VDT) plan

A VDT plan scaled in cm depth was developed using the area and depth of the yield limiting properties derived from the data found in Table 4-8. Cultivation depth was calculated as the depth of the largest maximum packing density value per cluster of each grid node + 3 cm. (The additional 3 cm was to ensure that the cultivator tine was sufficiently deep as to fully remove the compacted layer). The 40 cm depth layer was excluded from the tillage plan because of the distinctly different nature of the soil at that depth. Using the new the new depth attributes the data was interpolated using a nearest neighbour method to create a VDT plan (Figure 4-9).

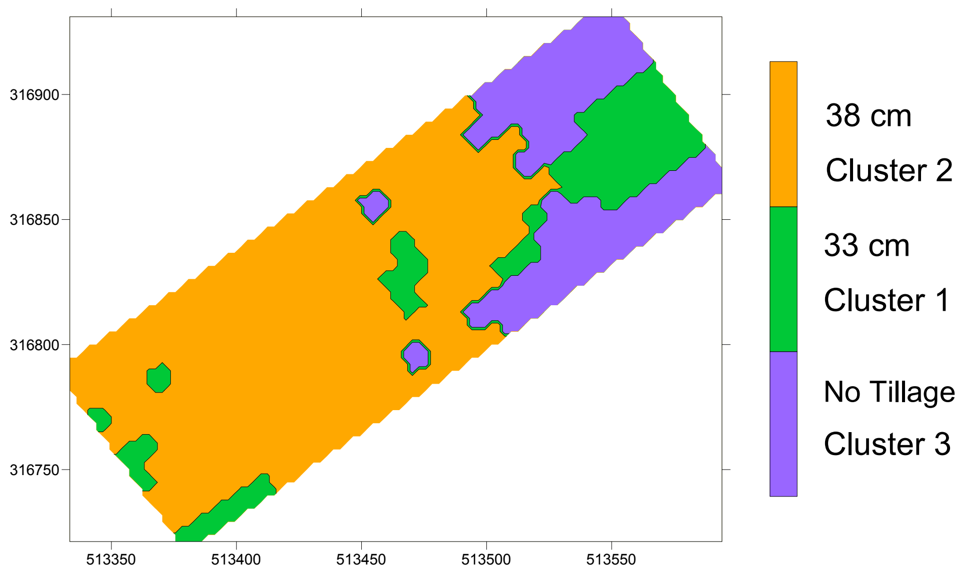

Figure 4-9 Variable depth tillage plan illustrating the spatial variation of cultivation depth, calculation based on the mean packing density values

From a visual assessment cluster 1 requires deep tillage down to 33 cm, cluster 2 requires deep tillage to 38 cm and cluster 3 requires no deep tillage, because at 23 cm the soil would be cultivated when the field is ploughed as part of the farms normal cultivation practice. On further analysis the depth zones within the VDT plan have a very close resemblance to the EMI scan results in Figure. (4-6). The deepest cultivation is required in the areas with the highest ECa values and vice versa. This is contrary to other studies where a negative correlation between recommended tillage depth and the soil ECa was found (Keskin et al 2011). In that study the soil was classified as Dothan sandy loam where the maximum ECa value was recorded at 7 mS/m^2 in comparison to the 46 mS/m^2 of the clay loam measured for this work. A possible reason for this contradiction could be that the current work takes into account all affecting factors to estimate the packing density, being the real parameter representing the soil compaction. This may also indicate the correct concept used in the current work and that the multi-sensor and data fusion approach is the way forward for optimising the variable depth tillage.

4.7 Predicted cost benefits

It is understood that as tillage depth increases, the cultivator tines contact more area, disturbing a larger volume of soil causing an increase in draught requirement in response to the soil property (Kichler 2008; Mouazen and Ramon, 2002). Therefore, any reduction in tillage depth which doesn't have an impact on crop growth and consequently yield will have a cost benefit. To run a simple cost-benefit analysis, from the VDT plan shown in Figure (4-9), it was possible to calculate the working area of each management zone (Table 4-9). Additionally, to explore the scope of the cost benefit to VDT, hypothetical working areas of two fields are also included in Table 4-9. Simulation one represents a situation where 66% of the field requires shallow tillage and simulation two represents a field where 66% requires deep tillage.

