

Employing Electromagnetic Induction Technique for the Assessment of Soil Compaction

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Received 2012-09-09; Revised 2012-10-10; Accepted 2012-11-07

ABSTRACT

An experiment on a sandy soil field was conducted to investigate the potential of determining soil compaction from apparent soil Electrical Conductivity (EC_a) measured by Electromagnetic Induction (EMI) technique. A soil conductivity meter (EM38) was used to measure EC_a under four soil Moisture Contents (MC) (4.965, 33.6, 94 and 8.0%) and a range of Soil Compaction (SC) levels (on the average, from 220 to 2070 kPa). At each MC and SC level, EM38 measurements were recorded at three EM38 heights above the ground (0, 20 and 40 cm) and at vertical and horizontal device orientation. Except at the MC of 8.0%, results revealed that the measured EC_a was proportional to SC at all considered soil conditions and modes of measurement (EM38 orientation and height). For all soil conditions and modes of measurement, an overall mean of the coefficient of correlation (R^2) of 0.66 was observed between SC and EC_a at soil MC of up to 6.94%. Thus, EC_a measurement can be an indicator of soil compaction, given that the MC is below 7% in sandy soil. For both EM38 orientations, higher correlations between SC and soil EC_a (average R^2 of 0.90) were observed with the EM38 placed on the ground (0 cm height) compared to those achieved at 20 cm and 40 cm height, where the average R^2 values were 0.62 and 0.47, respectively. At 0 cm height and MC of up to 6.94%, higher correlations between SC and EC_a were obtained at vertical EM38 orientation (average R^2 of 0.98) compared to those at horizontal orientation (average R^2 of 0.81).

Keywords: Electromagnetic Induction, EM38, Soil Compaction, Soil Electrical Conductivity, Precision Agriculture, Moisture Content

1. INTRODUCTION

Soil Compaction (SC), which is one of the physical soil properties, refers to the increase in soil density and strength and the reduction in soil macro-pores. Extensive use of heavy agricultural machineries can greatly contribute into the increase of SC in agricultural fields (Alexandrou *et al.*, 2002). Excessive SC exerts detrimental effects on crop production as it creates poor environment for root growth (poor aeration and excessive soil strength), reduces water infiltration and increases runoff, hence increases soil erosion. Krajco (2007) reported that soil was endangered by SC, as one of the various degradation processes that worked within the topsoil or subsoil layers. Compaction can restrict and interfere with root growth, reduce the amount and size of soil pores, decrease soil infiltration, cause water-logging

and lead to run-off. This was emphasized by Hoefler *et al.* (2010) who stated that higher soil strength, accompanied with higher soil penetration resistances, was considered as a limiting factor for root growth as it resulted in a lack of water and nutrient supply and caused poorer plant growth and higher vulnerability of the crop to diseases. In a similar study, Kulkarni (2003) stated the negative effects of soil compaction, which included the prevention of root growth and development of plants, reduction of water infiltration as compacted soil offered smaller pores and fewer natural channels, increase of surface wetness, runoff and erosion.

Conventional methods used for SC assessment, such as cone penetrometers, can provide accurate measurements. However, these conventional procedures for compaction measurement are characterized as time consuming, labor intensive and costly. Alternatively, in-

situ measurement of the apparent soil Electrical Conductivity (EC_a) using Electromagnetic Induction (EMI) technique is viewed as one of the most efficient non-contact methods that can be used to determine various soil properties. The soil EC_a is influenced by a combination of physico-chemical properties, including soluble salts, soil texture, clay content and mineralogy, soil water content, Cation Exchange Capacity (CEC), soil bulk density and compaction, organic matter, soil temperature and subsoil characteristics (Corwin and Lesch, 2003; 2005; Grisso *et al.*, 2009; Krajco, 2007; Pozdnyakova, 1999; Edward *et al.*, 2003; Padhi and Misra, 2009). It is evident that SC was considered, by several studies, as one of the key factors affecting the value of soil EC_a . Therefore, measurement of soil EC_a can be used as a direct indication of SC. However, it is important to understand the factors, for a specific soil, that have the largest influence on EC_a measurements. Corwin and Lesch (2003) reported that, for saline soils, salinity dominated the EC_a measurements and interpretations were often more straightforward. Estimation of SC with electrical signal is becoming increasingly viable as commercial and technological solution in the construction of highway embankments, earth dams and many other engineering structures (Chik and Islam, 2011). The performance of newly developed SC measurement techniques based on soil Electrical Conductivity (EC) system is thought to be reliable and robust. This was affirmed by Seladji *et al.* (2010) who stated that, among the geophysical tools used in soil science, electrical methods were considered as potentially useful to characterize SC intensity. This was attributed to the fact that the analysis of the petro-physical parameters derived from their experimental data suggested that the electrical tortuosity of the loamy agricultural soil was significantly affected by compaction. Compared with traditional methods of observing soil subsurface layer, electromagnetic induction techniques were noninvasive, less labor intensive and more economical (Doolittle *et al.*, 1994).

