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Technical note

Influence of trenches and soil water detection instruments on EM38-MK2 sensor readings

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Electromagnetic induction (EMI) sensors, such as the EM38-MK2, measure soil apparent electrical conductivity (EC_a). The EC_a values are then calibrated with soil water content, often determined by metal-containing instruments. Such instruments and soil trenches may interfere with EC_a measurements. This study established whether multi-sensor capacitance probes (small copper rings), neutron water meter access tubes (galvanized steel) and soil trenches interfere with EC_a measurements by EM38-MK2 sensors. The EM38-MK2 sensor was moved towards and away from the potential interfering obstruction in a horizontal or vertical mode without re-zeroing the device. The soil trenches had no significant influence on the measurement of EC_a. On the other hand, both the capacitance probes and the access tubes influenced the EC_a measurement of the EM38-MK2 sensor when it was operated closer than 1 m from the two devices. Measurements of EC_a were either less stable (only in the vertical mode) or lower. However, the magnitude of reduction in EC_a was so small that it would likely not have any practical influence. Nevertheless, in field surveys with the EM38-MK2 sensor, a distance of at least 1 m should be kept from either the capacitance probes or galvanized-steel access tubes to avoid interferences. When encountering such devices during field surveys, it should be safe to continue measurements without additional re-zeroing of the sensor.

INTRODUCTION

Measurement of soil apparent electrical conductivity (EC_a) is a non-invasive and, therefore, faster way of characterising spatial variability of soil properties in agricultural fields (Corwin and Lesch, 2003; Corwin and Lesch, 2005a, b; Sudduth et al., 2005; Kweon, 2012), with improved spatial resolution (Corwin et al., 2003; Lesch et al., 2005). Electromagnetic induction (EMI) sensors, such as DUALEM, Profiler EMP-400 and Geonics EMI devices (EM31, EM38 and EM38-MK2) offer instantaneous EC_a readings from the cumulative current applied by them over a specific depth range (McNeill, 1980; Mueller et al., 2003; Sudduth et al., 2003). The Geonics EM38 devices are currently agriculture's most widely used EMI sensors. The latest version, EM38-MK2, has been developed for near-surface application in agriculture (Gebbers et al., 2009; Doolittle and Brevik, 2014) due to its double receiver coils allowing shallow and deep soil measurements.

Several factors contribute to the measurement of EC_a, and these include soil properties like salinity, cation exchange capacity, clay mineralogy, porosity, clay, water and organic matter contents (Rhoades et al., 1976; Williams and Baker, 1982; McNeill, 1992; Sudduth et al., 2001). Measured EC_a can account for spatial variation of any of these soil properties through a direct calibration approach (Williams and Hoey, 1987; McBride et al., 1990; Rhoades, 1993; Lesch et al., 1995a, b; Heiniger et al., 2003; Hossain et al., 2010; Gangrade, 2012).

Another suggestion for the variation in EC_a measurements when conducting field surveys with EMI devices is instrument drift (Corwin and Lesch, 2005c). Instrument drift causes instability in EC_a readings over time (i.e., within a day's survey). It seems to result from a complex combination of instrument design and environmental factors such as soil and atmospheric temperature, air humidity and atmospheric electricity (Sudduth et al., 2001). In addition, EMI device operational speed and height, and positional offset between mobile EMI device and GPS can also cause inaccuracy in EC_a readings (Sudduth et al., 2001; Robinson et al., 2004; Minsley et al., 2012; Delefortrie et al., 2014; Huang et al., 2017).

Various correction measures have been followed to improve the reliability and accurate interpretation of EC_a data. Sudduth et al. (2001) suggested running a repeated drift row or fixed point EC_a measurement during a field survey, which can correct any drift in readings over the field. Other studies suggested warming up and shielding the EMI device before surveying to minimise the temperature effect (Robinson et al., 2004; Abdu et al., 2007; Huang et al., 2017), frequent in-phase nulling and zeroing at the same position every 5 to 20 minutes or within an hour during surveys (Sudduth et al., 2001), or to take a separate EC_a measurement on a transect line that crosses the entire field survey in a short time (Delefortrie et al., 2014).

