LUIZ GUILHERME MEDEIROS PESSOA

ANALYSIS OF SALT AFFECTED SOILS IN SEMIARID LANDSCAPES OF PERNAMBUCO, BRAZIL

RECIFE - PE
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Thankfully, there is always another day. And others dream. And others laugh. And other loves. And other people. And other things.

(Clarisse Lispector)

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LIST OF ACRONYMS

ARS	Agricultural Research Station
BD	Soil Bulk Density
BS	Percent Base Saturation
CEC	Cation Exchange Capacity
CNPq	National Counsel of Technological and Scientific Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico)
DI	Dispersion Index
EC	Electrical Conductivity
EMBRAPA	Brazilian Agricultural Research Corporation (Empresa Brasileira de Pesquisa Agropecuária)
EPIC	Erosion Productivity Impact Calculator
ESP	Exchangeable Sodium Percent
FI	Flocculation Index
GIS	Geographical Information Systems
GLASOD	Global Assessment of Human-induced Soil Degradation
GPS	Global Positioning Systems
IDW	Inverse-Distance-Weighting
INPE	National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais)
$\mathbf{K_0}$	Saturated Hydraulic Conductivity
NE	Northeastern (Nordeste)
OC	Organic Carbon
PD	Soil Particle Density
RAD	Solar Radiation
R	Correlation coefficient
$\mathbf{R^2}$	Coefficient of Determination
S	Sum of bases
SAR	Sodium Adsorption Ratio
SD	Standard Deviation

SiBCS	Brazilian System of Soil Classification (Sistema Brasileiro de Classificação de Solos)
SNLCS	National Service of Soil Survey and Conservation (Serviço Nacional de Levantamento e Conservação de Solos)
SOM	Soil Organic Matter
TAMU	Texas Agricultural and Mechanical University
TMX	Maximum Temperature
TMN	Minimum Temperature
TP	Total Soil Porosity
UFCG	Federal University of Campina Grande (Universidade Federal de Campina Grande)
UFPE	Federal University of Pernambuco (Universidade Federal de Pernambuco)
UFRPE	Federal Rural University of Pernambuco (Universidade Federal Rural de Pernambuco)
UNIVASF	Federal University of São Francisco Valley (Universidade Federal do Vale do São Francisco)
USDA	U.S. Department of Agriculture
WDC	Water Dispersible Clay

