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MAPPING OF SOIL SALINITY AND CLAY CONTENT BASED ON ELECTROMAGNETIC INDUCTION MEASUREMENTS BY EM38

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ABSTRACT The recent development in the field of electromagnetic induction (EMI) has made it easy to get rapid soil variability information, which can support precision agriculture. But the interpretation of the acquired ECa measurements is a complex process as ECa measurement depends on many influencing parameters. In this study the objective was to determine the main soil properties which influence the ECa measurement and to analyse the salinity levels after the 30 years of reclamation of salt affected areas in Wuqaio. Results show that for the irrigated sandy and non-saline fields, ECa maps correlate well with the cation exchange capacity (CEC) and the exchangeable cation such as Na^+ (with R^2 of 0.89). The multiple linear regression (MLR) calibration model predicted ECe from EM38 readings with accuracy of R^2 ranging from 0.356 to 0.803.

Keywords: EM 38, salinity, electromagnetic induction, North China Plain

INTRODUCTION The goal of precision agriculture is to properly manage heterogeneous areas within a field and, therefore, rely on accurate information about the soil characteristics that affect crop yield. Collecting information about key factors such as soil moisture status, soil texture and soil salinity to a good spatial resolution is expensive and time consuming because it requires intensive soil sampling and laboratory analysis. In contrast, using electromagnetic induction (EMI) sensor, information about the variability of the soil can be collected quickly over the large area. In addition, it is a non-invasive and non-destructive soil sampling method. The principle of EMI method is based on induction and reflection of a magnetic field. This technology measures depth weighted average of the soil electrical conductivity called as apparent electrical conductivity (ECa), which is closely related to soil salinity (electrical conductivity of the soil saturation-extract, ECe) (Corwin and Lesch, 2003;2005). The portable electromagnetic sensor EM38 (Geonics Ltd, Canada) has a vast application for agricultural purposes because the depth of measurement corresponds roughly to the root zone. It measures ECa typically to a depth of 0.75 and 1.5 m, respectively, depending on whether it is held in the horizontal or vertical mode of operation. However, there are several factors affecting the measurements, such as: clay content, soil temperature, salts, water content and metals (McKenzie *et al*., 1997; Mc Neill, 1992). For example, reading obtained with an EM38 meter increases with increasing clay, moisture and soluble salt content in the soil. And the areas with saline soils, salinity can account for 65% to 90% of the variations in the sensor readings (Nogues *et al*., 2006). A substantial research effort has been done to develop the relationship between ECa and clay percentage (Mc Neill, 1980; Banton *et al*., 1997), soil moisture (Hanson and Kaita, 1997; Khakural *et al*., 1998; Sheets and Hendrickx, 1995; kanchanoski *et al*., 1988; Waine *et al*., 2000), salinity (Lesch *et al*., 1992; Rhodes and Corwin, 1981) and temperature (Slavich and Petterson 1990). In addition to these direct indicators, some indirect correlation has also been found between ECa and soil properties like exchangeable Ca and Mg, cation exchange capacity (Mc Bride *et al*., 1990), sodium adsorption ratio (Amezketa, 2007) and crop productivity (Kitchen *et al*., 1999;Anderson-Cook et al., 2002).The use of ECa measurements with the position data obtained by GPS, thereby storing the data in a digital form to conduct reconnaissance soil mapping (Cook and Walker, 1992; Doolittle et al., 1995) has made the use of EM38 more convenient and easier. But the interpretation of the acquired ECa measurements is a complex process as ECa does not provide direct information about the physicochemical properties that influence the yield. Therefore, ground truth soil samples are necessary to interpret spatial measurements. And to augment efficiency in collecting and interpreting soil conductivity data, the U.S. Salinity Laboratory Staff (ARS-USDA, Riverside, California) developed conductivity modeling software (Electrical conductivity Sampling Assessment and Prediction-ESAP; Lesch et al., 1995a,b, 2000, 2002a). The present study is conducted in Wuqaio, Hebei Province in the North China Plain, where a variety of crops such as wheat, maize, cotton, soybean, and peanuts are grown. During the 1970s, 3,300,000 ha in the North China plain were salt-affected with low crop production of about 1000 kg of wheat per hectare (Chen et al., 2006). In the early 1980s, the Chinese government started a reclamation campaign and reclaimed the salt-affected soils by using fresh water from deep wells for irrigation and by deepening the drainage ditches for lowering the groundwater table. The objective of this study is to evaluate both salinity level and spatial salinity differences after 30years of reclamation with EMI measurements. Because the acquired ECa values reflect not only salinity but also other soil properties like clay content and corresponding attributes (cation exchange capacity, sodium absorption ration), investigations aimed also on ECa interlinkages with these parameters.

