CHARACTERIZATION OF SALT–AFFECTED SOIL IN THE SEMI–ARID REGION OF NORTHEASTERN BRAZIL[1] /

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Resumo

Com o objetivo de caracterizar a distribuição, superficial e em profundidade, de problemas de salinidade foram analisadas 525 amostras de solo, coletadas na profundidades de 0-20, 20-40 e 40-140 cm e correspondentes a 149 perfis de uma área de 504 hectares localizada no perímetro de irrigação de Morada Nova, Ceará, Brasil.

O mapeamento revelou que os solos sódicos e salino-sódicos ocorren em 25% da área estudada e que os problemas de salinidade e sodicidade aumentam em profundidade.

Características pecualiares foram verificadas nos solos sódicos e salino-sódicos. Os valores de pH predominantes situaram-se na faixa de 6.0 a 8.0, inferiores aos normalmente encontrados nesses solos. A relação Ca/Mg atingiu frequentemente valores inferiores à unidade. Sódico e cloreto foram os ions dominantes enquanto sulfato e bicarbonato ocorreram em pequenas quantidades notando-se ainda a ausência de carbonatos. Os valores de percentagem de sódio trocável (PST) foram mais elevados que os de relação de adsorção de sódio (RAS) quando determinados ou estimados. Baixos valores de condutibilidade hidráulica do solo saturado associados a altos conteúdos de argila, à predominância de argilo-minerais do grupo 2:1 a altos valores de PST representam dificuldades adicionais no manejo das áreas afetadas.

A variabilidade espacial das propriedades relacionadas, determinada através da amostragem intensiva de uma área de 0.8 hectares, situada no Perímetro de Irrigação de Pentecoste, revelou diferenças marcantes entre propiedades físicas e químicas do solo.

Introduction

Salt-affected soils of different origins occur extensively in northeastern Brazil. Soil association with a predominance of solodized solonetz, solodic planosol and solonchack, which contain variable amounts of sodium and/or sodium chloride, cover 13% of the state of Ceará (9). Alluvial soils, covering about 2% of the state's area, display salinity problems of variable degrees and are used extensively in irrigation agriculture. Due to their topographic position, the processes involved in their formation, and the climatic characteristics of the region, large areas of alluvial soils are presently salt-affected or pose salinity hazards, problems that increase in magnitude under irrigation practices. Evaluation and classification of salinity problems in irrigated areas constitute the first step in applying management practices to improve production, to prevent and control secondary processes of degradation and to reclaim areas already affected.

The objective of this study was to characterize salt-affected soils and determine the spatial variability of the related parameters in two representative areas of public irrigation districts established in alluvial soils.

1 Received for publication in July 26, 1985.

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Materials and methods

Soils

The alluvial soils studied occur in the rather narrow valleys of the main rivers of the state of Ceará and are used in irrigation agriculture due to their production, potential and position in relation to the large reservoirs that constitute the main source of water for irrigation. The location of the two public irrigation districts – Morada Nova and Pentecoste – where this study was conducted is shown in Figure 1. Soils are slightly developed, with layers of indiscriminate textures, and derived from sandy, silty and clayey sediments deposited during the Holocene (9). Their position in the general relief and in relation to other salt-affected soils of different origin is depicted in Figure 2 (14). The deficient natural drainage of some alluvial soils due to their texture and relatively low elevation above the river draining area, seepage from elevated adjacent areas, and periodic heavy rains contributes to the occurrence of shallow water tables that, with high evaporation rates, increase salinization hazards. Irrigation practice aggravates the drainage problem.

Climatic data of the areas studies are summarized below:

	Morada Nova	Pentecoste
Mean annual precipitation (mm)	600	699
Mean annual temperature (°C)	26.2	26.8
Mean daily evaporation (mm)	7.5	7.6

The rainy season is heaviest from January to July, followed by a six month dry period. The irregular temporal distribution and intensity of rainfall, as well as the ocurrence of droughts, are peculiar to both areas.

