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Mapping of Soil Salinity Using Electromagnetic Induction: A Case Study of East Nile Delta, Egypt

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THE OBJECTIVE of this study is to map the spatial distribution of the soil salinity at field scale for site-specific management using the electromagnetic sensor (Geonics EM38). The salinity of an area of 67.2 ha cultivated wheat pivot field at East of Nile Delta, Egypt, was analyzed by reading the apparent soil electric conductivity (ECa) using the EM38 sensor at 432 locations within the pivot field. Twenty soil sampling sites were chosen according to spatial response surface sampling design (SRS). At those sites, soil core samples were taken at 0.3 m intervals to a depth of 0.9 m. Four soil variables were analyzed which are soil salinity (ECe), soil clay content (clay), soil water content (WC), and soil organic matter (OM). The multiple linear calibration model (MLC) was used to predict the depth-specific soil salinity ECe values at the remaining non-sampled locations. The MLC calibration model predicted ECe from EM38 signal readings with R^2 ranging from 0.41 to 0.73 for the multiple-depth profile. Furthermore, the MLC model provided field range estimates of soil salinity. Ninety-one percent of the field had ECe values below 4 dS m^{-1}. The obtained salinity maps were helpful to display the spatial patterns of soil salinity for site-specific management.

Keywords : Soil salinity, Electromagnetic induction, Spatial response surface sampling design, Multiple linear calibration model, East Nile Delta.

Introduction

The soil apparent electrical conductivity (ECa) has a great potential for characterizing the soil limiting parameters (Mann et al., 2011 and Moral et al., 2010). The ECa correlates with various soil properties such as salinity (Rhoades et al., 1999), clay content (Triantafilis & Lesch, 2005 and Wuddivira et al., 2012), water content (Haimelin, 2008) and carbon content (Martinez et al., 2009). The ECa can be used as an indirect indicator for identifying some important soil properties including soil salinity, clay content, cation exchange capacity, soil moisture content, and temperature (McNeill, 1992 and Rhoades et al., 1999).

Electromagnetic induction (EMI) sensors non-invasively measure the spatial variations of soil apparent electric conductivity (Atwell et al., 2013; Bréchet et al., 2012 Rossi et al., 2013 and Wuddivira et al., 2012). Electromagnetic induction methods are much less labor, cost and time intensive as the volume of measurement is larger than traditional point soil sampling (Rhoades et al., 1999). The most of the EC signal is related to concentration of soluble salts in salt-affected soils, while, the EC variations are related to soil texture, organic matter, moisture content and cation exchange capacity in non-saline soils (McNeill, 1992; Rhoades et al., 1999 and Lund et al., 2001). Response surface soil sampling design is closely related area of statistical research studied specifically from the viewpoint of model estimation (Myers and Montgomery 2002). Lesch (2005) revealed that the response surface sampling design can outperform the probability based sampling technique with respect to some important model based prediction criteria, particularly optimal estimation of the fixed-effect part of a spatial linear model.

The soil salinity calibration model is an empirical spatially referenced regression model that includes the soil property being calibrated with ECa and trend surface parameters and takes into account the uncertainty of the variables and thus the predictions are probability distributions

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of the possible values (Corwin and lesch, 2005; Douaik et al., 2009). Only a limited number of samples are needed for the model calibration in this model-based approaches, compared to the designed-based sampling approaches to obtain the same level of the regression model accuracy. The objective of this study is to map the spatial distribution of the soil salinity at field scale for site-specific management using the electromagnetic sensor (Geonics EM38).

Materials and Methods

Site selection

An irrigated pivot field in Sixths of October Company for Agricultural Projects (SOAP) which located in El-Salhia Area, East of Nile Delta, Egypt was selected for soil salinity modeling (Fig. 1). It is bounded by 31º 58' 30" and 31º 59' 05" longitudes and 30º 25' 55" and 30º 26' 30" latitudes with a total area of 154 feddan.