MATERIALS AND METHODS The study was conducted at an irrigated plot planted with maize in an area of about 0.3 ha in Wuqaio, North China Plain during the rainy season. Thus, the soils were throughout close to saturation with volumetric moisture content of around 32%. The ECa data and soil samples were collected with crop established less than one month.

Soil ECa Data Collection The EM38 measurements were conducted along a grid of 5m x 2.5m. In total, ECa values were measured at 130 positions and their exact position was determined with a GPS device. The instrument was calibrated according to manufacturer instructions, prior to data collection. At each measuring position, two EM readings were made by placing the instrument in the horizontal and vertical position, respectively. Prior to the measurements, soil water content was measured in the upper soil layer (20cm) with time domain reflectometry (TDR). The ECa data was then transferred to ESAP software. The basic statistical analysis, such as mean, minimum value, maximum value and standard deviation were used to understand the basic features of the soil ECa.

Soil sampling and Analysis The ESAP-Response Surface Sampling Design (ESAP-RSSD) software (Lesch et al., 2002a) was used for the site selection of six soil sampling points out of measured 130. Automatic selection of calibration sites saves time and optimizes the calibration model. To calibrate soil conductivity data, samples were taken at a 0.3 m intervals down to a depth of 0.9 m with the help of auger and soil samples were transferred to the laboratory for the analysis of electrical conductivity of the saturation extract (ECe), saturation percentage (SP) and nutrient contents (Ca^{2+},Mg^{2+}, Na^{+} and K^{+}). Also cation exchange capacity (CEC) and sodium absorption ratio (SAR) were calculated. In addition, gravimetric soil water content (WC) was determined by oven drying the soil samples at 105°C for 24 hrs.

Spatial Regression Modeling A spatially referenced depth specific Multiple Linear Regression (MLR) model developed in the ESAP-Calibrate Program was used for converting EM38 readings (EMh and EMv) into ECe data. To predict the log soil salinity levels within a field from log transformed EM38 conductivity survey reading across the field was performed using the following regression model:

$$\ln(ECe) = b0 + b1[\ln(EMh)] + b2[\ln(EMv)] + b3[x] + b4[y]$$

where EMh and EMv represent the horizontal and vertical EM-38 survey readings, and x and y represent the spatial coordinate locations of the EM-38 survey data, and b0, b1, b2, b3, and b4 are the regression parameters. In practice, transformed and decorrelated signal data (i.e., the principal component scores) are often used in place of the raw signal readings as predictor variables in the regression equation. Thus, the depth specific MLR salinity prediction model was finally defined as:

$$\ln(ECe) = b0 + b1(z1) + b2(z2) + b3(u) \text{ and } b4(v)$$

where, z1 and z2 are the decorrelated signal readings and EMh and EMv were converted in z1 and z2 using:

$$z1 = a1(s1 - mean[s1]) + a2(s2 - mean[s2]) \text{ and } z2 = a3(s1 - mean[s1]) - a4(s2 - mean[s2])$$

where, a1, a2, a3, and a4 are determined by the principal components algorithm. The spatial coordinate location of the EM38 survey data were scaled as :

$$u = (x - \min[x]) / k; \quad v = (y - \min[y]) / k$$

where, k = the greater of (max[x] - min[x]) or (max[y] - min[y])

The selected model was then computed for the three increasing sampling depths and for the bulk average sample values (bulk profile) and the coefficients of the calibration equations were estimated.

RESULTS AND DISCUSSION

Spatial variability of ECa The EM38 readings in both the dipole mode were analyzed with the ESAP software package (vs 2.35R; Lesch et al., 2000). No outliers were detected and therefore no measuring point was excluded for the study. For a theoretical depth response function it is known that the difference between vertical and horizontal readings indicates whether the soil salinity increases or decreases with depth (Hendrickx et. al., 1992). A positive difference indicates an increase, a negative difference a decrease in salinity with depth. And therefore, is a good indicator of whether the water and salt movement in the soil profile is by capillary rise or leaching. The basic statistical analysis shows that there is a small difference between the average of EMv (78.68mS/m) and EMh (63.65mS/m) and at every point of measurement EMv is higher than EMh (Fig.2) and the coefficient of regression between EMh and EMv is 0.59 (Fig. 1), this shows that the irrigation water is the source of salinity and secondary salinization is not present.