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ABSTRACT

The sodification and salinization of soil are the main types of degradation of semiarid of Pernambuco. In extreme cases, the vegetation does not develop in these soils, making them desertified. Consequently, there is an abandonment of these areas. Nowadays, a may does not exist identifying these areas for Pernambuco state, which could be done through tools such as Remote Sensing and GIS. This study was conducted in order to identify and diagnose areas affected by salinization and sodification in the semiarid area of Pernambuco. A study was conducted in the laboratory to understand the spectral behavior of different types of salts in two representative soils. These soils were leached with saline solutions of $CaCl_2.2H_2O$, $MgCl_2.2H_2O$, KCl and NaCl at concentrations of 0.5, 1 and 2 mol L^{-1}. There was an increase in reflectance of crusts with increasing wavelength; however, there was a reduction in the reflectance with increasing salt concentrations of the solution applied to the four kinds of salts, in both soils. The intensity of reflectance was increased in the salts studied: NaCl > KCl > $MgCl_2.2H_2O$ > $CaCl_2.2H_2O$, where the Arenosol showed higher reflectance in relation to Fluvisol, between concentrations and different salts. Afterward, with the intent to understand the spectral behavior of different salt levels and their correlation with the soil properties, a field investigation was conducted in which soil samples were collected from four representative watersheds: Brígida, Terra Nova, Pajeú and Moxotó that have varying degrees of salinity and sodicity within the semiarid region of Pernambuco. It was observed that there was an increase in reflectance with increasing wavelength to the spectral response in all salinity and sodicity levels and the variable Exchangeable Sodium Percentage (ESP) had good correlation coefficients obtained with the positive spectral reflectance bands in virtually all soil sample tested, while the variable fine sand obtained negative coefficients. For the identification of these areas affected by salts and sodium, a map showing the spatial distribution of pH, electrical conductivity, ESP and sodium adsorption ratio (SAR) was done using a GIS tool. This study indicates that strongest association between cations and anions was the formation of sulfate and chlorides species where Na^+ ions (exchangeable and soluble), HCO_3^- and Cl^- ions are those that contribute most to the increase of salinity and sodicity in soils of the semiarid state of Pernambuco. The most area affected by sodium exchangeable and soluble is located especially on Moxotó watershed by the ESP and SAR levels. The Moxotó watershed indicated the worst levels of degradation by salinity and sodicity among the others. The EPIC model was used to assess how different management practices can predict corn yield and the soil salinity status. Three soil profiles from Moxotó watershed were used and the scenarios simulated included drip, furrow irrigation, and trigger irrigation (0.1 and 1 levels). This study found that the best irrigation strategy for corn yields grown was drip irrigation and trigger irrigation at a level of 0.1. However, for low water content applied, the trigger irrigation 1 should be used. Finally, with the intent to describe soil profiles in some critical areas, four soil profiles were evaluated. Soil samples were collected from the municipalities of Ibirimim, Parnamirim and Serra Talhada in Pernambuco. The soils studied have profiles with characteristic features of the Neossolos Flúvicos and Cambisolos soil. A strong relationship with these orders salinity problems in the semiarid region of Pernambuco was determined. The profiles in the study had high levels of salts and sodium with increasing depth. Furthermore, the predominance of fine particles in salt affected soils have been a factor which tended to complicate the recovery of these soils.

Keywords: saline and sodic soils, remote sensing, GIS, semiarid region.

1 - GENERAL INTRODUCTION

Detection of soil salinization and the evaluation of severity and extent, especially in its early stages, are of great importance in terms of management of sustainable agriculture (Farifteh, 2007).

An early detection of sodic and saline soils allows, among other advantages, the proposition of preventative or corrective action before the problem of salinity and or sodicity expands in a particular region, causing further damage on farm (Lobo, 1992). Mapping, monitoring, and prevention of soil salinization are best executed when assisted by the interaction of remote sensing tools, laboratory, and field data and the use of geographic information system (GIS) to facilitate processing, transformation and display data (Peng, 1998).

The development of methods for mapping salt affected soils using remote sensing data in combination with field measurements has been the subject of many studies during the last two decades (Everitt et al., 1988; Rao et al., 1998; Dehaan and Taylor, 2003). However, the identification of salt affected soils by remote sensing can be hampered by the way the salts are distributed on the soil surface, because of unequal occurrence, spatial variations and association with other soil properties that interfere in the reflectance of salts (Metternicht and Zinck, 2008).

It is of great importance to understand the spectral behavior of salt types by remote sensing in affected soils, as these soils have higher spectral response in the visible and near infrared regions (compared to non-saline soils). Thus, the understanding of absorption features in these regions may indicate the predominant type of salt in certain soils. These radiometric measurements help us understand the intensity of absorbance or reflectance at different wavelengths that each salt-affected soil will display depending on its composition.

Farifteh (2007) states that the salt-affected soils can be mapped more distinctly by the use of remote sensing, where the characteristics related to salinity are more pronounced on the surface, if the high percentage of exposed soil is available or when other indicators such as the type and density vegetation are taken into account.

Metternicht and Zinck (2008) state that the surface characteristics of salt affected soils are of great importance in assessing sodic and saline areas by remote sensing. Accordingly, some important aspects have to be taken into consideration when evaluating the spatial distribution of soil salinity such as the presence of salt crusts and efflorescence that occur in places where the salts precipitate directly onto the soil surface by rise capillary of saline solutions from subsoil or groundwater. The characteristics of these crusts and efflorescence vary widely with their spatial distribution, thickness, roughness and color.

