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A geostatistical method for soil salinity sample site spacing

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Abstract

A calibrated Four-Electrode Probe (FEP) was used for inexpensive and indirect determinations of salinity-sensor Electrical Conductivity (EC) in a plot at Cauto Valley, Cuba. Two transects were made in the North–South (N–S) and East–West (E–W) directions. Laboratory measurements of soil EC were also made from samples taken on a 50-m spaced square grid. A linear semivariogram was obtained for the salinity-sensor EC measurements at the E–W transect, which agrees with the topographical slope of the plot and with the expected soil salinity variation. It also coincides with the spatial structure of laboratory-measured soil EC. A cross-validation analysis has shown that EC semivariograms obtained from FEP measurements can characterize the soil EC spatial variation in a similar way as semivariograms of laboratory-measured soil EC. Thus, the distance between samples for soil salinity maps can be based on the semivariogram's range of salinity-sensor EC measurements. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: soil salinity; electrical conductivity; soil mapping; geostatistics; soil resistance measurements

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1. Introduction

Making soil salinity maps requires a considerable effort in taking soil samples and measuring electrical conductivity (EC); therefore, the selection of an optimal sampling design is an important subject when mapping soil salinity.

Geostatistics (Journel and Huijbregts, 1978; Webster, 1985; Warrick et al., 1986) has been recognized as a powerful tool in the selection of sampling design and mapping soil properties (Burgess and Webster, 1980; Bouma, 1984; Wilding, 1984). In geostatistical theory, the range of the semivariogram is the maximum distance between correlated measurements (Journel and Huijbregts, 1978; Webster, 1985; Warrick et al., 1986). This means that samples separated at smaller distances are generally not needed (Nielsen et al., 1983). Therefore, the range of EC semivariograms can be an effective criterion for the selection of a sampling design in mapping soil salinity.

Unfortunately, semivariogram determination requires many experimental data (Journel and Huijbregts, 1978; Webster, 1985; Webster and Oliver, 1992). Consequently, the use of geostatistics in a preliminary characterization of EC spatial variability does not result in any significant reduction in the number of measurements. Nevertheless, soil EC can be determined indirectly through calibrated saline sensors such as the Four-Electrode Probe (Rhoades and Ingvalson, 1971). The FEP allows determination of the ‘Apparent Electrical Conductivity’ (ECa) which correlates with the soil EC, although it also depends on soil moisture and other soil properties (Rhoades, 1974).

The objective of this study was to verify if indirect FEP-EC measurements can characterize the spatial structure of laboratory-measured soil EC, in order to use it in mapping of soil salinity.

2. Materials and methods

2.1. The experimental site

A plot of 33 ha (approximately 500 × 600 m) was selected in the Cauto Valley, Cuba, at latitude 20 46′06″N and longitude 76 37′36″W. The climate is semi-arid (mean annual precipitation, 977 mm; mean annual evaporation, 2339 mm) with two marked seasons, the dry season (October to March) and the wet season (April to September). The latter contributes 83% of total annual rainfall. Soil-surface salinity in the Valley is generally due to excess of irrigation water, which elevates the water table in lower lands.

The elevations and the general configuration of the plot are shown in Fig. 1. Bouziquez et al. (1992) found two soil units in the plot, associated with their

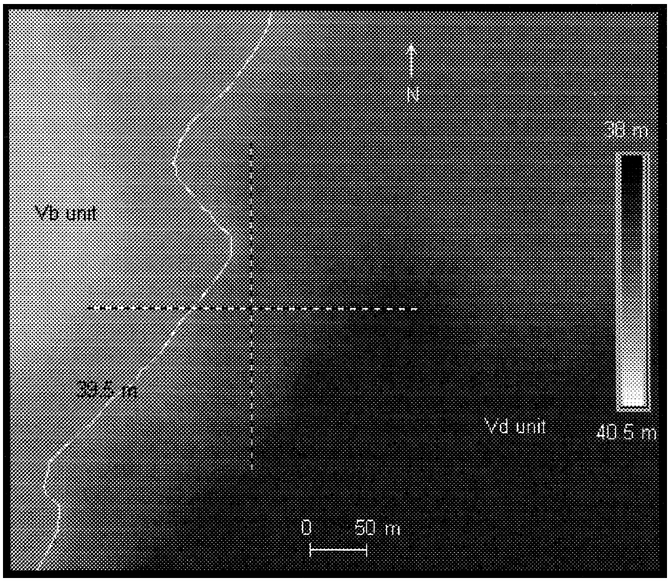

Fig. 1. Elevations of experimental plot. The Vb soil unit is above 39.5 m, whereas the Vd unit is below this elevation. The lines show the transect positions.