Table 1. Basic statistical analysis of soil ECa (mS/m) measurements

Soil ECa	Count No.	Min	Max	Mean	Std. Deviation
ECah	130	45.00	77.00	63.65	6.24
ECav	130	62.00	96.00	78.66	7.60

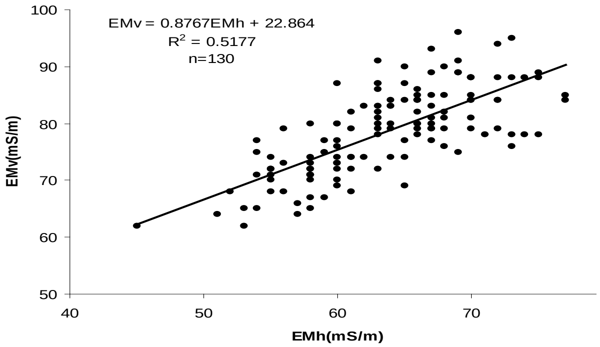

Figure 1. Signal correlation between the horizontal and vertical EM38 measurements

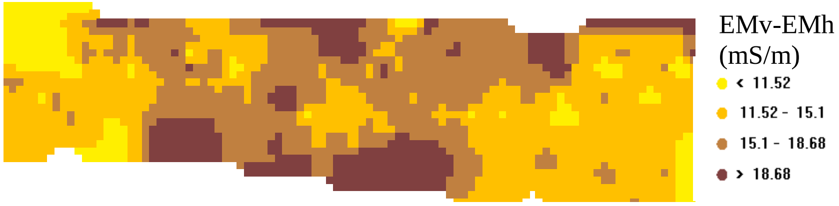

Figure 2 A raster map of the difference between EMv and EMh measurements

In addition a soil raster map was generated from the 130 measured ECa values for the average profile (0-90cm) with the help of ESAP-Salt Mapper Program which employs inverse-distance-squared interpolation (IDS) technique. The maps below show the spatial variability of the electrical conductivity (ECa) within the field. From the map, the ECa values in both horizontal and vertical position are high in the middle region. The field has a small inclination in the western side and therefore, the high ECa values in the middle region is due to the accumulation of soluble salts or clay that was brought down by the water. The same phenomenon is also reported by Aimrun et al., 2009 where the southern part is higher than the northern part of the study field and therefore in the middle of the field the ECa values are higher due to the accumulation of soluble salts or clay.

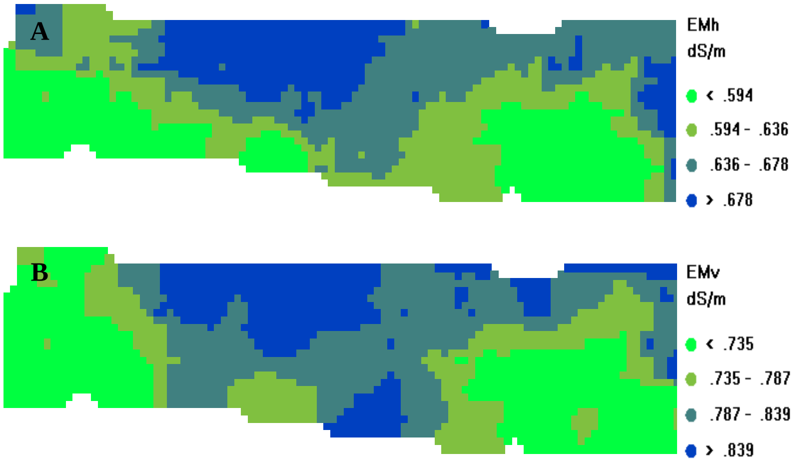

Figure 2. Raster maps of horizontal ECa [A] and vertical ECa [B]

Spatial analysis of soil properties The soil properties at different soil depths, such as soil salinity (ECe), soil water content (WC), saturation percentage (SP), cation exchange capacity (CEC) are presented in Table1. Both SP and WC show low spatial variability in the field having coefficient of variation less than 15%. Since a low variability of WC and SP in the field minimizes its effect on ECa measurement and maximizes correlation between ECa and salinity. Therefore, if the soil is saline then the interpretation of ECa measurement is straightforward, as salinity is the dominant factor influencing ECa measurement (Amezketa, 2007). The profile plot (fig.3) tells about the soil salinity conditions within this field. For example, all of the individual profile shapes are regular, and the near surface salinity levels (within the first two feet) are quite low. This implies that the field is well managed, and sufficient water is being applied to keep the soil salinity levels under control. Indeed perhaps, too much water is passing through the profile at certain locations, given some of the very low salinity levels at the 1.0 meter depth. Therefore, other parameters like CEC, SAR and exchangeable cations were determined to know the factors which influenced the ECa measurement.

