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New Calibrations for Determining Soil Electrical Conductivity—Depth Relations from Electromagnetic Measurements

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ABSTRACT

Soil salinity can be determined in the field from measurements of soil electrical conductivity (EC_a). Measurements of depth-integrated EC_a can be made remotely using electromagnetic induction (EM) techniques. A means of determining EC_a for the soil depth intervals of 0 to 30, 30 to 60, 60 to 90 cm, etc., from the EM measurements is needed for salinity appraisal. The EM and EC_a measurements were made at about 900 sites in the San Joaquin Valley of California. This large data set was used, along with rigorous statistical techniques, to obtain empirical coefficients used in equations to predict EC_a by depth intervals within the soil profile from EM readings taken above ground. Predictions were found to be more accurate using these new coefficients rather than those previously available.

A DEPTH-WEIGHTED VALUE of soil electrical conductivity, can be determined from above-ground EM measurements through a depth which depends on the coil orientation, the spacing between transmitter and receiver coils, and the electrical frequency of the instrument. Rhoades and Corwin (1981) demonstrated that bulk soil EC_a, within discrete depth intervals of the soil profile could be determined from EM readings made at a succession of heights above the ground (e.g., 0, 30, 60, 90, and 120 cm) by solving a set of empirical equations containing depth-specific coefficients. The values of the coefficients utilized in these equations were determined by multiple linear regression analysis of successive EM readings measured with a Geonics EM-38[1] device (Geonics Limited, Mississauga, Ontario, Can.), and of corresponding EC_a values for the soil-depth intervals of 0 to 30, 30 to 60, 60 to 90 and 90 to 120 cm measured using a Martek SCT[1] (Martek Instruments, Inc., Irvine, CA) four-electrode probe (Rhoades and van Schilfgaarde, 1976).

A simpler and almost as accurate method was later developed to determine the distribution of EC_a within the soil profile using only two EM measurements taken at the soil surface with the long axis of the EM-38 device's electromagnet oriented parallel (EM_H) and then perpendicular (EM_V) to the soil surface (Corwin and Rhoades, 1982). Equations containing depth-spe-

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[1] Product identification is provided solely for the benefit of the reader and does not imply the endorsement of the USDA.

cific coefficients were developed relating EC_a within specific soil-depth intervals to EM_H and EM_V.

Corwin and Rhoades (1983) later found that different coefficients were needed in the equations relating EC_a to EM_H and EM_V for soils in which EC_a decreased with depth, i.e., inverted salinity profiles, compared to soils in which EC_a increased with depth, i.e., normal salinity profiles. The data sets for these coefficients were quite limited. This paper presents new coefficients obtained from a more extensive data base using statistical techniques which account for the existence of collinearity between EM_H and EM_V measurements.

THEORY

Corwin and Rhoades (1982) related EC_a within a given depth interval, EC_{a,x_1-x_2}, to EM_H and EM_V by the equation

$$EC_{a,x_1-x_2} = k_1\, EM'_H - k_2\, EM''_H - k_3\, EM_V, \quad [1]$$

where EM'_H and EM''_H are adjusted values of EM_H (obtained empirically) and the values of k_1, k_2 and k_3 are depth-specific, empirically determined coefficients.

Substituting the appropriate equations describing EM'_H and EM''_H as functions of EM_H into Eq. [1] yields the equivalent relation

$$EC_{a,x_1-x_2} = k_H\, EM_H - k_V\, EM_V + k\,, \quad [2]$$

where k_H, k_V and k are empirically determined coefficients for the depth interval $x_1 - x_2$. The value k should ideally be zero, but often is not, due to experimental error or "noise" in the data which disallows a perfect fit of the EM–EC_a relations. In the results that follow, k was retained in the expression if it was significantly different from zero; otherwise zero-intercept regression techniques were used.

