American-Eurasian J. Agric. & Environ. Sci., 15 (6): 1059-1066, 2015
ISSN 1818-6769

DOI: 10.5829/idosi.aejaes.2015.15.6.12689

Performance of Electromagnetic Induction Meter (EM38-MK2-1) under Different Working Conditions in a Sandy Loam Soil

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Abstract: The objective of this study was to identify the optimum conditions at which the Electromagnetic Induction Meter (EM38-MK2-1) can be used for precision measurements of the apparent soil electrical conductivity (EC_a) measurements in a sandy loam soil of a 50 ha experimental field located in the eastern region of Saudi Arabia. A total of 25 locations were selected for apparent electric conductivity (EC_a) and extracted soil paste electric conductivity (EC_e) measurements with EM38 and Laboratory measurements. At all sampling points, observations were taken with EM38 device in both the horizontal and vertical orientation to the soil surface. Measurements were recorded for three EM38 heights above the ground: on the soil surface (i.e. 0.00 cm, 20 cm and 40 cm). These readings were recorded at soil moisture contents of 24.5, 21.9, 18.6 and 15.3%. Also, the EM38 device was tested at three different surveying speeds (21.22, 17.33 and 12.69 km h^{-1}) at 20 and 40 cm heights above the ground for both vertical and horizontal orientations. The results revealed that the height of EM38 device above the ground induced significant differences ($P<0.05$) in the measured EC_a under all the tested soil moistures for both the vertical and horizontal EM38 orientations. It was observed that placing EM38 on the soil surface induced the highest R^2 between EC_a and EC_e compared with other heights. The errors in predicting EC from the EM38 measured EC_a increased with the decrease in soil moisture and indicated that the highest measurement accuracy was obtained at the highest tested soil moisture (24.5%), except for 0.00 cm height above the ground, EC_a values for vertical mode were higher than that produced by horizontal mode at all moisture contents. The results also indicated that there was no definite trend associated to the tested surveying speeds at both EM38 heights above the ground (20 and 40 cm) for both vertical and horizontal modes.

Key words: Soil salinity · Electrical conductivity · EM38 · Precision agriculture

INTRODUCTION

Soil salinity mapping is one of the most precision agriculture requirements. Measurement of soil salinity in the laboratory is time consuming, expensive and labor intensive, especially for large scale measurements. Using EM38 with the help of vehicles and a Global Positioning System (GPS) for geo-referenced electrical conductivity (EC) measurements allows covering large area in a short time. Electrical conductivity (EC) measured by electromagnetic induction (EMI) using EM38 is inexpensive and rapid for precision agriculture purposes [1, 2, 3, 4]. EM38 device is appropriate to assess the temporal and spatial variability of several soil properties such as salinity, water content, texture and depth-to-clay mapping, width of soil boundaries and in applications for precision agriculture [5]. There are several factors affecting the accuracy of the EM38 device signal such as salinity level, soil moisture content, soil structure (porosity and clay percent), temperature and the position of the instrument (horizontal, vertical and height above the soil surface). O'Leary *et al*. [6] used EM38 for identifying sub-soil properties and concluded that, the electrical conductivity was well correlated with high soil

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moisture content and soil salinity. Also, Llewellyn and Filmer [7] stated that EM38 mapping was particularly useful as it usually correlated well with some soil characteristics that were associated with crop yield potential. Hossain [8] used EM38 to measure soil moisture content in a clayey soil. His results showed that volumetric soil moisture content measurements with accuracy of approximately ±0.007 m^3m^{-3} were recorded with EM38 in the vertical orientation. However, the horizontal orientation of EM38 was, in general, found to produce better accuracies of soil moisture prediction. Rhoades [9] stated that soil water content necessary for EC_a valid model is about 10% on a gravimetric basis, though it may be somewhat higher for coarse textured soils. However, Norman [10] found that the regression relationships between EC_a and EC_e were not significantly different for gravimetric moisture levels of 20 to 25% and for values greater than 25% in clay soils. Rahimain and Hasheminejhhad [11] observed that, in clay loam soil, more reliable regression equations could be derived at 35% moisture content in comparison with 25% moisture content at different depths of soil and horizontal/vertical orientations, with R^2 of 0.67to 0.85, respectively. Also, Abdel Ghany *et al*. [12] reported that, in clayey soil, the highest regression coefficient between EC_a and EC_e for vertical and horizontal modes of 0.85 and 0.72 at moisture content ranged between 32.2-38.9% and 38.9-45.5%, respectively. The EM38 is showing different responses to soil depth when it is placed upright on the soil surface (vertical dipole) and when it is laid on its side (horizontal dipole). McNeill [13] stated that 22% of the signal response comes from the top 0.4 m of the soil profile and 78% from below this depth for the vertical dipole. For the horizontal dipole, these figures are 53% and 47%, respectively. While, Rhoades and Corwin [14] mentioned that the EM38 device did not integrated soil EC_a linearly with depth. The depth intervals of 0-30, 31-60, 61-90 and 91-122cm contribute to the EC_a reading by about 43, 21, 10 and 6%, respectively. Therefore, lifting EM38 above the ground induced a significant decrease in EC_a values in both vertical and horizontal orientations of the EM38 [15, 16]. Padhi and Misra [17] 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. The influence of EM38 height on EC_a values was also investigated by Al-Gaadi [18] who stated that higher regression coefficients between soil compaction levels and soil EC_a (average of 0.90) were met with the EM38 placed on the ground (0 cm height) compared to those achieved with the EM38 positioned at 20 cm and 40 cm height above the ground. As mentioned above, the use of EM38 is affected by so many factors therefore, determination of the optimum conditions for EM38 measurements in specific soil is essential for high device accuracy.