Electromagnetic survey and analyses

The apparent soil conductivity (ECa) of the pivot field was measured using Electromagnetic Induction (EM38) sensor (Geonics Ltd., Mississauga, Ontario, Canada) in millisiemens per meter (mS/m) at each coil separation In-phase response in parts per thousand (ppt) of secondary to primary magnetic field at each coil separation before wheat planted. A number of 432 EM38 survey readings were measured vertically and horizontally along 10 transects grid across the pivot study area with 90 meters averaged distance between each transect. The readings were performed few days before tillage and planting and after an irrigation event where the soil water content was close to the field capacity. The maximum normalized residual test was applied to EM38 signal data for outlier's existence (Iglewicz and Hoaglin, 1993).

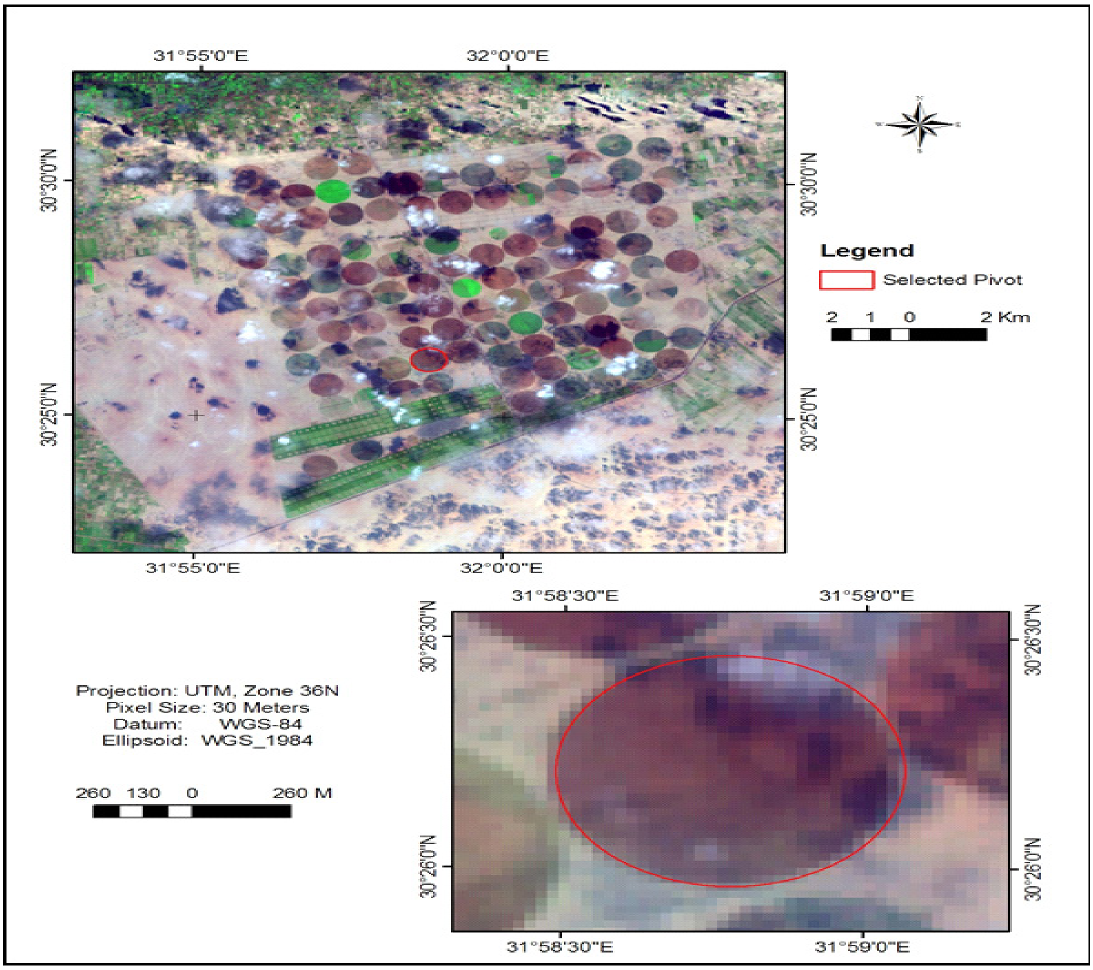

Fig. 1. The selected pivot for study area

Soil sampling and analyses

A spatial response surface design (SRS) (Corwin and lesch, 2005) was used to locate the best locations for soil sampling. Twenty soil sampling sites were located according to the selected SRS sampling design. Four soil variables were chosen for the selected SRS sampling sites which are soil salinity (ECe, dS/m), soil texture (clay, %), soil water content (WC, %), and soil organic matter (OM, %) at 30 cm depth intervals to a maximum depth of 90 cm (0-30, 30-60, and 60-90 cm). The soil samples were air-dried, crushed softly, and passed through a 2-mm sieve to get the ‘‘fine earth.’’ The fine earth was analyzed in the laboratory according to (Soil Survey Staff, 2014).