Methods of analysis

In the irrigation district of Morada Nova, an area of 504 hectares was selected for collection of 525 bulk soil samples from 149 soil profiles at depth intervals of 0-20, 20-40 and up to 140 cm according to changes in soil texture. Collection of undisturbed soil samples and *in situ* determination of saturated hydraulic conductiviy were performed in selected sites. Field textures were recorded at all profiles.

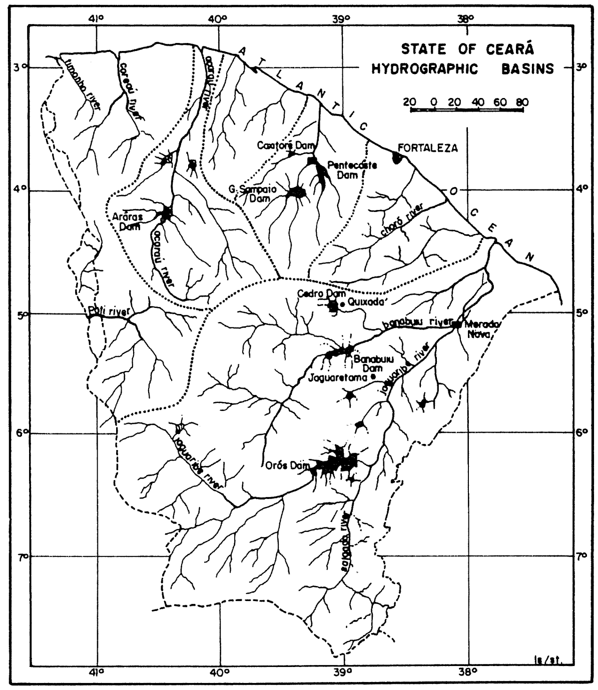

Fig. 1. Location of the study areas – Morada Nova and Pentecoste (■), and the cities of Quixadá and Jaguaretama (●) depicted in transect of Fig. 2.

Parameters determined were: pH (water, 1:1). electrical conductivity and soluble ions in the saturation extracts; Calcium and Ca + Mg by titration with EDTA 0.02 N and Mg estimated by difference; sodium and potassium by flame photometry; chloride by titration with $AgNO_3$ 0.025N; CO_3^{2-} and HCO_3^- by titration with H_2SO_4 0.01N (3); SO_4 estimated by difference and, in selected samples, determined by turbidimetry (12). Exchangeable cations Ca, Mg, Na and K were extracted in an excess of 1N NH_4Ac, pH 7.0, and measured by flame photometry; concentrations were corrected by subtracting the soluble cations determined in the saturation extract (22). Exchangeable H + Al were extracted in an excess of 1N CaAc, pH 7.0 and exchangeable H in 1N KCl, pH 7.0. Cation exchange capacity (CEC) was estimated by the sum of exchangeable cations.

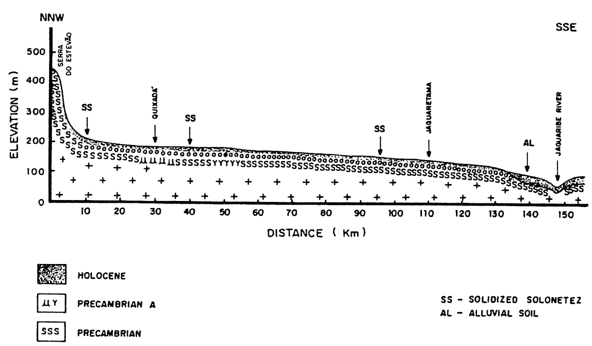

Fig. 2. Schematic cross section indicating topographic position of salt-affected soils different origins.

Sodium adsorption ratio (SAR), exchangeable sodium percentage (ESP) and exchangeable sodium ratio (ESR) were calculated according to Richards (19). Soluble sodium percentage (SSP = Na/Ca+Mg+Na+K) was also calculated. Water contents at 0.03 and 1.5 MPa were determined in porous plate extractors (19), aggregate stability by wet-sieving technique (15) and saturated hydraulic conductivity by the auger-hole method (2). X-ray difractograms of selected clay fraction samples were obtained.