The objective of this study was to identify the ideal conditions at which the optimum accuracy of EM38-MK2 in estimating the apparent soil electrical conductivity (EC_a) can be obtained under different soil moisture conditions of a sandy loam soil and to determine the effect of surveying speed on the accuracy of the measurements.

MATERIALS AND METHODS

Field experiments were conducted on a field in Todhia arable farm located in the eastern region of Saudi Arabia (N: 24° 05\ 41.23\\, E: 48° 21\ 2.25\\). The soil texture was sandy loam in nature with 14.07%, 16.08% and 68.85% clay, silt and sand, respectively. A total of 25 locations were selected for EC_a measurements with EM38 as well as taking soil samples for Laboratory measurements of electrical conductivity and soil moisture content.

Directly beneath the EM38, soil samples were collected by hand auguring at 0.2 m increments to an approximate depth of 1.4 m for laboratory measurements of soil salinity. Soil samples were air dried, grinded and sieved (< 2 mm) and soil paste salinity (EC_e) was measured following the standard methods [19]. Additional soil samples were taken for gravimetric water content (WC) measurements. This was calculated from the mass lost after drying at 105°C for 24 hours. At all points, six EM38 readings were taken, one with EM38 device positioned horizontally to the soil surface and the second one with the device positioned vertically. These positions were repeated for three EM38 heights above the ground: on the soil surface (i.e. 0 cm), 20 cm and 40 cm. These readings were recorded at soil moisture contents of 24.5, 21.9, 18.6 and 15.3%. Soil depth ranges for EC_a measurements at different EM38 heights were 150, 130 and 110 cm for the vertical orientation mode and 75, 55 and 35 cm for the horizontal orientation, respectively. A frame was fabricated from a Poly Vinyl Chloride (PVC) pipe (Fig. 1) to provide different heights of the EM38 above the ground (0, 20 and 40 cm), [18]. These readings were performed at soil moistures of 24.5, 21.9, 18.6 and 15.3%.

Another sets of field surveying experiments were conducted to evaluate the performance of the EM38-MK2-1 under three different forward speeds (21.22, 17.33 and 12.69 km h^{-1}) at soil moisture content of 21.55% with vertical and horizontal orientations when the EM 38 was

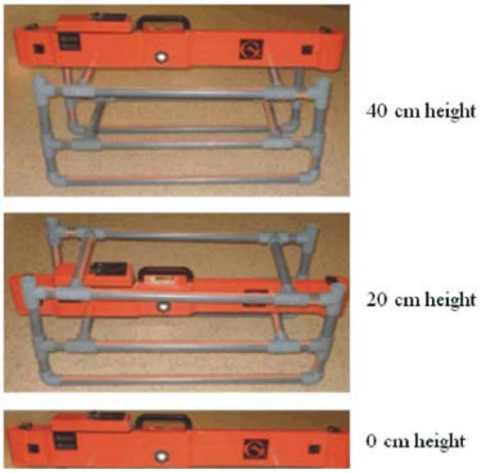

Fig. 1: EM38 with the frame at different heights above the ground

Fig. 2: Cart used for surveying speed experiments

operated at two heights above the soil surface (20 and 40 cm). Special cart was fabricated to be used for field surveying experiments (Fig. 2). The obtained data were statistically analyzed by analysis of variance and regression analysis using SPSS software.