For efficient precision farming systems, it is important to implement cost effective and efficient methods that can enhance the process of monitoring and mapping of different soil properties, like SC. Therefore, the overall goal of this study was to explore the possibility of using Electromagnetic Induction (EMI) technique for the assessment of SC. The specific objectives, however, are as follows:

- To assess Soil Compaction (SC) based on the EM38-measured apparent soil Electrical Conductivity (EC_a)
- To study the influence of soil Moisture Content (MC) on the measurements at different SC levels

- To investigate the effect of the modes of measurements (orientation of the EM38 and its height above the ground) on the data collected

1.1. Literature Review

Electrical Conductivity (EC) is defined as the ability of a material to transmit (conduct) electrical current and is commonly expressed in units of MilliSiemens per meter (mS/m), Grisso *et al.* (2009). The EC of soils is known to be proportional to the amount of moisture held by the soil particles. Therefore, low conductivity is associated with sandy soils; however, medium and high conductivities are associated with silt and clay, respectively (Fig. 1). Pozdnyakova (1999) reported that soil electrical properties were the parameters of natural and artificially created electrical fields in soils and were influenced by the distribution of mobile electrical charges, mostly inorganic ions, in soils. He also stated that relationships were developed between electrical properties and other soil physical and chemical properties, such as texture, stone content, bulk density, water content, cation exchange capacity, salinity and humus content. His results showed that the density of mobile electrical charges increased with soil compaction. Doolittle *et al.* (1994) defined the apparent soil conductivity as being the weighted average conductivity measurement for a column of earthen materials to a specified depth.

Krajco (2007) described the soil matter to be composed of three different environments; solid soil particles, water-filled soil pores and air-filled soil pores with different EC. Because the air is an extremely good insulator, the only three possible pathways for electrical current to flow are via: (i) solid-liquid (soil particles and pores fill with water), (ii) liquid (soil water) and (iii) straight through soil particles (Fig. 2).

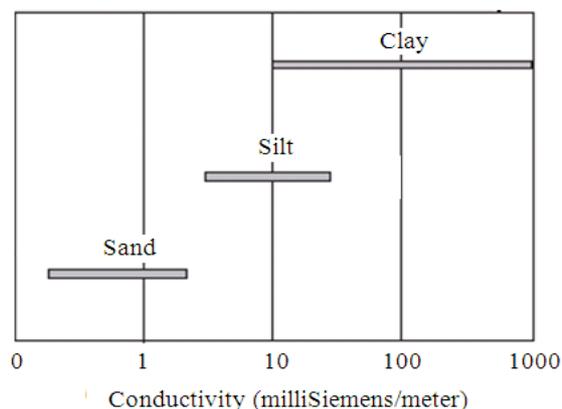


Fig. 1. Soil electrical conductivity for different soil types (Grisso *et al.*, 2009)

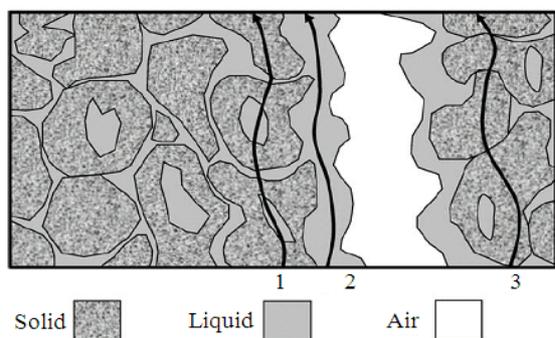


Fig. 2. Three different pathways of electrical conductance in soil (Krajco, 2007)

Soil EC is affected by various soil properties, such as soil pore connection, soil moisture, content of salts, cation exchange capacity, sensing depth and temperature (Krajco, 2007). The higher the ratio of soil pores filled with water, like in clay soils, the higher the EC. Higher moisture content provides higher conductivity, as the moisture presents the base for electrolyte by dissolving soil salts. Soil salts increase the consistency of electrolyte in soil matter, thereby, the EC. In addition, presence of positive charged ions (Ca, Mg, K, Na, NH_4 or H) in water solution causes the EC to increase. For both, direct contact and EMI methods, the sensing depth negatively affects the strength of sensor signal, thereby, the accuracy of EC measurement. The temperature of soil and air was also found to affect soil EC readings.