However, an additional factor contributing to the inaccuracy of EC_a measurements in field surveys is that EMI devices are sensitive to metallic objects within the survey area (McNeil, 1996; Geonics, 2003). Operators of EMI devices generally accept that metallic objects should be avoided when performing field surveys. However, this is not always desirable. For example, site-specific calibration of EMI devices for soil water estimation requires EC_a and soil water measurements to be taken as close as possible to one another for the most accurate results (Kachanoski et al., 1988; Stanley et al., 2014). Many instruments and coinciding access tubes that are applied to determine soil water content in fields contain metal. Hence, knowing how close EMI can be operated to these devices is necessary.

Only a single study has systematically explored the influence of metal objects on EC_a measured through EMI (Stanley et al., 2014). These researchers reported on the safe operation distance of the EM38-MK2 sensor, specifically to aluminium access tubes. However, other soil water measurement instruments contain metals, although they are not like most capacitance probes. Another aspect that justifies the investigation is the accuracy and instability of EC_a measurements after the EMI device encountered this metal object in the field.

Based on preliminary observations, it is also suspected that large soil trenches, often used on research farms, may interfere with EC_a measurements. The underlying theory was that, close to an open excavation, an EMI device would have a smaller volume of soil to measure, probably leading to a reduction in EC_a values. This is because the signal emitting from the EMI device moves into the soil in a loop as wide as its inter-coil space, i.e., approximately 1 m.

The main objective of this paper is to examine the interference of soil trenches, installed multi-sensor capacitance probes (containing a few copper rings of sensors over the probe length) and neutron water meter access tubes (galvanised steel) on EC_a measurements during an EMI field survey. We tried to establish, therefore, how close an EM38-MK2 sensor can be operated from the mentioned potential interferences before EC_a measurements are affected. Also, the accuracy and stability of EC_a readings after the EM38-MK2 sensor encountered various interferences were evaluated. This would help answer whether re-zeroing the EMI would be necessary immediately after such interferences are encountered during a field survey.

MATERIALS AND METHODS

Site description and experimental layout

The investigation was conducted at Kenilworth Experimental Farm (latitude = 29°01'47.6" S, longitude = 26°08'58.3" E and altitude = 1 366 m amsl), University of the Free State, South Africa. The soil of the experimental site has a fine sandy loam texture. It is classified as a Bainsvlei form belonging to the Amalia family, according to the South African Soil Taxonomy (Soil Classification Working Group, 1991), or Plinthustalf according to the USDA Soil Classification System (Soil Survey Staff, 2014). A preceding soil survey of the experimental site indicated that almost all evaluated soil properties were spatially homogenous and varied only over soil depth (Table 1). The homogeneity of the selected site was an advantage to the study as it would best show the EM38-MK2 sensor response to applied influences rather than to soil property variations.

The total size of the experimental area was 645 m² (43 m x 15 m). Four transects, 21 m each, were marked in 2 parallel lanes (Fig. 1). Each transect was marked at 1 m intervals, with a centre point (0 m) and 10 points on either side of the centre (totalling 21 points per transect). The centre point is where all treatments are applied and can be regarded as the point of influence.

Treatments and measurements

Treatments included (i) a control with no interference, (ii) capacitance probes, (iii) galvanised steel access tubes, and (iv) soil trenches. These treatments were applied at the centre of the same 4 plots on consecutive days (Fig. 2a, b and c). The control readings were taken on the first day because they required no material or soil disturbance. The only purpose of the control treatment was to use its readings to normalise EC_a values of interfering objects if variation in readings would occur between measurement points. Following this, 3 capacitance probes (DFM Software Solutions, South Africa) were installed at the centre of each transect, 0.3 m apart from each other and perpendicular to the transect (Fig. 2b). The spacing ensured that the entire length of the EM38-MK2 sensor, i.e., both receiver coils, had equal exposure to the source of interference. The capacitance probes used in this experiment were 1.2 m long with 6 copper ring sensors located at 0.2 m intervals along the probe.

After removing the capacitance probes, 3 galvanised steel access tubes were installed in the same positions. The length and internal diameter of the steel access tubes were 1.5 m and 0.07 m, respectively. Following the galvanised steel access tubes, a soil trench was made at the centre of each transect, 1 m wide and 1.5 m deep, in correspondence with the EM38-MK2 measurement depth (Fig. 2c).