Another aspect to be considered is the sealing surface appears in soils containing high contents of sodium and contributes to poor soil aggregation, causing the dispersion of soil colloids in sodic soils. This seal is commonly associated with the dissolution of organic matter at high pH and concentration of humates are dispersed, resulting in dark crusting on the soil surface. Thus, when using the indicators of surface soil salinity (crusts, surface sealing, etc.) these details should be noted because they exhibit distinct spectral characteristics and these differences must be taken into account when mapped.

1.1 Problem statements

The high concentration of salts in soils is one of the main types of soil degradation in semiarid Pernambuco. Over the years, humankind has significantly contributed to the expansion of the problem in the region by improper land management techniques such as irrigation which has impacted the soil health. Agricultural production areas have subsequently become degraded, reaching extremely high levels of salinization and or sodification, preventing the growth of crops in the fields, and contributing to regional desertification. As a result, these areas are abandoned and the cultivable area is reduced. There is also a reduction in food production in the region.

Field investigation of salinity usually involves soil, crop,and water measurements and monitoring activities that can be very costly and vary considerably spatially and temporally. This means that frequent field studies on an intensive scale may be required to adequately assess the status of the area being studies. The state of Pernambuco does not have any status indicating the the levels of soil degradation by salinization and or sodification and the spatial distribution of degradation in its the region. Also, reports do not exist on the dominant types of salts prevailing in local soils. There aren’t any studies regarding the levels of salts and how they can affect the development of plants grown in it as well.

Thus, given this lack of information, some questions can further studied: what is the variation in levels of salinity and sodicity in the semiarid region of Pernambuco? What are the main salts found in soils affected by salinization/sodification? What is the spatial distribution of these degraded areas in Pernambuco? What are the main soil orders correlated with salinity and sodicity in highly degradation areas?

This research was developed to create a baseline for sodic and saline soil data for Pernambuco. The contributions of this research are that the main areas that are degraded by salinization/sodification are identified in addition to reporting areas that need to be remedied, no degradation areas and areas that need special handling. This research also presents different levels of degradation found in semiarid region of Pernambuco, as well as major salts that predominate in these areas, and present how an appropriate irrigation management can contribute to the recovery and development of crops at different levels of degradation. Also, a case study is included that indicates the classification of some soils affected by salts and sodium. Baseline physical and chemical properties for the soils are included in this study for future research.

1.2 Research objetives

The main objective of this research was to make a field survey to indicate areas with salinity and sodicity degradation in four main watersheds named Brígida, Terra Nova, Pajeú and Moxotó from a semiarid region of Pernambuco state, Northeastern Brazil by the creation of a salinity map with remote sensing and geoprocessing tools.

The specific research objectives were to:

- Study the information content of soil spectra with respect to salt concentration and salt types under laboratory conditions.
- Investigate the relation among the salinity parameters (EC, pH, ESP and SAR) at different levels, by cluster analysis, and the spectral properties of soils.
- Examine the salt levels and identify the dominant salts in each study watershed and show the spatial distribution using a geoprocessing tool.
- Investigate predictions about the influence of different irrigation management on the salinity status and corn yield in the Moxotó watershed.

- Classify representative soils present in areas highly affected by salts and sodium.

1.3 Hypotheses

The research was conducted based on the following hypotheses:

- The techniques of remote sensing and GIS are useful tools to identify and map salt affected soils at different levels of degradation;

- The Erosion Productivity Impact Calculator (EPIC) model can be used to predict the salinity of soil and corn yield under different irrigations scenarios. Thus it can be an important tool for the sustainable management of the soil and to predict agricultural impacts in semiarid of Pernambuco State.

1.4 Outline of the Thesis

The research presented in this thesis is described in five chapters. It is a collection of five papers, chapters I-V. Additionally, the Introduction presents a brief overview of this thesis with objectives and hypothesis of this research.

In chapter I, “Spectral behavior of salt crusts in two soils from Pernambuco semiarid, Brazil”, a laboratory experiment was carried out and presented. The focus of this experimental study was on the use of laboratory spectroscopy to examine the contribution of the spectral information derived from the different salt minerals in different levels, in two soils from Pernambuco State.

