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TITLE PAGE

Title: Comparison of Geonics EM38 and Dualem 1S electromagnetic induction sensors for the measurement of salinity and other soil properties

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Abbreviations list: D-1S, Dualem 1S sensor; ECa, apparent soil electrical conductivity; EMI, electromagnetic induction; G-EM38, Geonics EM38 sensor;

Running title: Comparison of Geonics EM38 and Dualem 1S sensors

Abstract: The electromagnetic induction (EMI) Geonics EM38 (G-EM38) and Dualem 1S (D-1S) sensors are used frequently for assessment of soil salinity and other soil characteristics in irrigated agriculture. We compared these two sensors to determine if they could be used interchangeably for the measurement of apparent soil electrical conductivity (ECa) in horizontal (ECa-h) and vertical (ECa-v) coil receiver modes. Readings were taken at 201 locations identified in three irrigation districts in both modes and statistical comparisons were made on the raw data and from maps of a 2-ha irrigated field made using 1680 horizontal mode readings. Both sensors gave the same ECa-v readings (mean G-EM38 and D-1S difference = 0), whereas the ECa-h readings were slightly greater with the Geonics EM38 than with the Dualem D-1S (mean difference = 0.075 and 0.05 dS m^{-1} for the 201 and 1680 observations, respectively). The degree of coincidence between both sensors for soil profile ECa classification was acceptable: 82% for normal profiles (i.e., ECa-h/ECa-v < 0.9) and 90% for inverted profiles (i.e., ECa-h/ECa-v > 1.1) . In practical terms Geonics EM38 and Dualem 1S sensors could be used interchangeably with similar or very close results.

Keywords: soil apparent electrical conductivity, electromagnetic induction, soil profile classification, Soil Mapping, Soil Classification, Soil Use and Management.

Introduction

Electromagnetic induction instruments (EMI) have been used in the last three decades to perform apparent soil electrical conductivity (ECa) measurements (Hendrickx & Kachanoski, 2002). These cost-effective, non-invasive EMI are appropriate to assess the temporal and spatial variability of several soil properties such as salinity (Rhoades et al., 1999), water content (Sheets & Hendrickx, 1995; Brevik et al., 2006), texture and depth-to-clay mapping (Triantafilis & Lesch, 2005; Saey et al., 2009), width of soil boundaries (Greve & Greve, 2004), and in applications for precision agriculture (Corwin & Plant, 2005).

Several EMI instruments have been commercialized during the last 30 years. The Geonics EM38 (G-EM38; Geonics Inc., Mississauga, ON, Canada) is the oldest and most frequently used sensor for agronomic studies. The G-EM38 has two coplanar transmitter and receiver coils, 1-m apart. The coils may be positioned parallel (H-H orientation) or perpendicular (V-V orientation) to the earth's surface (Fig. 1). The more recently developed Dualem 1S (D-1S; Dualem Inc., Milton, ON, Canada) has three coils: one vertical transmitter coil and two receiver coils: vertical (coplanar, 1-m apart from the transmitter) and horizontal (perpendicular, 1.1-m apart from the transmitter) (Fig. 1), which provide for two simultaneous ECa readings (V-V and V-H, respectively). Table 1 summarizes some technical specifications of both sensors.

Theoretical relative responses of these sensors with respect to an increase of soil depth are the same in the V-V orientation. This orientation is insensitive at the ground surface but sensitivity increases with depth, peaking at 0.4 m. The relative responses for the G-EM38 in the H-H orientation and for the D-1S in the V-H orientation are somewhat different (Abdu et al., 2007), although both are most sensitive at the surface and rapidly decline with depth. In terms of cumulative responses (R), the depths of exploration for a 70% R are 1.55 m for the G-EM38 and D-1S V-V, 0.75 m for the G-EM38 H-H and 0.50 m for the D-1S V-H orientations. Thus, depending on soil profile characteristics, the ECa readings taken with both instruments should be similar for the V-V mode, but may differ for the G-EM38 H-H and D-1S V-H modes.