Apparent Electrical Conductivity (EC_a) of a soil profile can be used as an indirect indicator for a number of soil properties. Commercially available EC_a sensors can efficiently and inexpensively develop the spatially dense datasets desirable for describing within-field spatial soil variability in precision agriculture (Sudduth *et al.*, 2005). Electromagnetic Induction Meter (EM38), based on EMI technique, was used by many researchers in various soil applications. O'Leary *et al.* (2003) used an EM38 for identifying sub-soil properties. They concluded that, since electrical conductivity is well correlated with high soil water and salt content, the Electromagnetic Induction (EMI) technology coupled with accurate Global Positioning System (GPS) equipment could provide economic opportunities to map out areas of farms that are affected by subsoil constraints. According to Llewellyn and Filmer (2009), EM38-measured apparent soil Electrical Conductivity (EC_a) was affected by soil moisture content, salt levels and soil texture. They also stated that, although it was necessary to analyze soil core samples to calibrate and validate EM38 measurements, EM38 mapping was particularly useful as

it usually correlated well with important soil characteristics that were associated with crop yield potential. A study by Rahman (2011) revealed that EC_a , which was related to different soil physical properties, such as clay content, moisture content, bulk density, pH and salinity, can be conveniently used to determine soil spatial variability. Robinson *et al.* (2010) reported that as well as to salinity and soil moisture, the electromagnetic induction meter (EM38) could respond to factors including clay content, soil temperature and magnetic minerals. Pozdnyakova (1999) observed very strong exponential relationships of the electrical resistivity, which is directly related to soil EC_a , with soil bulk density and soil water content when measured in laboratory conditions (R^2 value ranging from 0.957 to 0.990). Hossain (2008) used an EM38 to measure soil moisture in a clay soil. His results showed that the EM38 was able to produce, in both vertical and horizontal orientation, a volumetric soil MC measurement with accuracy of approximately $\pm 0.007 \text{ m}^3/\text{m}^3$. However, the horizontal orientation of the EM38 was, in general, found to produce better accuracies of soil moisture prediction.

Using electromagnetic induction technique, which is characterized as time and cost effective method, for the assessment of soil compaction can greatly enhance the process of SC measurement. Krajco (2007) reported that conventional methods for SC mapping, such as penetrometers, provided accurate point measurements; however, time consuming and labor intensive. On-the-go EC measurements, such as the EMI techniques represented by EM38, are affected by key soil properties including texture, MC and SC levels; therefore, can offer a possible rapid alternative for compaction detection. Hoefler *et al.* (2010) used an EM38 for the detection of SC and compared the EM38-produced observations to soil penetration resistance measured by a penetrometer. A strong correlation was observed between the penetration resistance and the signal of the EM38, especially in the areas where high values of penetration resistance were recorded. A study was conducted by Malo *et al.* (2001) to determine the impact of soil moisture, bulk density and soil temperature on the measurements taken by Veris 3100 and EM38 soil sensors. A strong correlation was observed between EM38 and Veris 3100 measurements and soil MC values and to a less degree with soil bulk density and soil temperature. On the other hand, Jabro *et al.* (2005) compared soil penetration resistance expressed as Cone Index (CI) to the soil EC_a measured using Veris 3100 and Veris 3000 sensing technologies. They found that the soil EC_a and CI parameters were spatially distributed and noticed to exhibit a weak to a medium spatial dependency within the mapped field area.

2. MATERIALS AND METHODS

Research field experiments were conducted on a 16 by 20 m plot located in the educational farm of the College of Food and Agriculture Sciences, King Saud University, Riyadh, Saudi Arabia (**Fig. 3**). The soil of the study field was classified as sandy soil with average soil physical and chemical properties presented in **Table 1**.