RESULTS AND DISCUSSIONS

Performance of EM38 under Different Working Conditions: Average EM38 readings under different soil moisture contents and device height above the ground at vertical and horizontal orientation was compared to the laboratory measured soil electrical conductivity of the saturated soil-paste extract (EC_e) as shown in Figs. 3-6. Statistical analysis indicated that the height of the device above the soil surface had a highly significant effect on the apparent soil electrical conductivity ($P<0.01$). It is observed that at the different soil moisture contents and the device orientations, the highest values of EC_a were recorded when the device was contacted with the ground. On the other hand, the minimum values were obtained with 40 cm height above the ground. This results means by raising the device above the ground the sensitive of the EM 38 decreased. Rhoades and Corwin [14] mentioned that the 0-30, 31-60, 61-90 and 91-122 cm depth intervals contribute about 43, 21, 10 and 6%, respectively to the EC_a reading. So, lifting the device above the ground makes the highest contribution percentage in the air consequently, the sensitivity decreased. These results are in agreement with those obtained by Sudduth *et al*. [15] and Robinson *et al*. [16].

Considering the effect of moisture content on the performance of EM38, it is evident from Figs. 3-6 that an increase in the soil moisture led to increase the device readings at all device heights and orientations. Statistical analysis showed that EC_a values measured by the EM38 oriented vertically and horizontally were significantly affected by soil moisture content ($P<0.01$). The same findings were found by Mckenzie *et al*. [20], Baig and Chaudhry [21], Abdel Ghany *et al*. [12] and Rahimian and Hasheminejhad [11].

Regarding horizontal and vertical modes, it was observed that EC_a values measured by the EM38 were highly significant affected by device mode ($P<0.01$). Fig. 3 showed that EC_a values when the device positioned horizontally on the soil surface (0 cm above soil surface) were higher than that recorded with vertical mode at 0 cm height above soil surface. On contrary, the highest EC_a values were observed with the EM38 operated in the vertical mode at other device heights above the soil surface. EC_a values for EM38 inthe horizontal mode decreased more rapidly with the increasing EM38 height above the soil surface than for the vertical mode. Similar results were recorded by Sudduth *et al*. [15], Robinson *et al*. [16], Padhi and Mirsa [17] and Al-Gaadi [18].

Prediction of the Actual Electrical Conductivity (EC_e) from the EM38 Measured EC_a: The relationship between the EM38 measured soil electrical conductivity EC_a and the laboratory measured soil electrical conductivity EC_e was performed through the linear regression method considering EC_a as the independent variable and EC_e as the dependent variable. The developed linear relationships at all tested conditions are represented by the equations shown in Table 1.

The developed equations were further validated by using EM38 survey data (40% of the collected observations) from the same locations used in the study. The values of the laboratory measured soil electrical conductivity (EC_e) and the predicted soil electrical conductivity (EC_p) are presented in Table 2.

Table 1: Relationships for predicting soil electrical conductivity (ECe) from EM38 measurements (EC_a) at different EM38 orientations, EM38 heights above the ground and soil water contents

Soil Moisture	EM38 Orientation	EM38 Height (cm)	Regression equation	R^{2*}	S.E**
24.50%	Horizontal	0	$EC_e = 2.19\ EC_a - 76.68$	94.3	3.6
		20	$EC_e = 2.90\ EC_a – 54.76$	83.4	6.2
		40	$EC_e = 5.76\ EC_a - 72.49$	73.6	9.1
	Vertical	0	$EC_e = 2.62\ EC_a - 88.00$	79.6	4.6
		20	$EC_e = 2.62\ EC_a - 68.66$	77.3	4.8
		40	$EC_e = 3.47\ EC_a - 68.97$	75.6	6.6
21.90%	Horizontal	0	$EC_e = 1.42\ EC_a - 11.91$	75.5	7.8
		20	$EC_e = 2.40\ EC_a - 14.03$	67.6	8.7
		40	$EC_e = 2.32\ EC_a + 37.53$	19.7	14
	Vertical	0	$EC_e = 1.88\ EC_a – 33.91$	55.5	6.8
		20	$EC_e = 1.34\ EC_a + 08.63$	42.2	7.7
		40	$EC_e = 1.81\ EC_a + 12.24$	29.8	11.1
18.60%	Horizontal	0	$EC_e = 1.70\ EC_a - 15.62$	72.9	7.9
		20	$EC_e = 2.54\ EC_a - 03.11$	63.5	9.2
		40	$EC_e = 3.16\ EC_a + 37.23$	28.1	15.1
	Vertical	0	$EC_e = 1.60\ EC_a - 05.76$	46.6	7.4
		20	$EC_e = 2.11\ EC_a - 19.80$	42.4	7.7
		40	$EC_e = 2.32\ EC_a + 5.49$	19.3	12
15.30%	Horizontal	0	$EC_e = -1.56\ EC_a + 158.49$	39.7	10.9
		20	$EC_e = 4.78\ EC_a – 50.74$	40.3	12.5
		40	$EC_e = -2.00\ EC_a + 106.94$	18.1	16.1
	Vertical	0	$EC_e = 1.47\ EC_a - 13.00$	43.8	7.6
		20	$EC_e = 1.22\ EC_a + 32.64$	29.1	8.6
		40	$EC_e = 0.56\ EC_a + 66.93$	11.3	12.6

