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Identification and diagnosis of salt-affected soils in the Baixo-Açu irrigated perimeter, RN, Brazil[1]

Identificação e diagnóstico de solos afetados por sais no perímetro irrigado Baixo-Açu, RN, Brasil

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HIGHLIGHTS:
Spectral analysis is feasible to identify salinized areas.
The most saline areas are lowlands with deficiency of natural drainage.
The studied soils are saline in surface and saline-sodic in subsurface.

ABSTRACT: Soil salinization is one of the main environmental problems in arid and semi-arid regions. Thus, the objective of this study was to evaluate the problems of soil salinity in an area of the Baixo-Açu Irrigated Perimeter, RN, Brazil, through joint analysis using remote sensing, pedology and geostatistics techniques. The study was conducted in the Baixo-Açu Irrigated Perimeter (1500 ha), with soil salinity sampling at 42 points, used to correlate with the Salinity Index 1 (SI1) spectral index. After spectral analysis, one of the lots identified with salinity problems was selected and subjected to pedological analysis to classify the problems of soil salinity in surface and in subsurface. Subsequently, 45 points were sampled in the same lot to assess the spatial distribution of soil salinity and diagnosis of the problem of salinity using geostatistical analysis. The SI1 index in areas with Normalized Difference Vegetation Index (NDVI) < 0.33 showed the highest correlation with soil electrical conductivity. The soil in the evaluated area showed saline horizon in surface and saline-sodic horizon in subsurface. The areas most affected by salinity are concave areas, with deficiency of natural drainage.

Key words: electrical conductivity, geostatistics, pedology, remote sensing

RESUMO: A salinização do solo é um dos principais problemas ambientais em regiões áridas e semiáridas. Deste modo, objetivou-se avaliar os problemas de salinidade do solo em uma área do Perímetro Irrigado do Baixo-Açu, RN, Brasil, por meio de análise conjunta empregando técnicas de sensoriamento remoto, pedologia e geoestatística. O estudo foi desenvolvido no Perímetro Irrigado do Baixo-Açu (1500 ha), com amostragem da salinidade do solo em 42 pontos amostrais, utilizados para correlacionar com o índice espectral 'Salinity Index 1' (SI1). Após a análise espectral selecionou-se um dos lotes identificados com problemas de salinidade, no qual foram realizados estudos pedológicos, para fins de classificação dos problemas de salinidade do solo em superfície e subsuperfície. Posteriormente, no mesmo lote foram amostrados 45 pontos para avaliação da distribuição espacial da salinidade do solo e diagnóstico do problema de salinidade utilizando análise geoestatística. O índice SI1 em áreas com 'Normalized Difference Vegetation Index' (NDVI) < 0,33 apresentou a maior correlação com a condutividade elétrica do solo. O solo da área avaliada apresentou horizonte salino em superfície e horizonte salino-sódico em subsuperfície. As áreas mais afetadas pela salinidade são áreas côncavas, com deficiência de drenagem natural.

Palavras-chave: condutividade elétrica, geoestatística, pedologia, sensoriamento remoto

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Introduction

Soil is a natural resource of fundamental importance in the maintenance of human life. Besides being the main substrate used by plants for storage, cycling and consumption of nutrients necessary for development, it acts as an environmental filter in regulating the flow and infiltration of rainwater (Muggler et al., 2006).

Salt-affected soils occur worldwide, especially in regions where atmospheric demand is higher than precipitation and which have shallow soils on a basement of crystalline rocks. In Brazil, the main occurrence of these soils is in the semi-arid region, mainly in irrigated perimeters, where soils are characterized by high concentrations of soluble salts, exchangeable sodium and/or both, which restrict the development and yield of the main agricultural crops (Lima et al., 2010; Mesquita et al., 2015; Sá et al., 2015; Santos et al., 2019).

