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Spatial analysis of soil salinity in a mango irrigated area in semi-arid climate region

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Abstract

The salinization of irrigated areas in the semi-arid region of Brazil causes major problem for fruit production. Defining the spatial distribution of soil salinity provides important insight technique for improving the management of irrigated fruit-production areas. This work aimed to (1) assess the spatial distribution of soil salinity and (2) delineate management zones in an irrigated mango orchard in the semi-arid region based on soil salinity data. The experimental site in Juazeiro County, Bahia state, Brazil was defined by two sample grids, one under the canopy of the mango trees and the other in the row spacing with 96 georeferenced points spaced 8 x 8 m apart. Disturbed-soil cores were taken from the 0 to 0.2 m layer at each point. Soil texture, electrical conductivity (EC), exchangeable cations, and soluble cations were determined. Data were analyzed using descriptive data and geostatistical analysis. Soil salinity showed spatial dependence for samples collected in the row spacing of the mango trees. Exchangeable Na, and soluble Na, Ca, and Mg were the attributes that best defined the spatial distribution of soil salinity. Three management zones in the studied area were defined based on soil EC values, in which 63% classified as salic, 34% saline and 3% non-saline. This study clearly shows that soil-salinity problems associated with the development of mango plants may be due to an accumulation of salts in the spacing region between the plants.

Keywords: electrical conductivity, geostatistics, *Mangifera indica* L., precision agriculture.
Abbreviations: CV_Coefficient of variation classification; DSD_Degree of spatial dependence; EC_{spe}_Electrical Conductivity obtained by saturated paste extract; EC_{we}_Electrical Conductivity (1:2 soil/water extraction); ME_Mean Error; RC_Regression Coefficient; RMSE_Root Mean Square Error; SE_Standard Error.

Introduction

The most important fruit exporting region of Brazil is located in the Lower Middle São Francisco Valley in the semi-arid region and its production being mainly exported to Europe and the USA. The Petrolina/Juazeiro pole has the most successful fruit production in the São Francisco Valley region. The mango fruit is the second most important cultivated fruit species, covering 22.6 % of the mango cultivated area of Brazil (IBGE, 2013). Due to natural conditions of the semi-arid region, which is uneven distribution of rainfall, high rates of evaporation, and frequently shallow and sandy soils, it is commonly prone to salinization. Additionally, agricultural practice in the semi-arid region of Brazil is highly dependent on irrigation; therefore, irrigation and fertilization practices without proper management can increase salinization risk (Melo et al., 2008). Mango is considered sensitive to saline conditions; thus, salinization can drastically reduce mango yield. The salinity levels (as measured by Electric Conductivity - EC) between 4 and 5 dS m^{-1} caused losses of up to 50 % of mango yield in some fruit fields in the São Francisco Valley region (Amaral, 2011). Mango trees in this condition can present scorched leaf tips and margins, leaf curling, and in severe cases reduced growth, abscission of leaves and death of trees (Zuazo et al., 2004). Environmental variables usually show spatial dependencies among observations, which encourage researchers to use geostatistical methods to model the spatial distribution of observations (Juan et al., 2011). Salinity is a variable in space and time due to the dynamic nature of the effects and interactions of various edaphic-climatic factors (soil permeability, groundwater level, amount and distribution of rainfall, relative humidity, temperature, etc.) and anthropogenic factors (irrigation, cultural practices, etc.) (Zheng et al., 2009; Queiroz et al., 2010). Some works have studied the spatial distribution of soil salinity using geostatistics analysis. Juan et al. (2011) studied spatial variability of soil salinity (EC measurement) in a Mediterranean province of Southeast Spain through kriging and cokriging. They verified that soil salinity can change abruptly due to local characteristics. Also, the geostatistics methods can be useful in plans to mitigate soil salinity risks. Akramkhanov et al. (2011) studied the spatial distribution of soil salinity on flat irrigated terrain in an arid region in Uzbekistan and verified that soil salinity was highly variable even over short distances (40 m). Bilgili (2013) used multiple kriging techniques to study soil salinity in a semi-arid region in Southeastern Turkey. The author verified that soil salinity showed spatial dependence and the kriging techniques were efficient to interpolate soil salinity maps.

These works enhance the need of studies about the spatial distribution of soil salinity in areas of agricultural production to assist decision-making regarding the soil salinity and site-specific management (Zheng et al., 2009). However, there are no studies that aim to delineate management zones based on soil salinity in irrigated mango areas of the São Francisco Valley region. The hypothesis of this work is that the spatial distribution of soil salinity will assist in understanding the cause of salinity and will help to make decisions about soil and irrigation management in mango field in the semi-arid region. Therefore, this work aimed (1) to assess the spatial distribution of soil salinity; (2) to delineate management zones based on soil salinity data in an irrigated mango orchard in the semi-arid climate region.