The purpose of this study was to determine if both sensors could be used interchangeably. Consequently, we compared the V-V, V-H and H-H ECa measurements taken with the G-EM38 and D-1S sensors at 201 locations. Since the depths of penetration of the G-EM38 H-H and D-1S V-H orientations are not exactly the same, we further analyzed the differences in the ECa maps of a 2-ha irrigated field obtained with the G-EM38 and the D-1S in the H-H and V-H orientations.

Materials and methods

A total of 201 locations for ECa readings with the G-EM38 and D-1S sensors were selected in three irrigated areas located in the middle Ebro River Basin (north-east Spain): Calahorra (a moderately salt-affected, drip-irrigated grapevine orchard), Lerma (a salt-affected area that is being transformed into solid-set sprinkler irrigation), and Soto Lezcano (an experimental farm with non-saline alluvium soils located in the terraces of the Gallego River). The soils were low in stoniness, with non-swelling clays, non-sodic and from non-saline to very saline and ranged from sandy to clay loam in texture. The climate was Mediterranean, dry, subhumid and mesothermic. First, ECa readings were taken with the G-EM38 in H-H and V-V coil orientations. The D-1S was then placed exactly in the same location as the G-EM38 and the ECa readings (V-H and V-V coil orientations) were recorded immediately.

Soil temperatures were taken at 0.2 and 0.6-m depths at each location to convert the field values to ECa at a reference temperature of 25 ºC. Immediately after these readings, soil core samples were taken beneath the EMI sensors at 0.3 m increments to an approximate depth of 1.2 m. The samples were taken to the lab for analysis of gravimetric water content

(WC) and, after air-drying, they were ground and sieved (<2 mm), and the saturation percentage (SP) and the saturation extract electrical conductivity (ECe) were measured by standard methods (USSL Staff, 1954).

The extent of the ECa differences for the tested EMI's in their horizontal-coil receiver mode (H-H for G-EM38 and V-H for D-1S; Fig. 1) was further analyzed by comparing the ECa map of a 2-ha irrigated field obtained with each sensor. The number of ECa readings was 1677 with the G-EM38 and 1691 with the D-1S. For this purpose a mobile, geo-referenced EMI vehicle (Urdanoz et al., 2008) moved along transects 7.5-m apart with a 2-second reading periodicity. The ECa readings were interpolated into a 2 x 2 m regular grid by ordinary kriging (Goovaerts, 1997) using public domain SGeMS software (Remy, 2004).

Results and discussion

Comparison of individual G-EM38 and D-1S readings

For simplicity, the readings for the horizontal coil receiver mode (H-H for G-EM38 and V-H for D-1S) will be referred to as ECa-h, whereas those for the vertical coil receiver mode (V-V for both sensors) will be referred as ECa-v.

The more frequently used G-EM38 sensor was taken as the reference for comparison with the D-1S sensor. Some basic statistics of the ECa readings together with those of the soil at the measurement locations are given in Table 2. The ECa-v readings taken with both sensors were highly correlated (R^2 = 0.993***) and with similar frequency histograms (Fig. 2). The ECa-h readings were also highly correlated (R^2 = 0.948***), but a higher dispersion was observed, the standard error of the Y estimate was double that for ECa-v (Figs. 2 c, d), and the frequency histograms were somewhat different in the range between 0.5 and 1.5 dS m^{-1} (Figs. 2 a, b). Although the intercepts of both regressions were very small, they were significantly different from 0 ($P < 0.05$). The slopes of both regressions did not differ from 1 at the 0.01 level of probability.

Based on the paired t-test of the 201 ECa readings (after ln transformation), the mean standard errors (mse), after back transforming, were small, but larger for ECa-h (mse = 0.011) than for ECa-v (mse = 0.006). The mean of differences was zero for ECa-v and 0.075 (significantly different from 0 at $P < 0.001$) for ECa-h. These results agreed with the theoretical responses of these sensors, identical for ECa-v but somewhat different for ECa-h, and showed that both sensors produced the same ECa-v readings, whereas the ECa-h readings were slightly larger for Geonics than for Dualem sensors. These results were in agreement with those reported by Abdu et al., (2007) for the Dualem 1S and Geonics EM38-DD sensors.