Soil salinity calibration Modelling

A multiple linear calibration model (MLC) was performed to predict the soil electric conductivity levels within the pivot field using the EM38 signal readings. The soil variable which has the most strength of the relationship against the standard variables (EM38 signal data (z1), the secondary (z2) EM38 signal data, and both the X and Y survey coordinates) was chosen as the soil variable for the model. The all possible model combinations were analyzed and the model with the lowest prediction errors was chosen as the more accurate model.

Soil salinity mapping

Interpolation between sampling locations was made by ordinary Kriging (Deutsch and Journel, 1992) interpolation method using ArcMap 10.2 (ESRI, 2013). Ordinary Kriging was used to estimate the value of a continuous characteristic z at a non-sampled locations (u) using only the data on this characteristic [z (ua), α = 1, . . ., n] as a linear combination of neighboring observations.

Results and Discussion

EM data description

The obtained EM38 readings in the study pivot were subjected to descriptive statistical analyses. The statistical analyses results (Table 1) showed that, for the EM vertical readings (EMV) the data ranged between 12.00 and 333.00 with a mean of 64.35 and standard error of 2.79, also the lower and upper bounds of 95% Confidence Interval for Mean are 58.86 and 69.83 , respectively. While for the EM horizontal readings (EMh), the data ranged between 10.00 and 239.00 with a mean of 45.11 and standard error of 1.85, also the lower and upper bounds of 95% Confidence Interval for Mean are 41.48 and 48.75 , respectively. The data range for EMv and EMh readings was 321.00 and 229.00 , respectively. The results of variance are 3362.86 and 1479.46 for EMv and EMh readings respectively. Also, the standard deviation (SD) results are 57.99 and 38.46 for EMv and EMh readings , respectively. From percentiles and quartiles analyses, it appears that 50 % of EM readings lie between 12.00 and 36.50 for EMv readings and 10.00 and 28.00 for EMh readings, while 95 % of EM readings lie between 12.00 and 187.35 for EMv readings and 10.00 and 125.35 for EMh readings. The frequency distributions for EMv and EMh readings indicate that both vertical and horizontal EM readings follow nearly a bell-shaped Gaussian distribution as about 84.72% and 85.65% of EMv and EMh readings , respectively lie within one standard deviation of the mean.

Soil variables

Four soil variables were chosen for the selected SRS sampling sites (Fig. 2). The considered soil variables are soil salinity (ECe, dS/m), soil texture (clay, %), soil water content (WC, %), and soil organic matter (OM, %) at 30 cm depth intervals to a maximum depth of 90 cm. The statistical analyses of the soil variables (Table 2) show that the coefficients of variation (CV) of ECe were very high thus confirming the large variability in soil salinity within the pivot. In contrast, the coefficients variation of soil water content are the lowest of the four variables.

Soil salinity calibration modeling

A multiple linear calibration model was performed to predict the soil salinity levels within the pivot field using the EM38 survey readings acquired across the pivot. The correlation results (Table 3) between the sampled soil variables and the regression variables (the primary (z1) EM38 signal data, the secondary (z2) EM38 signal data, and both the X and Y coordinates) by depth showed that, the soil variable salinity is more correlated with the variables Z1 and Y than other soil variables. The OM soil variable is the poorest correlated variable while clay content and water content soil variables are similar in their relationship with the variables. The soil variables have a weak relationship with both z1 and X variables. The correlation between soil salinity variable with variables Z1 and Y other than the other variables shows that this variable is the appropriate variable for the soil salinity calibration model.