Table 2: Results of the validation process of the developed models under different conditions

Soil Moisture	EM38 Orientation	EM38 Height (cm)	EC_e	EC_a	Ec_p
24.50%	Horizontal	0	83.2	71.53	79.96
		20	83.8	45.79	77.93
		40	86.4	25.84	76.34
	Vertical	0	76.7	62.1	74.82
		20	77.2	54.42	73.71
		40	80.6	41.01	73.42
21.90%	Horizontal	0	83.2	61.5	75.36
		20	83.8	35.81	71.81
		40	86.4	11.89	65.15
	Vertical	0	76.7	56.22	71.56
		20	77.2	45.06	69.19
		40	80.6	29.12	65.07
18.60%	Horizontal	0	83.2	52.13	72.74
		20	83.8	28.11	68.3
		40	86.4	7.65	61.44
	Vertical	0	76.7	46.48	68.75
		20	77.2	40.26	65.23
		40	80.6	23.58	60.1
15.30%	Horizontal	0	83.2	59.01	66.38
		20	83.8	22.96	59.04
		40	86.4	28.33	50.31
	Vertical	0	76.7	38.63	69.64
		20	77.2	25.25	63.37
		40	80.6	6.12	70.38

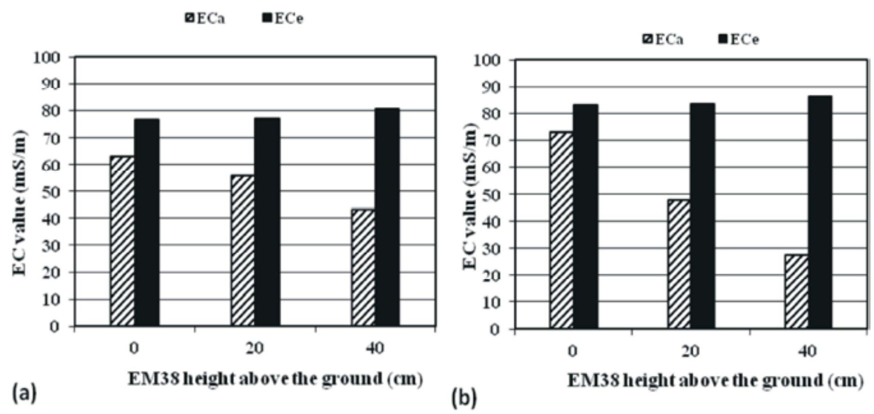

Fig. 3: Comparison of EC_e and EC_a at soil MC of 24.5% for (a) Vertical and (b) Horizontal EM38 Modes

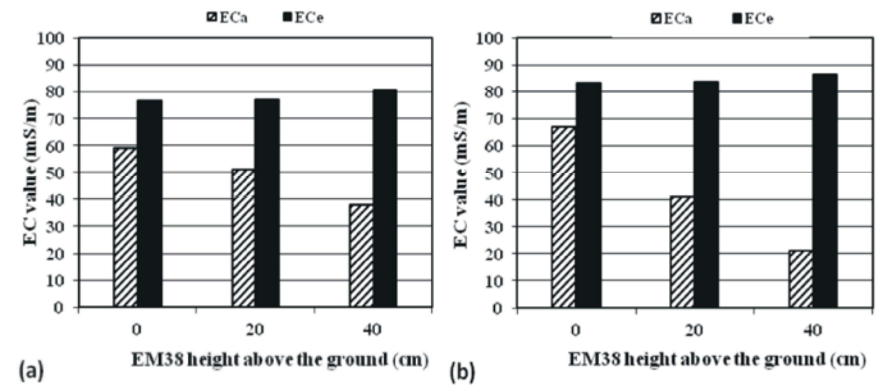

Fig. 4: Comparison of EC_e and EC_a at soil MC of 21.9% for (a) Vertical and (b) Horizontal EM38 Modes