EXPERIMENTAL PROCEDURE

The EM_H and EM_V were measured using the Geonics EM-38 device at 900 sites within a 39-km^2 area of the South Kings River Watershed of the San Joaquin Valley of California (representing at least 10 different soil types varying in texture from loamy sand to clay). At each site, corresponding values of EC_a were measured using the Martek SCT insertion probe for the intervals 0 to 30 and 30 to 60 cm; at every third site EC_a was also measured for the interval 60 to 90 cm. The EC_a was also measured at each site using an array of electrodes inserted into the soil surface in the Wenner configuration (see Rhoades, 1976). Inner-electrode spacings of both 30 and 60 cm were used in these measurements. The EC_a values for the 0 to 30-, 0 to 60-, and 30 to 60-cm intervals were estimated from the Wenner array measurements (Rhoades, 1976; Rhoades and van Schilfgaarde, 1976).

Exploratory data analysis techniques (Tukey, 1977) were used to determine the frequency distributions of the measured EM and EC_a data. The data were transformed in order to obtain normal distributions so that valid statistical analyses could be performed. This was necessary because the distributions of each parameter were highly skewed with a preponderance of low values and a substantially smaller number of high values. Three transformations were tried: natural log, square root and fourth root. As revealed by the Shapiro-Wilk test statistic (Shapiro and Wilk, 1965), the fourth-root transformation normalized all of the variables; consequently, all subsequent statistics were applied to fourth-root transformed data. Hereafter, the symbol ^ will be used to denote parameters which have been raised to the one-fourth power.

The normalized data set ($n = 900$ samples) was randomly split into two subsets, so that one set could be used to estimate the parameters k_H, k_V and k and the other to test the validity of Eq. [2] and the determined coefficients. Additionally, within each subset the EM_H and EM_V values were split by salinity profile condition (inverted or normal). Inverted profiles were those where $EM_H > EM_V$ and $EM_H/EM_V > 1.05$; normal profiles were those where $EM_H \leq EM_V$.

Regression analysis was used to solve Eq. [2] for k_H and k_V. Extreme collinearity between the EM_H and EM_V values was detected when the results of the two SCT data sets obtained using the Martek SCT probe were compared. This necessitated the use of statistical procedures which combat multicollinearity. Three techniques were evaluated for their effectiveness in obtaining stable and valid coefficients. They were: (i) ridge regression (Myers, 1986; Statgraphics, 1986), (ii) principal components analysis (Davis, 1986) and (iii) best linear combination transformation as ascertained by a SAS regression procedure (PROC REG; SAS Institute, Inc., 1985). These techniques were not applied to the two Wenner data sets because stable and valid coefficients were obtained in the regression analysis performed on these data sets.

A small set of EM_H, EM_V, and EC_a values ($n = 18$) was obtained after completion of the analysis of the major, extensive data set and used to evaluate the accuracy of the EC_a predictions made using the values of the k_H and k_V obtained from the extensive data set. These new data were acquired from within the same study area as previous samples, but this time multiple measurements of EM and EC_a were made at each of the sampled sites in order to obtain more representative readings of EM and EC_a, especially of EC_a within the soil volume measured by the EM-38 device. Eight readings of EM_H and EM_V were made at each site; the EM-38 device was read in both positions (H and V) when pointed at each of the eight cardinal compass directions. The EC_a was measured at eight locations within the 0- to 30-, 30- to 60- and 60- to 90-cm soil-depth intervals; these locations were 25 cm out from the site-center along each compass heading.

RESULTS AND DISCUSSION

No optimal stopping criterion was found for ridge regression and the tolerance level for the matrix multiplication was insufficient; hence, it was abandoned as a method to eliminate collinearity in the Martek SCT data sets.