Table 1. Summarized statistics showing the homogeneity of some properties of the Bainsvlei soil form per depth interval for the transects (n = 44)

Soil depth (m)	Parameter	Sand (%)	Silt (%)	Clay (%)	GWC (%)	Cations (me·L⁻¹)	EC_e (dS·m⁻¹)	Resistivity (Ω·m)
0–0.3	Mean	86.2	6.14	6.94	3.87	2.41	0.26	3 806
	F-values	1.9	0.37	0.76	2.25	1.09	1.36	0.76
	P > *F*	0.08	0.95	0.66	0.04	0.4	0.24	0.66
0.3–0.6	Mean	75.8	5.85	16.97	8.49	2.12	0.22	2 376
	F-values	0.88	0.41	1.04	1.73	0.72	1.36	1.05
	P > *F*	0.56	0.93	0.44	0.12	0.7	0.24	0.42
0.6–0.9	Mean	77.4	5.64	15.79	7.55	1.88	0.19	2 751
	F-values	0.37	0.67	1.87	0.93	0.81	0.65	0.33
	P > *F*	0.95	0.74	0.09	0.52	0.62	0.76	0.97
0.9–1.2	Mean	80.4	5.71	13.27	7.27	1.84	0.18	2 892
	F-values	1.07	0.99	0.29	0.42	1.11	1.4	0.48
	P > *F*	0.41	0.47	0.98	0.92	0.38	0.22	0.89
1.2–1.5	Mean	77.4	5.9	14.64	8.59	1.92	0.19	2 392
	F-values	0.27	1.27	0.84	0.09	0.21	0.18	0.67
	P > *F*	0.98	0.29	0.59	1	0.99	1	0.75

GWC = gravimetric soil water content; EC_e = electrical conductivity of a saturated paste extract

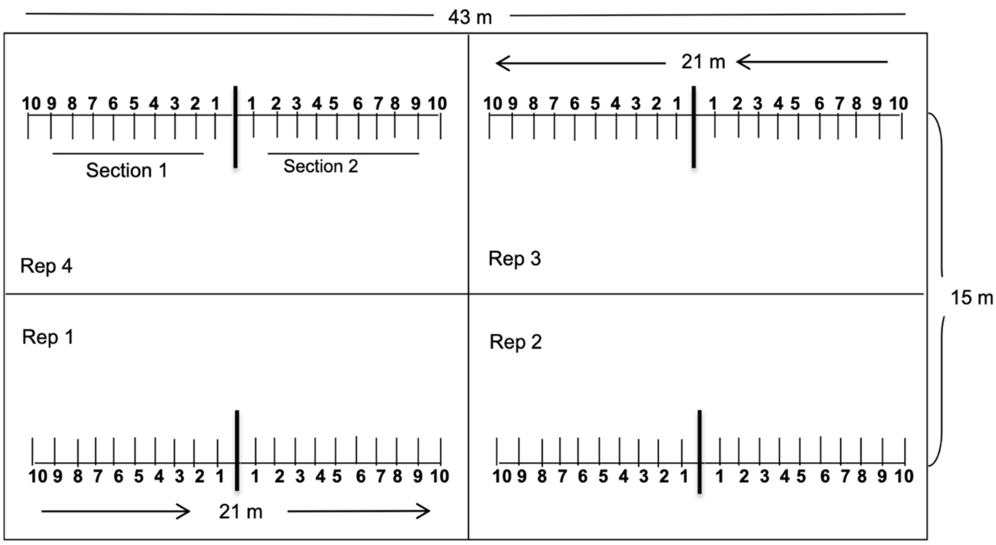

Figure 1. Schematic diagram showing experimental layout with 4 replicates (Rep 1 to 4) on the Bainsvlei soil form. Intervals between measuring points were 1 m, and centre of transects are indicated by thick vertical lines.

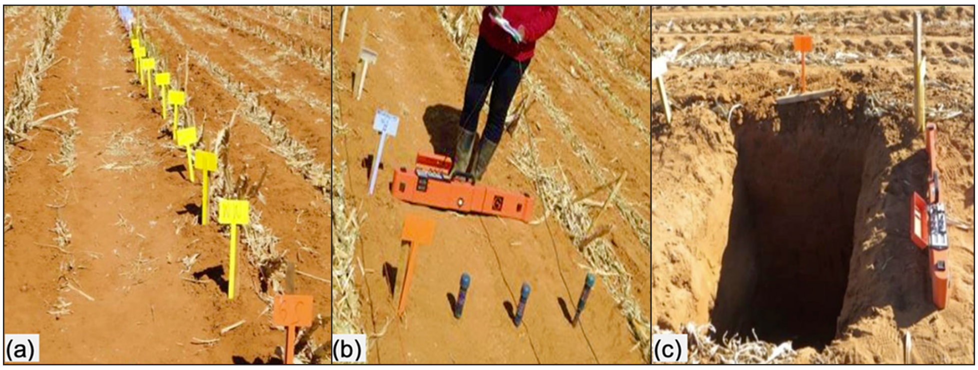

Figure 2. Experimental layout on the Bainsvlei soil form, showing (a) a transect with 1 m interval measuring points, (b) EM38-MK2 sensor at 1 m from the DFM capacitance probes, and (c) the EM-MK2 sensor near the edge of the soil trench

