UNIVERSITY OF SOUTHERN QUEENSLAND

# Technological and integrated approaches for practical and rapid assessment of compaction in agricultural soils

## A review

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# Contents

# Introduction

Soil compaction is a worldwide issue for agricultural production (Soane and van Ouwerkerk 1995) and is considered the utmost impact of modern agriculture on the environment (McGarry 2003). The importance of this issue is only heightened by challenges placed on agricultural industries to produce more food and fibre in an efficient manner, and with less land resource, in order to meet the demands of a growing world population (Fraiture *et al.* 2007). Soil compaction is defined as a reduction in the soil pore space (Keller *et al.* 2007), which consequently leads to an increased bulk density (Hamza and Anderson 2005; McGarry 2003). Additionally, increasing the compaction status of a soil leads to a change in associated soil characteristics, such as decreased saturated hydraulic conductivity (Dawidowski and Koolen 1987; Lipiec *et al.* 1998), increased soil strength (Horn and Rostek 2000; McGarry 1990; McGarry 1996), decreased aeration (Stepniewski *et al.* 1994), decreased matric potential (Assouline *et al.* 1997) and homogenous soil structural arrangement (Pagliai *et al.* 2000; Servadio *et al.* 2001; Young *et al.* 2001), potentially leading to mechanically induced soil dispersion (Rengasamy *et al.* 1984). Such changes can cause severe degradation of the soil environment resulting in reduced crop/pasture yield (Lipiec *et al.* 1991), due to decreased water and nutrient availability from the physical constraints imposed on root growth associated with increased soil strength and decrease porosity (Glinski and Lipiec 1990; McKenzie and McBratney 2001), particularly the decrease in macropores and mesopores (Kim *et al.* 2010). Hence, it is paramount that soil compaction be minimised in order to maximise the productivity of agricultural land.

Worldwide, 68 million hectares of soil are considered affected by compaction (Flowers and Lal 1998). Soil compaction due to vehicular traffic is considered to be the primary cause of this compaction (Lipiec and Hatano 2003). As vehicular traffic is an unavoidable process within the agricultural system, to minimise the risk of soil compaction it is vital that: 1) the occurrence of traffic is minimised, 2) traffic that must occur is controlled within permanent lanes, 3) the soil condition (primarily moisture content) be optimal prior to traffic, and 4) wheel load and contact pressure is minimised. However, farming processes are often time constrained, complex, limited by machine manufacturer, and limited economically, meaning that all four conditions will rarely be optimised to reduce soil compaction. Traffic may often need to occur frequently and within a set window of time, potentially irrespective of soil condition; in wet conditions such traffic can result in subsoil compaction due to deeper stresses (Van Den Akker and Stuiver 1989). Furthermore, larger and heavier self-propelled-machines and implements are increasingly being introduced into agricultural systems, which presents a significant cause of soil compaction and soil structural deterioration (Lipiec and Hatano 2003; Lozano *et al.* 2013). In order to limit these impacts, controlled-traffic is prescribed with permanent beds and permanent traffic lanes (see Tullberg *et al.* 2007). However, controlled-traffic in its true sense is often difficult to achieve due to machinery manufacturers producing machines/implements with different wheel track widths. Ensuring all machines and implements operate on the same track may be perceived as a costly exercise but research (Kingwell and Fuchsbichler 2011; Neale 2010) has demonstrated that fully controlled traffic farming systems are economically viable when compared against the cost of soil compaction. However, since the effects of soil compaction are often latent compared to those of say salinity or erosion (Hamza and Anderson 2005), conversion from conventional to controlled traffic farming is often not seen as an on-farm priority. Thus, the effect on subsequent crop/pasture production is often not linked to compaction as the cause by practitioners.

Subsoil compaction due to machine induced soil stress has been shown to pursue past subsequent cultivation, and soil structural degradation shown to increase post deep-ripping of compacted subsoil layers (Arvidsson and Hakansson 1996; Hamza and Anderson 2005; McGarry and Sharp 2001). In a study utilising an experimental soil compaction database from 21 sites comprised of 259 location-years, Arvidsson and Hakansson (1996) showed that the effects of soil compaction persisted after ploughing and that the persisting compaction caused a decrease in crop yield, dependant on soil clay content. Soils with finer texture (i.e. higher clay content) were observed to undergo yield decreases greater than 20% that lasted for up to 3–4 years. These reductions were attributed to changes in the mechanical properties of the soil that caused coarse/dry seedbeds, poor crop emergence, high aggregate tensile strength, and reduced nutrient uptake. Hence, while the effects of compaction might be latent, they are ongoing and could have significant impact on productivity and, thus, financial return. To help address this, it would therefore be of use to provide practitioners with the means by which to make agricultural system management decisions for soil traffic based on soil moisture condition and likelihood of compaction as a function of economic return, in terms of a cost-benefit analysis

However, measurement of soil compaction status is traditionally laborious and therefore expensive. Dry bulk density and total porosity are regularly used as indices of soil compaction, as these soil characteristics provide a clear link between compaction and a soil’s ability to store and transport air and water (Panayiotopoulos *et al.* 1994). However, they do not provide an absolute measure of soil compaction status, which means relative comparison of compaction between fields is not feasible, nor is the degree of compaction for that particular soil able to be calculated. For this reason, various authors have suggested methods by which to provide a soil with an absolute measure of soil compaction status. Hakansson (1990) suggested a ratio between the observed dry bulk density and a reference dry bulk density (uniaxial compression at 200 kPa), while Bennie (1991) calculates the maximum dry density (MDD) using the Proctor test, (AS 1289 5.1.1) and provides a ratio between the observed dry bulk density and the MDD (taking into account the minimum dry bulk density of the soil) corresponding to low, medium, high and very high degrees of compaction. These relative measures have been shown to be more useful than bulk density or porosity when investigating the effects of compaction on root and crop response, as well as for use as input parameters for modelling crop response to compaction (Lipiec and Hatano 2003). While these methods utilise dry bulk density, Hakansson and Lipiec (2000) recommend that bulk density in soils containing significant 2:1 clay minerals be measure at standardised moisture content to avoid issues caused by shrink-swelling phenomena at various water contents. Vertosols (Isbell 2002) contain 2:1 clay minerals and dominate Australian cotton soils, which will further increase the complications of traditional methods of soil compaction status determination.

Full implementation of CTF systems is heavily limited by machinery manufacturers (Tullberg *et al.* 2007). Hence, land managers make trade-offs concerning traversing moist soil against reaping harvests on a regular basis. Therefore, there is a requirement to understand both the potential effect of such a trade-off in partial CTF on compaction and the current compaction status of a soil. This might be addressed through the use of modelling machine impacts and likely soil response (Defossez and Richard 2002; Keller *et al.* 2007). However, modelling requires validation, which requires soil compaction to be determined, largely through bulk density measurement. This is laborious and therefore expensive, as previously discussed. So, rapid measurement methods that either directly or proximally (e.g. pedotransfer functions) acquire information about soil bulk density are therefore required. Various technologies and models exist and are relatively well discussed, but what is not apparent is how this technology might be used in rapid assessment or integrated to provide rapid assessment/prediction of soil compaction for use by the practitioner.

Consequently, this review aims to investigate means to inexpensively and rapidly measure soil compaction status, predict likely compaction due to machine traffic and utilise this information to make risk based assessments for soil traffic. In this review, discussions are limited to assessing soil compaction due to vehicular traffic, whereby assessment refers to both the prediction of likely compaction, as well as the direct measurement of the soil compaction status. A specific focus on Vertosol (Isbell 2002) soils has been provided, as these soils dominate the Australian cotton industry, for which this review has been prepared.

# Fundamentals of soil compaction

The soil solid phase consists of three major separates: sand, silt and clay, with particle size of these in Australia determined as 20–2000 µm, 2–20 µm, and <2 µm, respectively. Particle size is used to describe soil texture whereby a soil high in sand is considered coarse textured, while one high in clay is considered fine textured (Isbell 2002). In addition to the solid phase, a soil also contains a liquid phase (soil solution) and gaseous phase, which are contained in the soil pore network. The pore network is a network of voids between the solid phase individual units and ranges from soil macropores (>75 µm) and mesopores (30–75 µm) that control the majority of infiltration and plant available water, to micropores (<30 µm) containing water generally unavailable to plants, due to strong matric potential (very negative potential) (SSGTC 2008).

Soil compaction is generally described as the process whereby a given mass of soil is compressed due to mechanical stress resulting in a decrease in volume and increase in bulk density (Keller *et al.* 2007; Shroff and Shah 2003). Soil bulk density is not an intrinsic property of soils, being related to the void space between aggregates, and for a given soil is a function of the stress characteristics (magnitude, uniformity, contact area, and motion) applied, and the in situ soil characteristics (soil moisture, soil texture, clay type, and initial density). Soil compaction results in structural rearrangement of the soil separates, expulsion of air from the soil, increase in the packing density of the separates and reduction in soil pore diameter (Defossez and Richard 2002; Keller *et al.* 2007; Lipiec and Hatano 2003). Compaction alters physical characteristics of the soil, as well as being dependent on these characteristics. The following discussion concentrates on the major physical changes occurring in soil, due to an applied stress, and investigates the implication of these for measurement of soil compaction status.