Normal vs. inverted G-EM38 and D-1S ECa profiles

The characterization of soil salinity profiles as normal (i.e., salinity increases with depth) or inverted (i.e., salinity decreases with depth) is important because it allows the identification of soils with downward (normal profiles) or upward (inverted profiles) fluxes of water and salts. Normal profiles are typical of soils subject to leaching, whereas inverted profiles are typical of soils with shallow watertables, capillary rise of water and salts and evapo-concentration at the soil surface (Rhoades et al., 1999).

Based on the different depths of exploration for the horizontal and vertical EMI coil configurations, the ratio ECa-h/ECa-v was used to delineate these profiles. Ratios less than 0.9 (i.e., ECa-h < ECa-v) were classified as normal, ratios larger than 1.1 (i.e., ECa-h > ECa-v) were classified as inverted, and ratios between 0.9 and 1.1 were classified as uniform profiles.

Table 3 shows the classification of normal, uniform and inverted profiles obtained with G-EM38 and D-1S. ECa-h readings less than 0.2 dS m^{-1} were not included in this analysis because they were very sensitive to small variations in readings. Based on the 156 ECa-h readings larger than 0.2 dS m^{-1}, 82 % of the profiles classified as normal by G-EM38 were also classified as normal by D-1S (Table 3). Similarly, 90 % of the profiles classified as inverted by G-EM38 were also classified as inverted by D-1S (Table 3). The lower level of similarity between both instruments was for the uniform profiles (54 % coincidence level), due in part to the smaller ECa-h/ECa-v interval for this profile. The degree of coincidence between both EMI in classifying the soil profiles as normal or inverted was acceptable, so that they could be used interchangeably with comparable results.

The use of sites in the three irrigation districts provided typical variation intervals of the most important soil characteristics affecting EMI readings (i.e., texture, water content and salinity; Rhoades et al., 1999) so the results obtained would be applicable to most situations found in irrigated agriculture.

Comparison of G-EM38 and D-1S ECa-h maps

The map and frequency histogram of the ECa-h differences between Geonics and Dualem obtained in the 2-ha irrigated field showed that they were generally small (Fig. 3). However, a larger proportion of these differences were positive (Grey colour in the map), indicating that the G-EM38 produced larger ECa-h values than did the D-1S. Thus, the mean ECa-h was 6% higher for Geonics (mean ECah = 0.82 dS m^{-1}) than for Dualem (0.77 dS m^{-1}), the percentage of total readings with ECa-h < 0.6 dS m^{-1} was 9 % for Geonics and 16 % for Dualem, and the percent of total readings with ECa-h > 1.0 dS m^{-1} were 16 % for Geonics against 9 % for Dualem. Thus, even though these differences were small (mean difference = 0.05 dS m^{-1}), Geonics tended to give larger values than did Dualem, substantiating the previous results for individual readings.

Conclusions

The regression and paired t-test analysis of the 201 individual ECa-h and ECa-v Geonics and Dualem readings, and the ECa-h differences between Geonics and Dualem for the approximately 1680 readings taken from a 2-ha field indicated that both sensors produced the same ECa-v readings, whereas the ECa-h readings were slightly larger for Geonics than Dualem. The degree of coincidence between both EMI in classifying the soil profiles as normal or inverted was satisfactory. Hence, the general conclusion was that, although Geonics EM38 tends to produce slightly larger ECa-h values than did Dualem 1S, both sensors could be used interchangeably.

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Table captions

Table 1. Technical specifications of Geonics EM38 (G-EM38) and Dualem 1S (D-1S) electromagnetic induction sensors.

Table 2. Basic statistics of the 201 G-EM38 and D-1S ECa-h and ECa-v readings, and of soil saturation extract electrical conductivity (ECe), soil saturation percentage (SP) and gravimetric soil water content (WC) measured in 0-1.2 m depth soil samples taken in 152 points. CV = coefficient of variation.