The operating instructions of the EM38-MK2 sensor were followed according to the manufacturer's manual (Geonics, 2003) before starting with measurements for each treatment. This included battery check, initial in-phase nulling, instrument zeroing and final in-phase nulling. The EMI was zeroed before beginning to measure each new transect. However, it was not re-zeroed after encountering the applied interfering objects on a transect, in order to examine the instrument's response before and after the treatments. It took approximately 4 min to record EC_a data for each transect manually, and in total less than 30 min was spent per treatment, including re-zeroing between transects.

Measurements were made by placing the EM38-MK2 sensor perpendicular to the transect at each measuring point. From 10 m away, the device was moved towards the point of influence (Point 0), passed over it, and moved further up to 10 m away without zeroing the instrument. In-phase (IP) and quad-phase (QP) readings were manually recorded in both horizontal (shallow depth, 0.75 m) and vertical (deep depth, 1.5 m) dipole orientation of the EM38-MK2 sensor. The IP readings (ppt), a self-generated signal resulting from the soil's magnetic susceptibility, indicated how the EM38-MK2 sensor reacted towards the obstructions. Magnetic susceptibility is influenced by metallic objects, ferromagnetic minerals and soil disturbances. The QP readings, expressed as EC_a ($mS \cdot m^{-1}$), were primarily used to examine the effect of each interfering treatment. Note that IP readings should be as close as possible to 0 ppt, and an arbitrary threshold of ±10 ppt was chosen for this study. The arbitrary threshold was chosen based on the inherent noise level of the EM38-MK2 sensor and the high homogeneity of the soil. This threshold ensures that only significant deviations, indicative of interference, are captured, while avoiding false positives from minor natural variability. Readings beyond this threshold would indicate that there is interference. Repeated transect readings were taken for each treatment to verify the reliability of the EM readings.

The EM38-MK2 version of the EMI device used in this study is provided with new coil technology that reduces the effect of temperature-related drift on EC_a measurements (Geonics 2012). The study also took additional precautions to minimise the temperature effect during field measurements. The EC_a data for all treatments were collected during the early morning hours, between 7:00 and 9:00, over a time frame of less than 30 min, as mentioned earlier. Ambient temperature was not recorded in this study. However, the averaged profile soil temperature of 27°C (SD = 0.07; CV = 0.29%) was recorded using capacitance probes (at 20 mm increments up to 1.2 m depth) at the time EC_a was measured. This was used to correct for temperature in EC_a readings, as explained elsewhere. There were no rainfall events during the experiments.

Data analysis

The IP readings were only used as a first indication of interference during EM38-MK2 measurements. No statistical tests were performed on the IP data. However, graphs of IP values were developed using a broken y-axis to accommodate all values, as described by Blakeston (2014). Recorded EC_a data were first standardised to an equivalent conductivity of EC_{a25} at a reference temperature of 25°C using the exponential models of Sheets and Hendrickx (1995) suggested by Corwin and Lesch (2005c). Means and standard deviations of the EC_a values were calculated in Microsoft Excel for every measurement point and were used to develop a graph for each interfering treatment. EC_a data were then arranged into 2 groups for each treatment based on measurements taken before and after interference. A *t*-test was used to compare the means of these 2 groups using the SAS software program (Statistical Analysis System Institute Inc. 1999). The equality of variance was tested between the 2 groups. If there was an unequal variance between EC_a data collected before and after the point of influence, the Cochran method for unequal variance was used in the t-test to check for any significant difference between the means. If both groups had equal variance, the pooled method was used.

RESULTS

Magnetic susceptibility

The trend in IP readings for vertical (V) and horizontal (H) dipole modes is presented in Figs 3a and b, respectively. All interference treatments and the control gave consistent IP readings that were within ±5 ppt at all measurement points, except at 1 m from the point of influence, where the EM38-MK2 sensor began to sense the presence of steel access tubes in the H-mode, slightly exceeding the ±10 ppt threshold chosen for this study.