Since it was unclear how to account for differing soil depths in the two salinity profile conditions using principal components analysis (PC), all of the $\widehat{EM}_H$ and $\widehat{EM}_V$ measurements were used without distinction between soil depth or profile condition, and one overall weighting function was obtained. The result was

$$PC_{EM} = 0.4787\, \widehat{EM}_H + 0.5213\, \widehat{EM}_V\,. \quad [3]$$

The best linear combination method (SAS Institute, Inc., 1985) yielded six weighting functions for the entire Martek SCT data set. Each function corresponded to the appropriate soil depth and profile condition. The functions obtained for the case where $EM_H \leq EM_V$ were

$$\text{depth 0 to 30 cm, } \widehat{SAS}_{EM} = 3.050\, \widehat{EM}_H - 2.000\, \widehat{EM}_V\,, \quad [4]$$

$$\text{depth 30 to 60 cm, } \widehat{SAS}_{EM} = 2.585\, \widehat{EM}_H - 1.213\, \widehat{EM}_V\,, \quad [5]$$

depth 60 to 90 cm, $\mathrm{SA\hat{S}_{EM}}$

$$= 0.958\ \mathrm{E\hat{M}_H} - 0.323\ \mathrm{E\hat{M}_V}\,, \qquad [6]$$

and where $\mathrm{EM_H} > \mathrm{EM_V}$, they were

depth 0 to 30 cm, $\mathrm{SA\hat{S}_{EM}} = 0.830\ \mathrm{E\hat{M}_H}$

$$- 0.640\ \mathrm{E\hat{M}_V}\,, \qquad [7]$$

depth 30 to 60 cm, $\mathrm{SA\hat{S}_{EM}}$

$$= 0.591\ \mathrm{E\hat{M}_H} + 0.635\ \mathrm{E\hat{M}_V}\,, \qquad [8]$$

and depth 60 to 90 cm, $\mathrm{SA\hat{S}_{EM}}$

$$= -0.126\ \mathrm{E\hat{M}_H} + 1.283\ \mathrm{E\hat{M}_V}\,. \qquad [9]$$

The linear-combinations (Eq. [3]–[9]) were then used in the linear regression analysis (SAS Institute, Inc., 1985) to estimate the coefficients of Eq. [2] for the random-split data sets and the results were again examined to see if parameter stability could now be achieved. In order to test for significant differences in the parameter estimates between the different splits, a categorical variable (*DS*) was introduced into these equations to identify the subset. The analogous relations to Eq. [2] then became

$$\mathrm{E\hat{C}}_{a,x_1-x_2} = B_0 + B_1\ \mathrm{P\hat{C}_{EM}} + B_2\,(DS)\,, \qquad [10]$$

and

$$\mathrm{E\hat{C}}_{a,x_1-x_2} = B_0 + B_1\ \mathrm{SA\hat{S}}_{\mathrm{EM},x_1-x_2} + B_2\,(DS)\,. \qquad [11]$$

If a difference existed between the two data splits, the B_2 parameter would be significantly different from zero. Since the values of B_2 were not significantly different from zero in any case, we concluded that stability was achieved using Eq. [10] and [11] and that the two SCT data splits were equivalent (see Table 1). Therefore these two sets of data were combined and the remainder of the analyses were performed using the total data.

Our next step was to choose between Eq. [10] and [11] for establishing the coefficients of Eq. [2] for the Martek SCT data sets. Since both are essentially linear weighting functions and all of the transformations used were scaled similarly, the models could be directly compared. The criteria used for this comparison were the r^2, and the Press statistic[2] (SAS Institute, Inc., 1985; Myer, 1986). The results of this analysis are given in Table 2. The SAS linear combinations (Eq. 11) gave the better fits and prediction capabilities. Furthermore, the intercept value (B_o) was insignificant for four of the six models (Eq. [4]–[9]) and hence could be eliminated.

The SAS linear combination model was then used (since it was the better model) to calculate the coefficients of Eq. [2] (separately for each depth interval and for the two profile conditions) from the $\mathrm{E\hat{M}_H}$, $\mathrm{E\hat{M}_V}$ and $\mathrm{E\hat{C}}_a$ readings. For this purpose, the two random-split data sets have been combined, since the values of the coefficients to be obtained would be the same for the splits and the whole set, as is evidenced in the results given in Table 1 and as discussed above. These results are given in Table 3. The relatively high r^2 values show the good correspondence obtained between $\mathrm{E\hat{C}}_a$ and $\mathrm{E\hat{M}_H}$ and $\mathrm{E\hat{M}_V}$.