### *Soil strength*

Resistance to compaction and increased bulk density is a function of soil strength, which describes a soils ability to withstand an imposed stress without structural failure (Defossez and Richard 2002). This is a simple concept, but in actuality soil strength is hard to measure due to high variability (Hillel 1980). Soil cohesiveness and angle of internal friction describe a soils resistance to compaction, where cohesion refers to bonding of soil particles, and the angle of internal friction to the resistance of soil compelled to slide over soil. Considering soil from a mechanics perspective, irreversible compaction occurs when the applied stress exceeds a critical soil strength value known as the precompression strength. Defossez and Richard (2002) explain that a soil undergoing compaction combines aspects of elastic, plastic deformation and failure behaviours. When soils are dry, the precompression strength is high and the chance of plastic deformation and structural failure a low. In such circumstances where the prcompression strength is not exceeded by the imposed stress, the soil generally undergoes elastic, reversible compaction. However, soil strength, and thus the precompression strength, weakens rapidly as the soil moisture approaches field capacity (Van den Akker and Soane 2005). Hence, moisture content affects soil strength, and the moisture content a soil is subject to stress at is particularly important.

There is an optimum moisture content at which a stress will cause soil compaction (Hillel 1998), largely dictated by the clay content (Håkansson et al., 1987). When soils are dry there is a high degree of inter-particle bonding (cohesion), interlocking of particles and frictional resistance between particles (angle of internal friction), although as soil moisture is increased the intial effect is that of lubrication decreasing inter-particle friction. Further increases in soil moisture affect inter-particle bonding, causing a less cohesive soil prone to compaction, with the greatest compaction at the optimum moisture content (Hillel 1998). At moisture contents above optimum, the pore space filled by air is less and introduction of further water, an icompressible fluid, adsorbs the energy of compaction (Shroff and Shah 2003).

The effect of moisture on soil strength is also affected by soil texture. In coarse textured soils, strength is derived from a high angle of internal friction, whereby coarse fragments are more likely to interlock as they are forced to slide by one-another (Hillel 1980). On the other hand, the strenght of high clay soils depends heavily on the cohesiveness of the soil, and less so on the angle of internal friction, due to high electrical charge to surface area ratio (electrochemical propreties governing diffue double layer and clay swelling) (Hillel 1998; Sparks 2003; Sposito 1989). Clays such as smectite, contained in the Vertosols that dominate the Australian cotton industry (McKenzie 1998), are more highly affected due to this process than kaolinite clays (e.g. Chromosols; Isbell 2002).

### Soil hydraulic properties

Numerous researches has demonstrated that soil compaction results in a reduction of larger pores (macropores and mesopores) and increase in micropores (Assouline *et al.* 1997; Bottinelli *et al.* 2014; Kim *et al.* 2010; Motavalli *et al.* 2003; Schäffer *et al.* 2008a; Schäffer *et al.* 2008b; Van Dijck and Van Asch 2002). In compacted soils, lower volumetric water contents have been observed at high matric potential (~0 to −10 kPa), with higher water contents at low matric potentials (in the range −100 to −1550 kPa) and relatively little difference in the intermediate matric potential zone (Assouline *et al.* 1997; Ferrero and Lipiec 2000; Kutílek and Nielsen 1994). In the study of Kim *et al.* (2010) , a silt loam soil (Vertic epiaqualfs, Mexico) containing smectite and vertic properties (similar to Australian Vertosols) was compacted from 1.34–1.45 g $cm^{-1}$ where they found that macropores decreased by 69% and coarse mesopores (200–1000 µm) by 75%, which corresponded to a 69% reduction in soil hydraulic conductivity. Similarly, Bottinelli *et al.* (2014) studied the effects of heavy forestry machine traffic on soil macroporosity and found that this decreased by between 96–49% from 0–45 cm in two neoluvisol (ruptic) (WRB 2007). Soil pore networks control infiltration of water and nutrient movement into the soil, with macropores generally attributed the majority, or preferential, flow (Håkansson and Lipiec 2000; Jarvis 2007; Lipiec *et al.* 1998). As discussed above, compaction decreases macropores and thus saturated flow is observed to drastically decrease as compaction increases (Dawidowski and Koolen 1987; Debicki *et al.* 1993; Håkansson and Medvedev 1995; Kim *et al.* 2010; Lin 1999) Lin *et al.* (1996) demonstrated the importance of larger pores on total water flux where contributions of 10% for macropores (>0.5 mm) and 89% for mesopores (0.06–0.5 mm) were observed. This and the changes in volumetric water content at low and high matric potentials demonstrate that small increases in bulk density [8% in this case of Kim *et al.* (2010)] significantly decrease the major pore size distribution. Whilst this might lead to identification of dry and wet zones in comparison of compacted and uncompacted soil, respectively, the soil structural arrangement and effect of this on flow with depth also needs to be considered.

### *Soil structural arrangement*

Soil compaction alters aggregate dimensions and realigns separates homogenously (reduction of heterogeneity) into platy and massive soil structure. The effects of structural rearrangement and the ramifications for this on the continuity of pores is also a consideration. Active macropores have a significant effect on water flow (Lipiec and Hatano 2003). Compaction of soils not only decreases the macroporosity of a soil, but it also modifies the shape, orientation and continuity of soil pores (Boizard *et al.* 2013; Bottinelli *et al.* 2014; Bullock *et al.* 1985; Kim *et al.* 2010; Pagliai 1987; Pagliai *et al.* 2003). Using dye to trace infiltrating water in saturated and unsaturated conditions throughout a soil profile and subsequent computer supported image analysis of soil pits, Etana *et al.* (2013) showed that persistent subsoil compaction (up to 14 years) could enhance preferential flow. Where pore networks are bimodal, as could be expected in compacted soils, bypass flow is enhanced and the filtering capacity of the soil is reduced (Jarvis 2007). This should result in drier dense areas consisting of compacted soil and clear preferential flow paths, which may hold ramifications for soil compaction methods aimed at soil water differential measurements.

Lipiec and Hatano (2003) discuss advances in imaging technology such as computer assisted tomography (CAT) scanning, single photon emission computed tomography (SPECT) scanning, and various other scanners and high resolution cameras for assessment of soil structural arrangement. More recently, Marchuk *et al.* (2013) used X-ray computed tomography to assess soil structure. However, such technology is generally limited to laboratory analysis, often requiring dye or resin impregnated soil cores. Discussion of these techniques is avoided below, but as this equipment advances, the continuity and orientation of pores, and the structural arrangement of soil separates in the field could provide valuable rapid assessment of soil compaction status.

### *Aeration*

Furthermore, the increase in microscopic pores results in higher volumetric water contents at lower (more negative) matric potentials. Thus, these changes also affect soil aeration, and are often quantified as air-filled porosity, redox potential, air permeability and oxygen diffusion rate (Stepniewski *et al.* 1994). Compacted soils with similar air filled porosity to uncompacted soils were shown to have much smaller pores by Simojoki *et al.* (1991), which led Lipiec and Hatanto (2003) to conclude that a better reflection of compacted soil aeration might be obtained from transmission parameters and contribution of active pores. In measuring soil pore continuity, air permeability can be used as it is a measure of the ability to transport gas by convection. However, there is a dependence of air permeability on pore diameter and as such the variability is high, meaning that significant replication is required to obtain meaningful results (Gysi *et al.* 1999; Iversen *et al.* 2001; Koszinski *et al.* 1995). Soil compaction decreases the relative gas coefficient (Stepniewski *et al.* 1994), the oxygen diffusion rate (Dexter and Czyż 2000) and increases redox potential (Whalley *et al.* 2000). Lipiec and Hatano (2003) explain that these factors are best measured in wet soils, often near, or at, saturation.

## Soil thermal properties

Soil compaction alters the thermal properties of soils causing differences in soil temperature and affecting the spatial and temporal variation of this (Lipiec and Hatano 2003). Research has established that properties such as thermal conductivity, heat capacity and thermal diffusivity increase as soil compaction increases, with greater increase observed as soil moisture increases (Abu-Hamdeh 2000; Abu-Hamdeh and Reeder 2000; Guérif *et al.* 2001; Jassar *et al.* 1997; Malicki 1990; Usowicz *et al.* 1996). These differences between compacted and uncompacted soils are primarily ascribed to increased contact between soil separates associated with structural realignment from the imposed force during compaction. However, the water status of soil pores is also important whereby Horn (1994) showed that convection and diffusion of heat through connectivity of water filled pores also affected thermal differences. Additionally, bulk density was shown to be the primary driver of soil thermal spatial variability and that this is less variable in compacted soils (Usowicz *et al.* 1996) and to greater depths (Lipiec *et al.* 1991).