The apparent soil Electrical Conductivity (EC_a) was measured using the soil conductivity meter EM38 of Geonics Ltd., Canada (Model: EM38-MK2-1) (**Fig. 4**). With an intercoil spacing of one meter, the utilized EM38 could acquire measurements for the depths of 0 to 75 cm and 0 to 150 cm in the horizontal and vertical orientations, respectively. A frame was fabricated from a PolyVinyl Chloride (PVC) pipe (**Fig. 4**) to provide different heights of the EM38 above the ground (0, 20 and 40 cm). This was employed when investigating the effect of the device height above the ground on its response to soil EC_a .

A Spectrum Technologies Inc., USA (Model: Field Scout SC 900) (**Fig. 5**) soil compaction meter was used to measure SC in terms of soil resistance to penetration (Cone Index).

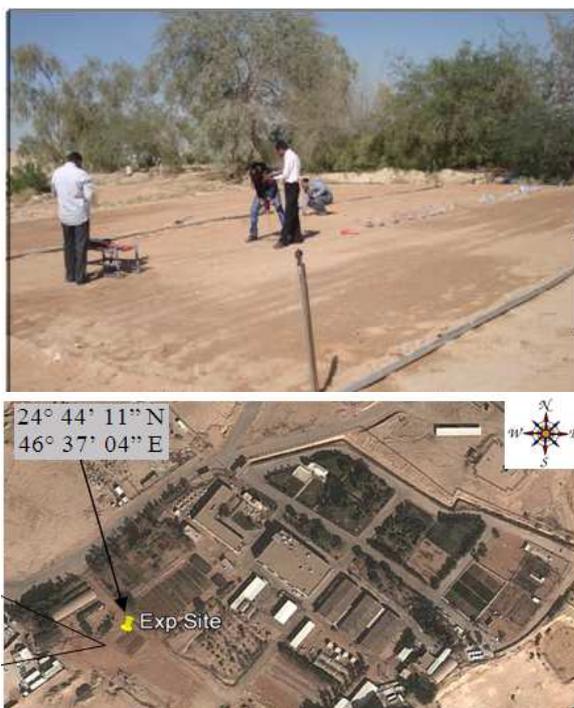


Fig. 3. The study field

Table 1. Soil properties of the study field

Soil texture	Coarse Sand = 76.4%
Texture class	Fine Sand = 12.3%
= Sandy soil	Silt = 7.5%
	Clay = 3.8%
Soil field capacity (Θ_{fc})*, %	12.88
Soil wilting point (Θ_{wp})**, %	4.25
Soil pH	7.81
Soil EC (dS/m)	1.61

*; Θ_{fc} is the maximum value of water content that can be maintained without the water draining rapidly (IAEA, 2008).**; Θ_{wp} is the fraction of soil water 'held' so strongly by soil that it is not available to plants (minimum 'available' water content) (IAEA, 2008)

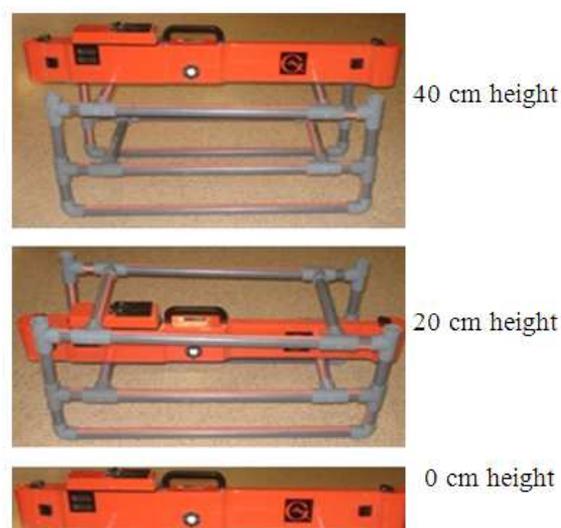


Fig. 4. EM38 with the frame



Fig. 5. The compaction meter



Fig. 6. The Compactor

Table 2. SC levels at different MC values

Soil moisture (%)	Average soil compaction, kPa		
	Compaction level 1	Compaction level 2	Compaction level 3
4.96	1861.64	1978.06	2061.10
5.33	860.42	1631.10	1841.71
6.94	468.05	1304.39	1511.31
8	220.61	867.95	1495.18

Table 3. Soil depth ranges for EC_a measurements at different EM38 heights

EM38 mode	Intercoil separation	EM38 Height above the ground (cm) Measurement range (cm)		
		0	20	40
Vertical	1.0 m	150	130	110
Horizontal	1.0 m	75	55	35

The compaction meter consisted of an electronic penetrometer and a built-in datalogger for storage and processing of the penetration resistance measurements. The device was equipped with an ultrasonic sensor located at the base of the meter which was used to measure the depth of penetration. The used Field Scout SC 900 compaction meter featured a measuring range of 0 to 45 cm and a Cone Index (CI) range of 0 to 7000 kPa.