An area of 0.8 hectares of alluvial soil, vertic torrifluvents (6), homogeneous in respect to soil classification, comprising 128 plots of 6 x 10 m, in the irrigation district of Pentecoste, was sampled to determine: a) soil bulk density (1), in 120 undisturbed cores obtained at 0-20, 30-40 and 50-60 cm depth from 40 plots randomly selected; b) percentage of water-stable aggregates (15), in 40 soil clods collected in the abovementioned plots; and c) the same chemical characteristics of the first study in 384 bulk samples collected at 0-30, 30-60 and 60-90 cm depth in the center of each plot.

Soil classification and mapping

To classify the soils according to EC and ESP values, five salinity and five sodicity classes were adopted (Table 1). The rationale for a detailed classification was to provide better interpretation of results for evaluation and monitoring evolution of salinity problems in the area studied. For mapping purposes, however, only four soil classes were used, as shown in Table 1, through grouping salinity and sodicity classes. Mapping was performed through isolines of EC and ESP.

Statistical analysis

To verify the correlation between characteristics studied, data were subjected to linear, quadratic, semilogarithimic and logarithimic regression analysis. To evaluate spatial variability of pertinent parameters in the Pentecoste area, overall mean, standard deviation and coefficient of variation were computed for the data. Number of sample (N) to estimate parametric mean (x) within a determined limit (f) at a significance level (t) was also computed by the expression $N = (CVt/f)^2$. Frequency distributions of bulk density, EC and ESP were also determined (13, 18, 23).

Results and discussion

Interpretation of field and laboratory data and soil classification and mapping revealed that sodic and saline-sodic soils cover approximately 25% of the 504 ha area studied in the public irrigation district of Morada Nova, with saline soils occurring in only 2.3% of the whole area.

Table 1. Salinity (A) and sodicity (B) classes, and soil classes used in mapping (C).

A

Salinity class	EC ($dS\ m^{-1}$)	Description	Map symbol
S 1	0–2	non-saline	A
S 2	2–4	slightly saline	B
S 3	4–8	moderately saline	C
S 4	8–16	strongly saline	C
S 5	16	very strongly saline	C

B

Sodicity class	ESP	Description	Map symbol
A 1	0–10	non-sodic	X
A 2	10–15	slightly sodic	Y
A 3	15–20	moderately sodic	Z
A 4	20–30	strongly sodic	Z
A 5	30	very strongly sodic	Z

C

Non-saline Non-sodic	Saline	Sodic	Saline-Sodic
S1A1	S3A1, S3A2	S1A3, S2A3	S3A3, S3A4, S3A5
S2A1	S4A1, S4A2	S1A4, S2A4	S4A3, S4A4, S4A5
S1A2	S5A1, S5A2	S1A5, S2A5	S5A3, S5A4, S5A5
S2A2			

Distributions of soil classes in one of the three plots that comprise the area (Figure 3a, b, c,) indicated that salinity and sodicity problems increase with depth. The percentage of salt-affected area is higher in the second plot and lower in the third, but the in-depth distribution is similar to that presented. Typical features of the sodic and saline-sodic soils mapped are fine texture, poor structural conditions, presence of cracks and low permeability.

Wide variety in field texture was detected, but 50% of the samples fell into clay loam, silty clay loam, silty clay and clay textural classes, half of these with more than 40% clay. Deteriorated structural conditions of sodic and saline sodic soils were indicated by the percentage or water stable aggregates of thirteen selected samples with wide ranges in ESP and EC and clayey textures. The lowest value of 1% aggregate stability corresponded to a sample with ESP of 35.6 and EC of 35 dS m^{-1}. Strong correlations were found between aggregate stability and ESP ($r = -0.74^{**}$). Low values of saturated hydraulic conductivity were associated with high contents of silt, clay and exchangeable sodium. Mean values for 37 layers of 16 selected sites were 2.31×10^{-6}, 5.79×10^{-6} and 34.72×10^{-6} ms^{-1} corresponding to clayey, loamy and sandy layers, respectively. Linear regression analysis of moisture content at saturation (water content of saturated paste) as a function of moisture content at 0.03 and 1.5 MPa showed significantly high correlation coefficients ($r = 0.81^{**}$ and 0.78^{**}, respectively).