The relations of Table 3 were then used to predict EC_a values from given $\mathrm{EM_H}$ and $\mathrm{EM_V}$ values. The correspondence between these predicted values of EC_a and the measured ones was good with relatively high values of r^2 obtained by linear regression analysis and with slopes and intercepts close to 1 and 0 respectively, as shown in Table 6. This close correspondence demonstrates the broad scale applicability of the equations and coefficients given in Table 3 for the prediction of $\mathrm{EC_a}$ from $\mathrm{EM_H}$ and $\mathrm{EM_V}$.

Table 1. Values of B_2 coefficients in Eq. [10] and [11] and their *F* probability levels, using SCT values of EC_a.

		Eq. [10]		Eq. [11]	
Profile	Depth, cm	B_2	$(P_r > F)$**	B_2	$(P_r > F)$**
$\mathrm{EM_H} \le \mathrm{EM_V}$	0–30	0.002	0.861	0.000	0.954
	30–60	−0.000	0.708	−0.004	0.667
	60–90	−0.021	0.261	−0.022	0.259
$\mathrm{EM_H} > \mathrm{EM_V}$	0–30	0.013	0.574	0.017	0.401
	30–60	−0.028	0.204	0.028	0.205
	60–90	−0.023	0.558	−0.018	0.644

** Probabilities greater than 0.01 were not considered to be significantly different from zero.

Table 2. Comparison of regression r^2 and press statistics values for the linear combination models (Eq. [10] vs. [11]).

				Model			
				Eq. [10]		Eq. [11]	
Profile	Depth	Data Set	*n*	r^2	Press Stat	r^2	Press Stat
$\mathrm{EM_H} \le \mathrm{EM_V}$	0–30	A	300	0.613	5.379	0.724	3.871
		B	372	0.545	8.592	0.739	4.930
	30–60	A	360	0.723	5.719	0.773	4.695
		B	287	0.719	7.044	0.790	5.260
	60–90	A	92	0.711	1.561	0.708	1.578
		B	114	0.747	2.049	0.753	2.002
$\mathrm{EM_H} > \mathrm{EM_V}$	0–30	A	60	0.787	1.032	0.860	0.669
		B	56	0.864	0.730	0.875	0.672
	30–60	A	59	0.824	0.785	0.824	0.785
		B	53	0.850	0.747	0.855	0.747
	60–90	A	26	0.777	0.460	0.763	0.489
		B	20	0.842	0.409	0.870	0.337

Table 3. Relations found between soil electrical conductivity in the different soil depth increments and the electromagnetic measurements made with the EM-38 device, where EC_a was measured with the Martek SCT insertion probe.

Depth, cm	Equations for electrical conductivity†	*n*	r^2
	for $\mathrm{EM_H} \le \mathrm{EM_V}$		
0–30	$\mathrm{EC_a^{\wedge}} = 3.023\ \mathrm{EM_H^{\wedge}} - 1.982\ \mathrm{EM_V^{\wedge}}$	673	0.731
0–60	$\mathrm{EC_a^{\wedge}} = 2.757\ \mathrm{EM_H^{\wedge}} - 1.539\ \mathrm{EM_V^{\wedge}} - 0.097$	639	0.835
0–90	$\mathrm{EC_a^{\wedge}} = 2.028\ \mathrm{EM_H^{\wedge}} - 0.887\ \mathrm{EM_V^{\wedge}}$	198	0.852
30–60	$\mathrm{EC_a^{\wedge}} = 2.585\ \mathrm{EM_H^{\wedge}} - 1.213\ \mathrm{EM_V^{\wedge}} - 0.204$	647	0.782
60–90	$\mathrm{EC_a^{\wedge}} = 0.958\ \mathrm{EM_H^{\wedge}} + 0.323\ \mathrm{EM_V^{\wedge}} - 0.142$	195	0.736
	for $\mathrm{EM_H} > \mathrm{EM_V}$		
0–30	$\mathrm{EC_a^{\wedge}} = 1.690\ \mathrm{EM_H^{\wedge}} - 0.591\ \mathrm{EM_V^{\wedge}}$	117	0.866
0–60	$\mathrm{EC_a^{\wedge}} = 1.209\ \mathrm{EM_H^{\wedge}} - 0.089$	147	0.917
0–90	$\mathrm{EC_a^{\wedge}} = 1.107\ \mathrm{EM_H^{\wedge}}$	54	0.903
30–60	$\mathrm{EC_a^{\wedge}} = 0.554\ \mathrm{EM_H^{\wedge}} + 0.595\ \mathrm{EM_V^{\wedge}}$	113	0.840
60–90	$\mathrm{EC_a^{\wedge}} = -0.126\ \mathrm{EM_H^{\wedge}} + 1.283\ \mathrm{EM_V^{\wedge}} - 0.097$	53	0.812