landscape position: Slightly hydromorphic and halomorphic Vertisol (Vb unit), located above 39.5 m over sea level and Very hydromorphic and holomorphic Vertisol (Vd unit), below this elevation. As can be seen in Fig. 1, the Vb unit is

Table 1
Texture, Exchangeable Sodium Percent (ESP), pH and Electrical Conductivity (EC) of the observed horizons of selected profiles in Vb and Vd units

Depth (cm)	Texture (%)			ESP (%)	pH	EC 1:5 dilution (dS/m)
	Clay	Silt	Sand			
Vb unit						
0–22	54.8	30.5	12.7	2.55	8.20	0.29
22–52	60.0	26.3	13.7	6.82	8.50	0.34
52–80	59.7	25.4	14.9	15.72	8.80	0.56
80–102	56.9	32.6	10.5	22.12	8.60	1.29
102–133	54.9	36.3	8.8	26.58	8.40	1.88
> 133	54.4	37.3	8.3	24.01	8.40	2.02
Vd unit						
0–14	53.9	25.5	20.6	36.9	8.10	6.17
14–50	54.0	36.9	19.1	34.5	7.90	6.15
50–90	57.4	23.4	19.2	15.8	8.20	1.50
90–118	49.5	31.9	18.6	11.9	8.50	1.86
118–135	50.3	33.1	16.6	11.8	8.60	5.85
> 135	49.8	35.4	14.8	13.2	8.70	5.29

extended as a narrow band in the North–South direction. The salinity change in the plot is expected to be mainly in the East–West direction, which agrees with the topographic slope, as pointed out by Bouziquez et al. (1992).

Some physical and chemical properties of selected profiles of each soil are given in Table 1. There is no great textural differences between the two soil units. The EC in the Vb unit is lower near the surface, increasing with depth, while it is higher in the Vd unit. The distribution of EC with depth in this unit is similar to any typical saline profile. The water table reaches 80-cm depth in the rainy season at the Vb unit, whereas in the Vd unit, it reaches the soil surface (Bouziquez et al., 1992). As can be seen in Table 1, Exchangeable Sodium Percentage is higher in both soil units at depths exceeding 80 cm due to the presence of a high saline water table (Bouziquez et al., 1992).

2.2. Soil salinity measurements and geostatistical procedures

A Four-Electrode Probe (FEP), a Megger 'Earth Tester', was employed in the Wenner Array. The inner-electrode spacing was selected as 60 cm, thus, the FEP measurements are related basically to the 0–60 cm soil depth (Rhoades, 1974). The Apparent Electrical Conductivity was measured in two transects, one in the North–South (N–S) and the other East–West (E–W) direction. Each transect had 30 points with a 10-m spacing. The transect positions are shown in Fig. 1. The ECa values were converted to EC for a 1:5 soil–water dilution following the Herrera et al. (1990) calibration, which was made at the same plot. These converted FEP-ECa–EC values were designated EC1.

Experimental semivariograms of EC1 in both transects were determined and automatically fitted to one of the authorized theoretical models, i.e., spherical, Gaussian, exponential or linear (Journel and Huijbregts, 1978). A weighted least-square procedure (Mac Bratney and Webster, 1986) was used in fitting the semivariogram models. The best model was selected according to the minimum value of Akaike's criterion. The semivariograms were determined only up to 150 m, which was half of the maximum separation distance, in order to keep sufficient numbers of pairs for semivariance calculations (Journel and Huijbregts, 1978). For the geostatistical analyses, the program GEOESTAD (Díaz et al., 1994) was used.

EC of 1:5 soil–water dilutions were measured for samples taken from 0–20, 20–40 and 40–60 cm depths of a 50-m spaced square grid (covering the whole plot), as well as from the composite 0–60 cm depth. Samples were taken at the same time as on the N–S and E–W FEP-measurement transects. Isotropic EC semivariograms, as well as N–S and E–W directional semivariograms were determined. The ability of EC1 semivariograms in characterizing soil EC spatial variability was evaluated with a cross-validation analysis (Webster, 1985; Warrick et al., 1986). The accuracy of EC kriging estimates using EC1 semivariograms were calculated with a Mean Square Error (MSE), between actual and estimated values. A comparison was performed by repeating the cross-validation analysis using the isotropic semivariograms obtained from the laboratory EC measurements.