Whilst soil compaction affects the soil thermal properties, there is a paucity of information pertaining to its usefulness as a proximal variable for rapid assessment. Some information on thermal property measurement is provided by Abu-Hamdeh and Reeder (2000), Oschner *et al.* (2001) and Abu-Hamdeh (2003), while information of thermal resistivity can be found in Singh *et al.* (2001) and Sreedeep *et al.* (2005). Further discussion has not been afforded to sensing of thermal properties in this review.

## Soil acoustic properties

The acoustics of a soil are affected by soil properties; specifically, the relative characteristic impedance and the propagation constant (Hess 1988; Kinsler *et al.* 1982). Moore and Attenborough (1992) state that these acoustic properties are dependent on the air-filled porosity connected to the surface, flow resistivity, pore shape, pore size and tortuosity of pores. In a compacted soil where these are reduced, changes in acoustic properties within the solid phase occur, as well as a reduction of sound wave transfer through liquid and air filled pores (Moore and Attenborough 1992; Shin *et al.* 2012). However, the moisture content is highly dynamic in soils throughout time, which means that point measurements of acoustic differences for compaction would need to be comparative at a single time point (reference soil versus compacted soil), or measured repetitively throughout numerous moisture contents. Shin *et al.* (2012) further discusses that most models used to derive soil physical characteristics from acoustic properties are usually either assumed to be 100% air-filled, or water saturated, which is rarely the case. Whilst Moore and Attenborough (2002) found relatively good relationships between acoustic properties and the predicted depth of a harder layer, the limit of acoustic predictive capacity was 10 cm for dry clay soil and 8 cm for wet clay soil. Furthermore, difficulties were encountered with cracking as soils dried. Shin *et al.* (2012) investigated linear Biot-Stoll theory using acoustic-to-seismic coupling in determining soil physical properties related to soil pores and found relatively weak predictions of soil strength to 50cm in sandy soils. They concluded that the current capacity to utilise acoustic properties is limited, even with the introduction of three soil layers of differing inherent properties (each assumed individually isotropic). However, the introduction of layers increased predictive accuracy and further research should occur. Hence, this technique has not been afforded discussion below.

# Determining soil compaction

There is a plethora of methods by which to measure the various factors affecting soil compaction, with many of these methods being time consuming and laboratory based (see Lipiec and Hatano 2003; McKenzie 1996). Hence, this review focuses on methods that allow rapid measurement of associated factors throughout the soil profile or bulk in order to consider both topsoil and subsoil compaction impacts. Additionally, this section discusses measurement of soil compaction once a stress has been imposed. Implications of imposing stress and the factors that affect stress impact are discussed in the section on predicting soil compaction.

## *Penetration resistance*

The use of a cone penetrometer to determine the penetration resistance at a known energy transfer (dynamic cone penetrometer; DCP) or insertion velocity (static cone penetrometer; SCP) is considered a traditional method by which to rapidly obtain information concerning soil strength. The relative inexpensiveness of the cone penetrometer (push rod, or vertical weight drop versions), as well as the fact it is easily transportable and simplistic to use (Rawitz and Margolin 1991), has seen this method favoured for field-scale and applied investigations (Smith 1987). Subsequently, practitioners regularly prefer this method and relate well to the use of the instrument, although can often be heard to describe it as a moisture probe. This is an apt description, as soil moisture affects the measurement of soil strength and varies considerably in both spatial and temporal dimensions (Vaz and Hopmans 2001). As discussed above, soil strength decreases in a non-linear fashion as the soil field capacity is approached (Van den Akker and Soane 2005), which means that *in situ* soil moisture is incredibly important in standardising the estimated soil strength, as penetration resistance also varies with this (Aksakal *et al.* 2011; Bayat *et al.* 2008; Busscher *et al.* 1997; Ley *et al.* 1993; Perumpral 1987; Şeker 1999; Topp *et al.* 2003).

Numerous authors have investigated the relationships between penetration resistance and soil water content finding linear (Ley *et al.* 1995), exponential (Ohu *et al.* 1988), and inverse (water content squared, Ayers and Perumpral 1982) relationships. While soil strength, and hence penetration resistance, are affected by numerous variables, water content is considered to be the most important, featuring in all empirical and conceptual models explaining penetration resistance in soils (Busscher *et al.* 1997). By examining literature data and using curve fitting software Busscher *et al.* (1997) suggested three equations to explain the relationship of penetration resistance to soil moisture, which were similar to other equations already in the literature:

$$\boldsymbol{C = aW^b} \qquad \text{Eqn 1}$$

$$C = a(1 - W)^b \qquad \text{Eqn 2}$$

$$C = ae^{bW} \qquad \text{Eqn 3}$$

where *C* is cone index in MPa, *W* is water content on a dry basis (g $g^{-1}$), and *a* and *b* are empirical parameters calculated using the least squares method for each interval/treatment. From these equations they further investigated the effect of water content using:

$$\boldsymbol{C_c = C_o + \frac{dC}{dW}(W_c - W_o)} \qquad \text{Eqn 4}$$

where *sC/dW* is the first derivative of any of Eqn 1–3 and the subscripts *c* and *o* denote the corrected and original, respectively, values for cone index (*C*) and water content (*W*). These equations were evaluated against existing experimental data and it was concluded that correction for water content (Eqn 4) caused significant improvement in treatment differences.

More recently, Aksakal *et al.* (2011) sought to determine the time dependent changes in penetration distribution in a 5 ha field. They use an equation similar to Eqn 3, but allowing for incorporation of measured water content and adjusting the penetration resistance to a water content of 10%. The justification for this appears to be on the basis of determining soil specific effects, as the calibration was done using intact cores of the loam soil (23% clay). Their exponential relationship produced a fit of $r^2=0.93$ for a moisture range of ~5–70% moisture content, which suggests the soil specific calibration process is of value. Comparatively, Lapen *et al.* (2004) used multivariate adaptive regression splines (linear regression based) to force linear piecewise trends to penetration data for tilled and no-till soils. It was found that cultivation caused any single penetration response trend to water content to be insufficient to predict penetration resistance throughout the season; that is, penetration resistance and water content relationships in cultivated soils are growing season time dependent. Perhaps if the point in the growing season that measurement of penetration resistance is made is kept constant, then the calculated relationship may remain suitable.

Vertosol soils present another problem, which is their shrink-swell properties, and none of the literature discussed above is representative of this. McKenzie (2001b) and McKenzie and McBratney (2001) showed that penetration resistance was a poor indicator of bulk density and performed poorly at high water content in Vertosols. The former paper indicated that a cone penetrometer provided valuable data when the Vertosol soils were close to the plastic limit. Therefore, Vertosol specific calibrations would need to be conducted and the effect of voids at soil moisture content less than the plastic limit should be considered.

Static cone penetrometers (SCP), or push rod penetrometers, require that the operator supply a constant velocity when pushing the cone into the soil in the vertical plane. However, it is notoriously difficult to supply constant velocity when manually operating a SCP, which means that variation within datasets and between operators is increased and analysis is fraught with error (Herrick and Jonesb 2002). Motorised versions of SCPs use platforms to hold the penetrometer upright and rigid and then supply a constant velocity to produce less variable datasets and remove operator effects (Topp *et al.* 2003), but in doing this the expense of equipment is increased and accessibility is therefore decreased. The DCP utilises a known weight dropped from a known height along the penetration rod. Therefore, kinetic energy is supplied at a constant rate, provided the rod is maintained in the vertical state. Maintaining this vertical state is just as important for penetration resistance with SCPs as it is for DCPs. By use of constant energy transfer, the operator effect is removed, and because a DCP can be cheaply constructed they are readily accessible as compared to motorised SCPs. The majority of field penetrometers utilise a penetration cone with diameters from 11–25 mm and semi-angles of 15° or 30° (ASABE 1999; Campbell and O'Sullivan 1991; Ehlers 1975). If a cone head that is smaller, or larger, than the soil structural unit (structured soils) is used, then the penetration resistance measured is related to intra-aggregate, or inter-aggregate, strength, respectively (Bradford 1986; Lowery and Morrison 2002). Small diameter, sharp penetrometers are more representative of roots, thus presenting better correlations to effect on roots, as compared to penetrometers with greater diameter that increase the friction component of total penetration resistance measured (Groenevelt *et al.* 1984; Lipiec and Hatano 2003; Voorhees *et al.* 1975; Whalley *et al.* 2000).

Godwin et al. (1991) developed a drop-cone penetrometer for rapid assessment of soil strength. It consists of releasing a 2 kg, 30° apex angle cone from a height of 1 m, and determining its penetration on the ground. The authors established linear relationships between soil moisture content and drop-cone penetration, and between this and tortional shear vane strength. Linear relationships were also found between rut depth and drop-cone penetration (Antille *et al.* 2013; Godwin *et al.* 1991), which enable prediction of soil damage (compaction) prior to field traffic.