The chapter II, “Soil properties and correlation with spectral reflectance at different salinity levels”, evaluate the chemical and physical properties of soils situated in four watersheds (Brígida, Terra Nova, Pajeú and Moxotó) from the semiarid region of Pernambuco and correlate with their spectral properties at different salinity and sodicity levels based on cluster analisys.

The chapter III, “Spatial distribution and characterization of soil salinity in semiarid region of Northeast Brazil”, presents the chemical properties of soils in each study watershed indicating the levels of cations and anions, the salt species dominants in each watershed, the relation among the ions and salinity parameters of soil (EC, pH, ESP and SAR), and additionally, this chapter presents spatial distribution of salinity parameters.

The chapter IV, “Predicting corn yield and soil salinity status under different scenarios of irrigation practices in semiarid Northeast from Brazil”, simulate the corn yield salinity status under different scenarios of irrigation practices in Moxotó watershed, using the Erosion Productivity Impact Calculator - EPIC software.

The last chapter (chapter V), "Classification of soils affected by salts in semiarid Pernambuco, Brazil – A case study" indicate the classification of some soils highly affected by salts and sodium, found in critical areas visualized on the map created from data presented in the previous chapters. This chapter includes all the morphological, chemical and physical properties of the soils studied.

Finally, the main findings and final considerations of the research and some recommendations for application of the current results and for the further research are synthesized after chapter V.

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2 - CHAPTER I

SPECTRAL BEHAVIOR OF SALT CRUSTS IN TWO SOILS FROM PERNAMBUCO SEMIARID, BRAZIL

Abstract

This study focuses on the the spectral characteristics of crusts of different salts formed in two soils of the semiarid region of Pernambuco, Brazil. A Fluvisol and an Arenosol, both from the city of Serra Talhada. Samples of these soils were leached with saline solutions of $CaCl_2.2H_2O$, $MgCl_2.2H_2O$, KCl and NaCl at concentrations of 0.5, 1 and 2 mol L^{-1}. After leaching, the spectra of salt crusts were obtained using a hyperspectral sensor,with fiber optic cable. There was an increase in crusts reflectance with increasing wavelength; however, there was a reduction in these reflectance with increasing salt concentration of the solution applied to the four kinds of salts, in both soils. This decrease in reflectance was less pronounced in the crusts of leachable soil with salt solutions of NaCl and KCl. It was observed that for all concentrations in both soils, the intensity of reflectance was increased in the following salts studied: NaCl > KCl > $MgCl_2.2H_2O$ > $CaCl_2.2H_2O$. The latter two salts had lower reflectance due to the presence of water molecules in it's composition. The Arenosol presented higher reflectance in relation to Fluvisol, between concentrations and different salts, due to the higher quartz content.

Keywords: saline soils; soil salinity; salt minerals; salt identification, reflectance

2.1 Introduction

Because of the dominance of evaporation rates in relation to rainfall, arid and semiarid regions tend to have soils degraded by salinity and sodicity. High concentrations of soluble salts on the surface or in the upper horizons of soil are a large problem in global agriculture, with serious economic and social consequences in the world (Farifteh et al., 2007). According to Pérez-Alfonseca et al. (2010), salinity is one of the main factors responsible for reduction of plant production and the main cause of the abandonment of land that could be used for agricultural uses.

Human activities have largely contributed to soil degradation by salinization or sodification, through inadequate irrigation management, generally related to the use of low quality water. Once saline, these areas become unsuitable for agricultural use. In extreme cases, the soil is identified and just a few tolerant cultures can survive under these conditions. In this context, these areas are abandoned and subjected to desertification, which is common in a semiarid region of northeast Brazil. Thus, the detection of impending salinization and the assessment of the severity and extent, especially in the land’s early stages, are pertinent in terms of management of sustainable agriculture (Farifteh, 2007). This is relevant, especially in arid and semiarid regions, where this process is more likely to occur. Identifying any indicator that could provide prior knowledge about the classes of salinity contributes to a more efficient management of the soil and possibly sustainable crop yields.