Table 3. Geonics and Dualem similarity analysis in the definition of normal, uniform and inverted soil profiles: percent of total G-EM38 ECa-h/ECa-v ratios that fall in each of the corresponding D-1S ECa-h/ECa-v ratios. Columns are interpreted separately. Total number of observations = 156.

Table 1. Technical specifications of Geonics EM38 (G-EM38) and Dualem 1S (D-1S) electromagnetic induction sensors.

	G-EM38	D-1S
Operating frequency	14.6 kHz	9.0 kHz
Power supply	9-V internal battery	12-V external battery DC
Dimensions	1.06 x 0.15 x 0.13 m	1.41 m long, 0.89 m diam.
Weight	3 kg	5 kg
Display	Yes	No
Receiver coil orientation	1 coplanar	1 coplanar, 1 perpendicular

Table 2. Basic statistics of the 201 G-EM38 and D-1S ECa-h and ECa-v readings, and of soil saturation extract electrical conductivity (ECe), soil saturation percentage (SP) and gravimetric soil water content (WC) measured in 0-1.2 m depth soil samples taken in 152 points. CV = coefficient of variation.

	G-EM38		D-1S		Soil properties		
	ECa-h	ECa-v	ECa-h	ECa-v	ECe	SP	WC
	---------------------- dS m^{-1} at 25ºC ---------------------					---------- % ----------	
Max.	3.76	3.91	4.13	3.84	40.7	58	24.8
Min.	0.06	0.04	0.03	0.00	0.54	25	2.5
Mean	0.70	0.91	0.63	0.91	5.0	39	15.7
CV (%)	95	97	103	101	113	25	17

Table 3. Geonics and Dualem similarity analysis in the definition of normal, uniform and inverted soil profiles: percent of total G-EM38 ECa-h/ECa-v ratios that fall in each of the corresponding D-1S ECa-h/ECa-v ratios. Columns are interpreted separately. Total number of observations = 156.

			G-EM38		
	ECa-h/ECa-v		< 0.9	0.9-1.1	> 1.1
		Profile	Normal	Uniform	Inverted
D-1S	<0.9	Normal	82 %	8 %	0 %
	0.9-1.1	Uniform	15 %	54 %	10 %
	>1.1	Inverted	3 %	38 %	90 %

Figure captions

Fig. 1. Transmitter and receiver coil orientations of Geonics G-EM38 and Dualem D-1S: (a) G-EM38 horizontal coplanar mode (H-H), (b) G-EM38 and D-1S vertical coplanar mode (V-V), (c) D-1S perpendicular or vertical-horizontal mode (V-H)

Fig. 2. ECa-h and ECa-v frequency histograms (a, b) and regression plots (c, d) of G-EM38 and D-1S sensors. Total number of observations = 201

Fig. 3. Map and frequency histogram of ECa-h differences between G-EM38 and D-1S sensors in a 2-ha irrigated field. Map: white, differences in between - 0.05 and + 0.05 dS m^{-1}; grey, differences > + 0.05 dS m^{-1}; black, differences < - 0.05 dS m^{-1}