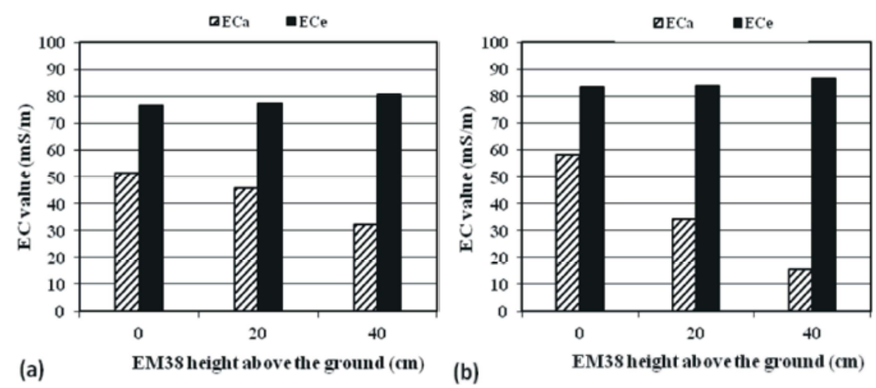

Fig. 5: Comparison of EC_e and EC_a at soil MC of 18.6% for (a) Vertical and (b) Horizontal EM38 Modes

The validation results showed good correspondence between the actual and predicted soil electrical conductivity (EC_e and EC_p, respectively) with varying levels of error calculated using the following equation:

$$Error, \% = \left| \frac{(EC_p - EC_e)}{EC_e} * 100 \right|$$

The calculated errors of EC measurements are presented in Fig. 7. These results revealed that the lowest errors were observed with EM38 in the vertical orientation under all working conditions. Also, a general trend of increasing errors was observed with the decrease in soil moisture content for both EM38 horizontal and vertical orientations at all the tested EM38 heights above the ground (0, 20 and 40 cm). These results are in agreement with Rhoades *et al*. [22] that the ability to accurately determine EC_e from EC_a decreases as soil moisture decreases. They recommended that EC_a measurements be limited to moisture contents that are not less than about one-half of field-capacity water content.

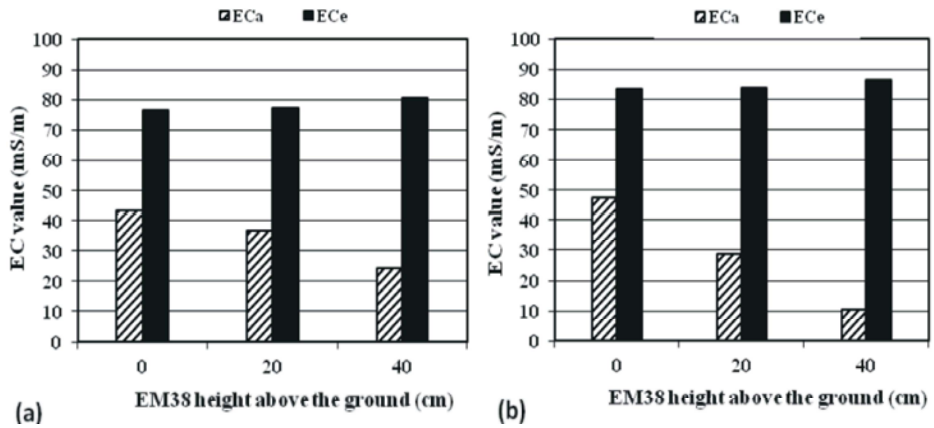

Fig. 6: Comparison of EC_e and EC_a at soil MC of 15.3% for (a) Vertical and (b) Horizontal EM38 Modes