Table 1 Distribution of soil parameters at different sampling depths.

Parameter	Soil depth [cm]	Mean	Std.Deviation	Minimum	Maximum
ECe	0-30	0.23	0.04	0.11	0.30
	30-60	0.31	0.07	0.25	0.44
	60-90	0.41	0.12	0.31	0.61
SP [%]	0-30	30.09	0.21	29.87	30.38
	30-60	30.15	0.34	29.86	30.78
	60-90	30.96	0.46	30.90	31.60
WC [volumetric]	0-30	0.34	0.19	0.33	0.35
	30-60	0.35	0.22	0.34	0.36
	60-90	0.35	0.29	0.33	0.38
SAR	0-30	1.33	0.64	0.90	2.19
	30-60	2.00	1.09	1.10	4.07
	60-90	4.14	2.32	1.73	6.59
CEC	0-30	7.33	0.43	6.91	8.07
	30-60	8.43	0.69	7.27	9.41
	60-90	11.48	1.76	9.03	13.99

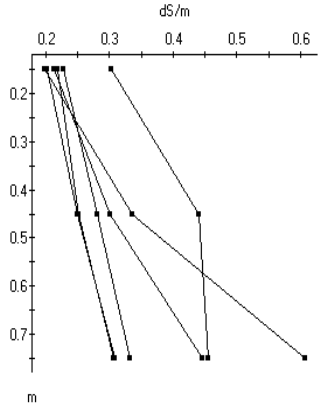

Figure 3. Salinity profile plot (0-90cm) measured at 6 locations.

DPCC Correlation analysis The DPPC (Dual Pathway Parallel Conductance) Model is an electrical conductance model developed by Rhoades (Rhoades et al., 1989) which described the relationship between bulk soil electrical conductivity (ECa), volumetric water content (Tw), and the electrical conductivity of the soil water (ECw). Mathematically, this model can be written as:

$$\mathrm{ECa} = \frac{(T_s + T_{ws})^2 EC_{ws}(EC_s)}{T_s(EC_{ws}) + T_{ws}(EC_s)} + T_{wc}(EC_{wc})$$

Where,

T_{ws} = volumetric water content in the soil-water pathway

T_{wc} = volumetric water content in the continuous liquid pathway

T_s = volumetric content of the solid phase of the soil

EC_{ws} = electrical conductivity of the soil-water pathway

EC_{wc} = electrical conductivity of the continuous liquid pathway

EC_s = electrical conductivity of the solid soil particles

A DPPC correlation analysis allows to estimate a set of soil conductivity readings, based on the input sample salinity, texture, and water content data values. These calculated soil conductivity readings can then be compared to the input soil data, and/or to measured EM-38 conductivity readings.

The correlation estimates between the depth specific and bulk average calculated conductivity (ECac) data is shown in table 2. The correlations between the log transformed bulk average ECac and the ECac associated with the 0.15 and 0.75 meter sample depths are 0.522 and 0.895, respectively. Additionally, the correlations between the calculated (ECac) and measured (z1-signal) conductivity readings (z1-signal data will represent an average of 2 readings at each site) shows that z1-signal data is highly correlated with the bulk average ln(ECac) data, r = 0.877, as well as the ln(ECac) data from the 0.45 and 0.75 sampling depths; r = 0.724 and 0.811, respectively. This high correlation between predicted ECa (calc ECa) and the measured ECa shows that the DPPC model is fairly robust and is validated by survey data.

Table 2. Calculated ECa Correlation structure and its relation with z1 signal

Parameters	Sample depth levels			
	0.15	0.45	0.75	Average
Ave ln (Calc ECa)	0.522	0.910	0.895	1.000
Z1-signal data	0.524	0.724	0.811	0.877

Table 3. Relationship of measured soil properties with ECa values

Soil property	Acquired ECa	Predicted ECa
ECe	0.71	0.73
SP	0.58	0.55
CEC	0.57	0.52
Vol. water content	0.20	-0.07
SAR	0.85	0.83
Na^+	0.89	0.67
K^+	0.48	0.31