The IP readings indicated a sharp effect as the EM38-MK2 sensor was placed closer than 1 m from the capacitance probes and galvanised steel access tubes. At the point of influence (0 m), the mean IP readings for capacitance probes were −33 ppt and −62 ppt, while for galvanised steel access tubes, −210 ppt and −506 ppt were recorded in V-mode and H-mode, respectively. The IP readings taken towards the interference treatments were consistently below the ±10 ppt threshold, with a similar trend for the control, except close to the point of interference treatments. This similarity was also observed in the measured EC_a. It was not necessary to use control measurements to normalise readings made towards the interfering treatments as stipulated in the methodology because there was no difference in EC_a point measurements between the interference treatments and the control. Hence, only the effects of the soil trenches, capacitance probes and galvanised steel access tubes on EC_a measurements are reported. The EC_a readings are reported as obtained after correcting for temperature.

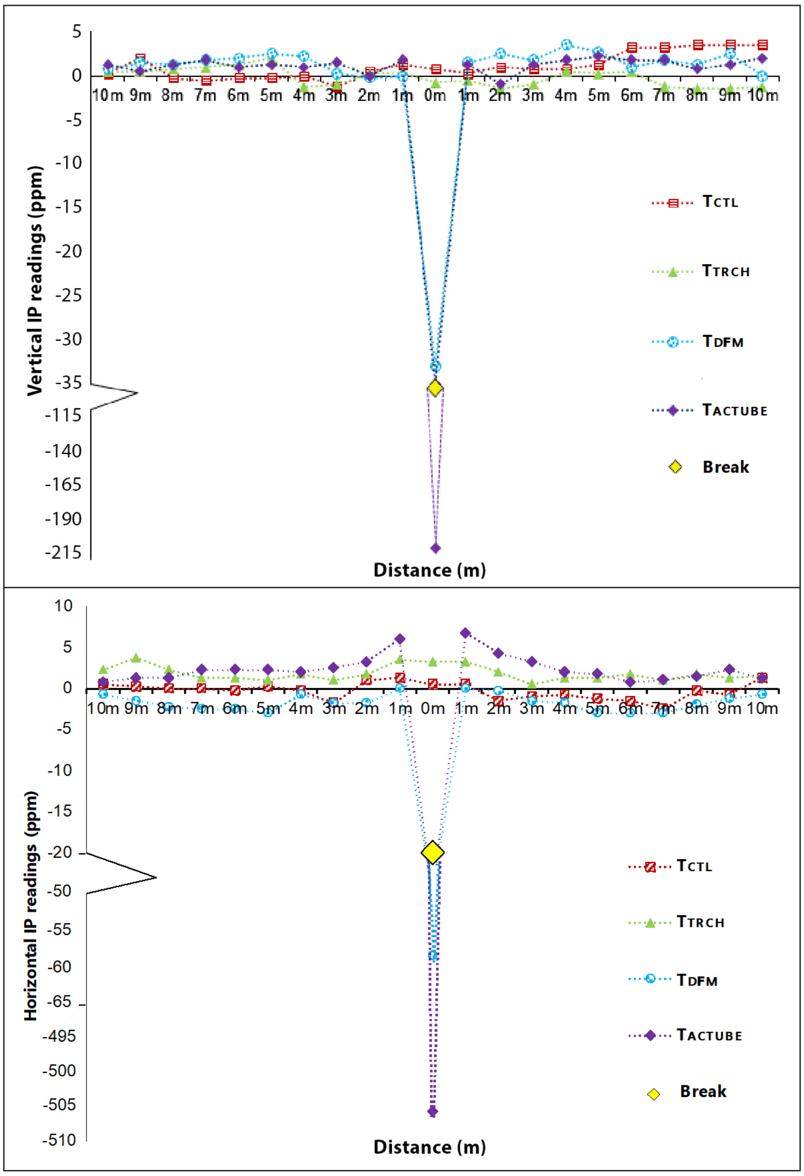

Figure 3. Average IP readings of the EM38-MK2 sensor on the Bainsvlei soil form in (a) vertical and (b) horizontal mode along a transect without interference (T_{CTL}), and with interference of soil trenches (T_{TRCH}), DFM capacitance probes (T_{DFM}) and galvanized steel access tubes (T_{ACTUBE})

Soil trenches

The response of the EM38-MK2 sensor toward soil trenches is displayed in Fig. 4. Measured values of EC_a were below 20 mS·m^{-1} in both V-mode and H-mode. With the EM38-MK2 sensor next to the soil pits, only a slight reduction in EC_a readings was observed in the V-mode. The descriptive statistics for EC_a measured before, at the point of influence, and afterwards are shown in Table 2. The EC_a values before and after the soil trenches had equal variance for V-mode readings, and the means were not significantly different (Table 2). An unequal variance between the 2 groups was observed in the H mode, but the means were not significantly different. This indicates that, under the conditions prevailing in this study, soil trenches did not significantly interfere with EC_a measured with the EM38-MK2 sensor.