Results and Discussion

Descriptive and spatial statistical analyses

The values of soil EC (electrical conductivity) sampled under the plant canopy ranged from 2.3 to 3.3 dS m^{-1} (Table 1), which were lower than the critical limit (< 4 dS m^{-1}) for mango trees in the São Francisco Valley region, according to Amaral (2011). Based on the coefficient of variation classification (CV) suggested by Warrick and Nielsen (1980), the variability of EC under the canopy was low (CV < 15 %). On the other hand, soil EC values sampled in the row spacing, showed much greater values comparing to the soil EC values collected under the canopy and they ranged from 2.6 to 30 dS m^{-1} (Table 1). These results indicate that there are regions in the mango orchard, where EC values were greater than the critical value and mango yield losses may be occurring. Additionally, the variability of EC in the row spacing was high (CV > 50 %) (Table 1). The low values of EC under the plant canopy are due to the furrow irrigation method which leaches out salts from the topsoil. Since the soil of the area is an Alfisol, characterized by a texture gradient (clay content increases in-depth), soil infiltration decreases in-depth. Thus, a considerable part of leachable salts flows into the row spacing of the mango trees and are associated with high evapotranspiration rate of the semi-arid region. It can explain the high values and variability of soil EC in the row spacing. Based on mean values of soil texture both under the canopy and row spacing, the soil was classified as sandy loam; however, minimum and maximum values indicate that there is a high variability in the study field, mainly for clay and silt content (Table 1). The high CV values for silt content are expected since in soil texture analysis, the fraction is obtained by difference causing greater estimated error. In addition, this soil texture fraction does not have charges to form soil aggregates, thus silt is very mobile in the soil. For clay content, the high variability could be related to clay dispersion which can be common in Alfisols and the furrow irrigation method which can use too much water. Similar results were found by Rodrigues et al. (2015) in an irrigated guava field in the semi-arid region of Brazil, which verified that even in small fields, soil texture can vary considerably. Therefore, wrong decisions could be made when water and fertilizer management are defined by average values. The mean values of soil pH, both under the canopy and in the row spacing, showed adequate for mango cultivation. Soil pH had the minimum variability (Table 1). Cemek et al. (2006) also found the lowest variability of soil pH in Alluvial soils in the semi-humid region of North Turkey, when assessing spatial variability of some soil attributes as related to soil salinity and alkalinity. A lower CV was expected for soil pH because its values typically vary over a narrow interval. Moreover, the CV of pH cannot be compared to other properties because it is measured on a logarithmic scale (Rodrigues et al., 2012). Spatial dependence was observed for soil texture, both under the canopy and in the row spacing. The degree of spatial dependence {DSD = $[(C_o/C+C_o) \times 100]$} was classified as moderate (DSD = 50-75 %) for all particle size, except for the sand content collected in the row spacing, which was classified as strong (DSD < 25 %) (Table 2). Soil EC and pH did not show spatial dependence in the canopy region, whereas these variables in the row spacing showed strong and moderate spatial dependence, respectively (Table 2). Souza et al. (2008) studied the spatial variability of soil salinity in a Fluvisol in the semi-arid region and observed moderate spatial dependence for soil EC and strong spatial dependence for clay, sand and silt in a carrot crop field. Soil texture is a very stable soil attribute because it is more related to parent material and pedogenetic processes than to anthropogenic processes such as soil and irrigation management. Thus, the spatial distribution pattern is difficult to be changed and this may explain the spatial dependence of soil texture for samples collected both under the canopy and in the row spacing. On the other hand, soil EC and pH are soil attributes which can be modified by soil and irrigation management. As aforementioned, the furrow irrigation method leaches out salts in the canopy region, generating random variability, eliminating the spatial dependence in this region for soil EC and pH. Confirming this hypothesis, Costa (2008) studied an alluvial soil in the semi-arid region and found that the spatial variability of soil EC is characterized based on use and irrigation scheduling. Based on the preliminary data, it was verified that soil EC values were lower than the critical limit for mango cultivation in the canopy region and did not show spatial dependence. Therefore, soluble and exchangeable cations were determined only for the samples collected in the row spacing. According to the criteria determined by Genú and Pinto (2002) for mango cultivation in the Lower Middle São Francisco Valley region, the average level of soil exchangeable Ca^{2+} (20-40 $mmol_c$ kg^{-1}) as well as the soil exchangeable Mg^{2+} (8-15 $mmol_c$ kg^{-1}) were classified as medium, while the average level of soil exchangeable K^+ (31-45 $mmol_c$ kg^{-1}) was classified as high. However, the minimum and maximum values indicate that there are regions in the study field where level ranges from low to high for exchangeable calcium and magnesium and from medium to very high for exchangeable potassium. Exchangeable Na^+ ranged from 0 to 5.2 $mmol_c$ kg^{-1} (Table 1). The K:Ca:Mg ratio generated with the mean values of exchangeable cations was 1:9:3. According to Holanda et al.

(1998), ratios between 1:9:3 and 1:25:5 are considered proper for most crops. These authors pointed out that the imbalance in the relationship of these cations is admitted as the most important issue for the establishment of crops, even more than sodium saturation. The CEC varied from 31.3 to 93.8 $mmol_c\ kg^{-1}$. All values of ESP were lower than 15 % (Table 1) which is the limit for sodic soils and showed the highest variability of exchangeable cations (CV = 81 %).

The mean values of soluble cations can be considered very high (Table 1) comparing to those found by Santos et al. (2013b) in a Fluvic Cambisol and by Melo et al. (2008) in a Fluvic Neosol all salinized in the semi-arid region of Brazil. Similar to results found in previous studies we found that the concentrations of cations in soil solution was in Na>Ca>Mg>K order. The highest value of soluble sodium in soil solution and the lowest value in soils exchange complex can be expected, since among the exchangeable cations sodium is located in the last position of the lyotropic series (adsorption selectivity = H^+ >>> Al^{3+} > Ca^{2+} > Mg^{2+} > K^+ > NH^{4+} > Na^+), due to its valence and the greatest hydrated ionic radius (Holanda et al., 1998). Thus, the other cations (Ca^{2+}, Mg^{2+}, and K^+) displaced Na^+ from the soils exchange complex to the soil solution. The soluble cations showed the highest variability based on the CV values among all studied variables, except for K^+.

Based on coefficients of asymmetry and kurtosis and the normality test, only silt from the canopy region showed normal distribution of data. The clay content, pH, exchangeable Ca^{2+}, Mg^{2+} and K^+ in the row spacing showed normal data distribution (Table 1). Even though Li and Heap (2011) have reported that normality of data may affect the performance of spatial interpolation methods. Wu et al. (2006) demonstrated that the quality of maps from normal and non-normal data set was very small. For this reason we chose to avoid normalization of data for interpolating.