A strong correlation between soil moisture and ECa is being reported (Kachanowski et al., 1988; Waine et al., 2000) however these studies used a wide range of soil texture and moisture regimes. In comparison the present study was conducted only at one location at one time. Therefore, it uses only one soil texture and water content with a low variation within the field, which showed that ECa was not such a good predictor of soil moisture and soil texture in this study. Clay had a weak correlation with ECa, which contradicts to other reports where clay is one of the dominant influencing factors (Hedley *et al*., 2004). A good correlation was found out between ECa and ECe even though ECe values does not reach the threshold to be classified as saline soils(less than 4dS/m) at any of the measuring location. Amazketa, 2007 reported a very strong correlation between ECa and ECe (r^2=0.94), where 81% of the field had ECe values above 4dS/m. The cation exchange capacity and the proportion of it occupied by exchangeable bases is a useful indicator of fertility. Farahani, 2005 found that for sandy (clay content= 9 -14%) non-saline soils ECa may be used as a surrogate map for CEC(r^2=0.86 to 0.94). In our study a weak regression between ECa and CEC was found. This is due to the less amount of clay (3-5%) present in the soil. The exchangeable cations Mg^{2+}, Ca^{2+}, $K^{+,}$ and Na^+ are the important contributors of plant growth. The higher R^2 value show, which cation dominates on charged clay surfaces and in the soil solution where ECa values are largely controlled. As reported in Table 3. Na^+ accounts for more of the variation in ECa than any other exchangeable cations or any of the other single soil property. It was observed that Na^+ values increases with depth and thereby suggesting that the Na^+ originates in the parent material rather than as a fertilizer addition to the soil surface, however, a detailed study is needed to study the soil mineralogy. The other reason is the leaching of Na^+ due to the low CEC in the subsoils. The fields containing high concentration of salts, ECa measurements effectively portray both the nature and the main cause of ECa variability (i.e., relative salinity). In contrast, ECa in non-saline sandy fields depicts spatial variability without clearly identifying the dominant cause(s) of variability. This explains the reason why in the present study ECa did not relate clearly neither with the clay content nor with the salinity, which is in contrast to the previous studies where either of them is higher than the other. The results therefore, suggest that ECa best predict soil properties that relate to charged clay surface rather than presence of clay or salinity

Analysis of calibration equation The calibration equation used to convert EM38 measurements into ECe data for our data set was: Table 4 shows the R^2 values of the regression models vary from 0.36 to 0.80 for the different sample depths.

$$\ln(ECe) = b0 + b1(z1) + b2(z2)$$

Table 4. Multiple linear regression model summary statistics at three sampling depth and average profile.

Depth	R^2	MSE
0-30	0.761	0.010
30-60	0.803	0.015
60-90	0.367	0.080
Bulk (0-90)	0.654	0.022

The MLR calibration model was used to predict the depth specific - ECe values at the remaining non-sampled locations. The salinity distribution reveals that the whole arable land does not reach the threshold value and therefore the irrigated plot is non-saline.

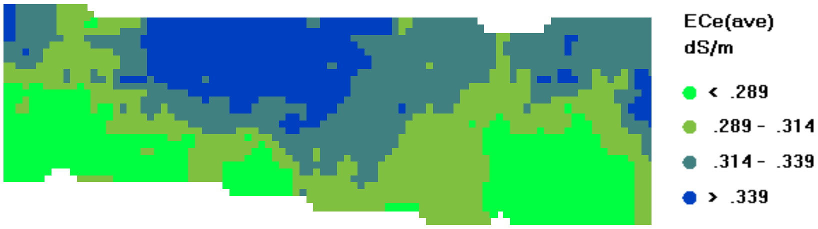

Figure 4. Raster map of ECe for the average profile (0-90cm) using selected calibration

CONCLUSIONS Electromagnetic induction surveys provide a rapid, affordable approach to investigate the soil variability. The detailed soil salinity map proves very helpful in displaying the sources of soil salinity and its variability. In the present study, the salinity levels are very low. Therefore, even after 30 years of soil reclamation the soil condition is very good in terms of its management practices. The detailed ECa maps proved to be useful in identifying the sources of salt loading. In fields containing high salt concentration of salts, ECa interpretation is straightforward. While, in non-saline fields ECa spatial variability is depicted without clearly indentifying the dominant causes of variability. ECa values, determined by using EM38 device in horizontal and vertical mode, gave good correlation with ECe (R^2=0.71), SAR (R^2=0.89) and exchangeable Na^+ (R^2=0.83) in this soils. Exchangeable Na+ correlates better than other exchangeable cation (Ca^{2+}, Mg^{2+} and K^+) which is due to the soil minerals releasing sodium upon weathering. Therefore, a detailed study of soil mineralogy is strongly recommended. Our experimental results are specific to the irrigated sandy, non-saline soil with low variation in clay content and thus may not apply to other soils.

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