Whilst cone penetrometers provide rapid and inexpensive measurement of spatial soil strength distribution, and potentially temporal distribution depending on correction for soil moisture, they do have limitation in terms of measurement reliability. Spatial variation of penetration resistance is affected by numerous factors and can vary over centimetres (Lipiec and Hatano 2003). Thus, high amounts of replication are required, with the suggestion of 10 replicates at small plot scale (size unspecified) and 20 measurements post compaction along the wheel rut (assuming wheeled traffic) (Smith 1987). The spatial dependence of penetration resistance was also shown to increase in loose soil, as compared to compacted soil, meaning that smaller sampling intervals need to be used in loose soil (Lipiec and Hatano 2003; Lipiec and Usowicz 1997; Perfect *et al.* 1990). O'Sullivan *et al.* (1987) state that penetration resistance can be related to compaction, but that interpretation can be difficult. This is partially due to the effect of compaction on soil pore relations, whereby soil saturation content is decreased and differences in penetration resistance may be masked by the changes in matric potential and hydraulic conductivity (Campbell and O'Sullivan 1991). Thus, soil strength should be measured as soon after traffic as possible if to be compared to prior compaction or a reference soil (without adjusting for moisture content). Furthermore, Sun *et al.* (2011) discusses the complications with describing the transferred energy and compares the SCP and DCP concluding that ideal solutions require further investigation.

It is apparent that soil moisture and spatial sensitivity associated with using a cone penetrometer to rapidly determine *in situ* soil compaction status at multiple points in time present some issues for interpretation of data, although a major advantage is the low associated cost and the fact that practitioners relate well to the method of measurement. Comparing relative differences in penetration resistance at a single point in time, or over a short period of time (e.g. day before and after soil traffic) where moisture content could be assumed to be unchanged, or fairly distributed, improves the usefulness of the data. Further developments of the cone pentetrometer have introduced combined probes for penetration and soil moisture estimation (see Kosugi *et al.* 2009; Masaoka *et al.* 2012; Vaz *et al.* 2001; Vaz and Hopmans 2001).

## *Electromagnetic induction*

The electromagnetic induction (EMI) survey technique induces alternating currents within the soil that are linearly related to the soil electrical conductivity (EC) using a varying magnetic field (McNeill 1980). The below-ground response is then analysed to determine electromagnetic fields and the ramification of differences depending on the depth response of the instrument. The EM38 (Geonics, Ontario, Canada) is predominantly used in precision agriculture due its depth response functions relating to shallower soil depths that correlate with plant rooting depths (Corwin and Lesch 2005). EMI instruments use a transmitting and receiving coil to interrogate electromagnetic field response, and the coils used in an EM38 are situated 1.0 m apart. The transmitting coil is excited using sinusoidal current (EM38 – frequency 14.6 kHz), which creates a time-varying magnetic field that induces eddy currents (secondary magnetic field within the primary magnetic field) within the soil (Lamb *et al.* 2005). It is the magnitude of these eddy currents that is proportional to soil EC, and the receiver intercepts a fraction of these which are returned as an amplified summation in the form of an output voltage. While this method is considered a measure of EC, it is actually measuring the apparent EC (ECa) which is the EC integrated throughout the depth of measurement; a depth weighted EC according to the theoretical respective depth response functions (McNeill 1980). Hence, at any single point of measurement, the ECa returned by the instrument is an integration value determined by both the depth related sensitivity and the predominant, depth dependent, drivers of the soil EC (Hossain *et al.* 2010; Sudduth *et al.* 2001). As explained by Roades et al. (1989) the current flows through three pathways: 1) a liquid phase pathway (soil pore water and it salt content); 2) a liquid-solid phase pathway (exchangeable ions associated with clay minerals); and, 3) a solid pathway (direct, continuous contact between soil separates). However, the soil matrix does not provide sufficient direct, continuous contact between soil separates for continuous current flow. For further understanding of the physical theory and principles of EMI, readers are directed to Hendrickx *et al.* (2002) and Hendrickx and Kachanoski (2002).

When producing field-scale maps using EMI instruments, such as the EM38, the ECa point values are interpolated to provide spatial mathematical prediction between point predicted measurements, which further affects the accuracy attributed to the output results (O'Leary and Peters 2004). However, due to the rapid and non-destructive nature of EMI instruments, spatial interpolation of point predictions provides a valuable tool to precision agriculture for determining the spatial trends of ECa driving edaphic properties (Corwin and Lesch 2005; Friedman 2005; Johnson *et al.* 2005).

The EC of a soil is governed by multiple soil properties (McKenzie *et al.* 2008), predominantly: 1) Pore network characteristics (primarily defined by clay content and type) and connectivity; 2) Water content with depth; 3) Concentration of dissolved salts in the soil water; and, 4) Temperature and phase of the pore water (phase referring to frozen/unfrozen). Hence, soil bulk density (and compaction) is considered to affect ECa measurement (Corwin and Lesch 2003; Corwin and Lesch 2005; Hossain *et al.* 2010). According to McBratney *et al.* (2005) if a soil has a profile thickness deeper than the effective measuring depth of an EM38, then volumetric moisture content and clay content are the primary drivers of ECa, with soil moisture being the single most important factor (Brevik and Fenton 2002). This describes increased accuracy ascribed to predicting soil moisture in homogenous medium, such as the uniform soil profile of a Vertosol. Hossain *et al.* (2010) showed that use of an EM38 provided reliable prediction of soil moisture in a Vertosol, provided propagation models, rather than an inversion model, was used in the prediction of depth specific soil moisture. It was also shown that the horizontal dipole configuration was better suited to depth related volumetric soil moisture, as compared to the vertical dipole configuration.

Guyonnet *et al.* (2003) compacted a pond clay liner (62–71% clay) using eight passes of a 20 Mg roller at optimum moisture content (20% moisture) to achieve a soil bulk density between 83–92% of the soil maximum dry density (1.55 g cm$^3$) using 20 cm lifts to a thickness of 1.0 m. They introduced heterogeneous zones within the clay liner that consisted of loosened soil (0–30 cm) and backfilled uncompacted topsoil, sand and gravel mixture (60–100 cm), although the subsequent overlying layers were compacted above these latter heterogeneities. They found that the EM38 was capable of identifying heterogeneities in the horizontal dipole configuration, but not the vertical dipole configuration. However, this method did not clearly detect the heterogeneities at depth. Hoefer and Bachmann (2012) reported high correlations between soil strength (measured as penetration resistance) and EM38 ECa values in detecting subsoil compaction in a typic Luvisol (10–17% clay) derived from loess at depth 30–40 cm.

Further studies by Hoefer *et al.* (2010), Krajco (2007) and Malo *et al.* (2001) all detailed reasonable relationships between ECa measured using an EM38 and measures of soil compaction (bulk density, penetration resistance etc.). Furthermore, Al.Gaadi (2012) used a sand soil (3.8% clay, 88.7% sand) to demonstrate the capability of an EM38 to detect soil compaction as a result of surface applied force. They imposed compaction at a force between 220 and 2061 kPa, depending on soil moisture treatment (between 5.0, 5.3, 6.9 and 8.0%), using a small, hand propelled, vibrating plate compactor. Their results showed that ECa generally correlated with soil compaction, although at 8% moisture content correlations between soil compaction and ECa were weak. They attributed this to soil moisture dominating the effect on ECa and suggested that at moisture contents above 8% the EM38 may not be suitable, although Guyonnet *et al.* (2003) found suitable identification at 20% soil moisture in a clay soil. Furthermore, the depth extent of soil compaction was only measure to 17.5 cm by Al-Gaadi (2012) and the effect of compaction past this point is questionable given the packing phenomena in high sand content soils, due to the high angle of internal friction causing interlocking of coarse particles. Given the integrated nature of ECa measurement, dilution of compaction effect in the EM38 response at either horizontal or vertical dipole configuration might have occurred, which could also have affected the ability to detect changes in soil compaction.

The use of EM38 in identifying soil compaction has been shown to yield some promise, although issues concerning the depth of detection and the moisture content at which detection occurs for soil compaction should be provided further attention. Hossain *et al.* (2010) found good agreement between ECa and soil moisture in Vertosols. Using a similar experimental approach, the corresponding depth and moisture content at which soil bulk density is outweighed as an ECa driver in high clay content soils could be investigated.

### Electrical resistivity tomography

Electrical resistivity tomography (ERT) works on similar principles to EMI, but instead measures the resistance distribution of the soil medium. Electrical currents are applied to the soil, normally using two probes to supply the current and two probes to record the resulting differences in potential. These differences in potential supply information the electrical properties and form of heterogeneities within the soil (Kearey *et al.* 2002). Differences in resistance between soil, water and air (solid, liquid and gaseous phases in soil) supplies information that can be used as a proxy for soil physical properties (Banton *et al.* 1997), and the greater the electrical property contracts between the soil and heterogeneities, or imposed factots such as compaction, the easier these are to detect using ERT (Samouëlian *et al.* 2005). Thus, it is imperative to identify the optimal ranges of various soil physical properties that allow the greatest contrast in ERT response. The primary factors that affect electrical resistivity are as for EMI, so the reader is directed to the section on EMI.