All cations (exchangeable and soluble) showed spatial dependence and their range varied from 19 to 75 m, which were greater than the grid sample spacing (Table 2). This means that the grid spacing was enough to allow modeling spatial dependence in this study area (Rodrigues et al., 2012). All cations showed moderate spatial dependence, except soluble Ca^{2+} and Mg^{2+} which showed high spatial dependence (Table 2). CEC and ESP did not show spatial dependence; thus, maps for these variables were not performed.

Cross-validation of the soil maps

The best models are those with a regression coefficient (RC) closer to 1 (Machado et al., 2015). Observing the RC and standard error (SE) of all studied variables, it was verified that the RC values were statistically equal to 1, except for soil EC and soluble K^+ in the row spacing (Table 2). However, even for soil EC and soluble K^+, considering their SE values, the RC values were close to 1. These results indicate that the condition for estimation was ideal. Similar results were found by Machado et al. (2015) for soil apparent electrical conductivity, organic matter, base saturation, exchangeable potassium, and CEC in an Oxisol under conventional tillage and degraded grassland in the state of Mato Grosso do Sul, Brazil, who verified that the RC values were close to 1.

Mean error (ME) is used for determining the degree of bias in estimates and is often referred to as “bias” (Li and Heap, 2011). Most of the variables show ME close to 0 which suggest that the predictions are relatively unbiased. High ME values were found for soil EC, soluble Ca^{2+}, Mg^{2+}, K^+ and Na^+ in the row spacing (Table 2). Also, the highest values of Root Mean Square Error (RMSE) were found for soil EC and soluble cations (Table 2). These results are expected since these variables show the highest variability (Table 1). In addition, RMSE provides a measure of error size, but it is sensitive to high values as it places a lot of impact on large errors (Li and Heap, 2011), which was observed for soil EC and soluble cations. Since the main aim of this study is not to apply fertilizers at variable rates but rather to delineate management homogeneous zones, the cross-validation results can be considered quite satisfactory.

Soil mapping and correlation analyses

Mapping salinity is a preliminary step towards decision making such as the delineation of contaminated areas and detection of zones that need remediation or adapted management (Bilgili, 2013). The attributes related to soil salinity in the row spacing were mapped using ordinary kriging (Figure 1 and Supplementary Figure 2, 3, and 4). Nevertheless, visual comparison of maps is not a reliable method to verify similarity in spatial distribution pattern between variables. Therefore, two approaches were used in order to identify which variables can determine the spatial distribution pattern of soil EC in the study area, the spatial correlation matrix of maps (data not shown) and cross variograms (Figure 2).

It was not possible to find similarities by visually comparing the soil texture maps (Supplementary Figure 2) to the soil EC map. These results were confirmed by the lower spatial correlation coefficients that were found between soil EC values and sand (r = -0.14), clay (r = -0.37), and, silt (r = 0.04) content. Natural factors such as parent material, soil type, geology, climate, and topography, combined with anthropogenic factors such as inappropriate irrigation and fertilization practices are the controlling factors for the spatial distribution pattern of soil salinity (Bilgili, 2013). Soil texture largely influenced salt content (Akramkhanov et al., 2011). However, in this study, the spatial variability of soil salinity is more likely related to irrigation and fertilization practices than natural factors. This can explain the low spatial correlation between soil EC and soil texture.

Based on soil EC map (Figure 1e), we verified that only 3 % of the orchard is suitable for mango cultivation, i.e., soil EC values lower than 4 $dS\ m^{-1}$. While 34 % of the area was classified as saline (soil EC between 4 and 7 $dS\ m^{-1}$), 63 % classified as salic (soil EC greater than 7 $dS\ m^{-1}$). About 18 % of the area was alkaline (Supplementary Figure 2). However, all soil pH values were lower than 8.5 which characterizes saline soils but not sodic soils (Queiroz et al., 2010). It was confirmed by the low ESP values. Soil pH map did not show visual similarities with soil EC map (Supplementary Figure 2), confirmed by the lower spatial correlation coefficient (r = -0.34). These results indicates that the spatial variability of soil pH is probably related to other ions that were not determined in this study (Cl^-, CO_3^{2-}, HCO_3^-, SO_4^{2-}).

Table 1. Descriptive statistics of soil attributes from 0 to 0.2 m depth in an irrigated mango field in the semi-arid region, Brazil.

Variable	Mean	Min.	Max.	Variance	CV (%)	Asy.	Kurt.	p-value	Normality
	Soil samples collected under the canopy								
Sand (%)	77.6	53.6	87.4	61.9	10	-1.17	0.70	<0.01	Non-N
Clay (%)	12.1	3.0	32.3	32.9	48	1.31	1.36	<0.010	Non-N
Silt (%)	10.3	5.1	30.8	7.0	33	0.40	-0.61	0.07	Normal
pH	6.7	5.8	7.4	0.14	5	-0.55	-0.28	0.02	Non-N
EC	2.7	2.3	3.3	0.04	7	1.06	1.38	<0.01	Non-N
	Soil samples collected in the row spacing								
Sand (%)	79.2	65.4	84.3	12.9	5	-1.84	3.93	<0.01	Non-N
Clay (%)	12.2	5.6	19.5	5.6	19	0.08	0.74	>0.10	Normal
Silt (%)	8.4	2.7	17.9	6.2	30	0.94	1.54	<0.01	Non-N
pH (H_2O)	6.7	5.3	8.1	0.26	8	0.08	0.64	>0.10	Normal
EC	8.7	2.6	30.6	37.1	70	1.82	2.94	<0.01	Non-N
Ca^{2+} (E)	30.4	18.2	41.6	29.0	18	0.30	-0.71	0.073	Normal
Mg^{2+} (E)	9.3	4.3	16.1	8.1	31	0.10	-0.69	>0.10	Normal
K^+ (E)	3.6	1.0	6.7	1.5	34	0.38	-0.56	>0.10	Normal
Na^+ (E)	1.5	0	5.2	1.3	74	0.93	0.93	0.03	Non-N
CEC	47.6	31.3	93.8	164.6	27	1.77	3.33	<0.01	Non-N
ESP	3.4	0	14	6.3	81	1.11	1.57	<0.01	Non-N
Ca^{2+} (S)	490.8	30.3	2156.3	248097	101	1.76	2.45	<0.01	Non-N
Mg^{2+} (S)	326.9	9.6	1708.9	115558	104	1.96	3.65	<0.01	Non-N
K^+ (S)	167.2	11.8	612.6	10493	61	1.45	3.16	<0.01	Non-N
Na^+ (S)	1438.3	18.4	6447.3	1848998	95	1.87	4.36	<0.01	Non-N