† $\mathrm{EC_a^{\wedge}}$, $\mathrm{EM_H^{\wedge}}$ and $\mathrm{EM_V^{\wedge}}$ are the fourth roots of EC_a, $\mathrm{EM_H}$ and $\mathrm{EM_V}$.

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[2] The Press statistic is the sum of squares of the residuals calculated by taking the difference of the i^{th} observed value and the i^{th} predicted value, where the latter value is obtained from a regression equation derived from the $i-1$ data points. Thus in choosing a best model, one selects the model with the lowest Press statistic (Myers, 1986, p. 106–111).

The Wenner data was also tested for parameter stability, using the following relation

$$\widehat{\mathrm{EC}}_{a,x1-x2} = B_0 + B_1\,(\widehat{\mathrm{EM}}_\mathrm{H} + \widehat{\mathrm{EM}}_\mathrm{V}) + B_2\,(DS). \quad [12]$$

The values of B_2 were not significantly different from zero in any case (see Table 4); thus, parameter convergence was obtained using Eq. [12]. Since collinearity was not a problem and parameter stability was obtained with the two Wenner split data sets, a comparison between $\widehat{\mathrm{EM}}_\mathrm{H}$, $\widehat{\mathrm{EM}}_\mathrm{V}$ and $\widehat{\mathrm{EC}}_a$ values was made by multilinear regression analysis using the combined data set. Results are given in Table 5. The larger r^2 values obtained with the Wenner method of measuring EC_a compared to the Martek SCT method are most likely due to differences in the two instrument's sampling volumes. The sample volumes for the Wenner and EM methods are similar, while the volume sampled by the SCT is much smaller.

The equations given in Table 5 were used to predict EC_a values from given EM_H and EM_V values. The predicted values compared well with the actual values of EC_a (Table 6).

To compare the new relations established herein with those previously obtained by Corwin and Rhoades (1982, 1983), linear regression analyses were performed between the measured and predicted values of EC_a in the 0- to 30- and 30- to 60-cm depths. For this purpose the Martek SCT coefficients of Table 3 were used, since this method of measurement was common to both studies. The new relations consistently give slopes and intercepts closer to 1.0 and 0.0, respectively, and frequently higher r^2 values (see Table 7). The values of r^2 are generally good.

The highly sampled data set (consisting of 18 sites) was used to evaluate the accuracy of the EC_a values predicted from EM_H and EM_V using the values of k_H and k_V established with the extensive data set. The data and results are given in Tables 8 and 9; predicted

Table 4. Values of B_2 coefficients in Eq. [12] and their F probability levels, using Wenner values of EC_a**

Profile	Depth, cm	B_2	$\Pr < F$
$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–30	−0.004	0.517
	0–60	−0.000	0.967
	30–60	0.001	0.911
$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–30	−0.005	0.647
	0–60	−0.004	0.561
	30–60	0.002	0.853

** Probabilities greater than 0.01 were not considered to be significantly different from zero.

Table 5. The relations between soil electrical conductivity (EC_a) as measured by the Wenner array and electromagnetic (EM) measurements made with the EM-38 device.