Capacitance probes

The EC_a values measured along the transects with the installed capacitance probes ranged from 7 mS·m^{-1} to 29 mS·m^{-1} in V-mode and H-mode. Only at the point of influence was a substantial effect on the EC_a readings noted (Fig. 5). The EM38-MK2 sensor recorded a mean EC_a value of −43.5 mS m^{-1} in the Vmode and −79.5 mS·m^{-1} in the Hmode (Table 2). Note, however, that the standard deviations of these means were quite large, indicating a highly variable response of the EM38-MK2 sensor to the capacitance probes.

After the EM38-MK2 sensor encountered the capacitance probes, EC_a readings were relatively variable in the V-mode, and the *t*-test showed that the means of this EC_a group before and after encountering capacitance probes had unequal variance (Table 2). The CV for EC_a readings was 15% before encountering capacitance probes and 28% after. However, the means before and after the point of influence were not significantly different. In the H-mode, there was equal variance between the EC_a measured before and after the installation of the capacitance probes, but the means were significantly different (p = 0.0029). The mean EC_a after encountering the capacitance probes was 9% or 0.88 mS·m^{-1}, smaller than the mean EC_a before encountering the capacitance probes (Table 2).

Galvanised-steel access tubes

In Fig. 6, the EC_a readings of the EM38-MK2 sensor are shown when the device moves towards the installed galvanised steel access tubes. An almost constant reading was recorded from 10 m away to 1 m from the installed access tubes, with EC_a values ranging from 6 to 22 mS·m^{-1} for both V-mode and H-mode. At the point of influence, the access tubes responded strongly with negative mean values of −30 mS·m^{-1} for the V-mode and −1 041 mS·m^{-1} for the H-mode. The response was highly inconsistent, with high standard deviations of 103 and 655 mS·m^{-1} in the V- and H modes, respectively (Table 2).

Statistically, the measured EC_a values before and after encountering the galvanised steel access tubes had an equal variance in the V-mode. However, the means of these two groups' readings were significantly different ($p < 0.001$; Table 2). The EC_a value recorded

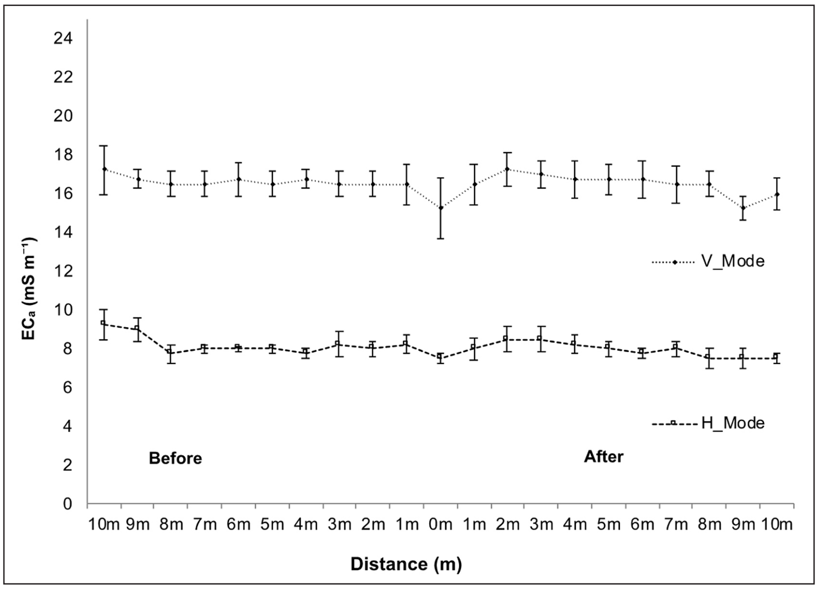

Figure 4. Measured apparent soil electrical conductivity (EC_a) by electromagnetic induction (EMI) on the Bainsvlei soil form in the vertical (V) and horizontal (H) mode before and after encountering the soil trenches