Min = Mininum; Max. = Maximum; Asy. = Asymmetry; Kurt. = Kurtosis; CV = Coefficient of variation; p-value (0.05) of normality test; Normality = Ryan-Joiner normality test; Non-N = Non-normal; EC = Electrical conductivity (dS m^{-1}); E = Exchangeable cation ($mmol_c$ kg^{-1}); CEC = Soil cation exchange capacity; ESP = Exchangeable sodium percentage; S = Soluble cation ($mmol_c$ L^{-1})

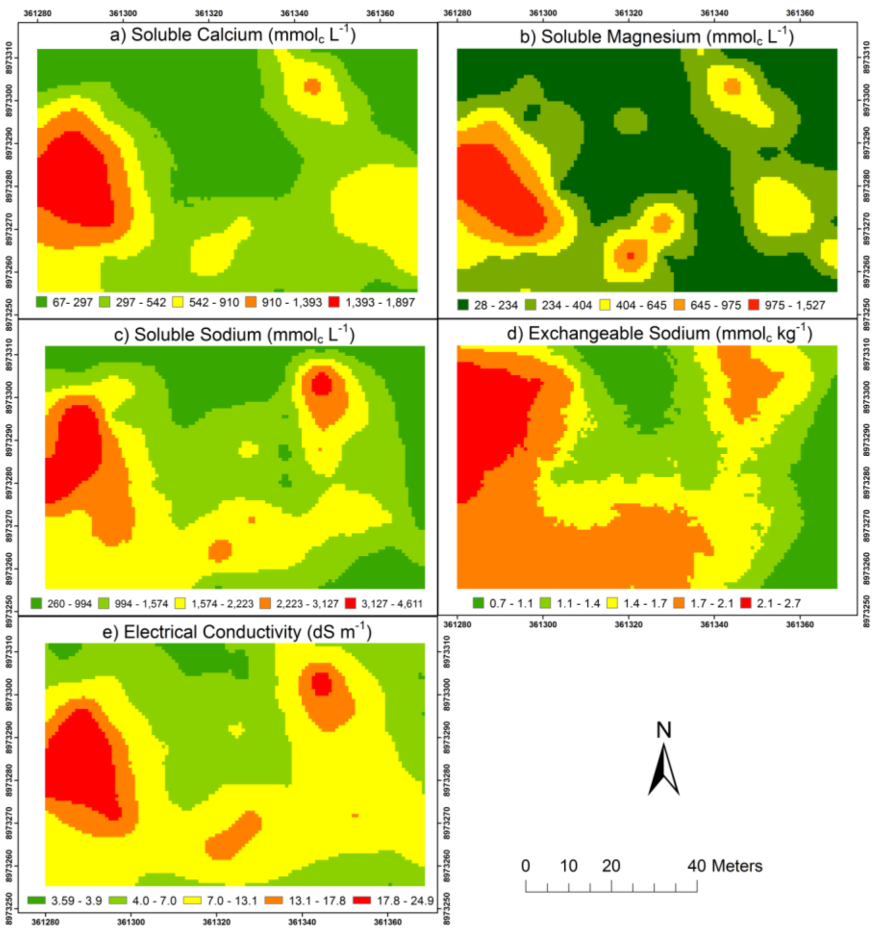

Fig 1. Mapping soluble calcium (a), magnesium (b), sodium (c), exchangeable sodium (d) and electrical conductivity collected from 0-0.2 m depth in the row spacing of an irrigated mango field in the semi-arid region, Brazil.

Table 2. Variogram model parameters and cross validation analysis of soil attributes from 0 to 0.2 m depth in an irrigated mango field in the semi-arid region, Brazil

Variable	Model	C_o[a]	Sill (C_o+C)	Range (m)	[C_o/C+C_o]x100	Cross validation analysis			
						RC[b]	SE[c]	ME[d]	RMSE[e]
	Soil samples collected under the canopy								
Sand (%)	Exp.[f]	33.100	71.580	78	46	1.069	0.180	0.022	6.6
Clay (%)	Exp.	12.220	23.400	20	52	1.010	0.247	-0.059	5.2
Silt (%)	Sph.[g]	6.620	13.250	64	50	0.977	0.187	0.012	3.0
pH	PNE.[h]	0.137	0.137	-	100	-	-	-	-
EC[i]	PNE.	0.035	0.035	-	100	-	-	-	-
	Soil samples collected in the row spacing								
Sand (%)	Sph.	3.410	16.100	67	21	1.033	0.104	0.14	2.2
Clay (%)	Sph.	3.370	6.741	81	50	0.695	0.241	-0.107	2.1
Silt (%)	Sph.	2.160	7.317	62	29.5	0.951	0.132	0.032	1.9
pH (H_2O)	Exp.	0.1453	0.2916	45	50	1.034	0.178	-0.003	0.43
EC	Sph.	6.138	36.753	18	17	0.756	0.138	-1.029	4.17
Ca^{2+} (E)[j]	Sph.	11.683	30.385	19	38	0.901	0.203	0.029	4.84
Mg^{2+} (E)	Sph.	3.510	10.880	80	32	1.138	0.132	-0.092	2.02
K^{+} (E)	Exp.	0.505	1.596	17	32	0.842	0.211	-0.059	1.08
Na^{+} (E)	Exp.	0.909	1.354	75	67	0.749	0.293	-0.005	1.08
CEC[k]	PNE.	164	164	-	-	-	-	-	-
ESP[l]	PNE.	7.77	7.77	-	-	-	-	-	-
Ca^{2+} (S)[m]	Sph.	50600	247400	32	20	0.932	0.111	-8.95	370
Mg^{2+} (S)	Exp.	8500	120700	33	7	0.916	0.130	-5.79	271
K^{+} (S)	Exp.	3756	11270	23	33	0.741	0.249	-2.311	97.75
Na^{+} (S)	Exp.	642259	1793000	19	36	1.031	0.211	-54.9	1201