Laboratory relationships between resistivity and volume of water were established by McCarter (1984) whereby clay resistivity is a function of both moisture content and the degree of saturation. In investigating this, soils were initially equilibrated to a known moisture content (range 4.1 to 23.3%), which was held constant for each core, but the level of compaction was changed incrementally to decrease pore volume and therefore saturation content. McCarter's (1984) results demonstrated that resistivity decreased as moisture content increased and degree of saturation increased, which thus also demonstrated that compaction of soil decreases resistivity. This was further confirmed by Seladji *et al.* (2010) for a clay (38.5% clay), loam (20.0% clay) and high organic matter loam (23.3% clay, 4.2% organic matter). They concluded that resistivity is sensitive to an increase in soil bulk density, irrespective of soil texture and at gravimetric water content <25%. Three bulk densities were investigated (1.1, 1.3 and 1.6 g $cm^3$) with clear contract in resistivity between all densities for the clay and loam soil, although the high organic content loam exhibited no clear distinction in resistivity between i.1 and

1.3 g $cm^3$. They explain that this may be attributed to organic matter reducing surface charges, but concede that better information on the effect of organic matter of soil electrical properties, and thus compaction, is required. The literature (Islam *et al.* 2012; McCarter 1984; Seladji *et al.* 2010) agrees for a range of clay contents (~<15–54% clay, with or without silt fraction included) that the optimal range of moisture content for difference in bulk density to be detected by ERT in soil is 10–25%, although this depends on the degree of saturation, which is a function of clay content, soil moisture and compaction level. This range appears sufficient for use in Vertosols, where the specific volume of soils with vertic properties (shrinkage) ranges from approximately 0.6–0.75 $cm^3$ g for soil moisture 10–25% (Figure 1) (Vervoort *et al.* 2003).

The smectitic content and vertic properties result in shrink-swell phenomena in Vertosols and the subsequent cracking can cause issue with measures of compaction, as discussed in some of the above sections. However, these cracks in Vertosols are an important hydraulic mechanism. Greve *et al.* (2012) and Greve *et al.* (2012) used ERT to show how Vertosols initially wet non-uniformly from within the profile due to cracks, important for subsoil water storage. Thus, these cracks control important processes for deeper storage of water that are likely affected in compacted soils due to changes in structural arrangement and internal swelling pressures. Tabbagh *et al.* (2000) identified electrical resistivity as an important tool for identification of soil structural horizionation and Besson *et al.* (2004) further showed that electrical resistivity was an important tool for the characterisation of cultivated soils. Subsequently Tabbagh *et al.* (2007) have produced a method by which to quantify the cracking patters of Vertosols based on this work. Tang *et al.* (2008) investigated the effect of increasing the thickness of a soil layer in the laboratory using reconstructed soil slurries and found that increasing the soil layer thickness the average crack length, width, aggregate area and crack intensity factor are enhanced, as well as the primary distribution ranges of those parameters. The reconstructed nature of the soils in this experiment, and known structural homogenous realignment soil separates in compacted soil, implies that similar behaviour could be expected in compacted soils. This reinforces that in compacted clay soils, the compaction conditions affect the drying behaviour of the soil (Daniel and Yung-Kwang 1993;

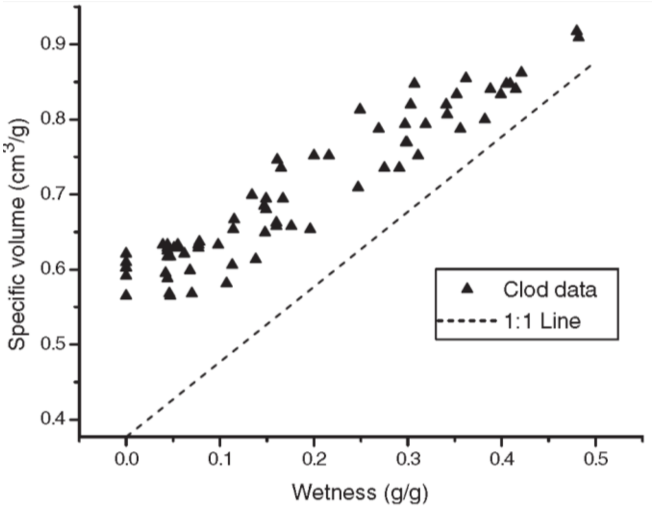


***Figure 1. Shrink-swell data for Vertosol clods (100 mm depth) from the Gwydir valley, indicating the typic S-shaped curve, although with indistinct shrinkage phases (Vervoort et al. 2003).***

Holtz and Kovacs 1981). Differences in cracking patters between compacted and uncompacted soils, as measured using ERT, might prove to be a useful index of soil compaction and its effect on the soil system. While other methods of measurement are impeded by soil cracking patterns inherent to Vertosols, the capacity of ERT to determine compaction status and structural behaviours in these soils appears promising.

### *Time domain reflectometry*

The time domain reflectometry (TDR) method determines the dielectric constant ($\kappa$) by way of an electromagnetic wave pulse generator and measurement of the propagation time of these waves (Noborio 2001). Simple electrode rods (commonly stainless steel or brass) are inserted into the soil and the elecytromagnetic wave passes along the probes being reflected back at the full extent of the probe. An incident electromagnetic wave is also reflected at the start of the probe due to an impedance difference between the probe and the cable. By way of knowing the physical probe length and the distance between the initial and final reflections, the dielectric constant of the soil can be calculated (Baker and Allmaras 1990). Hoekstra and Delaney (1974) explain that difference in the dielectric constant between soil and water is stark and that because of this is it reasonable to measure the volumetric moisture content of moist soils by obtaining the apparent dielectric constant. The equation of Top *et al.* (1980) is most generally used for homogenous soils to calculate the volumetric moisture content ($\vartheta$):

$$\boldsymbol{\theta} = \mathbf{-5.3 \times 10^{-2} + 2.92 \times 10^{-2}}\mathrm{K} \mathbf{- 5.5 \times 10^{-4}}\mathrm{K}^{\mathbf{2}} \mathbf{+ 4.3 \times 10^{-6}}\mathrm{K}^{\mathbf{3}} \qquad \text{Eqn 5}$$

It was found that the apparent dielectric constant was not strongly sensitive to temperature, soil texture bulk density (non-vertic soils) or soluble salt content (Topp *et al.* 1980). The calibration curve of Topp *et al.* (1980) has been confirmed by numerous investigations for soil textures ranging from sand to clay, with ferric and non-ferric properties and with saline/non-saline soil water (Drungil *et al.* 1989; Grantz *et al.* 1990; Nadler *et al.* 1991; Patterson and Smith 1981; Reeves and Elgezawi 1992; Smith and Patterson 1984; Topp and Davis 1985; Topp *et al.* 1982; Topp *et al.* 1984). However, Eqn 5 has been found to underestimate volumetric moisture content in vertic soils (Bridge *et al.* 1996) and over estimate it in soils with saline water (Dalton *et al.* 1990; Noborio 2001). Subsequently, it has been shown that soils high in organic matter, or of fine texture, change the relationship between the apparent dielectric constant and volumentric water content (Dasberg and Hopmans 1992; Dirksen and Dasberg 1993b; Dobson *et al.* 1985; Roth *et al.* 1992). This change in relationship was attributed to soil density and texture by Abdulla *et al.* (1988) and Ponizovsky *et al.* (1999), although Dirksen and Dasberg (1993a) showed that the change was more due to density than texture.

In an effort to extend TDR to geotechnical applications, Siddiqui and Drnevich (1995) adapted calibrations to convert soil moisture from volumetric to gravimetric. Their specific purpose was to develop procedures for use of TDR in geotechnical compaction control. They undertook laboratory calibration to obtain soil-dependent constants for subsequent field measurements. Field testing involved determining the apparent dielectric constant from four coaxially configured spikes driven into the soil and then immediately repeating this on the soil excavated from under the spikes and compacted in a mould. The assumption is that the gravimetric water content remains the same for both tests. Then the two apparent dielectric constants (field state and compacted) are used with the known total density of the soil in the mould to calculate gravimetric soil water content and dry density. Further evaluation of this method has shown is to be sufficiently reliable geotechnical purposes (Drnevich *et al.* 2001; Drnevich *et al.* 2002; Lin 1999; Siddiqui *et al.* 2000). Xiong *et al.* (2004) adapted this procedure further removing the requirement of mould compaction in order to create a onestep procedure. They observed satisfactory results for a variety of soils, but found that high clay content with high water content produced unsatisfactory results due to unclear reflection of the electromagnetic waves.