Table 4-9 Calculated working areas of experimental site and hypothetical working areas from simulated sites for cost analysis comparison.

Depth cm	Experimental Site	Simulation One	Simulation Two
No tillage req.	0.53	0.00	0.00
25	0.00	1.61	0.00
33	0.38	0.41	0.41
38	1.52	0.41	0.41
45	0.00	0.00	1.61
Total ha	2.43	2.43	2.43

An attempt was made to calculate the cultivation cost per depth at the experiment site using the variable depth tillage system described previously (Figure 3-12). Unfortunately due to a technical issue with the tractor's telemetry these values were not reliable. Therefore, as a solution, values of a similar experiment by Keskin et al. (2011) were found in the literature and were included in this analysis. Keskin et al. (2011) compared constant depth tillage (CT) with variable depth tillage (VDT), where the subsoiler was set slightly below the root impeding layer at 25 cm, 33 cm, 38, cm and 45 cm. Using a randomised complete block design with five replications (five plots) an instrumented tractor was used to obtain the energy and fuel consumption for both the VDT and CT treatments, as shown in Table (4-10).

Table 4-10 Summary table of fuel consumption comparing Variable-Depth Tillage (VDT) and Conventional Tillage (CT) (After Keskin et al., (2011)

Tillage system	Tillage depth (cm)	Field size (ha)	Fuel consumption (L)
VDT	25	0.202	2.95
	33	0.202	3.13
	38	0.202	3.27
	45	0.202	3.46
	Total	0.808	12.81
CT	45	0.404	9.71
	45	0.404	9.64
	Total	0.808	19.35
	Total savings with VDT vs. CT		34%

Fortuitously the three cultivation depths calculated using the MSDF approach (23 cm, 33 cm, 38 cm,) all but match those of Keskin et al. (23 cm, 33 cm, 38 cm, 45 cm). So for cost analysis purposes the areas of the experimental site management zones were transposed into the summary table with the fuel consumption figures recalculated pro rata (Table 4-11), along with values from the simulated fields.

Table 4-11 A comparison of fuel consumption figures between variable-depth tillage (VDT) and conventional tillage (CT) per management zone (MZ) area.

Tillage system	Tillage depth (cm)	Management zone area (ha)	Est. Fuel consumption l/ha by depth	Calculated fuel consumption (l/ha)
Conventional deep tillage	No tillage req.	0.00	0.00	0.00
	45	2.43	17.30	59.00
	Total	2.43	------	59.00
Experiment Results	No tillage req.	0.53	0.00	0.00
	25	0.00	14.75	0.00
	33	0.38	15.65	5.90
	38	1.52	16.35	24.90
	Total	2.43	------	30.80
Simulation 1 66% shallow VDT	No tillage req.	0.00	0.00	0.00
	25	1.61	14.75	23.70
	33	0.41	15.65	6.40
	38	0.41	16.35	6.70
	45	0.00	17.30	0.00
	Total	2.43	-------	36.90
Simulation 2 66% deep VDT	No tillage req.	0.00	0.00	0.00
	25	0.00	14.75	0.00
	33	0.41	15.65	6.40
	38	0.41	16.35	6.70
	45	1.61	17.30	27.90
	Total	2.43	-------	41.00

Table 4-12 A summary table of the percentage fuel saving benefits for variable depth tillage (VDT) over conventional deep tillage (CT).

Tillage system	Calculated fuel consumption (l/ha)	Percentage fuel benefit of VDT over CT
Experiment Results - VDT	30.80	48%
Simulation 1 66% shallow VDT	36.90	38%
Simulation 2 66% deep VDT	41.00	31%

Even though the areas from the experimental MZ's are different from Keskin's et al. (2011) work, the percentage fuel saving shown in table 4-12 by implementing VDT over CT was found to be 48%. This exceeds the performance of Keskin et al. (2011), whose study found a 33% fuel saving, but is in line with Fulton et al. (1996) who reported a 50% fuel saving. In other work Raper et al. (2007) reported a 27% fuel saving in a medium depth experiment (35 cm) compared to uniform deep subsoiling at 45 cm respectively which is comparable with the hypothetical results from simulation 2 (Table 4-12).