Remote Sensing appears to be an alternative of low cost and high precision to evaluate and characterize salt affected soils (Elnaggar and Noller, 2010). The crusts and efflorescence of salts can be easily detected by satellite imagery due to the superficial white spots promoted by high salt concentrations (Mandal and Sharma, 2001). According to Mougenot et al. (1993), the surface of saline soils can reveal the salt presence in two different ways: either directly by the soil of interest with efflorescence and crusts of salts orindirectly through the kind of predominant vegetation or wet conditions. These authors state that the salt surface reflectance increases with increasing wavelength; however, the salts induce to a relatively higher reflectance in the blue band due to the masking of iron oxides. Tilley et al. (2007) contribute that the type and vegetation growth can also provide a spatial view of the distribution of salinity.

Remote sensing has been widely used to identify and map saline areas at various levels of degradation (Farifteh et al., 2006; Evans and Cacceta, 2000; De Jong, 1992, Sharma and Bhargava, 1988). Everitt et al. (1988) reported that salt crusts and efflorescences are always associated with high reflectance in the visible and near infrared spectrum. These authors indicated that salt crusts on the soil surface are smoother surfaces than non-saline surfaces, giving them high reflectivity. However, Metternicht and Zinck (2008) emphasize that chemical composition and the mineralogy of the types of salts as the main factors that control its spectral behavior, highlighting the importance of these components in the remote sensing of salt affected soils

Minerals are rarely pure in nature, since trace elements are often attached to the crystal lattice during crystallization. This affects the reflectance properties of minerals (Hunt and Salisbury, 1971). Saline soils usually have high concentrations of Na^+, Mg^{2+}, Ca^{2+}, Cl^- and/or SO_4^{2-} in soil solution. These ions, after evaporation, form crusts and efflorescence of salts on the soil surface. The success in determination of saline areas in different grades can be increased if the spectral characteristics of salt affected soils and the underlying factors are examined. In this respect, more attention should be given to the analysis of spectral reflectance obtained from soils containing various amounts of salts. Through a laboratory experiment, the contribution of spectral information derived from minerals in mineral identification and discrimination of saline areas can be examined (Farifteh, 2007).

Spectral information of salt affected soils in semiarid regions are scarce or nonexistent; however, such studies have been highlighted in journals of international circulation. Surveys that will provide such information, emphasizing the orders of soils prone to degradation by salinity and sodicity, will provide a major contribution to remote sensing of soil salinization, especially in research that emphasize the detection level of soil salinity, and detection of the main salts present.

The objective of this study is to determine the spectral characteristics of different salts crusts formed on two soils from Pernambuco semiarid, aiming to provide knowledge of spectral information that lead to a better understanding of the spectral behavior of salt affected soils

2.2 Material and methods

2.2.1 Collection and preparation of soil samples

Soil samples were collected in two soils without degradation problems by salinity and sodicity, an Arenosol and a Fluvisol, both from Serra Talhada county. The soils samples were collected in the surface layer (0-20 cm). They were air-dried, crushed and sieved in a sieve with 2 mm mesh, obtaining the air-dried soil, for soil characterization and experiment assembly. The chemical characterization was carried out according to USSL STAFF (1954), and the physical characterization, according to EMBRAPA (1997) (Tables 2.1 and 2.2).

2.2.2 Experiment assembly and conducting

The assembly of the experiment was conducted in the laboratory, through the packaging of 150 g of air dried soil in funnels with filter paper, for the leaching of soils with the respective salt solutions. These were composed of chloride salts, $CaCl_2.2H_2O$, $MgCl_2.2H_2O$, KCl and NaCl, at concentrations 0.5, 1 and 2 mol L^{-1}, in a total of 12 saline solutions with three replications in each soil class, totaling 72 samples.