Alaoui and Helbling (2006) used changes in soil porosity and pore connectivity to explore the use of TDR in determining compaction effects. Their experiment consisted of auguring holes and installing probes at different depths. They showed that wheeled traffic caused a change in soil structure in the 0–0.1 m depth that stopped significant water movement to lower probes. However, this method is focused on evaluating the effects of soil compaction, rather than determining an indication of the compaction status of the soil.

## Predicting soil compaction

An important aspect to managing soil compaction within the farming system is the ability to make operational decisions concerning when to traffic the soil. However, as has been discussed, understanding when to traffic soil is complex, due to the various contributing factors such as soil water status, soil texture, soil organic content and type, machine characteristics and climate (Raghavan *et al.* 1990; Troldborg *et al.* 2013) that affect soil compaction, as well as the competing tensions, such as risk of rain ruining harvest. Prediction of likely soil compaction due to traffic of a specific machine, given the current soil condition, is more useful for maintaining soil productivity than measuring soil compaction after the fact. Hence, the use of modelling of soil compaction degree provides a useful means to provide estimates of compaction likelihood prior to traversing the field.

Soil compaction models can be separated into two main categories: 1. analytical (often referred to as pseudo-analytical models); and 2. numerical (finite element models – FEM) (Abu-Hamdeh and Reeder 2003; Defossez and Richard 2002; Keller *et al.* 2007). However, both categories include determination of loading force propagation throughout the soil, resulting from machine imposed forces acting on contact at the wheel-soil interface, and modelling of stress-strain behaviour of the soil; stress-strain behaviour describes the relationship between the applied stress and the subsequent changes in soil volume (Defossez and Richard 2002). The main difference between these two model categories is the determination of loading force propagation, whereby the propagation calculus for analytical models uses semi-empirical formulas (Fröhlich 1934) derived from the analytical solution of Boussinesq (1885) and the propagation calculus of numerical models linearise the equation describing static deformation of a soil body in order to create a soil displacement field based on nodal points. Defossez and Richard (2002) comprehensively evaluated analytical and numerical models that had been tested in laboratory soil bins or the field in their review in order to establish the suitability of these to simulate realistic agronomic situations. While they concede that the experimental conditions differed between model validations and that simulations could not be conducted over a wide range of conditions due to the number of soil and wheel variables influencing compaction, they submit that even though numerical models might supply a more accurate representation of likely compaction, the analytical modelling approach was adequate at a wide range of field conditions when simulating homogenous layers 0.5–1.0 m deep. Given the large number of parameters required to satisfy the complexity of numerical models and the demonstrated practicality of analytical models (Defossez and Richard 2002; Keller *et al.* 2007; Keller and Lamandé 2010; Keller *et al.* 2013), analytical models are discussed here. Specifically, SoilFlex (Keller *et al.* 2007) is presented because of its ability to remain flexible (important to farming systems), incorporate differing wheel configurations and its relative simplistic use.

### *SoilFlex*

Whilst numerous analytical models exist such as those presented in Gupta and Larson (1982), Diserens and Steinmann (2002) – 'TASC', Van Den Akker (2004) – 'SOCOMO', Johnson and Burt (1990) and O'Sullivan *et al.* (1999) – 'Compsoil', SoilFlex (Keller *et al.* 2007) provides the user greater flexibility and thus greater practicality. Readers are directed to Seig (1985) Keller *et al.* (2007) and Defossez and Richard (2002) for a discussion of the differences between existing models. Chi et al. (1993) predicted stress and strain of a sandy loam, and a clay soil, and indicated that the assessment of soil parameters required by models is the main source of error. Hence, soil compaction models which can account for a range of soil conditions are valuable for machinery manufacturers at the design stage to pre-assess soil impact derived from vehicular traffic under such soil conditions. For example, these models may enable investigation of tyre specifications and axle configuration. The main advantage of COMPSOIL (O'Sullivan et al. 1999) over SOCOMO (van den Akker 2004) or TASC (Diserens and Steinmann 2002) is that it enables quantification of soil density increases resulting from traffic as opposed to a simple indication of soil compaction danger for given load and inflation pressure.

SoilFlex was given its name due to the flexibility provided in describing soil surface stress, modelling of the stress-strain behaviour, and estimation of soil mechanical parameters by use of pedotransfer functions (PTFs), including the ability to add PTFs to the model (Keller *et al.* 2007). Unlike other analytical models, SoilFlex contains decision points that affect the output comprehensiveness (provide the flexibility); these being: wheel configuration; distribution of normal stress; consideration of traction; calculation of stress only; consideration of shear strain; and which stress-strain relationship to use. Based on the user decisions, output supplied can include the vertical stress state only, the complete stress state only, or the complete stress state along with resultant bulk density and vertical soil displacement. Thus, SoilFlex is a 2-dimensional model that estimates the stress state, induced bulk density changes and vertical displacement of soil due to wheeling ruts (Keller *et al.* 2007). SoilFlex uses existing contact area functions (Janosi 1962; Keller 2005; O'Sullivan *et al.* 1999; Soehne 1953), stress propagations equations (based on the concentration factor; Boussinesq 1885; Cerruti 1888; Fröhlich 1934; Soehne 1953) and stress-strain relationships (Bailey and Johnson 1989; Larson *et al.* 1980; O'Sullivan and Robertson 1996). An in depth discussion of the calculations and decisions involved in SoilFlex is avoided here (readers are directed to Table 2 and 3 in Keller *et al.* 2007), as the purpose of this discussion is to demonstrate the usefulness of the modelling approach.

Keller *et al.* (2007) calculated the vertical stress and vertical displacement of soil due to wheeling from a single passage of a sugar beet harvester (tyre inflation pressure 100 kPa, wheel load 86 kN) on a moist Eutric Cambisol (loam 0-30 cm depth and silty clay loam >30 cm depth) and compared this to measured values. Whilst the vertical stress calculated agreed well with that measured, in all instances (models for calculation of vertical displacement) vertical displacement in the subsoil was overestimated and under estimated in the topsoil, resulting in rut-depth underestimation. A similar result was obtained by Defossez *et al.* (2003), who used 'Compsoil' (O'Sullivan *et al.* 1999), which they speculated was due to not considering lateral displacement, although in the case of SoilFlex lateral displacement is accounted for. Keller *et al.* (2007) thus attribute this underestimation due to the difficulty in easily obtaining soil mechanical parameters (cohesion, angle of internal friction, and shear modulus). They conclude through sensitivity analysis that accurate soil displacement is contingent on accurate values for these parameters. However, these parameters are notoriously hard to measure. SoilFlex provides flexibility to obtain information that does not include the vertical displacement, or reasonable estimates of these paramters could be used based on empirical data, or laboratory determination, such as Keller *et al.* (2007) undertook. When comparing SoilFlex to other an FEM model used by Gysi (2001) it was found that the predicted mean normal stress and bulk density agreed well with the FEM model. Hence SoilFLex as an analytical approach to stress distribution calculation is justified (Keller *et al.* 2007).

While SoilFlex provides a flexible model structure for calculation of vertical stress and vertical displacement, the model has not been extensively tested on a wide range of soils and would require further investigation for us in prediction of soil compaction in Australian Vertosols. Keller *et al.* (2007) also point out that soil deformation is a time dependent process and that SoilFlex does not account fot this. Thus, they suggest that future iterations could couple SoilFLex with SISOL (Roger-Estrade *et al.* 2000), which models time dependent changes in soil structure sue to various management practices.

### Challenges for analytical modelling

Keller and Lamande (2010) have produced a comprehensive paper on future directions for analytical soil compaction modelling. Readers are directed to their paper for a more inclusive discussion on the following summarised points. The main challenges that they identified were: 1) need for better characterisation and estimation of the upper boundary condition (that defining the soil contact area, as well as the magnitude and distribution of the contact stress); 2) requirement for more accurate means by which to measure soil stress (i.e. transducers and stress sensors requiring greater accuracy and an understanding of their limitations); 3) need to develop analytical models that can handle changes in soil structural layers such as those between A and B horizons in texture contrast soils; and 4) better assessment of soil compaction is required whereby field determination is the focus, as laboratory stress experiments have been shown to largely differ to the field. Furthermore, the precompression stress calculated in the laboratory was found to not be useful for calculation in the field. In relation to point 4, Keller and Lamande (2010) recommend that *in situ* stress-strain behaviour needs to be determined for short-term and dynamic loading with research to clarify the relationship between this and soil mechanical properties in standard laboratory tests.