[a]Nugget Effect; [b]Regression coefficient; [c]Standard error of RC; [d]Mean error; [e]Root mean square error; [f]Exponential model; [g]Spherical model; [h]Pure Nugget Effect; [i]Electrical conductivity (dS m^{-1}); [j]Exchangeable cation ($mmol_c$ kg^{-1}); [k]Soil cation exchange capacity; [l]Exchangeable sodium percentage; [m]Soluble cation ($mmol_c$ L^{-1})

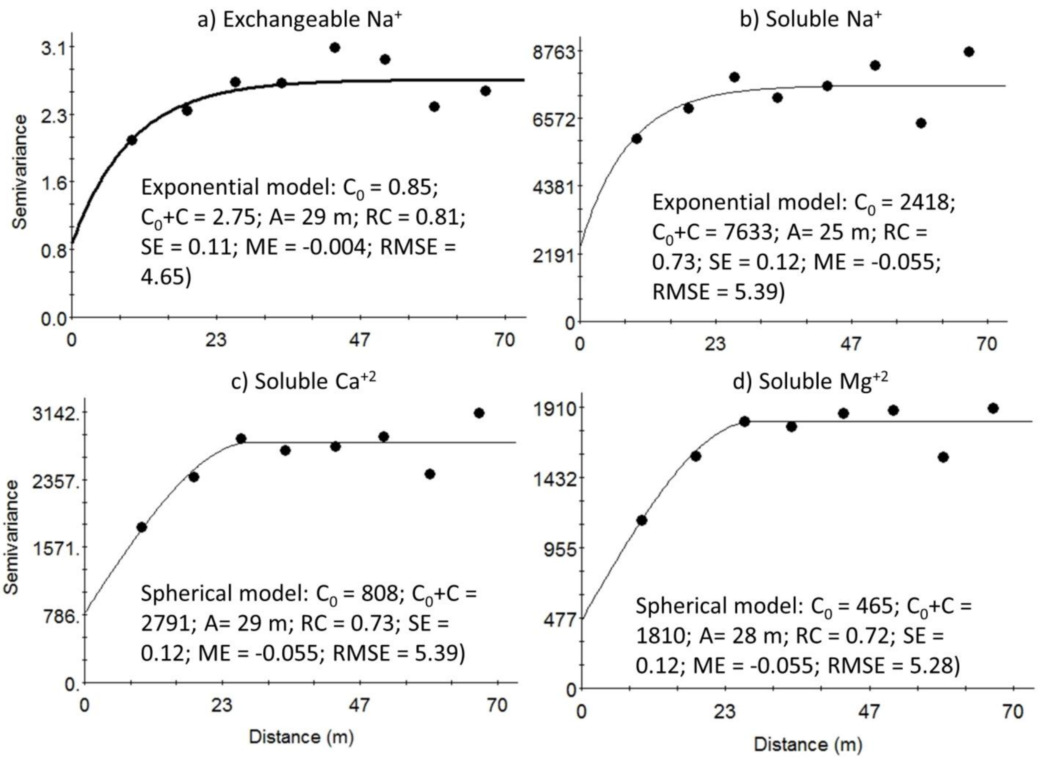

Fig 2. Cross variogram between soil electrical condutivity and soil exchangeable sodium (a), soluble sodium (b), calcium (c) and magnesium (d) collected from 0-0.2 m depth in the row spacing of an irrigated mango field in the semi-arid region, Brazil.

Visual similarity between soil EC map and exchangeable cations maps (Supplementary Figure 3) was not observed, except for exchangeable sodium (Figure 1d). It indicates that the spatial distribution pattern is not determined by these exchangeable cations. However, it is possible to observe a visual similarity between soil EC map and soluble Ca (Figure 1a), Mg (Figure 1b) and Na (Figure 1c) maps.

The results of spatial correlation confirmed the visual comparison of maps, showing that higher spatial correlation coefficients were found between soil EC and exchangeable Na^+ (r = 0.58) and soluble Ca^{2+} (r = 0.91), Mg^{2+} (r = 0.90) and Na^+ (r = 0.93), which were all statistically significant (p-value < 0.05) and positive. Soluble Ca^{2+}, Mg^{2+} and Na^+ maps can be classified as highly correlated to soil EC map since spatial correlation coefficients were greater than 0.90. These results are in accordance with those found by Bilgili (2013), who verified positive correlation between soil EC and exchangeable Na^+, soluble Ca^{2+}, Mg^{2+}, K^+ and Na^+ in soils that have been formed on calcareous materials (Vertisols, Fluvisols, Calcisols, Cambisols, and Leptosols - FAO classification) in the semi-arid region of Southeastern Turkey.

Cross-variograms fitting

In addition, cross-variograms were fitted to confirm spatial dependence between soil EC and the soil variables (Figure 2). Corroborating with spatial correlation coefficient results, cross-variograms were fitted only between soil EC and soil exchangeable Na^+, soluble Na^+, Ca^{2+} and Mg^{2+} (Figure 2). Montenegro and Montenegro (2006) fitted cross-variograms between EC and silt content and hydraulic conductivity in a loamy and sandy loam soil in the state of Pernambuco, Brazil. The range of spatial dependence between EC and these variables were very similar (range = 25-29 m) (Figure 2). These results are very important because they indicate which variables are defining the soil EC spatial distribution pattern. Therefore, decisions about management can be taken based on this information.