TABLE 1. Descriptive statistics of EM readings

Statistic	Reading		Statistic	Reading	
	EMv	EMh		EMv	EMh
Mean	64.35	45.11	Variance	3362.86	1479.46
Confidence -95%	58.86	41.48	Std.Dev.	57.99	38.46
Confidence +95%	69.83	48.75	Confidence SD -95%	54.36	36.06
Median	36.50	28.00	Confidence SD +95%	62.14	41.22
Minimum	12.00	10.00	Coef.Var.	90.12	85.26
Maximum	333.00	239.00	Standard Error	2.79	1.85
Skewness	1.90	2.05	Lower Quartile	26.00	20.00
Std.Err. Skewness	0.12	0.12	Upper Quartile	87.00	59.00
Kurtosis	3.87	4.93	Range	321.00	229.00
Std.Err. Kurtosis	0.23	0.23	Quartile Range	61.00	39.00

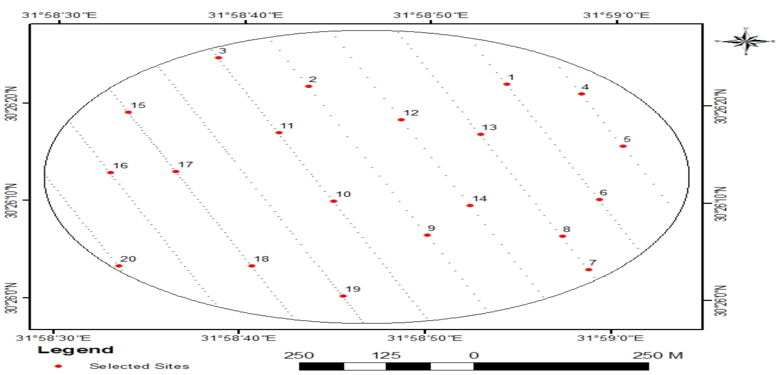

Fig.2. Selected SRS soil sampling sites

TABLE 2. Statistical analyses of the four soil variables

Soil variable	Depth level	Mean	std. dev	CV %	min	max	Soil variable	Depth level	mean	std. dev	CV %	min	max
ECe	30	1.617	1.811	112.00	0.21	5.98	WC	30	0.174	0.029	16.67	0.13	0.22
	60	2.542	2.347	92.33	0.34	6.95		60	0.169	0.032	18.93	0.12	0.23
	90	2.227	2.167	97.31	0.19	6.38		90	0.162	0.031	19.14	0.12	0.22
% Clay	30	11.588	4.497	38.81	5.15	19.15	OM	30	0.397	0.074	18.64	0.269	0.538
	60	10.778	4.596	42.64	4.75	18.83		60	0.172	0.114	66.28	0.076	0.538
	90	9.817	4.306	43.86	4.55	18.17		90	0.138	0.114	82.61	0.042	0.454

TABLE 3. Correlation coefficients between soil and regression variables

Soil variable	Depth (cm)	Z1	Z2	X	Y
EC	30	0.76	0.19	0.15	-0.85
	60	0.67	0.31	0.36	-0.71
	90	0.60	0.07	0.10	-0.63
Clay	30	0.60	0.12	0.42	-0.41
	60	0.51	0.15	0.42	-0.33
	90	0.56	0.18	0.49	-0.43
WC	30	0.66	0.10	0.37	-0.48
	60	0.56	0.17	0.39	-0.37
	90	0.58	0.17	0.45	-0.44
OM	30	0.04	0.20	0.22	0.04
	60	-0.17	-0.31	-0.04	0.08
	90	0.51	0.03	0.32	-0.36

The results of the calibration model parameters combinations analyses indicated that, the Z1/Y parameters combination is the combination which produced the more accurate calibration model. The resulted calibration model for predicting soil salinity within the pivot field using the EM38 conductivity survey readings is in the form :

$$\ln(ECe) = b0 + b1(Z1) + b2(Y)$$

where :

ECe is the soil salinity,
Z1 and Y are the model variables and
b0, b1, and b2 are model parameters

The calibration model was fitted to the bulk average, in addition to fitting to each set of depth values. The calibration model summary statistics for each fitted depth are shown in Table 4.