This analysis confirms that the ultimate benefit of variable depth tillage is dependent on the factors which make up the tillage operation such as soil type, previous cropping, implement design and depth; however it is clear from this and other research that VDT has a potential economic benefit to the farmer between 27% and 50%.

In addition to the direct economic benefit, environmental benefits are clear and may have more impact on the society as compared to the economic benefit. This is because when energy consumption is reduced with variable depth tillage the greenhouse gas (GHG) emission is also reduced.

The proposed development of a multi-sensor and data fusion approach to map the spatial and in depth variation in soil compaction will be a valuable tool to Natural England to support their two schemes, enhancing soil protection from runoff and soil erosion. It can also support the England Catchment Sensitive Farming Initiative in making a difference to local water quality by eliminating soil compaction and enhancing rainfall infiltration in a targeted manner. The proposed tillage technology will assist SOYL (the sponsor of this thesis) to build on the research being already carried out to minimise compaction by adopting variable depth tillage. Finally, farmers would profit through increased crop yields by correctly remediating soil compaction, reduce their cost of production by eliminating inappropriate tillage and maintain the nutrient status of their fields by reducing soil run-off and erosion.

5 Conclusions

In this thesis the assessment of soil compaction, indicated as packing density was successful carried out for eight separate soil layers based on a multi-sensor data fusion approach. Measured values of soil penetration resistance (PR), apparent electrical conductivity (ECa), clay content (CC), bulk density (BD) and soil moisture content (MC) were fused by means of k-means clustering to delineate per layer management zone maps. A multiple linear regression (MLR) analysis was adopted to develop models that could predict BD as a function of penetration resistance, ECa_{40} and moisture content. The decision to cultivate or not to a certain depth was derived by calculating the packing density of each delineated zone. From the results of this research the following conclusions can be made:

1. The multi-sensor data-fusion approach can be used successfully to provide key information sufficient to derive a soils state of compactness as an indicator of whether to cultivate or not to a certain depth.

2. K-means multivariate clustering enabled the affecting soil physical soil parameters on soil compaction to be fused together to delineate management zones suitable for variable depth tillage. The user can also control the size and number of management zones thus reconciling the practical field management implications.

3. Bulk density models can be derived from physical soil parameters using MLR analysis. The prediction in compact soils was good (r^2 = 0.71) whereas the prediction of bulk density in transient layers between the loose and compact soils were very poor (r^2 = 0.09-0.17).

4. Because packing density is dependent on soil texture (e.g. per cent clay), it is a more suitable indicator of soil compaction than bulk density for variable depth tillage.

5. Fuel savings of approximately 35% could be achieved by using the MSDF approach to variable depth tillage over the uniform constant depth tillage.

6 Future Work

- Implement the concept on a broader scale than one field.
- Run cost-benefit analysis at larger scale using real data collected with the variable depth tillage system of SOYL.
- Further work on multivariate modelling is needed to improve the models to predict bulk density by using non-linear multivariate methods e.g. non-linear multiple regression, artificial neural network, support vector machine etc.

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Appendix A - Bulk density and moisture content results