A TOKU, Malaysia, Vibratory Plate Compactor (model: 5.0 Robin EY 20-3) (Fig. 6) was used for the purpose of obtaining different levels of SC at different soil MC values. Different MC of the field soil (averaged at 4.96, 5.33, 6.94 and 8%) was obtained by applying different drying periods after irrigation. Average SC levels associated with the different average MC values are illustrated in Table 2. At each MC and SC level, three data points of soil apparent Electric Conductivity (EC_a) were recorded by the EM38 adjusted at an intercoil

separation of 1.0 m to produce maximum measurement depth of 150 and 75 cm for the vertical and horizontal orientation modes, respectively (Table 3). At each point, readings were taken at the three heights of the device above the ground (0, 20 and 40 cm) and at both orientations (vertical and horizontal) with three replicates producing 810 data points. The SC meter was used for the measurement of soil resistance to penetration (Cone Index, CI) which was used as an indicator of SC at different SC and MC levels. Observations were taken at 2.5 cm increments to a depth of 17.5 cm.

3. RESULTS AND DISCUSSION

At the different moisture content values considered in this study, the EM38-measured soil EC_a values were plotted versus associated SC values determined by the use of the SC meter (Fig. 7-10). Figure 7-9 suggest that the general trend of the relationship between EC_a and soil compaction is linearly proportional with an average R² value of 0.66. The obtained results are in agreement with the results of several studies (Kulkarni, 2003; Sudduth *et al.*, 2002; Hoefler *et al.*, 2010; Rahman, 2011; Malo *et al.*, 2001; Krajco, 2007). At MC value of 8.0% (Fig. 10), the general trend does not apply and there is no definite trend for the relationship between the two variables (soil compaction and EC_a). Therefore, the soil EC_a measurement may not be used as an indicator of the soil compaction at this level of soil moisture content for the sandy soil of the study field.

The collected observations were subjected to statistical analysis using SAS software. Statistical results indicated that the measured soil EC_a values produced by the EM38 oriented vertically were significantly affected by the level of SC (p<0.05). In contrary, the effect of the SC level on the EC_a measured with the EM38 in the horizontal orientation was found to be not significant.

Figure 7-10 show that the value of the correlation coefficient of the relationship between soil EC_a and soil compaction varies depending on the level of soil moisture and mode of measurement (EM38 orientation and height above soil surface). To study the influence of soil Moisture Content (MC) and EM38 measurement mode on the relationship between soil compaction and EC_a, the values of the correlation coefficient (R²) under all moisture levels were plotted versus EM38 height (Fig. 11). Figure 11 shows that the correlation trend was not affected by the soil moisture level up to an MC of 6.94%. At an MC value of 8.0%, absence of the general trend was observed. This was attributed to the

assumption that, at this MC level in sandy soil, the effect of soil moisture may have dominated the effect of soil compaction on EC_a measurements. In relation, Seladji *et al.* (2010) showed that soil resistivity was sensitive to density increase for gravimetric water contents lower than 0.25 gg^{-1} . Consequently, they suggested that the study and the monitoring of soil compaction in the field had to be conducted for soils in a dry state. Excluding data associated with MC value of 8.0% from the discussion hereafter, higher correlation between soil compaction and EC_a can be obtained with the EM38 operated in the vertical orientation at 0 cm height at all MC values. The highest R^2 value of almost 1.0 was observed when the EM38 was operated vertically on the soil surface at an MC value of 6.94%. At 0 cm height, the average values of the correlation factors between SC and EC_a across all soil MC values were 0.98 and 0.81 for the vertical and the horizontal orientation, respectively. Therefore, it can be generalized that higher correlation can be produced when the EM38 operated vertically

and placed on the soil surface (i.e., at 0 cm height above the ground). This is in part consistent with the results obtained by Doolittle *et al.* (1994). However, the horizontal orientation of the EM38 produced, on the average, higher R^2 values at 20 cm height across all MC levels (Fig. 11). On the contrary, Krajco (2007) stated that the contact-less device EM38 operated in horizontal mode was able to distinguish the areas with no compaction above 0.3 m with less precision and that when EM38 operated in vertical mode; it had no sufficient sensitivity to distinguish the soil with different bulk densities.