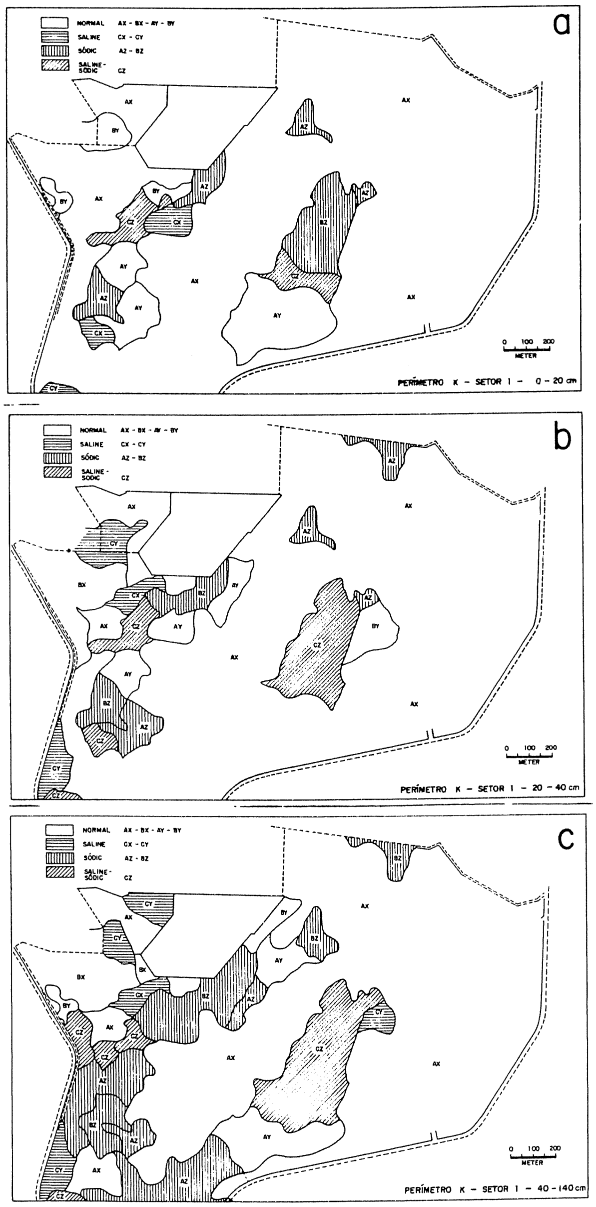

Fig. 3. Distribution of normal and salt-affected soils in plot 1 of Morada Nova study area, at depths of 0-20 (a), 20-40 (b) and 40-140 cm (c).

Some chemical characteristics of three typical profiles of non-saline non-sodic, sodic and saline-sodic soils are reported in Table 2. Results of analysis of the 525 samples revealed that 11.5% have an EC > 4 dS m^{-1}, with 75% of these in the range of 4-9 dS m^{-1}. The salinity problem is always associated with sodicity, saline soils being nearly absent in the studied area. Approximately 28% of the samples have an ESP > 15. The pH values ranged between 6.0 and 6.9 in 65% of the samples, and about 25% of the soils are slightly alkaline (pH between 7.0 and 8.0).

This suggests that a large number of soils studied are degraded sodic soils (19) with absence of carbonates and low pH values due to exchangeable hydrogen influenced by the periodic rains that occur in the region. However, their physical characteristics are typical of sodic soils. Most of the sample have high values of CEC, due to the presence of clayey soils with a predominance of 2:1 clay minerals, suggested by other soil characterisitcs and confirmed by mineralogical analysis of clay fraction of selected samples. Calcium and magnesium are the dominant exchangeable cations. In saline-sodic soils, low Ca/Mg ratios are typical and decrease with depth as shown in Table 2. High values of exchangeable magnesium were found by Moreira (14), in solodized solonetz soils located in the same hydrographic basin (Figure 2), and reported by Jansen and Moss (10) in solodized solonetz soils of Saskatchwan and by Sandoval and Shoesmith (20) in soils of glacio-lacustrine origin of North Dakota. Sodium and chloride are the dominant soluble ions. Carbonates are absent and HCO_3^- and SO_4^{2-} are present in minute quantities.