Table 2. Statistical differences in apparent soil electrical conductivity (EC_a) measurements through electromagnetic induction with the EM38-MK2 sensor before and after the application of the treatments to the Bainsvlei soil form (n = 40)

Interferences	Difference (after – before)			Method	Variances	DF	*t*-value	Pr > |*t*|
	Mean	SD	SE					
DFM, V-mode	0.65	4.2983	0.9611	Cochran	Unequal	39	0.68	0.5029
DFM, H-mode	−0.875	1.2739	0.2848	Pooled	Equal	78	−3.07	0.0029
Steel tubes, V-mode	−2.075	2.0124	0.45	Pooled	Equal	78	−4.61	<.0001
Steel tubes, V-mode	−1.275	1.9822	0.4432	Pooled	Equal	78	−2.88	0.0052
Trench, V-mode	−0.075	1.4123	0.3158	Pooled	Equal	78	−0.24	0.8129
Trench, H-mode	−0.375	1.2943	0.2894	Cochran	Unequal	39	−1.3	0.2027

SD = standard deviation; SE = standard error

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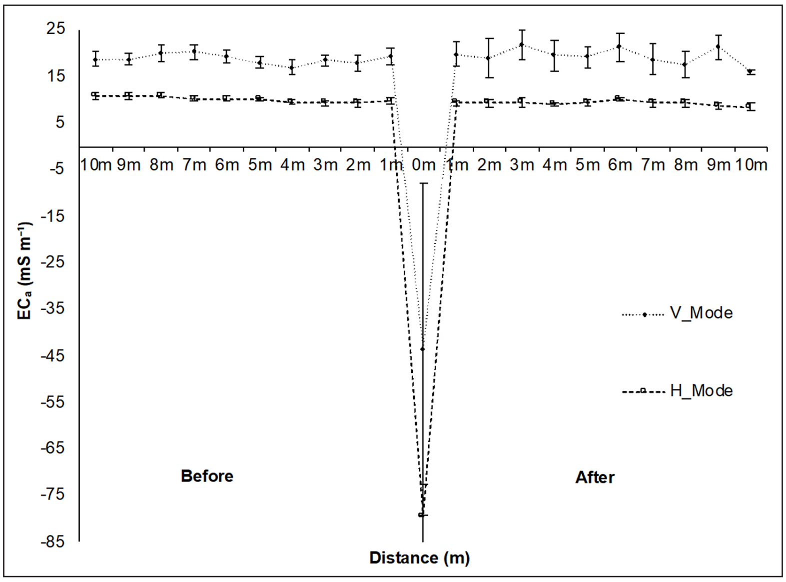

Figure 5. Measured apparent soil electrical conductivity (EC_a) by electromagnetic induction (EMI) on the Bainsvlei soil form in the vertical (V) and horizontal (H) mode before and after encountering the DFM capacitance probes

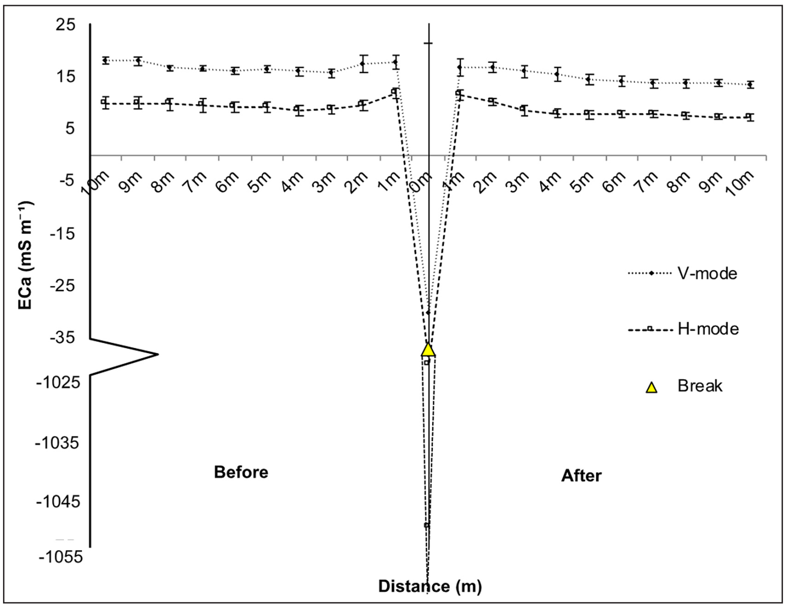

Figure 6. Measured apparent soil electrical conductivity (EC_a) by electromagnetic induction (EMI) on the Bainsvlei soil form in the vertical (V) and horizontal (H) mode before and after encountering the neutron water meter (NWM) galvanized steel access tubes