I.D.	Dry Tin #	Mass of Tin	Mass of tin + moist sample	Wet Wt	Tin + oven dry sample g	Dry Wt	MC %	Bulk Density
1.1	SP40	46.18	185.33	139.15	141.52	95.34	45.95	0.97
1.2	SP43	46.32	173.44	127.12	138.3	91.98	38.20	0.94
1.3	SP56	46.1	194.63	148.53	152.68	106.58	39.36	1.09
1.4	70B	45.94	201.18	155.24	156.61	110.67	40.27	1.13
1.5	16B	45.92	212.81	166.89	164.94	119.02	40.22	1.21
1.6	SP17	46.75	221.56	174.81	178.05	131.3	33.14	1.34
1.7	56B	46.04	218.55	172.51	175.71	129.67	33.04	1.32
1.8	38B	46.03	229.01	182.98	193.04	147.01	24.47	1.50
2.1	SP90	46.02	207.43	161.41	164.54	118.52	36.19	1.21
2.2	37B	46.04	221.59	175.55	179.76	133.72	31.28	1.36
2.3	13B	49.34	212.72	163.38	174.3	124.96	30.75	1.27
2.4	43	46.35	243.95	188.6	195.67	149.32	26.31	1.52
2.5	1584	49.37	220.97	171.6	177.48	128.11	33.95	1.30
2.6	123B	46.94	229.23	182.29	182.13	135.19	34.84	1.38
2.7	SP14	46.59	206.08	159.49	163.2	116.61	36.77	1.19
2.8	Sp73	46.28	211.92	165.64	170.5	124.22	33.34	1.27
3.1	1627	46.08	184.83	138.75	138.68	92.6	49.84	0.94
3.2	21f	45.68	192.47	146.79	147.12	101.44	44.71	1.03
3.3	1661	49.28	194.67	145.39	152.64	103.36	40.66	1.05
3.4	NH6	45.86	201.73	155.87	158.2	112.34	38.75	1.14
3.5	628	45.83	211.92	166.09	168.15	122.32	35.78	1.25
3.6	4b	46.26	215.64	169.38	171.2	124.94	35.57	1.27
3.7	40	45.97	229.08	183.11	180.26	134.29	36.35	1.37
3.8	126b	46.65	199.33	152.68	157.9	111.25	37.24	1.13
4.1	sp80	46.23	193.61	147.38	153.24	107.01	37.73	1.09
4.2	17	46.03	198.56	152.53	144.52	98.49	54.87	1.00
4.3	sp74	46.62	191.15	144.53	154.04	107.42	34.55	1.09
4.4	1564	46.7	190.06	143.36	153.6	106.9	34.11	1.09
4.5	SP84	46.21	203.85	157.64	154.83	108.62	45.13	1.11
4.6	73b	46.5	209.36	162.86	172.91	126.41	28.83	1.29
4.7	354	46.32	201.55	155.23	173.7	127.38	21.86	1.30
4.8	833	46.16	192.51	146.35	156.16	110	33.05	1.12
5.1	513	46.31	196.45	150.14	152.81	106.5	40.98	1.08
5.2	1515	45.68	202.03	156.35	156.53	110.85	41.05	1.13
5.3	1653	49.69	203.48	153.79	161.66	111.97	37.35	1.14
5.4	SP16	45.94	196.73	150.79	156.63	110.69	36.23	1.13