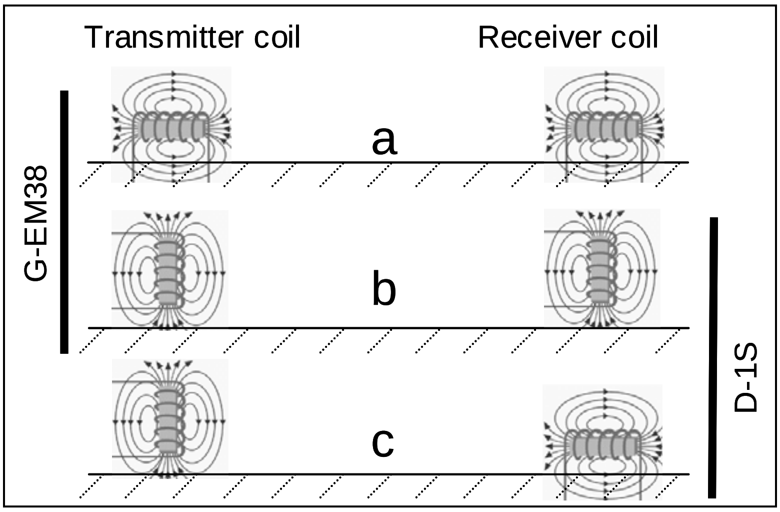

Fig. 1

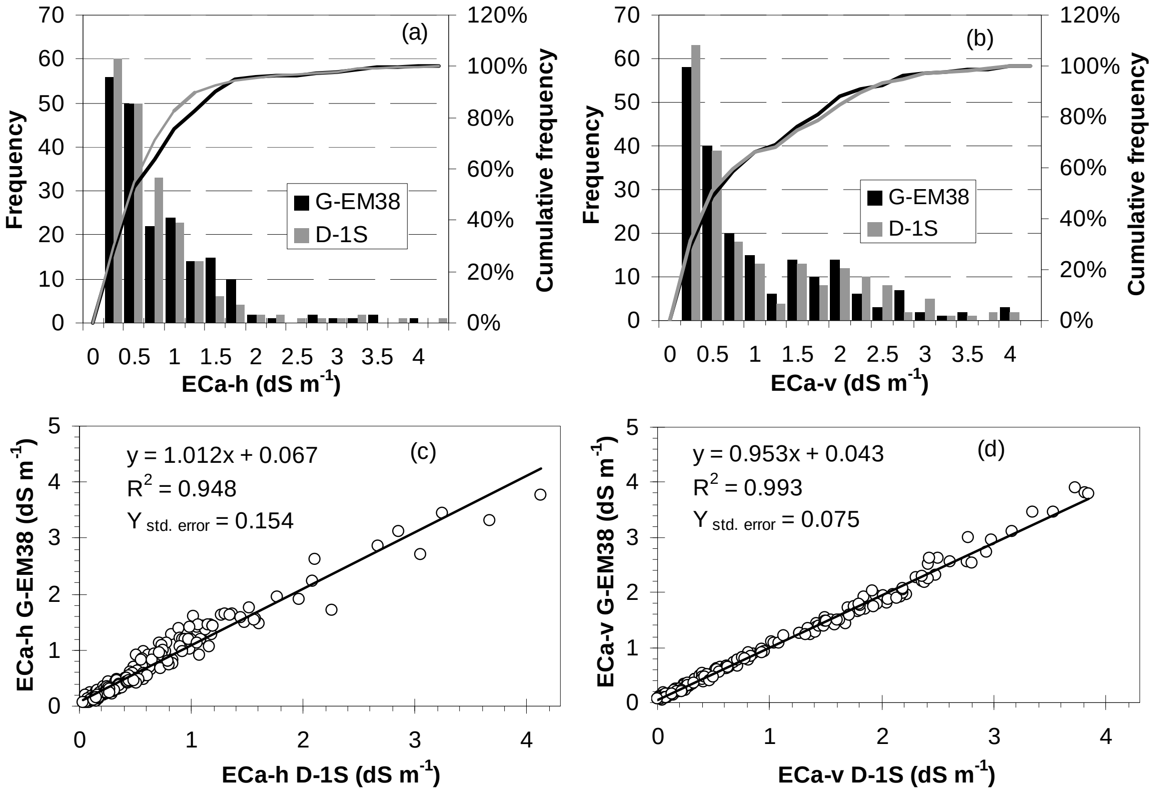
(a)
G-EM38
D-1S
Frequency
Cumulative frequency
ECa-h (dS m-1)
(b)
ECa-v (dS m-1)
(c)
y = 1.012x + 0.067
R2 = 0.948
Y std. error = 0.154
ECa-h G-EM38 (dS m-1)
ECa-h D-1S (dS m-1)
(d)
y = 0.953x + 0.043
R2 = 0.993
Y std. error = 0.075
ECa-v G-EM38 (dS m-1)
ECa-v D-1S (dS m-1)