The average values of the correlation factors between soil compaction and EC_a across all soil moisture values and EM38 orientations were determined. On the average, positioning the EM38 on the ground (0 cm height) produced the highest R^2 value (0.90) at all other soil conditions and modes of measurement compared to those produced at 20 cm and 40 cm heights (0.62 and 0.47, respectively).

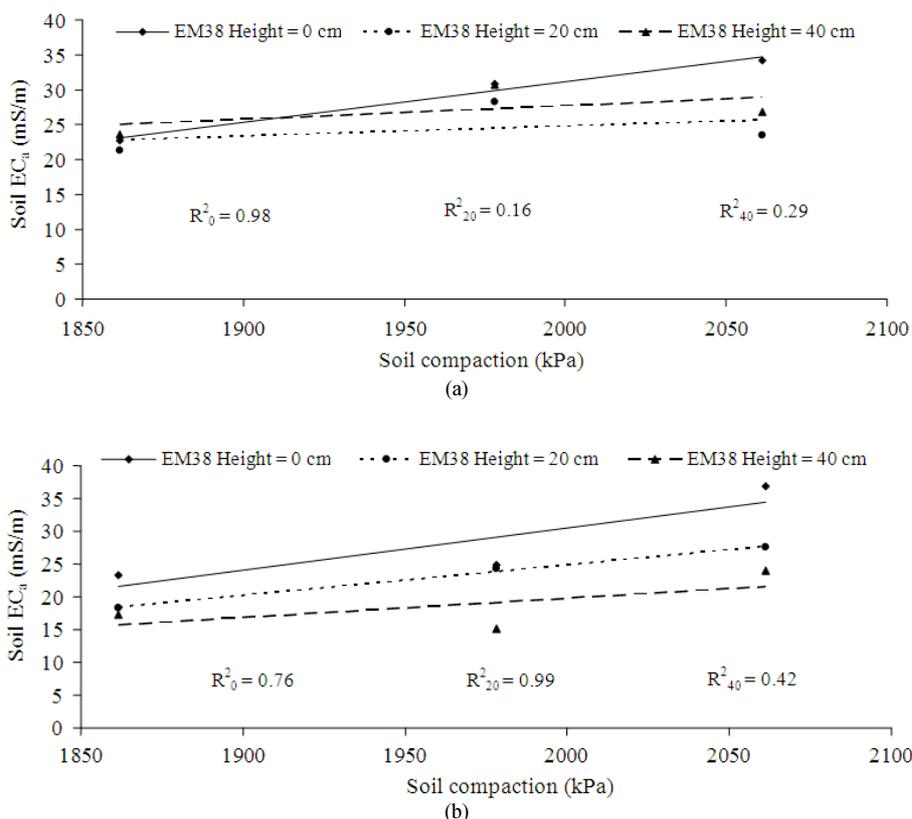


Fig. 7. EC_a Vs SC at soil MC of 4.96% for (a) vertical and (b) horizontal EM38 orientation