Depth, cm	Equations for electrical conductivity†	n	r^2
	for $\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$		
0–30	$\widehat{\mathrm{EC}}_a = 2.539\,\widehat{\mathrm{EM}}_\mathrm{H} - 1.413\,\widehat{\mathrm{EM}}_\mathrm{V} - 0.068$	759	0.810
0–60	$\widehat{\mathrm{EC}}_a = 2.092\,\widehat{\mathrm{EM}}_\mathrm{H} - 0.81\,\widehat{\mathrm{EM}}_\mathrm{V} - 0.179$	761	0.895
30–60	$\widehat{\mathrm{EC}}_a = 1.894\,\widehat{\mathrm{EM}}_\mathrm{H} - 0.407\,\widehat{\mathrm{EM}}_\mathrm{V} - 0.292$	758	0.840
	for $\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$		
0–30	$\widehat{\mathrm{EC}}_a = 1.164\,\widehat{\mathrm{EM}}_\mathrm{H} - 0.078\,\widehat{\mathrm{EM}}_\mathrm{V}$	165	0.922
0–60	$\widehat{\mathrm{EC}}_a = 0.640\,\widehat{\mathrm{EM}}_\mathrm{H} + 0.568\,\widehat{\mathrm{EM}}_\mathrm{V} - 0.114$	163	0.969
30–60	$\widehat{\mathrm{EC}}_a = 1.367\,\widehat{\mathrm{EM}}_\mathrm{V} - 0.209$	162	0.919

† $\widehat{\mathrm{EC}}_a$, $\widehat{\mathrm{EM}}_\mathrm{H}$ and $\widehat{\mathrm{EM}}_\mathrm{V}$ are the fourth roots of EC_a, EM_H and EM_V.

Table 7. Comparison of measured EC_a values with those predicted by new and previous relations.†

Relation‡	Profile	Depth, cm	n	Slope	Int	r^2
New	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–30	88	1.15	−0.22	0.86
Previous	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–30	88	1.41	−0.45	0.86
New	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	30–60	85	1.10	−0.05	0.85
Previous	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	30–60	85	2.77	−1.32	0.67
New	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	60–90	32	1.28	−0.11	0.82
Previous	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	60–90	32	1.51	−0.10	0.71
New	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–60	85	1.02	0.06	0.90
Previous	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–60	85	1.76	−0.54	0.84
New	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–90	30	1.06	0.07	0.83
Previous	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$	0–90	30	1.80	−0.47	0.79
New	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–30	698	1.09	0.01	0.70
Previous	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–30	698	1.29	−0.13	0.61
New	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	30–60	671	0.92	0.22	0.80
Previous	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	30–60	671	1.39	0.45	0.80
New	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	60–90	216	0.95	0.17	0.75
Previous	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	60–90	216	0.57	1.24	0.72
New	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–60	663	0.96	0.10	0.85
Previous	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–60	663	1.44	0.07	0.85
New	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–90	206	1.03	−0.01	0.85
Previous	$\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–90	206	0.89	0.62	0.86
New	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$ & $\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–30, 30–60 & 60–90	1790	0.99	0.11	0.80
Previous	$\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$ & $\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$	0–30, 30–60 & 60–90	1790	0.98	0.56	0.61

† Measured EC_a = (slope) predicted EC_a ± intercept; n = number of samples; r^2 = coefficient of determination.

‡ EC_a values measured with four-electrode insertion probe (Rhoades and van Schilfgaarde, 1976) and values predicted using relations developed herein (Table 3) and those of Corwin and Rhoades (1982, 1983).

Table 6. Results of linear regression between predicted (Tables 3 and 5) and measured values of EC_a by soil depth interval, profile condition and method of measurement of EC_a (SCT vs. Wenner).