Results of regression analysis reported in Table 3 revealed significant and useful relations between parameters. Relations [1], [2] and [3] indicated strong correlations between EC and dominant soluble ions. Though the coefficients of determination are higher for the quadratic function, the differences are too small to disregard the use of the simplest linear expressions. Relation [4], ESR as a function of SAR, shows that the two variables are linearly correlated. The equation is included in Table 4, among other regression equations of the same relationship found by Pereira *et al.* (16), with 27 soil samples from the public irrigation district of São Gonçalo, Brazil, by Elseewi *et al.* (7) with 31 samples from the Nile Delta, Egypt, and by Bower (5), and that reported by Richards (19) with 59 soil samples from the western United States. The regression line of equation [4] passes close to and above the origin, as does Bower's (5) line, with the intercept lower than that of Elseewi *et al.* (7). However, the slope is close to those of the Pereira *et al.* (16) and Bower (5) regression lines. The population size (478 samples) and the inclusion of a large proportion of non-saline, non-sodic soils must be taken into account when comparing equations and correlation coefficients in Table 4. Based upon equation [4], the following equation, similar to that of Richards (19), was developed to calculate ESP from SAR values:

Table 2. Chemical characteristics of three alluvial soils from the public irrigation district of Morada Nova.

Depth (cm)	pH	EC dSm^{-1}	Exchangeable cations Ca	Mg	K	Na	H + Al	CEC	Ca/Mg	ESP
			c mol (p+) kg^{-1}							
PROFILE No 50 NON-SALINE, NON-SODIC ALLUVIAL SOIL										
0–20	6 40	0 45	16 63	3 22	0 83	0 33	3 13	24 25	5 0	1.36
20–40	6 40	0 35	17 95	3 15	0 74	0 72	2 64	25 20	5 7	3 06
40–80	6 50	0 34	14 45	7 70	0 51	0 66	1 98	26 30	2 0	2 51
80–140	6 70	0 60	2 77	2 46	0 14	0 15	0 66	6 18	1 1	2 43
PROFILE No 79 SODIC ALLUVIAL SOIL										
0–20	6 70	0 64	10 22	9 78	0 36	5 00	1 32	26 68	1 04	18 74
20–40	7 30	1 70	15 85	8 98	0 37	5 60	0 00	30 80	1 76	18 18
40–140	7 50	2 84	13 11	9 54	0 29	6 35	0 00	29 29	1 35	21 67
PROFILE No 64 SALINE-SODIC ALLUVIAL SOIL										
0–20	6 40	8 60	10 57	7 65	0 42	5 80	0 82	25 26	1 38	22 96
20–40	7 00	5 90	7 67	8 01	0 37	3 63	0 00	19 68	0 96	18 45
40–120	7 60	4 20	8 70	13 59	0 21	4 58	0 00	27 08	0 64	16 91
120–140	7 70	2 80	5 90	8 20	0 13	5 21	0 00	19 44	0 72	26 80

Table 3. Coefficients of determination and equations obtained by regression analysis between: electrical conductivity (EC), soluble sodium (Na^+) and chloride (Cl^-), sum of soluble cations (Σcat), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), exchangeable sodium ratio (ESR) and soluble sodium percentage (SSP).

No.	Variables Y	X	r^2	Equation
[1]	EC	Σ cat	0 978*	Y = 0 084 X −0 018
			0 982*	Y = −0 821 X 10^{-4} X^2 + 0 094 X −0 123
[2]	EC	Na^+	0 915*	Y = 0 086 X + 0 535
			0 962*	Y = −1 26 X 10^{-4} X^2 + 0 178 X + 0 209
[3]	EC	Cl^-	0 946*	Y = 0 071 X + 0 209
			0 991*	Y = −8 88 X 10^{-5} X^2 + 0 097 X + 0 258
[4]	ESR	SAR	0 501*	Y = 0 0200 X + 0 0144
[5]	ESP	SAR	0 597*	Y = 1 038 X + 3 258
			0 656*	Y = −0 0135 X^2 + 1 6099 X + 1 1486
			0 663*	Y = 45 745 log(X + 5 716) − 36 527 (§)
			0 649*	log Y = 0 9435 log(X − 0 0192) + 0 1531 (§)
[6]	ESP	SSP	0 594*	Y = 0 509 X − 15 441
			0 683*	Y = 0 0099 X^2 − 0 5968 X + 10 403
			0 797*	log Y = 0 0228 X − 0 4743

* – Significant at 1% level

(§) Optimized transformation log $(X + X_0)$; value of X_0 indicated in the equation.