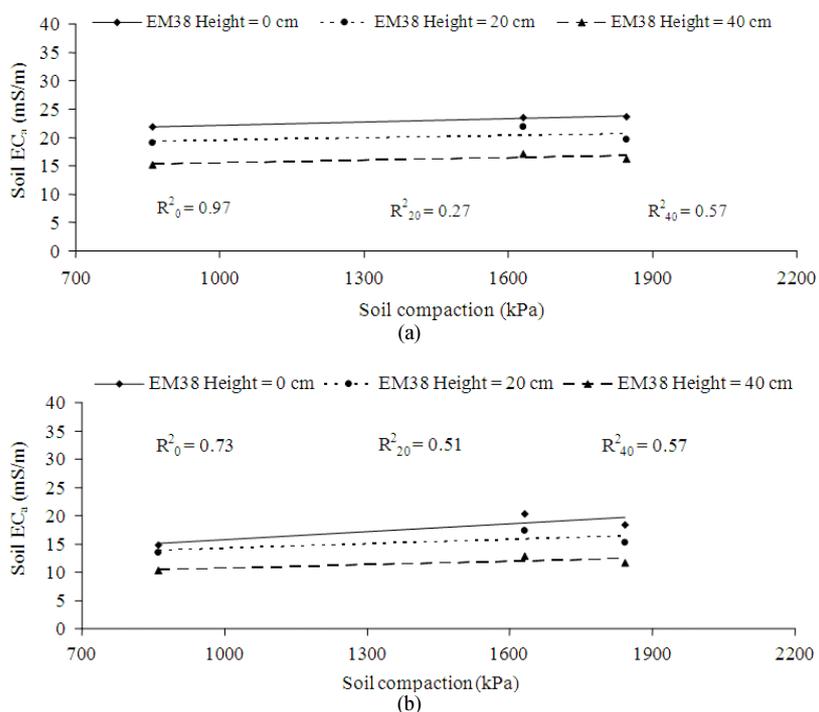


Fig. 8. EC_a Vs SC at soil MC of 5.33% for (a) vertical and (b) horizontal EM38 orientation

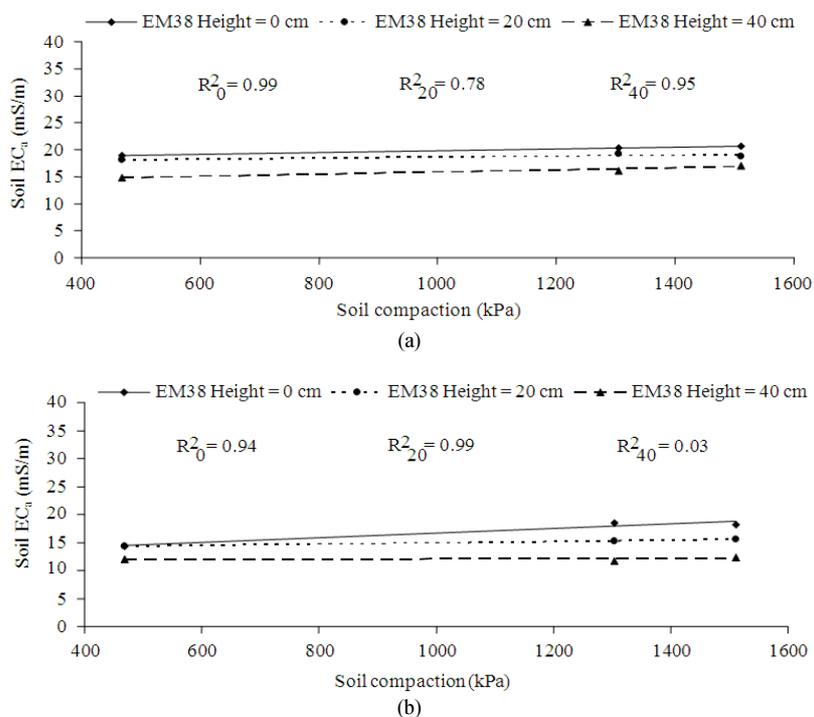


Fig. 9. EC_a Vs SC at soil MC of 6.94% for (a) vertical and (b) horizontal EM38 orientation