From the above challenges, point 3 is perhaps the most important for practical use of analytical soil compaction models. In using the analytical approach, currently only one homogeneous layer for stress propagation can be considered, which is a serious limitation considering many soils contain texture contrasting layers. However, (Keller *et al.* 2007) suggests that the error may not be large for many of the simulated cases. Furthermore, the homogenous layer limitation may not be as important for soils that are considered uniform to have uniform soil texture profiles, such as Vertosols. This needs to be considered further through field validation, however. In this sense, future research is required to define the application limits for analytical models (Defossez and Richard 2002; Keller and Lamandé 2010; Keller *et al.* 2013). Keller *et al.* (2007) also point out that the concentration factor used in SoilFlex, and analytical models based on solution of Boussinesq (1885), is not a directly measurable factor, which should be considered as a weak point of the analytical approach. In strengthening the approach, better calculation, estimation or measurement of the proximal soil mechanical factors affecting the concentration factor are required.

### *Pedotransfer functions*

A further consideration for analytical modelling is that soil deformation computation strongly depends on soil mechanical properties (Keller *et al.* 2007; Van Den Akker 2004). There is a lack of easily accessible and representative soil mechanical properties, which speaks to point 2 of Keller and Lamande (2010), thus creating a major hurdle to accurate soil deformation calculation. A clear requirement for development of PTFs functions that estimate soil mechanical properties was identified by Van Den Akker (2004) and then by Keller *et al.* (2007). Wosten (1999) discuss the reliability and use of PTFs soil hydraulic properties, although there remain few PTFs for soil mechanical parameters. Additionally, the performance of these has not been properly evaluated in a range of circumstance, as far as we are aware, and therefore the reliability of these is not well understood.

### *Using soil moisture deficit to predict risk*

From the discussion above, it is observed that soil plasticity increases with increased soil moisture and further that the timing of traffic has a significant effect on soil compaction due to this. Ayres (1987) suggests that soil volumetric moisture content is a good indicator of vulnerability to soil compaction. However, it is somewhat difficult to accurately predict soil volumetric moisture content, which led Vero *et al.* (2013) to consider the use of a soil moisture deficit hybrid model (Schulte *et al.* 2005) for predicting the soil compaction vulnerability. This model predicts the soil wetness relative to the field capacity of the soil, which can be defined as the water held after a period of drainage (Kerebel *et al.* 2010). This period is, however, somewhat contentious depending on whether the soil is used for irrigation or dryland farming. Vero *et al.* (2013) consider three soil classes based on drainage ability (poorly-, moderately- and well-drained soil) and found that SMD significantly affected the changes in soil bullk density and rut area, indicating that the SMD hybrid model is an effective proximal measure for soil trafficability prediction. From the study of Vero et al. 2013 and the earlier work conducted by Earl (1997), it appears that prediction of soil vulnerability to compaction is particularly important at moisture deficits lower than 10 mm. However, they concede that the model requires further testing, especially in relation to trafficking of the soil during wetting phases. Importantly, this method could be used to forecast soil traffic based decisions in non-CTF systems, although further in-field observation and testing of this approach is required. This should consider a wider range of soil types as well as vehicular traffic and running gear.

## Integrated approaches and future directions

According to Lipiec and Hatano (2003) there are few integrated systems capable of measuring more than one property explaining soil compaction. While we tend to agree with this, based on the reviewed literature, they were only referring to direct measurement of soil properties simultaneously; for example, the coupling of a TDR probe with a soil penetrometer. Keller et al. (2013) reviewed compaction based soil deformation from an interdisciplinary approach where compaction was considered from both a soil physics and soil mechanics point of view (in our review we have tried to incorporate this approach also), specifically geomechanics, geophysics, and physics of granular media. Subsequently, they investigated and discussed data collection through modelling and non-destructive measurement techniques of soil structure and deformation to develop integrated approaches.

We define integration more closely aligned to that of Keller *et al.* (2013) where numerous approaches including modelling are utilised to flesh out the complex framework of variables contributing to soil compaction. As communications technology advances and the cost of *in situ* semi-/ permanent measurement devices (e.g. soil moisture probes) become more affordable, the integration of hardware with software and data analytics approaches becomes more feasible on the individual farming scale. In this respect, we see two focuses for integration of technology: 1) integration for more accurate and complete measurement/prediction of soil compaction; and 2) integration of information and devices to provide broader predictive advice for on-farm decision making processes. The first is a reductionist approach conducive to rigorous and traditional scientific methodology. On the other hand, the latter approach moves away from the traditional reductionist scientific method and seeks to utilise existing data (literature, on-farm etc.), predictive tools and expert opinion to build a functioning and practical understanding of a system. Both approaches are important to advancing soil compaction research.

An important consideration for integration of approaches is the time scale dependency of soil structural state and the behaviour associated with this. Keller *et al.* (2013) and Keller and Lamande (2010) discuss that analytical modelling treats the soil as an isotropic medium with a single layer, although this is not the case of soils in field state. The former investigation suggests that soil needs to be considered as anisotropic and phase dependent; for example in soils with vertic properties (e.g. Vertosols) in a drier state, where soil has shrunk and cracking patterns have developed, the structural deformation changes might better be described by granular medium physics, while when swollen and moist it might be more appropriate to consider the soil as a continuum. This highlights the importance of using semi-/ permanent *in situ* measurement devices that measure soil properties with strongly developed relationships to soil compaction (e.g. soil moisture potential). Thus, field dynamics are encapsulated for use with other approaches, or to augment other approaches. What follows is some discussion on the use of various indicators and soil properties toward an integrated approach.

## *Plant response as a potential indicator*

Plant response can provide an indication of soil compaction impact on the farming system, but plant productivity is affected by many other variables. Hence, compaction effects may not be observed in productivity, or alleviation of compaction may not result in increased productivity. For example, the plant can compensate the effects of compaction by increasing root development near the surface, and if water and nutrients supply are not limiting, crop yield may be unaffected (Hamza and Anderson 2005). Lipiec and Hatano (2003) discuss the fundamentals of soil compaction in relation to plant response and we further discuss the effects of compaction on cotton and common Australian cotton-rotation crops in Antille et al. (2014 – to be submitted to Cotton Research and Development Corporation). However, the plant provides a useful potential long-term, or trend based indicator of soil compaction that could be usefully factored into an integrated approach.

Jensen *et al.* (2001), Radford *et al.* (2001), Botta *et al.* (2007), Chan *et al.* (2006), Braunack (2008), and Neale (2010) have all demonstrated that soil compaction can relate in reduction in grain yield, although this varies spatially and throughout seasons, sometimes not being detected through yield expression in subsequent seasons. Thus, if yield were monitored with each harvest and traffic records kept from GPS guidance systems, then this data might provide useful trends over the lifetime of a producing field. Most modern harvesters are equipped with GPS and yield monitors, although yield is monitored usually for the entire frontage of the machine, which would likely dilute the impact of compaction on yield. However, if monitoring of yield could occur on a row basis, which is achievable where individual picker heads are utilised like in cotton harvesting, then wheel track impact on immediate row yield could be determined (Jensen *et al.* 2001). Such information compiled over time could be used as input for a farming system based model (see section on Bayesian belief networks below) or be subject to big-data analytics. The latter option is emerging in agriculture, but currently the value placed on data by practitioners, the willingness to share this data and the record keeping of such is not well understood.

## *Use of visual methods to inform soil compaction status*

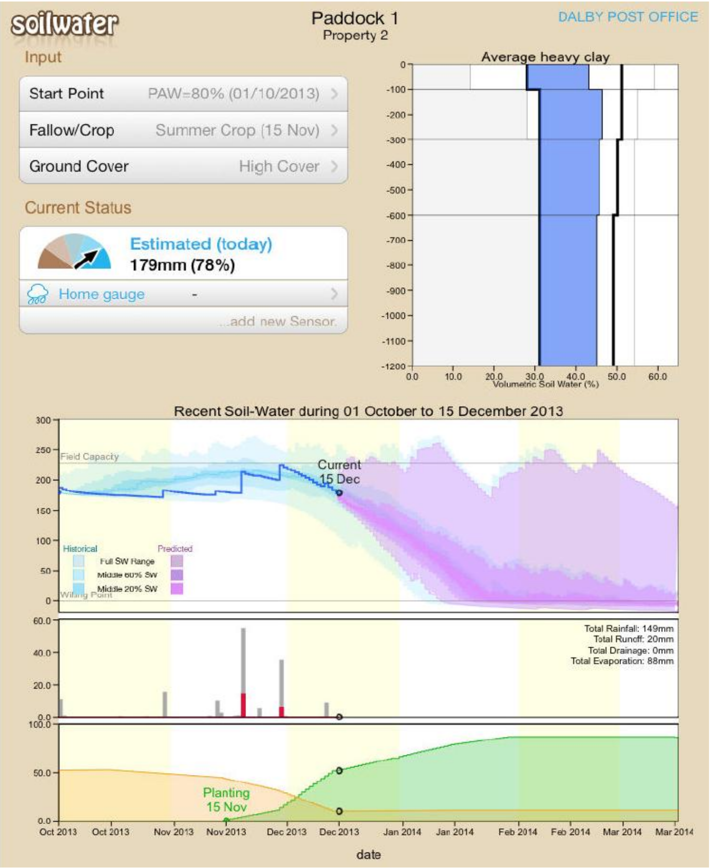
Irrespective of whether a predictive tool for soil compaction is used, an understanding of the initial soil compaction status is required to truly understand the implications of further traffic and management methods. A major criticism of the traditional methods, and the more rapid methods discussed in this review, is that they are expensive, require expertise external to the farming system and/or are time consuming. In-field, rapid visual assessment may help alleviate this, or augment predictive models. In the 1980s and 1990s, the cotton industry invested strongly in understanding the interaction of Vertosol soils with the irrigated cotton farming system. Daniells *et al.* (1996) produced SOILpak for cotton growers as a result of this work, which focussed on empowering practitioners in assessing their soil systems; a component of this was a visual soil structural assessment approach with a compaction component (Daniells and Larsen 1991) based on Peerlkamp (1967) and Batey's (1988) modification of this. McKenzie (2001a) was concerned that operator bias was a major issue, due to the requirement for *well-trained* operators, of the structural assessment method in Daniells and Larsen (1991). He suggests a revised SOILpak scoring procedure that deals with contradictory component scores and allows for important soil features (e.g. macropore continuity and smeared layers). However, it is conceded that the system is highly reliant on skilled operators and that inexperienced operators would require frequent calibration.