3. Results

3.1. EC1 and EC spatial variabilities

Table 2 summarizes the sample means (m), standard deviations (s) and Coefficients of Variation (CV's) of laboratory-measured EC at each depth increment, as well as the EC1 values for the two transects. The EC means are higher at the surface and decrease with depth, corresponding to an inverted soil salinity profile. CV values are high, but such variation is commonly found in this soil property (Warrick and Nielsen, 1980). For the 0–60 cm average-depth, the CV is lower than for the individual depths. The EC1 mean found for the N–S transect was higher than for the E–W transect. As shown in Fig. 1, the N–S transect is completely below a 39.5-m elevation, thus, it is inside the Vd soil and is parallel to the contour line. The E–W transect crosses the two soil boundaries and its CV is much higher. The skewness shown in Table 2 suggests that EC1 and EC are both lognormally distributed, which agrees with the most frequently reported results (Vauclin, 1982).

The experimental EC1 semivariograms of each transect are shown in Fig. 2. The selected models, nuggets, sills and ranges are given in Table 3. As shown in Fig. 2 and in Table 3, the E–W transect yields a linear semivariogram, whereas the N–S transect shows only a small spatial structure. According to Journel and Huijbregts (1978) and Mac Bratney and Webster (1986), no second-order stationarity must be expected if the semivariance increases linearly with the

Table 2
Mean (m), standard deviation (s) and Coefficients of Variation (CV) of the laboratory-determined EC and ECa–EC converted values

EC data	m (dS/m)	s (dS/m)	CV (%)	Skewness	Kurtosis
EC 0–20	4.22	3.29	77.92	1.1405	4.0626
EC 20–40	3.68	2.66	72.38	2.2675	13.6058
EC 40–60	3.08	2.25	73.03	1.6519	7.0584
EC 0–60	3.66	2.34	63.83	0.9098	3.8023
EC1[a]	7.89	1.13	14.40	0.3836	2.3407
EC1[b]	6.41	1.60	25.01	0.5979	2.1708

[a] North–South transect.
[b] East–West transect.

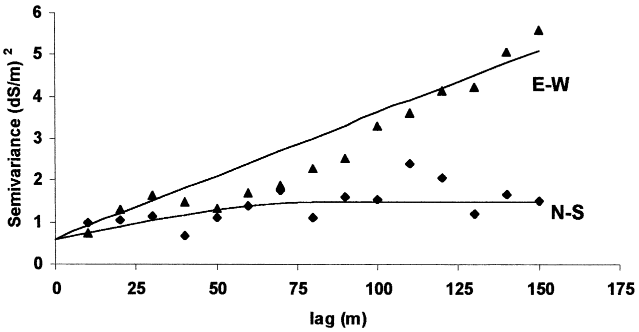

Fig. 2. EC1 semivariograms of each transect. The solid lines show the theoretical semivariogram models.

separation distance, although the intrinsic hypothesis of geostatistics (weaker stationarity) still holds. Consequently, for the E–W transect EC1 data, the intrinsic hypothesis of geostatistics is valid. As to the EC1 E–W semivariogram, a linear model was fitted, its range is larger than the highest separation distance between the measurements, i.e., 150 m in this case. Consequently, soil samples for EC measurements at this plot could be taken separated as 150 m. Samples taken closer to each other than this distance yield spatially-correlated EC measurements and thus, they could be considered as the same measurement

Table 3
Model (M), nugget, sill and range of the adjusted EC1 and EC semivariograms

EC data	M	Nugget (dS^2/m^2)	Sill (dS^2/m^2)	Range (m)
EC 0–20[a]	L	6.5	12.5[d]	500
EC 0–20[b]	S	3.0	10.5	300
EC 0–20[c]	L	6.0	16.0[d]	500
EC 20–40[a]	G	4.5	7.0	128
EC 20–40[b]	S	2.0	6.5	200
EC 20–40[c]	L	3.0	11.0[d]	500
EC 40–60[a]	S	1.9	5.4	135
EC 40–60[b]	S	1.2	4.4	120
EC 40–60[c]	L	4.6	6.7[d]	500
EC 0–60[a]	S	1.4	4.7	291
EC 0–60[b]	S	0.5	2.3	200
EC 0–60[c]	L	3.0	5.5[d]	500
EC1[b]	S	0.6	1.9	80
EC1[c]	L	0.6	5.1[d]	150

[a] Isotropic.
[b] North–South.
[c] East–West.
[d] Sill in linear semivariograms has only a fitting meaning.
L: Linear semivariogram; G: Gaussian semivariogram; S: spherical semivariogram.

(Nielsen et al., 1983). According to Bouma (1984), this procedure for selecting the inter-sample distance is one of the most important results that geostatistics can provide for soil surveying.