Table 4. **Regression equations used in calculating ESA from SAR of saturation extract.**

Regression equation	r	Source
ESR = 0.0144 + 0.0200 SAR	0.710*	This study
ESR = 0.0135 + 0.0212 SAR	0.930	Pereira *et al* (16)
ESR = 0.0273 + 0.01457 SAR	0.934*	Elseewi *et al* (7)
ESR = 0.0057 + 0.0173 SAR	–	Bower (5)
ESR = 0.0126 + 0.01475 SAR	0.923	Richards (19)

* Significant at 1% level

ESP = 100 (0.0144 + 0.0200 SAR) / 1+ (0.0144 + 0.0200 SAR) [7]. It yields mean values of ESP higher than SAR values. Relation [5] between observed values of ESP and SAR is depicted in Figure 4, were we note the parallelism of regression and the 1:1 lines. Quadratic regression, described by the parabolic curve, shows a higher coefficient of determination than linear regression. Observed values of ESP tend to be higher than SAR in these soils. This could be due to an increase of adsorbed sodium in the soils' exchange complex (21), occurring in clayey soils of low hydraulic conductivity through the accumulation of bicarbonates as root respiration produces CO_2 (8, 11), and resulting from the application of irrigation water. Pratt and Bair (18) attributed the values of ESP:RAS > 1, observed in their study, to the presence of water-insoluble sodium compounds that are soluble in the extracting solution. Finally, estimation of exchangeable cations, by subtracting the concentrations in saturation extract from the total concentrations, tends to yield higher values of exchangeable sodium (4). Results of the regression analysis of ESP as a function of soluble sodium percentage (SSP) showed increases in the coefficient of determination from the linear to the semi-logarithimic function (Table 3), and a marked increase of ESP at SSP values higher than 50.

A summary of data obtained in the soil variability study of the public irrigation district of Pentocoste reported by Coelho (6) is presented in Table 5. Variability of soil bulk density was higher in the 0-20 cm layer, CV of 5.5%, than in the 30-40 and

Table 5. **Mean, standard deviation, coefficient of variation (CV), and approximate number of samples required to estimate mean values within 5% and 10% at the 0.05 significance level, of physical and chemical characteristics.**

Characteristics	Depth	Mean	Standard deviation	CV %	Number of samples 5%	Number of samples 10%
Soil bulk density ($Mg\ m^{-3}$)	0–20	1.493	0.0824	5.5	5	1
	30–40	1.587	0.0325	2.0	1	1
	50–60	1.575	0.0347	2.2	1	1
Water stable aggregate (2.0–0.25 mm) (%)	0–20	42.23	10.72	24.8	100	25
pH	0–30	6.49	0.31	4.8	7	4
	30–60	6.55	0.36	5.6	8	4
	60–90	6.98	0.40	5.7	8	4
ESP	0–30	15.25	4.57	30.0	141	37
	30–60	19.70	7.47	37.9	224	58
	60–90	22.54	6.47	28.8	131	35
SAR	0–30	10.57	3.48	32.9	170	45
	30–60	14.16	4.89	34.6	187	45
	60–90	13.67	5.28	38.6	232	60
Na ($mmol\ (p+))\ l^{-1}$)	0–30	23.08	9.13	39.6	244	63
	30–60	30.48	12.53	41.1	262	68
	60–90	26.51	11.86	44.7	311	80
Cl ($mmol(e-))\ l^{-1}$)	0–30	29.18	11.12	38.1	226	59
	30–60	35.84	14.63	40.8	259	67
	60–90	29.65	13.48	45.4	320	82