High levels of soluble Ca^{2+} and Mg^{2+} may be related to soil correctives and some fertilizers used in this experimental field condition, such as calcium nitrate. Additionally, calcium nitrate is used to induce flowering in mango trees every year. Calcium and magnesium may replace Na^+ in soils exchange complex to move Na^+ to the soil solution (Holanda et al., 1998). These results also explain low values of ESP in this study.

Practical implications of salinity mapping

Based on the results of this study, some practical implications about soil and irrigation management can be made. First of all, the general results of this paper showed that soil salinity in the row spacing can be harmful to plants, mainly for older trees like the ones in this study (13 years old), since their root system is reaching the row spacing. Thus, this present work showed that the recommended way to collect soil samples from mango in the canopy region is not always the most efficient way and perhaps other approaches should be considered.

Apparently, the high soil salinity is mostly due to inappropriate irrigation management in the semi-arid region of Southeastern Turkey Bilgili (2013). Therefore, change in irrigation method may be an alternative to reduce soil salinity and sprinkle irrigation methods should be preferred over furrow irrigation to decrease the amount of irrigation water used (Cemek et al., 2006). Since ESP showed low values (< 15 %), soil corrective application such as agricultural gypsum is not necessary. However, the concentration of sodium in soil solution is very high and can implicate sodicity in the future. The Ca^{2+} and Mg^{2+} ions are less soluble than Na^+. In the semi-arid climate, when soil solution is concentrated due to high evapotranspiration, Ca^{2+} and Mg^{2+} precipitate before Na^+. As a result, Na^+ may become the predominant cation in the soil solution. If this continues, Na^+ can displace other cations from the soil exchange complex by mass action, even though its adsorption selectivity is lower than Ca^{2+} and Mg^{2+}. (Ribeiro, 2010).

The excess of soluble salts should be removed by a soil washing and some underground drains should be built, so that the excess water from rainfall or irrigation can be removed. In an experiment carried out by Santos et al. (2013b) phytoremediation with *Atriplex nummularia* (halophyte plant adapted to the semi-arid region of Brazil) showed to be alternatively efficient in reducing the levels of salts in the soil in a saline-sodium soil in the state of Pernambuco. It assists in maintaining soil structure (expansion of the area occupied by the roots) and contributes to carbon sequestration, besides being a great alternative source of protein for ruminants. Therefore, this plant species can be cultivated in the row spacing of mango trees. Fertilizer management in the study area is done by putting fertilizers in the soil in the region of the plant canopy with few technical criteria. This is not very efficient and over-fertilization is often performed. Thus, more efficient fertilization methods such as ferti-irrigation should be adopted.

In agreement with Zheng et al. (2009), evaluation of spatial variability of soil salinity and mapping the spatial distributions of these soil properties can help farmers and agricultural managers to make effective site-specific management decisions. Thus, the spatial predictions from an economical point of view have a special and particular importance for fruit farming (Juan et al., 2011).

Materials and Methods

Site description

This experiment was carried out in the Maniçoba irrigated perimeter, Juazeiro County, in the state of Bahia, northeastern Brazil, (9°17' 8.617'' S, 40° 15' 46.742'' W, elev. 375 m a.s.l.) (Supplementary Figure 1). The climate of the region, according to the Köppen classification, is of the ‘hot semi-arid’ (Bsh') type, characterized by high temperatures (average 26 ºC), low humidity, high evaporation rates, and especially marked by the scarcity and irregular rainfall distribution (400 mm). The soil of the experimental area was classified as an Alfisol - American Classification Soil Taxonomy (Soil Survey Staff, 2014) or Luvissolo Háplico - 'Sistema Brasileiro de Classificação de Solos' (Santos et al., 2013a). The water used in irrigation from the São Francisco River showed electrical conductivity = 0.106 dS m^{-1}, Na^+ = 0.586 $mmol_c$ L^{-1}, Ca + Mg = 0.120 $mmol_c$ L^{-1}, and sodium absorption ratio = 2.390 (mmol$_c$ L^{-1})$^{0.5}$, classified as low salinity (C1) and sodicity risk (S1) (Ayers and Westcot, 1985).

The experimental area was a 13-year-old (2002-2015) commercial mango orchad (cv. Tommy Atkins) irrigated by furrow. Previously, from 1992 to 1997, the area was used for livestock farming. After that, oleraceus crops (tomatoes, melon, watermelon, and pumpkin), cassava and corn were cultivated from 1997 to 2002. Commonly practiced in many farms in the region, fertilization is mostly based on the experience and intuition of farmers, thus, many of them rarely use soil analysis and correct fertilizer recommendation, which may aggravate the salinization problem. The fertilization management was performed as the following: 300 g per plant of potassium chloride, 200 g per plant of 15-07-32 (N-P-K), 60 g per plant of monoamonic phosphate (MAP), 35 g per plant of granulated fertilizer of micronutrients (2.5 % of Boron, 7.5 % of Copper, 12.0 % Manganese, 5.0 % of Zinc and 6.0 % of Iron), 300 g per plant of calcium nitrate was applied three times during the fruiting stage every year.

Soil sampling and laboratory analysis

The experiment was performed based on observation of necrotic leaves in his orchard, indicating a salinity problem (Zuazo et al., 2004). However, the soil analysis did not indicate high values of electrical conductivity when the soil sampling was performed in the canopy of the plant, which is the recommended way to collect soil samples. Due to this fact, it was decided to establish two soil sample grids, one in the canopy region and another in the row spacing, to verify the influence of irrigation on the spatial distribution of soil salinity. One of them consisted of soil samples collected under the canopy of the mango trees with 96 georeferenced points, which correspond to the number of mango trees spaced 8 × 8 m. The other one consisted of 96 georeferenced points, but the samples were collected in the row spacing (8 × 8 m). Thus, two dataset were obtained and analyzed separately.