Fig. 2

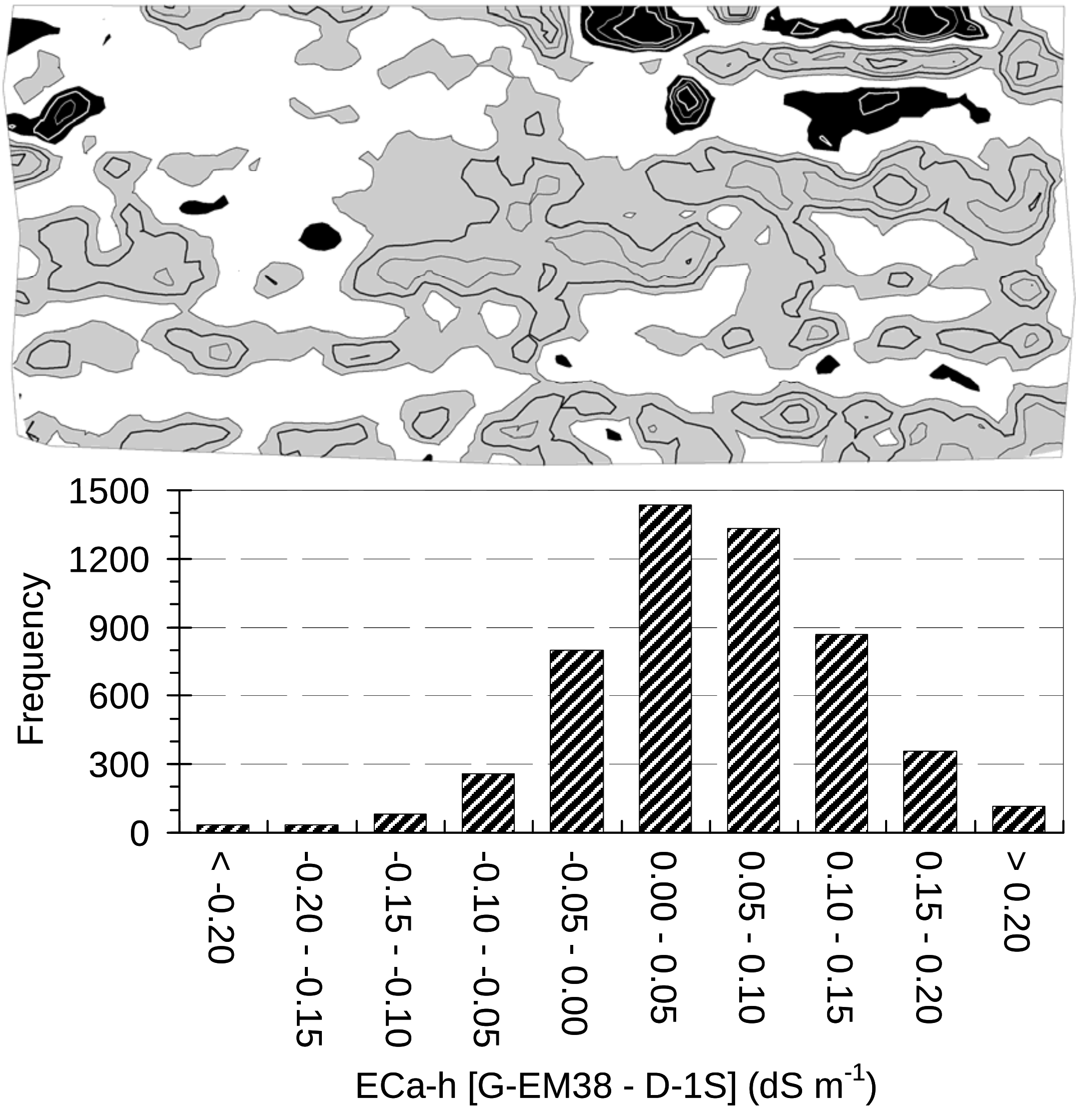
1500
1200
900
600
300
0
Frequency
< -0.20
-0.20 - -0.15
-0.15 - -0.10
-0.10 - -0.05
-0.05 - 0.00
0.00 - 0.05
0.05 - 0.10
0.10 - 0.15
0.15 - 0.20
> 0.20
ECa-h [G-EM38 - D-1S] (dS m-1)

Fig. 3