The use of mapping and identification technologies as well as the mapping of salinized areas have been widespread worldwide (Lemos Filho et al., 2017), since the identification of salinization in its initial stage is of fundamental importance for the application of preventive or corrective techniques to reduce the impact of the problem (Farifteh et al., 2007). The use of spectral indices of images obtained by satellites is shown to be a promising tool for the detection and evaluation of salinized areas (Allbed & Kumar, 2013; Yahiaoui et al., 2015; Scudiero et al., 2016). In addition, the study of spatial variability of salinity contributes with additional information for soil management and reclamation (Resende et al., 2014; Carolino et al., 2017). Thus, the objective was to evaluate soil salinity problems in an area of the Baixo-Açu Irrigated Perimeter, RN, Brazil, through joint analysis using remote sensing, pedology and geostatistics techniques.

Material and Methods

The study was carried out in the Baixo-Açu Irrigated Perimeter, RN, Brazil, in an area with approximately 1500 ha. It is geographically located between the coordinates 5° 20' and 5° 30' of South latitude and between the coordinates 36° 30' and 36° 50' of W longitude, at an mean altitude of 16 m. The climate of the region is BSw'h', hot and semi-arid, with average annual temperature of 27.5 °C and mean annual precipitation of 570 mm, with 66.6% of the rains concentrated in the months from March to May (Diniz & Pereira, 2015). The irrigated perimeter is supplied by the waters of the Piranhas-Açu River, from its upstream damming. Water quality is classified as C1S1, water with low risk of salinization and problems with sodium accumulation in the soil (Ayers & Westcot, 1985).

To evaluate the spectral characteristics of exposed areas with salinization problems, images of OLI/Landsat-8 sensors with spatial resolution of 30 m were used. The images were submitted to the atmospheric correction process. To characterize the dynamics of the spectral behavior of the sampling points with exposed soil under salinization, spectra of the Salinity Index 1 ($SI1 = (Green \times Red)^{1/2}$) were extracted according to Khan et al. (2001).

To use the spectral index, 42 points were selected in the irrigated perimeter. The samples were collected in the 0-10 cm layer between September and December 2017 (dry season). The sampling points were georeferenced with a Garmin e-Trex GNSS device. The electrical conductivity of the saturation extract was determined according to the methodology described by Richards (1954).

In order to understand the interference of vegetation in the use of spectral indices, the collection points were divided into two groups: the first composed of all points, and the second composed of all points that had Normalized Difference Vegetation Index (NDVI) below 0.33, which characterizes areas with exposed soil (Moreira et al., 2015).

After spectral analysis of the soils with salinity problems in the Baixo-Açu Irrigated Perimeter, lot 79 (7.3 ha) was selected for classification and diagnosis of salinity problems. For classification of the soil, a soil profile was opened within lot 79, in an area cultivated with banana (*Musa paradisiaca*), which corresponds to a plot of approximately 1.0 ha with spacing in double rows (4 x 2 x 2 m), with four years of implementation located on a flat elevation top (interfluve).

The soil of the area is classified as Inceptisol with solodic character, with 6-15% exchangeable sodium percentage (ESP) in one or more horizons or layers within 150 cm from its surface (Santos et al., 2018). For this, the horizons (Ap, Bi and BC) were identified and classified according to salinity and sodicity, based on the attributes ESP (Teixeira et al., 2017), electrical conductivity (ECse) and pH (pHse) of the saturation paste, obtained by the methodology proposed by Richards (1954).

In the soil of lot 79, geostatistical analysis was applied to diagnose the causes of the soil salinization problem. The chosen area has 7.3 ha, where a grid with five rows and nine columns was established in order to perform the collection at the points of intersection, thus totaling 45 collection points equidistantly spaced by 40 m. The data were geolocated in UTM coordinates, which is a metric system that provides better applicability to geostatistical analyses due to the minimal deformation of the area. The samples were collected in the 0-20 cm layer using an auger, identified, and sent to the laboratory for the determination of electrical conductivity by the methodology proposed by Richards (1954).

Classical statistics was applied in order to obtain measures of position (mean, maximum values, minimum values) and dispersion (standard deviation and coefficient of variation). In the fits of the theoretical models to the experimental semivariograms, Gs+ 7.0 software (Gamma Design Software) was used to obtain the values of nugget effect, structural variance, sill and range. Regarding the coefficient of variation, the interpretation proposed by Warrick & Nielsen (1980) was used, in which the coefficient of variation can be classified as low, medium and high, for the respective intervals $CV \leq 12\%$, $12\% < CV < 60\%$ and $CV \geq 60\%$.