The parameters of the EC isotropic, N–S and E–W semivariograms calculated from the 120 EC measurements at each depth are given in Table 3. In this case a linear semivariogram was adjusted to the isotropic and E–W 0–20 cm semivariograms, whereas a small difference between sill and nugget was found in the N–S semivariogram. It agrees with the EC1 found results and with the higher top soil salinity (see Table 2). The E–W EC semivariograms at all depths also show a linear behavior. It means that the combined-profile salinity variation is connected to topography. Bouziquez et al. (1992) came to the same conclusion. Nevertheless, according to the difference between sills and nuggets, a weaker spatial structure was found in the isotropic semivariograms at 20–40 cm and almost a pure nugget effect (Journel and Huijbregts, 1978; Webster, 1985; Warrick et al., 1986) for the isotropic semivariograms at 40–60 cm depth. The disagreement in salinity between the Vd and the Vb unit decreases with depth. As shown in Table 1, there are lower EC values in the Vb unit only above the 80 cm depth, whereas at greater depths the EC is similar in both soil units. Therefore, the spatial structure of EC also decreases with depth.

The ranges of the EC isotropic semivariograms are higher than those of the EC1 semivariograms, because the distance between measurements in the transect was 10 m, whereas the grid spacing was 50 m. A similar result was found by Gajem et al. (1981). They showed that the ranges of the semivariograms are higher for greater distances between measurements, due to different causes (microtopography, soil-type changes, etc.). In addition, EC1 semivariograms were determined only in two transects, whereas EC semivariograms were obtained in a grid covering the whole plot. The EC1 and EC values were obtained from different sampling schedules, which according to Warrick et al. (1986) and several other authors, could affect the resulting semivariograms. Likewise, as shown in Table 3, the nuggets of the EC semivariograms are considerable higher than for EC1. Webster (1985), Warrick et al. (1986) and many others pointed out that the nugget is related to the spatial variability at smaller distances than the lowest separation distance between measurements. Hence, as the FEP-ECa measurements were 10 m spaced, the EC1 nuggets are lower than the EC nuggets. As can be seen in Table 2 and in Fig. 2, N–S and E–W EC semivariogram nugget values at 0–60 cm are somewhat similar to the semivariance values at 50 m in the corresponding EC1 semivariograms. Thus, the EC1 semivariograms may be considered nested (Webster, 1985) into the EC semivariograms.

The Mean Square Errors (MSE) obtained by cross-validation, using the EC1 semivariograms and the EC isotropic semivariograms, are shown in Fig. 3. The lowest MSE values were found for the isotropic EC semivariograms. This is expected because estimations are performed with the same data. Nevertheless,

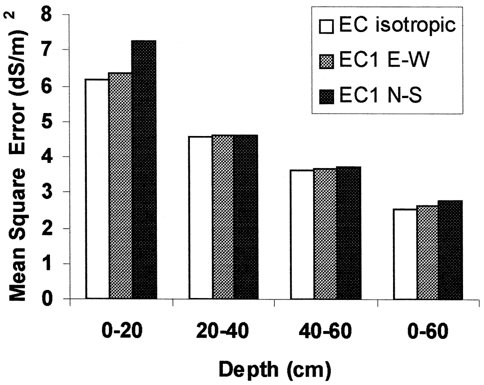

Fig. 3. Mean Square Errors in estimating EC by kriging, using isotropic EC semivariograms at each depth, as well as the EC1 semivariograms.

MSE values obtained by the EC1 E–W semivariogram are similar to those found with the isotropic EC semivariograms. MSE values using the EC1 N–S semivariograms are somewhat higher. In the N–S direction, there is little change in soil salinity, in comparison with the E–W direction. The main soil-salinity spatial variation is in the E–W direction. Therefore, lower MSE were found when the E–W semivariogram is used for kriging. For all the considered semivariograms, MSE values decrease with depth. This agrees with the CV shown in Table 2 and the semivariogram nuggets given in Table 3. All the MSE values are lower than the total variances shown in Table 2 for the same depths because of the kriging accuracy, as is recognized in many papers (Webster, 1985; Warrick et al., 1986; Mac Bratney and Webster, 1986).

As was reported, the kriging accuracy is related to the nugget of the semivariogram. This can be considered as the non-explained spatial variability (Webster, 1985). Therefore, the kriging results are better when lower CV values and smaller semivariogram nuggets are found. As may be concluded from Fig. 3, the semivariograms of EC1 can characterize the spatial variability of laboratory measured EC. Both are equivalent in size to asses the soil salinity spatial variation.

4. Conclusions

The Four-Electrode Probe Apparent Electrical Conductivity measurements can be used in characterizing soil Electrical Conductivity spatial variability. The semivariograms of Apparent Electrical Conductivity can be a useful tool in selecting the distance between soil samples for laboratory Electrical Conductivity determinations.

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