Hatley *et al.* (2005) reviewed and compared visual assessment methodologies and concluded that SOILpak was comprehensive and considered pedological and edaphic linkages (strengths), although was time consuming and required skilled operators (weaknesses). SOILpak, VSA (Sheppard 2000) and the root growth method (Spoor *et al.* 2003) appear to be more useful than other methods reviewed. However, whilst (Spoor *et al.* 2003) presents a basic methodology without the need for highly skilled training, and considers the soil profile to >1.0 m, it involves opening up pits, which may not be desirable on a regular basis. Especially as once a pit site has been used and back-filled it is no longer representative of the paddock and cannot be used for subsequent assessment. Sheppard (2000) presents a method that requires little training as a result of the use of reference photographs and figures linked to easily understood scoring sheets. Furthermore, this method provides a comparison between trafficked and untrafficked soil as part of the assessment. The main issue with this method is the fact is only provides ability to assess the topsoil.

Visual assessment, irrespective of the method use, is a relatively simple method of assessment compared to geophysical and soil mechanics based approaches. The information could be linked with long-term plant trends and targeted sampling undertaken. This is not a new concept and is the premise of precision agriculture. The results can be semi-quantitative, but are largely based on a qualitative approach. Training of operators appears to be an issue as the method becomes more comprehensive, but importantly the visual assessment method empowers practitioners. Such an approach, as Spoor *et al.* (2003) suggests, could be integrated with other tools to provide powerful relative trend differences linked back to quantitative information.

## *An integrated approach to predicting soil moisture*

The National Centre for Engineering in Agriculture in conjunction with the Grains Research and Development Corporation (GRDC) is currently undertaking a project (USQ00014; pers. comm. Raine 2013) developing an application for smart-phones and tablets where soil water is estimated rapidly and reliably. The importance of this project is providing practitioners with the ability to makes decisions and manage costs that are soil moisture dependent (e.g. planting) within their farming system. Figure 2 depicts a prototype view of the application, which is based on water-balance simulation, online climate data, local rainfall data and soil descriptions, with a view to integrating automatic rain gauges and soil water sensors. The prototype view shows the soil water estimates up to the current point (15 December 2013 in this case) based on the simulations and historic data and then forecasts the likely soil water as a function of climatic forecasts and simulations of crop water requirement. The application aims to take in multiple data sources and synthesise them in order to simply depict complex relationships as easy to understand information for practitioners. Thus, complex farming systems based decisions become more informed and planning is improved.



Paddock 1
Property 2

Input

Start Point PAW=80% (01/10/2013)
Fallow/Crop Summer Crop (15 Nov)
Ground Cover High Cover

Current Status

Estimated (today) 179mm (78%)
Home gauge -

***Figure 2. Prototype view of the Soilwater application for rapid and reliable estimation of soil water status***

Vero *et al.* (2013) presented a similar notion for aiding in decision making process through their use of soil moisture deficit to predict suitable traffic soil water content (discussed previously). Their work supports the concept of a forecasting approach in providing important information for soil traffic decisions. Importantly, they highlight that a forecasting approach allows informed decisions to be made on site specific conditions rather than on a broad calendar basis, as is the current common practice. Soil moisture deficit is one proximal variable for estimating soil compaction likelihood, but using a similar forecasting based approach further proximal variables could be identified and incorporated to provide an integrated and reliable soil compaction predictive model using all available information.

### Bayesian belief networks

Soil compaction processes are complex and driven by numerous variables, such as soil specific conditions (water content, soil texture, soil structure) and the characteristics of the imposed stress (wheel load, contact area, shear forces). Bayesian belief networks offer an alternative to the reductionist approach and allow incorporation of numerous data sources to provide diagnostic and forecasting probabilities. Bayesian belief networks (BBN) to determine the susceptibility of Scottish soils to soil compaction at a national level were investigated by Troldborg *et al.* (2013). BBNs are probabilistic models that take into account variables that contribute to an outcome (in this case soil compaction) and represent the complex relationships between these variables. They have more recently been provided greater attention and increased popularity based on their ability to accommodate uncertainty and variability in modelled predictions through the probabilistic approach (Henriksen *et al.* 2007; Uusitalo 2007). Thus, they are able to analyse complex systems. The major advantage of a Bayesian approach is that where empirical data are not available, the network can use a mixture of both qualitative and quantitative data to information to strengthen outcomes (Henriksen and Barlebo 2008). Additionally, they have the capability of producing both diagnostic and predictive outcomes. By incorporation of existing empirical data, discrete data, derived data (e.g. PTFs) and expert knowledge, Troldborg (2013) demonstrated that reasonable predictions could be made for susceptibility of soils to compaction.

The modelling approach normally seeks to simplify the system of interest via assumptions, whereas the BBN approach captures the complexity of the system and explicitly accounts for uncertainties in it (Troldborg *et al.* 2013). Tranter *et al.* (2007) developed a PTF using multiple linear regression to determine soil bulk density and concluded that increased model complexity does not necessarily improve model accuracy. They showed that their PTF outperformed both an artificial neural networks PTF and a regression tree based PTF. However, they further concede that more complex approaches would likely fare better with larger more comprehensive datasets. Predicting soil compaction is inherently complex, as discussed throughout this review, and being able to account for that complexity is desirable. Hence, the ability for BBNs to account for complex relationships and variable data quality appears attractive.

Developing the network is the most important aspect to the BBN approach and is done through determination of the contributing variables and their relationships. While Marcot *et al.* (2006) provides general guidelines to generic model structure, a conceptual confluence diagram containing the key drivers of the system is initially very important (Troldborg *et al.* 2013). The conceptual confluence diagram produced by Troldborg *et al.* (2013) was based on the generic model (Marcot *et al.* 2006), but importantly was developed using existing literature, author knowledge and external experts. In the instance of future research to predict soil compaction at the paddock scale, their confluence diagram will be useful. Future research using BBN should also consider the use of climatic and economic data to help drive practitioner decision making processes. By using the BBN to produce both a diagnostic of soil compaction status, that could be ground-truthed, and a predictive soil compaction status based on current variable status and future variable likelihood, it could be possible to provide a means by which to demonstrate expected compaction to practitioners and produce alternative options based on expected changes in the contributing variables.

# Conclusion

To address more accurate determination of soil structural deformation due to soil compaction, effort needs to be concentrated on more accurate input data for models and more accurate direct sensing by reducing assumptions associated with isotropic medium and homogenous soil state behaviours. On the other hand, to provide a predictive framework of soil compaction likelihood that provides practical information on which to base on-farm traffic decisions, the approach should focus on encapsulating the complexity of the system, including climate forecasts and economic data, moving away from the reductionist approach. Importantly, both approaches require attention and further development in the immediate future.

Regarding in field determination of soil compaction status, ERT presents the most promising approach for Vertosol soils, with an ability to account for cracking patters and clear relationships developed for compaction and soil moisture potential. However, the moisture measurement limit thresholds need to be further understood in high smectitic clay content soils.

In terms of providing practical decision making frameworks for practitioners, the fundamental changes in the soil medium resulting from soil deformation due to compaction need to be considered, an appropriate suite of tools needs to be utilised to collect numerous data for integrated use, and this data needs to be augmented with expert opinion and semi-qualitative data to inform predictive models. Bayesian belief networks present one opportunity and novel soil property determination approaches, such as soil moisture deficit as a predictor for compaction likelihood, should be afforded further research. Analytical models, such as SoilFlex, should provide useful information that could augment a BBN, or similar framework, to help develop risk assessments. As a priority for industry integration, future research needs to focus on integrated whole system methodologies and data collection networks with forecasting capabilities.

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