The spherical model was selected, as it showed the best fit and is the most commonly found model for soil attributes (Bertolani & Vieira, 2001). After tabulation of the data, interpolation was performed, in which estimates of unsampled points were obtained by cross-validation. QGIS software was used to construct the digital elevation model.

Results and Discussion

Of the sampled points, 50% had electrical conductivity less than 4 dS m^{-1} (non-saline soils), The Salinity Index 1 (SI1) showed higher correlations (above 0.8) using the MSI/Sentinel2 images, with Normalized Difference Vegetation Index (NDVI) < 0.33 (Table 1).

In the evaluation of all points, the correlation coefficient (r) was low (Table 1). Spectral mapping in saline areas has some limitations regarding regions with no salt concentration on soil surface and areas dominated by salt-resistant plants (halophytes) (Zhang et al., 2011).

Using the SI1 index and MSI/Sentinel2 images, applied only to areas with exposed soil (NDVI < 0.33), since areas considered with some type of surface vegetation were not considered in this classification (white areas), it is possible to classify them into four salinity classes (0-1; 1-5; 5-10 and >10 dS m^{-1}), according to the electrical conductivity (dS m^{-1}) (Figure 1).

The largest portion of the classification in the Baixo-Açu Irrigated Perimeter is considered to have low salinity (0 - 1 dS m^{-1}); however, it has areas with electrical conductivity greater than 10 dS m^{-1}, to a lesser extent. In the area of lot 79, soils belonging to all four salinity classes are identified, with predominance of classes 2 (1-5 dS m^{-1}), 3 (5-10 dS m^{-1}) and 4 (>10 dS m^{-1}), shown in Figure 1.

Table 1. Salinity index used in the mapping and its respective correlation coefficients (r) with the electrical conductivity of the soil, for areas with NDVI < 0.33 and all the points

Soil salinity index	r (NDVI < 0.33)	Satellite	r (all points)	Satellite
SI1	0.803	SENT	0.400	LAND

SI1 - Salinity index 1; NDVI - Normalized difference vegetation index

According to the classification of Richards (1954), the soil of the evaluated area is classified in surface as saline horizon and in subsurface as saline-sodic. Therefore, the Saline-Sodic classification prevails because it is a very deep profile and the root system of the crop has the highest accumulation of roots within the range of 0-30 and 0-60 cm (Table 2).

Table 3 shows the values of nugget effect, sill, range, coefficient of determination and degree of dependence (DD). The best method and fitting model were selected considering the evaluations of results obtained by the degree of dependence and coefficient of determination. According to the evaluation, the model adopted was spherical, agreeing with Bertolani & Vieira (2001), who discuss that this model is the most frequent when soil attributes are evaluated. According to the spatial dependence scale discussed in Cambardella et al. (1994), the data obtained for the analyzed attribute showed strong spatial dependence (DD > 75%).

The coefficient of variation, used to analyze the dispersion behavior of the data considering the mean value and the standard deviation, was equal to 17.82% (Table 3). Thus, the studied attribute showed medium variation. As for skewness, the positive result, with median lower than the mean, indicates

Table 2. Classification of soil profile[1] regarding salinity based on electrical conductivity, hydrogen potential and exchangeable sodium percentage of soil of lot 79 in the Baixo-Açu Irrigated Perimeter, Alto do Rodrigues, RN, Brazil

Horiz.	Layer (m)	Classification			
		pHse	ECse	ESP	USSL
Ap	0-0.15	8.52	4.11	13.54	Saline Horizon
Bi	0.15-0.33	8.32	4.91	16.04	Saline-Sodic Horizon
BC	0.33-0.60	8.06	7.76	22.63	Saline-Sodic Horizon

ECse - Electrical conductivity of the saturation extract; ESP - Exchangeable sodium percentage; [1] Richards (1954)