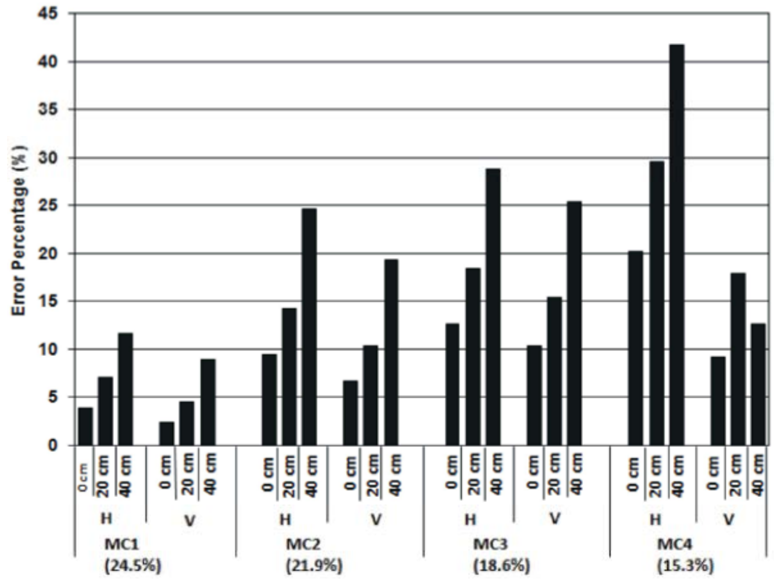

Fig. 7: Error % of EC_p compared to EC_e at different soil moistures, EM38 orientations: Vertical (V) and Horizontal (H) and three EM38 heights above the ground (0, 20 and 40 cm)

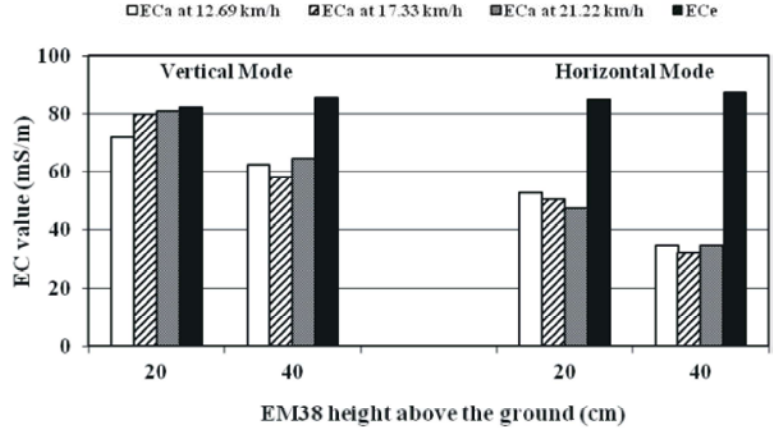

Fig. 8: Effect of the working speed on the performance of EM38 at both horizontal and vertical modes and twodevice heights above the ground (20 and 40 cm)

Therefore, it could be concluded that the best accuracy of EM38 for measuring soil EC under sandy soil was obtained with the device in the vertical orientation and placed on the ground (0.00 cm height).

Effect of the Working Speed on the Performance of EM38: Data collected to investigate the effects of EM38 measurement (surveying) speed on the accuracy of the estimated EC_a are presented in Fig. 8. The results indicated that the forward speed had no significant effect on EC_a data at the tested conditions. Also, there was no definite trend associated to the tested surveying speeds at both EM38 heights above the ground (20 and 40 cm) for both vertical and horizontal modes. Similarresults were reported by Sudduth *et al*. [23] on clay soil which showed that the sensitivity of EC_a to variations in soil conductivity sensor (EM38) operating speeds was relatively minor. They observed that, for EM38 in the vertical mode, EC_a decreased slightly with increasing the operating speed (-0.4 mSm^{-1} per 1.0 $mS\ m^{-1}$).

CONCLUSIONS

- The results revealed that the height of EM38 device above the ground induced significant differences ($P<0.05$) in the measured EC_a under all the tested soil moistures for both the vertical and horizontal EM38 orientations.
- On the average, using EM38 in the horizontal orientation was associated with low readings of EC_a compared to the vertical orientation under all the tested conditions.
- The decrease in soil moisture was associated with a significant decrease in the EM38 measured EC_a.
- The errors in predicting electrical conductivity from the EM38 measured apparent electrical conductivity increased with the decrease in soil moisture.
- There was no definite trend associated to the tested surveying speeds at both EM38 heights above the ground (20 and 40 cm) for both vertical and horizontal modes.

ACKNOWLEDGMENTS

This Work was funded by the National Plan for Science, Technology and Innovation (MAARIFAH), King Abdulaziz City for Science and Technology, Kingdom of Saudi Arabia, Award Number (11-SPA1503-02).

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