50-60 depths, but lower than that of water stable aggregates in the same layer, with CV of 24.8% . Marked differences in spatial variability were detected in the chemical characteristics studied, as indicated by data on the most important parameters presented in Table 5. Taking the coefficient of variation as a measure of variability, results indicate that ESP, EC, SAR and soluble sodium and chloride follow pH in increasing order of variability; this is also reflected in the number of samples required to estimate mean values of these parameters, within 5% and 10% at the 0.05 significance level. Frequency distributions of soil bulk density at the three depths, and of water stable aggregate values, are close to normal distributions, with a mode/mean ratio within the range of 0.995 to 0.999 for bulk density and of 0.914 for water stable aggregates. The mode/mean ratios for EC and ESP values, at three depths, are within the range of 0.810 to 0.864 and of 0.817 to 0.877, respectively, indicating that deviations from normality are large and would result in errors ranging from 13% to 19% when using the mean instead of the mode, i.e. assuming that the values were normally distributed. However, for a set of measurements with CVs ⩽ 40%, both normal and log-normal distributions may be equally adequate (18).

Conclusions

The percentage of salt-affected soils found to occur in the area studied is not uncommon to other irrigation districts in Northeastern Brazil, due to climatic conditions, topographic position and problems that were aggravated under irrigation practice. It was found that peculiar characteristics were associated with dominant sodic and saline-sodic soils. Soil pH values are rather lower than those specified in the U.S. Salinity Laboratory classification (19). Exchangeable magnesium levels are high, often surpassing exchangeable calcium levels. Sodium and chloride are the dominant ions, while carbonates are absent and HCO_3 as well as SO_4 exist in minute quantities. ESP values are higher than SAR, when measured or estimated by the equation [7]. Low values of saturated hydraulic conductivity, found to be associated with high clay and silt contents, predominance of 2:1 clay minerals and high ESP levels, are an additional burden to soil management in these areas. Soil variability was also found to be an important factor in dealing with these soils. It was concluded that adequate tecniques for management and reclamation need to be developed, and further research, especially of hydrologic parameter characterization, must be performed to evaluate feasibility of reclamation of the most affected soils.

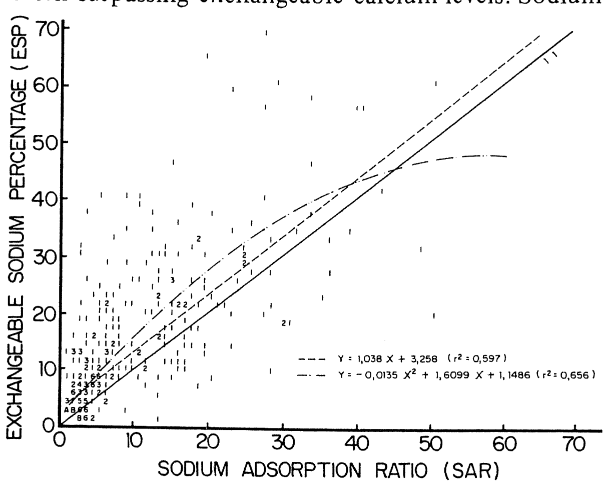

Fig. 4. Relation between observed values of ESP and SAR. Digits correspond to number of samples and letters: A = 10 to 14 samples and B = 15 to 19 samples.

Summary

Aiming to characterize the surgace and in-depth distribution of salt problems, 525 soil samples were collected in 149 soil profiles comprising an area of 504 hectares located in the irrigation district of Morada Nova, state of Ceará, Brazil. Results indicate that sodic and saline-sodic soils cover 25% of the area studied and the salinity and sodicity problems increase with depth. In was found that peculiar characteristics were associated with the sodic and saline-sodic soils. In general pH values were in the 6.0 to 8.0 range. The Ca/Mg ratio frequently reached values below unity. Sodium and chloride are dominant, while carbonates area absent and HCO_3, as well as SO_4, exist in minute quantities. ESP values are higher than SAR, when measured or calculated. Low values of saturated hydraulic conductivity were associated with high clay and silt contents, predominance of 2:1 clay minerals and high ESP levels. Spatial variability of pertinent parameters evaluated through intensive sampling in a 0.8 ha area revealed marked differences between physical and chemical properties. The variability of chemical properties increases with depth.

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