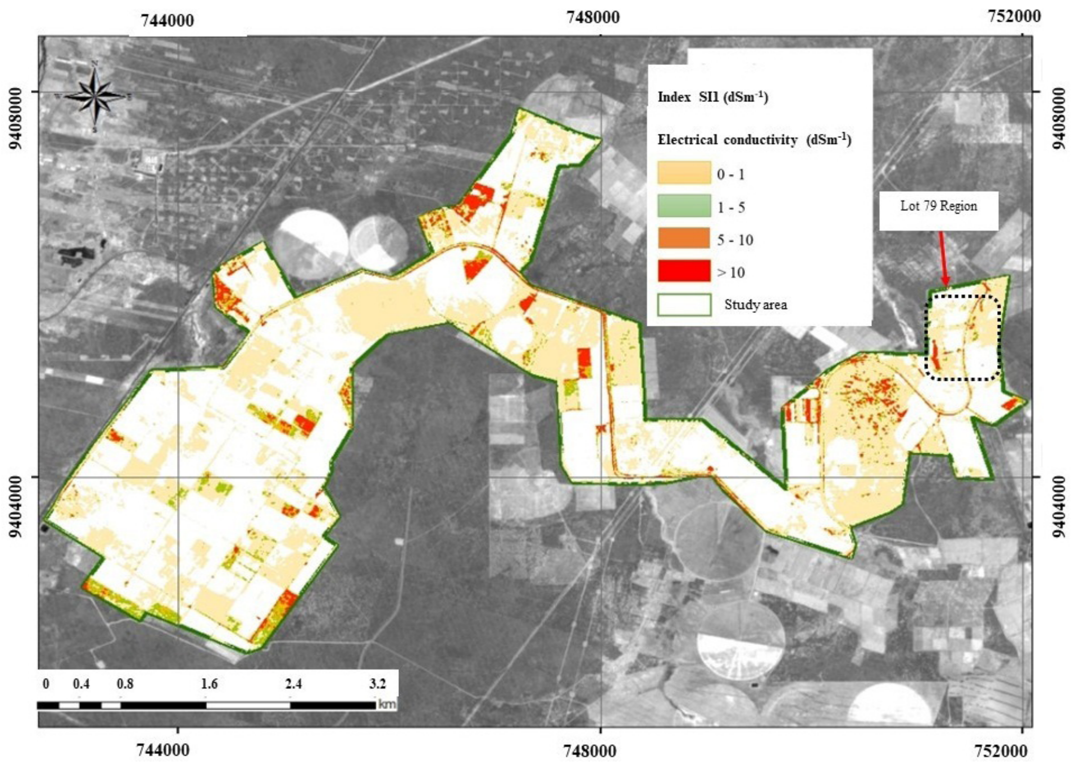

Figure 1. Spatialization of soil salinity in the study area for regions of exposed soil, with application of Salinity Index 1 (SI1) and MSI/Sentinel2 images

Table 3. Values of arithmetic mean ($\bar{X}$), standard deviation (S), maximum value (Vmax), minimum value (Vmin), skewness (Skw), kurtosis (Kur) and coefficient of variation (CV), nugget effect (C_0), Sill (C_0 + C), Range (A), coefficient of determination (R^2) and degree of spatial dependence (DD)

Variable	$\bar{X}$	S	Vmax ($dS\ m^{-1}$)	Vmin ($dS\ m^{-1}$)	Skw	Kur	CV (%)
ECse	3.419	4.222	25.4	0.53	3.75	15.66	17.82

Model	C_0	C_0 + C	A (m)	R^2	DD
Spherical	1.8	23.48	173	0.971	0.923

ECse - Electrical conductivity of the saturation extract

the higher frequency of ECse values lower than the mean. For the studied attribute, the positive kurtosis indicates lower spatial variability (Table 3).

In the geostatistical evaluation applied to lot 79 of the irrigated perimeter, considering only electrical conductivity as a factor, 46.66% of the sampling points had salinity problems (Figure 2). Within the lot, the results of ECse showed great variation, with values of 0.53 dS m^{-1} and even places with ECse of 25.4 dS m^{-1} (Table 3). The mean value obtained in the area was 3.419 dS m^{-1}, which indicates a limiting environment for the yield of some salinity-sensitive crops.