5.5	SP10	46.63	203.88	157.25	160.6	113.97	37.97	1.16
5.6	1510	46.35	204.29	157.94	167.8	121.45	30.05	1.24
5.7	TIN6	45.93	225.24	179.31	194.88	148.95	20.38	1.52
5.8	151b	45.7	241.99	196.29	171	125.3	56.66	1.28
6.1	51B	45.73	202.78	157.05	157.88	112.15	40.04	1.14
6.2	28	46.69	195.27	148.58	174.3	127.61	16.43	1.30
6.3	99B	46.07	194	147.93	157.65	111.58	32.58	1.14
6.4	SP84	46.55	190.79	144.24	154.83	108.28	33.21	1.10
6.5	76b	50.12	210.92	160.8	170.56	120.44	33.51	1.23
6.6	132b	45.97	227.08	181.11	191.74	145.77	24.24	1.48
6.7	SP11	46.49	247.48	200.99	222.25	175.76	14.35	1.79
6.8	JU18	45.87	246.37	200.5	217.33	171.46	16.94	1.75
7.1	45B	45.9	179.18	133.28	146.3	100.4	32.75	1.02
7.2	101B	46.93	201.73	154.8	157.59	110.66	39.89	1.13
7.3	80B	45.14	191.97	146.83	148.96	103.82	41.43	1.06
7.4	Sp36	46.27	172.31	126.04	137.74	91.47	37.79	0.93
7.5	1537	49.25	169.52	120.27	135.88	86.63	38.83	0.88
7.6	539	46.22	193.74	147.52	151.5	105.28	40.12	1.07
7.7	338	49.24	210.54	161.3	166.78	117.54	37.23	1.20
7.8	Tin1 1	45.61	184.5	138.89	144.52	98.91	40.42	1.01
8.1	739	45.63	181.1	135.47	142.32	96.69	40.11	0.98
8.2	63b	46.64	199.71	153.07	148.6	101.96	50.13	1.04
8.3	30	45.97	188.4	142.43	152.11	106.14	34.19	1.08
8.4	95	46.89	187.81	140.92	150.92	104.03	35.46	1.06
8.5	Tin3 3	46.19	199.26	153.07	158.06	111.87	36.83	1.14
8.6	ORD 6	45.67	195.79	150.12	154.4	108.73	38.07	1.11
8.7	A6	45.63	189.46	143.83	149.87	104.24	37.98	1.06
8.8	tin16	46.32	197.11	150.79	156.7	110.38	36.61	1.12
9.1	Sp14	46.16	192.49	146.33	147.22	101.06	44.80	1.03
9.2	876	45.66	200.45	154.79	155.12	109.46	41.41	1.12
9.3	20b	46.57	182.45	135.88	143.18	96.61	40.65	0.98
9.4	7	46.68	168.33	121.65	134.59	87.91	38.38	0.90
9.5	34b	45.99	182.23	136.24	144.2	98.21	38.72	1.00
9.6	27	46.49	208.29	161.8	158.8	112.31	44.07	1.14
9.7	50B	46.35	187.98	141.63	151.43	105.08	34.78	1.07
9.8	1697	49.99	218.28	168.29	189.5	139.51	20.63	1.42
10.1	127B	46.57	169.43	122.86	128.4	81.83	50.14	0.83
10.2	SP14	46.31	202.38	156.07	154.87	108.56	43.76	1.11
10.3	57B	46.76	203.09	156.33	157.88	111.12	40.69	1.13
10.4	17b	46.72	190.04	143.32	144.52	97.8	46.54	1.00
10.5	Sp18	45.79	182.04	136.25	144.79	99	37.63	1.01

10.6	15	46.88	202.58	155.7	147.94	101.06	54.07	1.03
10.7	23	46.2	200.74	154.54	158.12	111.92	38.08	1.14
10.8	1027	46.45	199.83	153.38	160.06	113.61	35.01	1.16
11.1	578	46.9	170.62	123.72	131.54	84.64	46.17	0.86
11.2	1006	45.84	185.99	140.15	147.94	102.1	37.27	1.04
11.3	SP18	45.89	180.81	134.92	146.17	100.28	34.54	1.02
11.4	86b	46.65	174.21	127.56	138.31	91.66	39.17	0.93
11.5	65b	46.47	190	143.53	148.6	102.13	40.54	1.04
11.6	46a	45.79	197.67	151.88	149.87	104.08	45.93	1.06
11.7	Sp15	45.71	186.16	140.45	144.67	98.96	41.93	1.01
11.8	133B	46.72	203.71	156.99	164.71	117.99	33.05	1.20
12.1	141B	46.52	174.12	127.6	137.3	90.78	40.56	0.92
12.2	SP17	45.34	186.61	141.27	146.2	100.86	40.07	1.03
12.3	91B	46.54	183.85	137.31	151.41	104.87	30.93	1.07
12.4	33	46.61	179.26	132.65	142.01	95.4	39.05	0.97
12.5	SP15	46.4	197.12	150.72	153.27	106.87	41.03	1.09
12.6	Sp59	46.01	192.96	146.95	151.6	105.59	39.17	1.08
12.7	SP15	46.35	191.81	145.46	149.44	103.09	41.10	1.05
12.8	NH1 1	46.78	212.27	165.49	176.97	130.19	27.11	1.33
13.1	83b	46.64	209.51	162.87	167.57	120.93	34.68	1.23
13.2	265	46.52	200.16	153.64	160.86	114.34	34.37	1.16
13.3	16	46.51	197.72	151.21	157.9	111.39	35.75	1.13
13.4	2	46.49	195.52	149.03	155.32	108.83	36.94	1.11
13.5	SP70	46.8	208.01	161.21	170.94	124.14	29.86	1.26
13.6	652	45.91	215.63	169.72	191.75	145.84	16.37	1.49
13.7	5	46.09	198.86	152.77	176.31	130.22	17.32	1.33
13.8	8	46.02	204.2	158.18	167.72	121.7	29.98	1.24
14.1	SP11	46.34	197.77	151.43	160.21	113.87	32.98	1.16
14.2	135B	46.13	201.6	155.47	164.71	118.58	31.11	1.21
14.3	SP17	45.91	191.06	145.15	157.4	111.49	30.19	1.14
14.4	SP14	46.15	194.72	148.57	161.43	115.28	28.88	1.17
14.5	1184	49.05	218.03	168.98	158.8	109.75	53.97	1.12
14.6	87b	49.19	230.87	181.68	200.84	151.65	19.80	1.54
14.7	643	46.19	212.76	166.57	174.21	128.02	30.11	1.30
14.8	78B	46.06	229.35	183.29	200.71	154.65	18.52	1.58
15.1	SP13	46.37	176.46	130.09	137.66	91.29	42.50	0.93
15.2	SP11	46.52	197.62	151.1	157.11	110.59	36.63	1.13
15.3	SP13	45.68	185.97	140.29	149.57	103.89	35.04	1.06
15.4	38	46.07	181.49	135.42	143.67	97.6	38.75	0.99
15.5	SP16	45.51	203.26	157.75	161.22	115.71	36.33	1.18
15.6	SP78	46.25	213.53	167.28	140.5	94.25	77.49	0.96
15.7	335	46.35	212.49	166.14	170.68	124.33	33.63	1.27