after the EM38-MK2 sensor encountered the galvanised steel access tubes was 2.1 mS·m^{-1}, smaller than the EC_a measured before encountering the galvanised steel access tubes (Table 2). In the H-mode, EC_a measured before and after encountering the galvanised steel access tubes also had equal variance, but the means were significantly different ($p = 0.0052$). The mean EC_a after encountering the galvanised steel access tubes was 13% or 1.3 mS·m^{-1}, smaller than before (Table 2).

DISCUSSION

Generally, each time the EM38-MK2 sensor encounters interference, the influence depends on the current flowing from the device and the electrical force coming from the conductive object. The IP results indicated that only the capacitance probes and galvanised steel access tubes influenced EMI, evident from the measured ppt readings.

This study observed that soil trenches did not influence the EC_a readings of the EM38-MK2 sensor, while capacitance probes and galvanised steel access tubes containing metal influenced the readings. Similar results were reported by Stanley et al. (2014) with aluminium access tubes. This study's capacitance probes and galvanised steel access tubes elicited a strong response only when the EM38-MK2 sensor moved closer than 1 m. The galvanised steel access tubes resulted in more pronounced and erratic EC_a readings than the capacitance probes. This is probably because the capacitance probes contain only small copper rings of sensors over the probe length and are coated in a thick resin cast, compared to the galvanised-steel access tubes comprising considerably more metal (1.5 m length). When the EM38-MK2 sensor was close to capacitance probes and galvanised-steel access tubes, EC_a readings were negative. The EC_a response to these two devices was more sensitive when the EM38-MK2 sensor operated in the H-mode than the V-mode orientation.

More importantly, after the EM38-MK2 sensor encountered the capacitance probes and galvanised steel access tubes, there was a significantly measurable effect on EC_a readings. The EC_a was either less stable (in the V-mode for capacitance probes) or lower (in the H-mode for capacitance probes and in both modes for galvanised steel access tubes). The instability observed in the V-mode after encountering capacitance probes was relatively small. The standard deviation of the EC_a readings increased from 2.81 mS·m^{-1} before to 5.39 mS·m^{-1} after encountering the probes (Table 2). However, the small differences recorded would probably not have a meaningful effect in a field survey.

Other researchers did not report on the extent of this effect when EMI encounters metal-containing devices during a field survey. It has been generally advised to avoid any sort of metal within the proximity of the EC_a survey, as Geonics (2003) suggested. Considering the two-step process for determining soil water content, devices that might contain metals should be avoided when calibrating EM38-MK2 sensors to determine soil water content. Also, it should be noted that the gravimetric method of calibrating an EM38-MK2 sensor is destructive, due to excessive soil sampling, and is very expensive for extensive commercial farming. The ideal step would be re-zeroing the EMI if the EM38-MK2 sensor accidentally detected any form of metal within its measurement line during a field survey. This would be quite time-consuming, since the operator must return to the same location where the instrument was first zeroed, and this is almost completely impractical in mobile EC_a surveys. Although statistically significant, the extent to which EC_a values were affected in this study was relatively small and not practically relevant. From an operational point of view, the slight increase in accuracy obtained by additional re-zeroing would likely not be worth the effort at the large field scale.

CONCLUSION

The soil trenches did not influence the EMI's EC_a measurements by the EM38-MK2 sensor. In contrast, the installed capacitance probes and galvanised steel access tubes influenced EC_a readings significantly when the EM38-MK2 sensor was closer than 1 m from these metal-containing devices. The effect of the galvanised steel access tubes was more pronounced than that of the capacitance probes. This can probably be attributed to the capacitance probes containing only small copper ring sensors. The EC_a readings of the EM38-MK2 sensor were either inconsistent or smaller because of the interference devices. Although their influence on EC_a measurements was significant, it was too small to justify an additional re-zeroing of the EMI sensor during a field survey. However, depending on the prevailing atmospheric condition, the stability of EC_a readings obtained with an EMI sensor should be monitored during a field survey.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

JA Edeh – data curation, formal analysis, writing-original draft; JH Barnard – conceptualization, supervision, writing-review editing; LD van Rensburg – conceptualization, resources, supervision, writing-review editing; CC du Preez – conceptualization, writing-review editing.

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