Table 2.1. Soils samples physical attributes

Soil Class	Sand	Silt	Clay	CDW[1]	DFC[2]	DCD[3]	SBD[4]	SPD[5]	TP[6]
	———g kg^{-1}———				——%——		—g cm^{-3}—		%
Arenosol	874.1	77.0	48.9	27.9	57.06	42.94	1.47	2.66	44.74
Fluvisol	191.6	420.0	388.4	289.6	25.44	74.56	1.21	2.7	55.0

[1] Clay Dispersion in Water; [2] Degree of Flocculation of Clay; [3] Degree of Clay Dispersion; [4] Soil Bulk Density; [5] Soil Particle Density; [6] Total Porosity.

Table 2.2. Soils samples chemical attributes

Attribute	Soil Class	
	Arenosol	Fluvisol
Soil Exchangeable Cations		
pH $_{water}$ (1:2,5)	7.54	7.1
Ca^{2+} (cmol$_c$ dm^{-3})	4.98	8.54
Mg^{2+} (cmol$_c$ dm^{-3})	1.51	3.23
Na^{+} (cmol$_c$ dm^{-3})	0.08	0.3
K^{+} (cmol$_c$ dm^{-3})	0.25	0.49
CEC[1] (cmol$_c$ dm^{-3})	8.61	15.86
ESP[2] (%)	0.93	1.89
Saturation Paste Extract		
pH	7.26	7.4
EC[3] (dS m^{-1})	0.79	0.85
Ca^{2+} (mmol$_c$ L^{-1})	0.5	5.12
Mg^{2+} (mmol$_c$ L^{-1})	0.61	3.7
Na^{+} (mmol$_c$ L^{-1})	1.96	2.46
K^{+} (mmol$_c$ L^{-1})	4.92	0.61
SAR[4] (mmol$_c$ L^{-1})^{0,5}	2.63	1.17

[1] Cation Exchange Capacity; [2] Exchangeable Sodium Percentage; [3] Electrical Conductivity; [4] Sodium Adsorption Ration.

After packaging in the funnels, each soil sample was leached with a layer of saline solution equivalent to 5 times the volume of pores according to their soil class. After leaching, the soils samples were air-dried, crushed and sieved (2 mm mesh sieve). Later, these soils samples were placed in Petri dishes, which were acrylic, with 13.5 cm in diameter. For each class of soil, 100 g of soil sample was placed, subjected to leaching with their saline solutions in Petri dishes. Then we applied a layer of saline solution equivalent to the pore volume of each soil class on the plates containing soils. Consequently, the soils studied were taken to forced air circulation oven at 65°C for 72 hours to promote the formation of soil crusts.

2.2.3 Laboratory Hyperspectral Analysis

To collect spectral data in the laboratory, we used the hyperspectral sensor, FieldSpec Spectroradiometer with fiber optic cable, which covers the spectral range between 450 and 2,500 nm with spectral resolution of 1 nm and between 1100 and 2500 nm with spectral resolution 2 nm.

We used a standard white plate, with 100% reflectance and then carried out spectral reading of the soil samples contained in the plates. The ratio of spectral radiant flux reflected by a sample by the radiant flux reflected by the reference material generates the bidirectional spectral reflectance factor, from which the curve is fitted reflectance (Nicodemus et al., 1977). Six readings were performed on each sample, which an average of these curves was subsequently taken, generating a single curve for each sample. Also, after three repititions a mean curve was drawn, generating a single curve for each treatment.

2.2.4 Statistical analysis

For recognizing the soil salinity status, some key spectral ranges in the visible (550–770 nm), near-infrared (900–1030; 1270–1520 nm), and middle infrared (1940–2150; 2150–2310; 2330–2400 nm) were identified according to Csillag et al. (1992). In this study, nine representative spectral bands from the continuum of wavelengths measured were evaluated statistically by comparison between the mean values of these intervals.