TABLE 4. Calibration model Summary Statistics

Depth	R-square	Root MSE	Est. %CV
30 cm	0.73	0.60	66.44
60 cm	0.51	0.85	103.41
90 cm	0.41	1.02	135.73
Bulk average	0.53	0.80	94.60

The R^2 values of the calibration models for the different soil sampling depths and the bulk average ranged between 0.41 for 90 cm soil depth and 0.73 for 30 cm soil depth. The R^2 is being significant at $P< 0.001$ for the 30 cm depth and significant at $P< 0.01$ for the remaining sampling depths and bulk average. Thus, the calibration model accounted for 41% to 73% of the observed salinity variability at the different sampling depths. The pivot field salinity was interpolated between sampling locations for the specified sampling depths by ordinary kriging interpolation technique. The spatial distribution of soil salinity for the specified sampled soil depths are shown in Fig. 3.

Conclusions

The EM38 sensor provided non-invasive measurements of the apparent electrical conductivity (ECa) with less labor, cost and time intensive over other conductivity methods. The spatial response surface (SRS) sampling design allowed minimizing the number of samples required number of soil samplings to only a small set of 20 soil sampling sites to optimally estimate the spatially referenced regression model between the EM apparent electric conductivity (ECa) and the sampled soil electric conductivity. The sampled soil salinity correlated linearly with the EM signal data and indicated the incorporation of the trend surface parameters in the calibration modeling. The multiple linear calibration (MLC) model proved to be reliable for predicting the soil salinity at the field scale for site-specific management.

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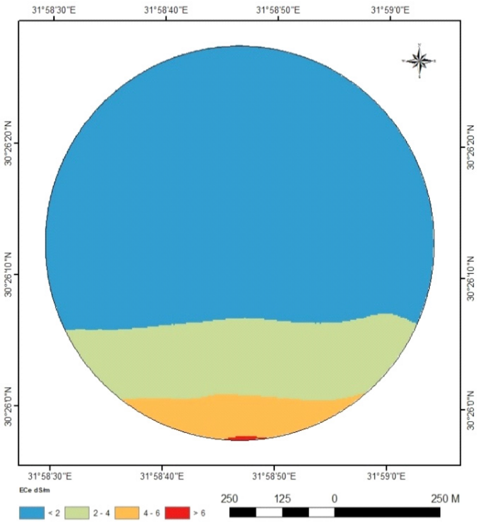
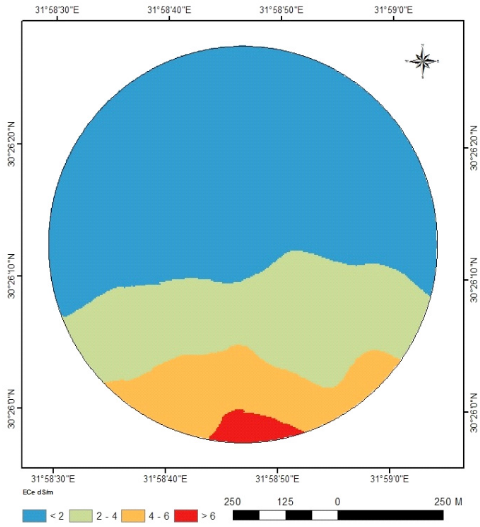
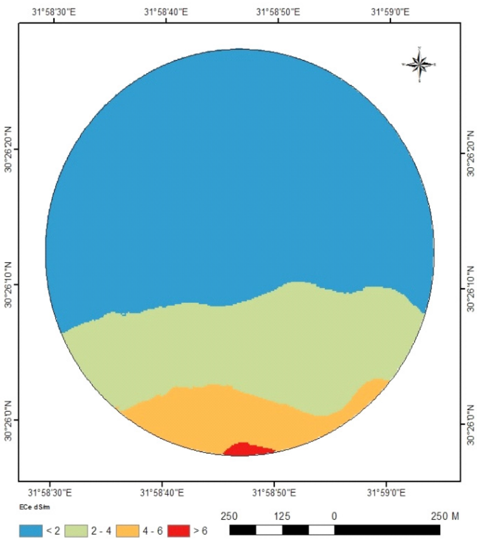