Soil samples were collected in each georeferenced point using a Dutch auger (0.2-m depth). Samples were dried at room temperature and passed through a sieve with apertures of 2.0 mm. Each soil sample was analyzed for particle size (pipette method), pH (1:2 soil/water mixture) and soluble and exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) in saturated paste extract and ammonium acetate (NH_4OAc – 1.0 mol L^{-1} and pH 7.0) extract, respectively (USSLS, 1954). The cation exchange capacity ($CEC_{pH7.0}$) was determined from index cation extraction method using sodium acetate (NaOAc – 1.0 mol L^{-1} pH 7.0) and ammonium acetate (NH_4OAc – 1.0 mol L^{-1} and pH 7.0) (USSLS, 1954). Soil exchangeable sodium percentage (ESP) was calculated (ESP = ([Na^+/$CEC_{pH7.0}$]x100) (USSLS, 1954). Electrical Conductivity (1:2 soil/water extraction - EC_{we}) was also determined (Souza et al., 2013). As observed by Souza et al. (2013), the EC_{we} values were lower than those obtained by saturated paste extract (EC_{spe}) method, which is the recommended method of soil EC analysis in Brazil. Therefore, in order to convert EC_{we} to EC_{spe} values, a regression analysis was performed. Solutions corresponding to 0, 10, 20, 30, 40 and 50 mmol L^{-1} concentrations of KCl were performed and EC was measured by both methods, water extraction method and saturated paste extract method. The following regression equation was used to convert EC_{we} to EC_{spe} (Eq. 1. R^2 = 0.92; p < 0,05).

$$EC_{spe}=2,3503+5,2006(EC_{we}) \qquad (1)$$

Preliminary statistical analyses

Descriptive statistical analyses (mean, maximum, minimum and coefficient of variation - CV, the coefficient of asymmetry and kurtosis) were calculated. The variability of soil attributes were classified according to the method of Warrick and Nielsen (1980). To test the hypothesis of normality, the Ryan-Joiner test was conducted.

Geostatistical analyses and mapping

Spatial dependence of samples was estimated using experimental semivariogram and theoretical mathematics models (Oliver and Webster, 2014). Cross-validation method was used for comparing the semivariogram models and indicated which model gave the best results (Sun et al., 2009). This method involves consecutive remove of a data point, interpolating the value from the remaining observations and comparing the predicted value with the measured value (Xie et al., 2011). Four indexes were used to determine the best semivariogram models which were: Regression Coefficient (RC), Standard Error (SE), Mean Error (ME), and Root Mean Square Error (RMSE). The RC represents a measure of the goodness of fit for the least-squares model describing the linear regression equation. A perfect 1:1 fit would have a regression coefficient (slope) of 1.00 (Machado et al., 2015). The SE refers to the standard error of the regression coefficient. The ME and RMSE calculated from the measured and interpolated values using the model tested were used to compare the accuracy of the predictions (Li and Heap, 2011). The ME is defined by (Equation 2):

$$ME = \frac{1}{n_v}\sum_{i=1}^{n_v} v_i \qquad (2)$$

Where; v_i was the difference between predicted value and observed value at location s_i, i 1,…, n_v, and n_v was the number of values in the check data set.

The RMSE was the sum of accuracy and precision, and it represents the error in the variable unit. It was defined in Equation (3):

$$RMSE = \sqrt{\frac{1}{n_v}\sum_{i=1}^{n_v} v^2{}_i} \qquad (3)$$

Where; v_i^2 was the difference between the square of predicted value and observed value at location s_i, i 1,…, n_v, and n_v was the number of values in the check data set. Smaller ME and RMSE values indicate fewer errors.

After the estimation of experimental semivariograms and adjustment of theoretical models, the data were interpolated using ordinary kriging, generating soft maps. Kriging is a generic term for a range of least squares methods to provide the best linear unbiased predictions, best in the sense of minimum variance (Oliver and Webster, 2014).

In order to verify which soil attribute(s) better explain the spatial pattern variability of soil salinity, two approaches were performed. First, a correlation matrix of maps between soil EC and the other variables were applied. Secondly, cross-semivariograms were estimated. EC was used as a dependent variable and the other soil attributes as a covariate. The soil variables were used to estimate the cross-semivariogram only when presented simple semivariograms, i.e., presented spatial dependence (Li and Heap, 2011).

Conclusion

Soil salinity assessed by electrical conductivity showed spatial dependence in the row spacing of the mango trees. The soil attributes which better defined the spatial distribution pattern of soil salinity were exchangeable sodium content and soluble sodium, calcium, and magnesium content. In addition, it was possible to determine three management zones based on their soil EC values, which were classified as salic 63 % of the area, saline 34 % of the area, and not saline, 3 % of the area. This study clearly showed that possible soil salinity problems in the development of mango plants may be due to the accumulation of salts in the plant spacing and not in the canopy region, where the soil sampling for fertilization is usually recommended.

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References

Akramkhanov A, Martius C, Park SJ, Hendrickx, JMH (2011) Environmental factors of spatial distribution of soil salinity on flat irrigated terrain. Geoderma. 163(1-2): 55-62.

Amaral FCSD (2011) Sistema brasileiro de classificação de terras para irrigação: Enfoque na região semiárida. 2th edn. Embrapa Solos, Rio de Janeiro.

Ayers RS, Westcot DW (1985) Water quality for irrigation. Food and Agriculture Organization of the United Nations, Rome. (FAO Irrigation and Drainage Paper, 29).

Bilgili A (2013) Spatial assessment of soil salinity in the harran plain using multiple kriging techniques. Environ Monit Assess. 185(1):777-795.