15.8	284	46.88	243.65	187.77	206.6	159.72	17.56	1.63
16.1	668	46.33	197.66	151.33	156.64	110.31	37.19	1.12
16.2	36	46.42	190.55	144.13	153.37	106.95	34.76	1.09
16.3	2	46.39	190.95	144.56	155.67	109.28	32.28	1.11
16.4	154	46.67	186.67	140	150.16	103.49	35.28	1.05
16.5	1646	46.65	207.1	160.45	169.2	122.55	30.93	1.25
16.6	888	46.4	215.11	168.71	180.03	133.63	26.25	1.36
16.7	SP10	46.59	215.05	168.46	187.77	141.18	19.32	1.44
16.8	SP16	46.22	206.9	160.68	166.07	119.85	34.07	1.22

Appendix B - Summary table of terms

Term	Definition	Measurement method	Unit
Bulk density	The mass of dry soil per unit of bulk volume, including the air space.	Kopecky ring Proctor test	g/cm^3
Cone Index	The force per unit basal area required to push a cone penetrometer through a specified increment of soil	Soil Penetrometer	MPa
Draught	The force require to pull an implement	Octagonal ring transducer Linear load cell	kN
Electrical conductivity	The capacity of a substance to conduct or transmit electrical current		Siemens /metre
Electrical Magnetic Induction (EMI)	A proximal sensing method which measures apparent electrical conductivity	EMI sensor	milli-Siemens /metre
Packing density	Allows for the transformation of bulk density into a clay independent indicator	Mathematical calculation	t/m^3
Particle density	The mass per unit volume of the soil particles		g/cm^3
Pore size distribution	The volume of various sizes of pores in a soil	Laboratory analysis	% of bulk volume
Porosity	The volume percentage of the total soil bulk not occupied by solid particles	Direct measurement, Optical methods	%
Soil compaction	The process by which the soil particles are rearranged to decrease void space and bring them into closer contact with one another.	Direct and Indirect methods. Refer to page 21.	Various

Soil consistency	The state of soil – whether it is solid, plastic or liquid.	Atterberg Limit test as a measure of the critical water content of fine grained soil.	
Soil strength	A transient property related to the soils solid phase cohesion and adhesion.	Mohr-Coulomb	
Soil structure	The combination or arrangement of primary soil particles into secondary particles, units or peds. These secondary units may be , but usually are not arranged in the profile in such a manner as to give a distinctive characteristic pattern.	Visual assessment	
Soil texture	The relative proportions of the various soil separates in a soil.	Hand texturing, Particle size distribution	