	SCT method				Wenner method			
Depth, cm	n	Slope	Intercept	r^2	n	Slope	Intercept	r^2
				for $\mathrm{EM}_\mathrm{H} \leq \mathrm{EM}_\mathrm{V}$				
0–30	698	1.088	+0.011	0.702	784	1.065	−0.007	0.812
0–60	663	0.965	+0.102**	0.854	786	1.042	+0.016	0.875
0–90	206	1.031	−0.013	0.854	—	—	—	—
30–60	671	0.922	+0.220**	0.801	782	1.040	+0.022	0.807
60–90	216	0.953	+0.168	0.751	—	—	—	—
				for $\mathrm{EM}_\mathrm{H} > \mathrm{EM}_\mathrm{V}$				
0–30	88	1.149	−0.218	0.857	101	1.179	−0.138**	0.924
0–60	85	1.019	+0.060	0.899	99	1.101	−0.048**	0.968
0–90	30	1.057	+0.066	0.830	—	—	—	—
30–60	85	1.099	−0.048	0.851	99	1.099	−0.049	0.926
60–90	32	1.275	−0.112	0.816	—	—	—	—

** Intercept is significant at the 0.01 alpha level.

Table 8. Measured values of EM_H, EM_V and EC_a and predicted values of EC_a to small, well-sampled data set.

Site number	Measured, dS/m					Predicted EC_a, dS/m		
	EM		EC_a					
	H	V	0–30†	30–60	60–90	0–30†	30–60	60–90
1	4.30(0.08)‡	3.49(0.04)	7.1 (0.3)	4.5 (0.3)	4.5 (0.5)	7.0	6.7	4.7
2	0.73(0.01)	0.83(0.00)	0.72(0.03)	0.49(0.07)	1.21(0.05)	0.66	1.1	1.22
3	0.80(0.00)	0.78(0.00)	0.94(0.04)	0.94(0.02)	1.13(0.02)	0.98	1.5	1.30
4	2.40(0.02)	2.18(0.01)	3.5 (0.3)	2.9 (0.2)	2.2 (0.1)	3.7	4.0	2.9
5	0.36(0.00)	0.42(0.00)	0.39(0.03)	0.26(0.02)	0.50(0.05)	0.31	0.46	0.55
6	1.21(0.01)	1.04(0.01)	1.29(0.06)	0.68(0.05)	0.78(0.06)	1.9	1.9	1.29
7	0.42(0.00)	0.59(0.00)	0.18(0.01)§	0.17(0.02)§	—¶	0.23	0.44	—¶
8	1.77(0.04)	1.48(0.03)	3.4 (0.1)	1.3 (0.1)	0.44(0.04)	2.8	2.8	1.9
9	0.41(0.00)	0.16(0.00)	1.25(0.08)	—¶	—¶	0.92	—¶	—¶
10	1.13(0.01)	1.11(0.01)	1.32(0.07)	1.65(0.06)	2.09(0.08)	1.37	2.19	1.92
11	2.79(0.03)	1.83(0.04)	5.1 (0.1)	4.5 (0.1)	2.31(0.08)	5.0	3.9	2.31
12	0.68(0.01)	0.76(0.00)	0.56(0.04)	1.02(0.05)	1.00(0.04)	0.62	1.03	1.13
13	1.09(0.01)	1.27(0.01)	0.64(0.05)	1.37(0.08)	1.69(0.06)	0.94	1.74	1.94
14	3.30(0.08)	2.79(0.07)	5.9 (0.3)	5.1 (0.2)	2.6 (0.1)	5.2	5.3	3.7
15	0.53(0.01)	0.52(0.00)	0.55(0.03)	0.82(0.04)	0.91(0.01)	0.64	0.89	0.81
16	1.70(0.02)	1.45(0.01)	2.65(0.08)	1.7 (0.1)	1.67(0.07)	2.7	2.7	1.85
17	1.08(0.02)	1.11(0.01)	1.16(0.08)	2.22(0.04)	1.24(0.03)	1.20	2.0	1.85
18	2.58(0.05)	1.86(0.04)	3.3 (0.2)	2.5 (0.1)	1.5 (0.1)	4.4	3.8	2.4

† Soil depth interval, centimeters.
‡ ( ) = Standard error of mean.
§ $n = 6$ instead of 8 as for all other sites.
¶ Unable to insert SCT into this soil depth interval.