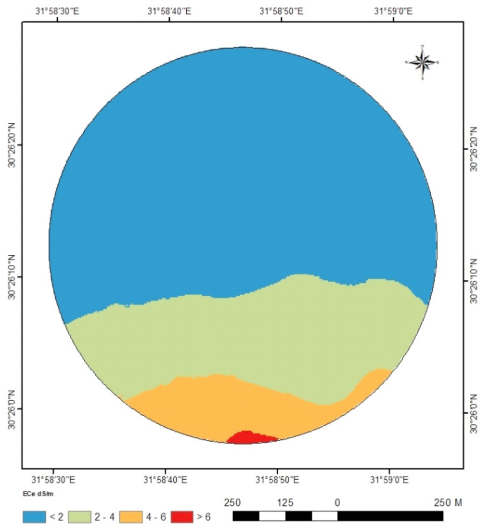
Mapped soil salinity at 30 cm depth



Mapped soil salinity at 60 cm depth



Mapped soil salinity at 90 cm depth



Mapped soil salinity (bulk avarage)

Fig. 3. Soil salinity maps at sampled depths

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تخريط ملوحة التربة باستخدام الحث الكهرومغناطيسي بمنطقة شرق الدلتا – مصر

احمد مسعد صالح ، عبدالعزيز بلال عبدالمنطلب بلال و السيد سعيد محمد
قسم علوم الأراضى - الهيئة القومية للاستشعار عن بعد وعلوم الفضاء - القاهرة - مصر

الهدف من البحث هو استخدام مستشعر الحث الكهرومغنطيسى لانتاج خريطة توزيع ملوحة التربة علي مستوي المزرعة بهدف الادارة الدقيقة لها .تم اختيار مساحة ١٥١ فدان (بيفوت) مزروعة بمحصول القمح و تعتمد علي تقنيات الري بالرش باراضي شركة السادس من اكتوبر – منطقة الصالحية – شرق الدلتا حيث تم تقدير درجة التوصيل الكهربي الظاهرى باستخدام جهاز EM٣٨ بعدد ٤٣٢ موقع بالبيفوت .تم تحديد ٢٠ موقع بمنطقة الدراسة طبقا لنموذج الاستجابة المكانية ((spatial response surface sampling design(SRS) وذلك لاخذ عينات التربة علي اعماق ٣٠ و ٦٠ و ٩٠ سم بهدف تحليل بعض الخصائص مثل ملوحة التربة ونسبة الطين و نسبة المادة العضوية ومحتوي التربة من الرطوبة .

وقد تم استخدام نموذج المعايرة الخطي المتعدد (multiple linear calibration model (MLC)) للتنبؤ بالعمق الفعال للملوحة في الاماكن التي لم ياخذ منها عينات وكذلك تقدير درجة الملوحة من خلال قراءات جهاز EM٣٨ حيث تم انتاج خرائط ملوحة التربة على أعماق القياس المختلفة ٣٠ و ٦٠ و ٩٠ سم وعلى متوسط القطاع. وقد تم ايجاد علاقات الارتباط بين الخصائص التي تم تحديدها وبيانات جهاز EM لمعرفة اي خصائص التربة أكثر ارتباطا معنويا مع بيانات EM٣٨ وقد اوضحت بيانات الارتباط أن ملوحة التربة هى الاكثر ارتباطا من باقي الخصائص .وقد تم معايرة النماذج المتحصل عليها حيث اظهرت النتائج انه يمكن الا عتماد علي قراءت EM٣٨ في تتبع وتقدير ملوحة التربة بنسبة مربع خطأ وصلت ل ٠,٧٣ في الطبقة السطحية (٠- ٣٠ سم) بينما قلت مع العمق لتصل الي ٠,٤١ علي عمق ٩٠ سم .بالاضافة الي ذلك فانه وبتطبيق هذا النموذج علي قراءات جهاز EM٣٨ التي تم قياسها في الحقل حيث اوضحت النتائج ان ٩١ بالمئة من المنطقة المدروسة تتصف بملوحة اقل من ٤ ديسيسيمنز/م. ومن هنا فان الخرائط التي تم انتاجها للملوحة توضح التوزيع المكاني للاملاح بالمزرعة وبالتالي يمكن التعامل مع كل جزء علي حدة حسب نسبة تركيز الاملاح بالتربة وذلك للتخفيف من اثار الاملاح علي الانتاج الزراعي وهو ما يعرف بالادارة الدقيقة .