Cemek B, Güler M, Kiliç K, Demir Y, Arslan H (2006) Assessment of spatial variability in some soil properties as related to soil salinity and alkalinity in bafra plain in northern turkey. Environ Monit Assess. 124(1):223-234.

Costa DMAD (2008) Impactos da irrigação na variabilidade espacial e temporal da salinidade de um solo aluvial no semi-árido potiguar. Holos. 5(2):62-71.

Genú PJDC, Pinto ACDQ (2002) A cultura da mangueira. Embrapa Informação Tecnológica, Brasília.

Holanda JS, Vitti GC, Salviano AAC, Medeiros JDF, Amorim JRA (1998) Alterações nas propriedades químicas de um solo aluvial salino-sódico decorrentes da subsolagem e do uso de condicionadores. Rev Bras Cienc Solo. 22(3):387-394.

IBGE-Instituto Brasileiro de Geografia e Estatística (2013) Sistema IBGE de recuperação eletrônica (SIDRA). Available from: http://www.sidra.ibge.gov.br. [Last accessed on 2016 August 2].

Juan P, Mateu J, Jordan MM, Mataix-Solera J, Meléndez-Pastor I, Navarro-Pedreño J (2011) Geostatistical methods to identify and map spatial variations of soil salinity. J Geochem Explor. 108(1):62-72.

Li J, Heap AD (2011) A review of comparative studies of spatial interpolation methods in environmental sciences: Performance and impact factors. Ecol Inform. 6(3–4):228-241.

Machado FC, Montanari R, Shiratsuchi LS, Lovera LH, Lima EDS (2015) Spatial dependence of electrical conductivity and chemical properties of the soil by electromagnetic induction. Rev Bras Cienc Solo. 39(4):1112-1120.

Melo RM, Barros MDFC, Santos PMD, Rolim MM (2008) Correção de solos salino-sódicos pela aplicação de gesso mineral. Rev Bras Eng Agríc Amb. 12(4):376-380.

Montenegro AAA, Montenegro SMGL (2006) Variabilidade espacial de classes de textura, salinidade e condutividade hidráulica de solos em planície aluvial. Rev Bras Eng Agríc Amb. 10(1):30-37.

Oliver MA, Webster R. (2014) A tutorial guide to geostatistics: computing and modelling variograms and kriging. Catena. 113:56-69.

Queiroz JE, Gonçalves ACA, Souto JS, Folegatti MV (2010) Avaliação e monitoramento da salinidade do solo. In: Gheyi HR, Dias NS, Lacerda CF (ed). Manejo da salinidade na agricultura: estudos básicos e aplicados, Instituto Nacional de Ciência e Tecnologia em Salinidade, Fortaleza. 63-82.

Ribeiro MR (2010) Origem e classificação dos solos afetados por sais. In: Gheyi HR, Dias NS, Lacerda CF (ed) Manejo da salinidade na agricultura: Estudos básicos e aplicados, Instituto Nacional de Ciência e Tecnologia em Salinidade, Fortaleza. 11-19.

Rodrigues MS, Corá JE, Fernandes C (2012) Spatial relationships between soil attributes and corn yield in no-tillage system. Rev Bras Cienc Solo. 36(2):599-609.

Rodrigues MS, Santana MC, Uchôa ALP, Menezes AXDSMD, Cavalcante ÍHL, Lima AMN (2015) Delineation of management zones based on soil physical attributes in an irrigated guava field in the semi-arid region, Brazil. Afric J Agric Res. 10(45):4185-4192.

Sun Y, Kang S, Li F, Zhang L (2009) Comparison of interpolation methods for depth to groundwater and its temporal and spatial variations in the minqin oasis of northwest china. Environ Modell Softw. 24(10):1163-1170.

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF (2013a) Sistema brasileiro de classificação de solos. 3 rd edn. Embrapa Solos, Rio de Janeiro.

Santos MA, Freire MBGS, Almeida BG, Lins CMT, Silva EM (2013b) Dinâmica de íons em solo salino-sódico sob fitorremediação com atriplex nummularia e aplicação de gesso. Rev Bras Eng Agríc Amb. 17(4):397-404.

Soil Survey Staff. Keys to soil taxonomy (2014) 12th edn. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

Souza ER, Montenegro AADA, Montenegro SMGL, Santos TEMD, Andrade TDS, Pedrosa ER (2008) Variabilidade espacial das frações granulométricas e da salinidade em um neossolo flúvico do semi-árido. Cienc Rural. 38(2):698-704.

Souza ERD, Melo HFD, Almeida BGD, Melo DVMD (2013) Comparação de métodos de extração da solução do solo. Rev Bras Eng Agríc Amb. 17(5):510-517.

USSLS-United States Salinity Laboratory Staff (1954) Diagnosis and improvement of saline and alkali soils. United States Department of Agriculture, Washington, DC.

Xie Y, Chen T-B, Lei M, Yang J, Guo Q-J, Song B, Zhou X-Y (2011) Spatial distribution of soil heavy metal pollution estimated by different interpolation methods: Accuracy and uncertainty analysis. Chemosphere. 82(3):468-476.

Warrick AW, Nielsen DR (1980) Spatial variability of physical properties in the field. In: Hillel D, (ed). Applications of soil physics, Academic Press, New York. 319-344.

Wu J, Norvell WA, Welch RM (2006) Kriging on highly skewed data for DTPA-extractable soil Zn with auxiliary information for ph and organic carbon. Geoderma. 134(1-2):187-199.

Zheng Z, Zhang F, Ma F, Chai X, Zhu Z, Shi J, Zhang, S (2009) Spatiotemporal changes in soil salinity in a drip-irrigated field. Geoderma. 149(3-4): 243-248.

Zuazo VHD, Raya AMN, Ruiz JA (2004) Impact of salinity on the fruit yield of mango (*Mangifera indica* L. cv. 'osteen'). Eur J Agron. 21(3):323-334.