The kriging map with the spatial distribution of ECse and its relationship with the relief of the area are presented in Figure 2. It can be observed that the highest values of ECse were found in areas where the relief is lower. Souza et al. (2000), in analysis of areas regarding the susceptibility to salinization, considered areas with lower relief vulnerable to the development of salt accumulation, because they received influence from the higher areas, in addition to the difficulty of flow in lower areas and, consequently, greater propensity for salinization.

Inceptisols are soils of great agricultural relevance in the State of Rio Grande do Norte, including for banana cultivation, and require differentiated management due to their distinct physical, chemical and mineralogical characteristics (Costa et al., 2016). Studies indicate that the processes of soil formation, as well as nutrient and sediment transport, in Inceptisols are influenced by variations in microrelief (Oliveira et al., 2013; Artur et al., 2014; Costa et al., 2016). Oliveira et al. (2013), evaluating Inceptisols in

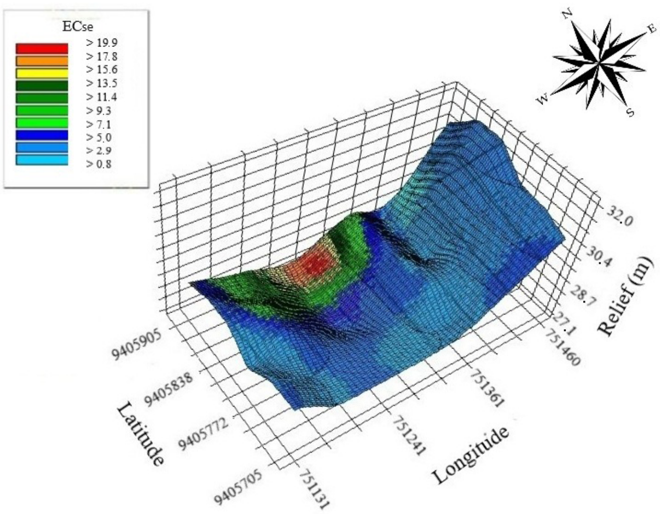

Figure 2. Spatial variation of soil electrical conductivity (ECse), estimated by kriging, with relief curves distributed in the evaluated area

the Apodi Plateau, verified that water dynamics and microrelief variations favored the formation of shallow soils on the convex surface of the terrain and deeper soils on the concave surface. Costa et al. (2016), evaluating the nutrient content and the viability of banana cultivation in Inceptisols with different depths, stated that Na^+ concentration was higher in plants that grew in deep soil and that the Na^+ contents in the two studied soils were above the critical content of 165 mg kg^{-1}.

The microrelief influences the drainage pattern and, consequently, the horizontal and vertical movement of water in the profile, accelerating the chemical reactions of weathering and promoting the transport of solids or materials in solution (Artur et al., 2014). Thus, there is an increase in the spatial variability of soil chemical attributes, favoring the identification of salt-affected soils. Resende et al. (2014), using ECse values for each sampling point and field observations, in the Califórnia Irrigated Perimeter in Sergipe, found that the extreme values of salinity were associated with deficient areas regarding the natural drainage network.

In the present study, it was verified that the most concave region of the microrelief is the most affected by salinity problems (Figure 2) and, although the nutritional study is not part of this approach, there is a strong tendency to problems with sodium toxicity in plants cultivated in the study area, since the soil has not only the saline character, but also the sodic character (Table 2). The risks with the excess of salts, mainly sodium, in the soil of lot 79 are clear, and it is necessary to adopt a management to reclaim the area, with installation of a drainage system for leaching salts from soil, as well as the intervention with chemical conditioners to displace the exchangeable sodium (Mesquita et al., 2015; Sá et al., 2015; Sá et al., 2018; Santos et al., 2019).

Conclusions

1. Salinity Index 1 (SI1) in areas with NDVI < 0.33 showed a higher correlation (r = 80.29%) with soil electrical conductivity.

2. The soil of the evaluated area has a saline horizon in surface and a saline-sodic horizon in subsurface.

3. The areas most affected by salinity are the concave ones, with deficiency of natural drainage.

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