Table 9. Results of linear regression between predicted (from coefficients of Table 3) and measured values of EC_a for a small, well-sampled data set (Table 8).†

Soil depth, cm	n	r^2	Slope	Intercept
		For $EM_H \leq EM_V$		
0–30	9	0.92	0.91(0.10)‡	0.01(0.09)
30–60	8	0.82	0.96(0.17)	−0.21(0.24)
60–90	8	0.79	0.82(0.17)	0.11(0.25)
		For $EM_H > EM_V$		
0–30	9	0.92	1.01(0.11)	−0.07(0.47)
30–60	8	0.74	0.93(0.22)	−0.70(0.93)
60–90	8	0.84	1.03(0.18)	−0.71(0.51)
		For both profile types		
0–30	18	0.96	1.01(0.05)	−0.06(0.15)
30–60	16	0.84	0.81(0.09)	−0.13(0.27)
60–90	16	0.82	0.84(0.11)	−0.06(0.24)

† Measured EC_a = (slope) predicted EC_a ± intercept; n = number of samples; r^2 = coefficient of determination.
‡ Values within ( ) are standard errors.

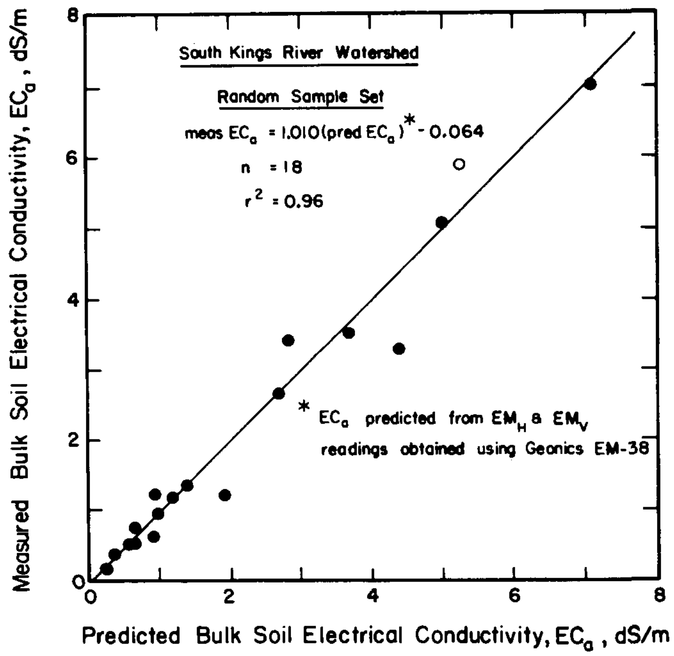

Fig. 1. Correspondence between measured and predicted soil electrical conductivities (EC_a) for a random sample set of soils from the South Kings River Watershed, 0 to 30-cm depth.

and measured EC_a values for one depth (0–30 cm) are given in Fig. 1 to facilitate the visualization of the degree of correspondence obtained. Higher r^2 values between predicted and measured values of EC_a were obtained in this more accurate data set, especially in the 0- to 30-cm soil-depth interval, compared to the major data set. The better relationship is attributed to the multiple Martek SCT measurements that were made in the acquisition of these data, which gives a closer approximation of the mean EC_a value of the relatively large soil volume sensed by the Geonics EM-38.

Predicted and measured EC_a values often differed considerably from the EM_H and EM_V values per se (see Table 8). The closer correspondence existing between measured and predicted EC_a values than between measured EC_a and EM_H and EM_V values shown in these data clearly demonstrates the advantage of using the predictions of EC_a from EM_H and EM_V in lieu of the values of EM_H and EM_V per se for the purpose of salinity appraisal. Even though the predictions are not as accurate as desired in the 30- to 60- and 60- to 90-cm depths, they are still reasonable estimates that should provide more meaningful information with which to interpret soil salinity within the plant root zone than the EM values themselves.

CONCLUSION

The equations given in Tables 3 and 5 yield estimates of EC_a within the soil-depth intervals of 0 to 30, 30 to 60 or 60 to 90 cm from EM_H and EM_V measurements that should be more generally applicable than those previously given in Corwin and Rhoades (1982, 1983), since they are based on a more extensive data set and have been developed using statistical techniques designed to combat the inherent interdependence between the EM_H and EM_V measurements.

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