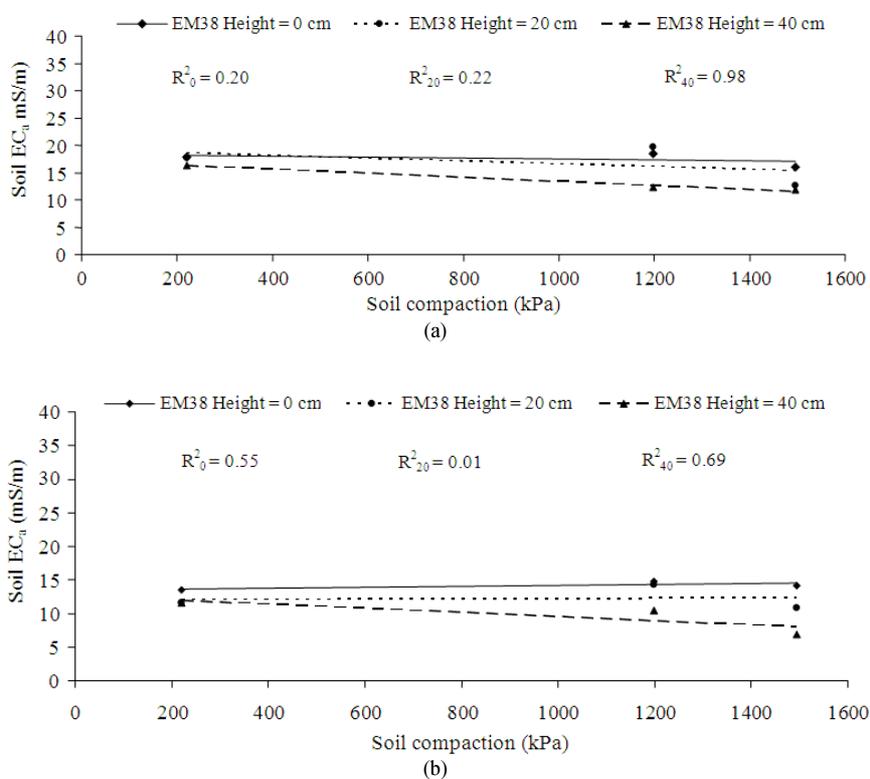


Fig. 10. EC_a Vs SC at soil MC of 8.0% for (a) vertical and (b) horizontal EM38 orientation

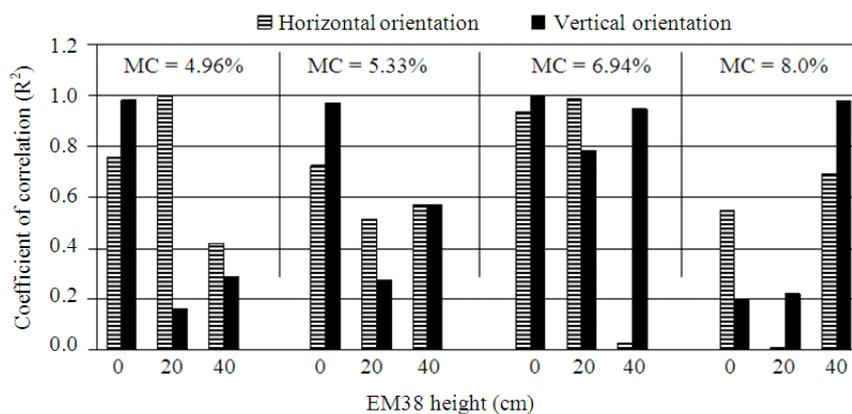


Fig. 11. Effect of soil MC and EM38 measurement mode on the R² value of the relationship between SC and EC_a

This was attributed to the fact that lifting EM38 above the ground induced a significant decrease in EC_a measurements in both orientations of the EM38 (Sudduth *et al.*, 2002). Statistical analysis showed high significant differences ($p < 0.001$) between EC_a values at different EM38 heights above the soil surface. Padhi and

Misra (2009) used EM38 to monitor soil moisture and observed that the values of the EC_a in the horizontal mode appeared to decrease more rapidly with increasing EM38 height above the ground than in the vertical mode. That was attributed to the difference in effective response depth, which represented less soil water. They also observed that

the EC_a changed linearly with soil water when EM38 was placed at 0.1 m height above the ground, but exponentially when it was placed at 0.4 m height above the ground. Robinson *et al.* (2010) stated that raising EM38 to higher positions slightly reduced sensitivity. They attributed the effect of EM38 height on EC_a values to the smaller volume of the sampled soil as the height of EM38 increased. Due to the difference in weighting functions, the horizontal dipole EC_a reading decreased more quickly with height above ground than the vertical dipole EC_a reading (Sudduth *et al.*, 2002).

4. CONCLUSION

A field study was conducted to explore the possibility of assessing Soil Compaction (SC) by measurement of apparent soil Electrical Conductivity (EC_a) using EM38. In general, soil EC_a was found to positively correlate with SC. Hence, EC_a measurement could provide a potential for an effective and efficient means of SC assessment. Specific conclusions of the study include the following:

- The EC_a was found to be positively correlated with SC. The overall mean of the R^2 value of the relationship between EC_a and SC was 0.66
- High correlations between SC and EC_a values were observed for soil MC values of up to 6.94%. At a higher MC value of 8.0%, low correlations were observed. Therefore, for a better assessment of soil compaction, it is recommended to acquire EM38 measurements at low soil MC values (less than 7% in case of sandy soils)
- For EM38 vertical and horizontal orientations, higher correlations between SC and EC_a were observed when the EM38 was placed on the ground (EM38 height of 0 cm) with an average R^2 value of 0.90. The average R^2 values of 0.62 and 0.47 were obtained for 20 and 40 cm heights, respectively
- At 0 cm height, vertical orientation was found to produce, on the average, a better correlation between SC and EC_a . An average R^2 value of 0.98 was achieved with vertical orientation compared to 0.81 with horizontal orientation

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