The spectral behavior of salt crusts was compared between the concentrations in each soil within the same saline solution; between the types of salts within the same concentration in each soil; and, finally, between the soils within same saline solution. The spectral curves were also interpreted as the absorption features, shapes and intensities of reflectance.

2.3 Results and discussion

There was a reduction in reflectance with increasing salt concentration of the solution applied with the four kinds of salts forboth soils (Figures 2.1 and 2.2). This decrease in reflectance was less pronounced in the crusts of the soils leached with NaCl saline solutions. Thus, the intensity of reflectance was reduced in the following order of concentration of saline solution applied: 0.5 mol L^{-1} > 1 mol L^{-1} > 2 mol L^{-1}. In crusts of soils leached with $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$ saline solutions, this reduction in reflectance was more pronounced because these salts have water molecules in its composition, which are more hygroscopic salts, contributing to a higher moisture content in these soils.

In both soils there was a spectral pattern of the crust reflectance, regardless of the salt concentration of the applied solution, where the shape of the curves was maintained by changing only the levels of reflectance. All crusts showed low reflectance in the visible region and near infrared, which according Demattê et al. (2005) can be attributed to strong absorption due to the effect of the presence of forms of Fe^{3+} at wavelengths shorter than 540 nm.

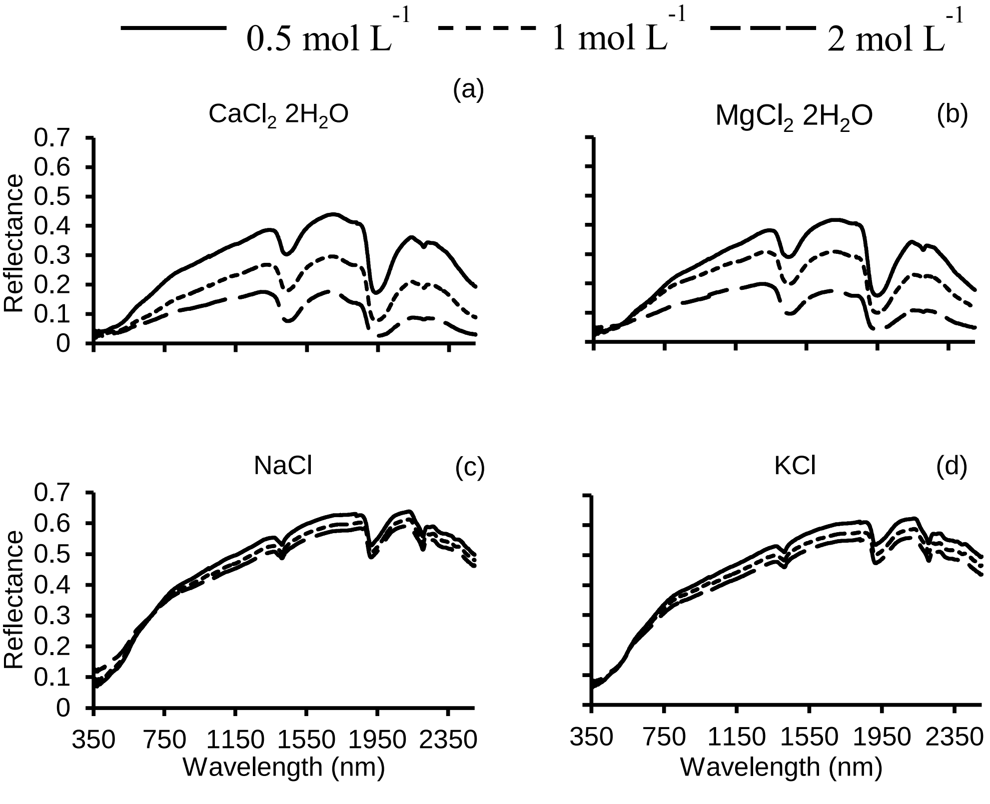

Figure 2.1. Spectral curves of Arenosol crusts leached with saline solutions of (a) $CaCl_2.2H_2O$, (b) $MgCl_2.2H_2O$, (c) NaCl and, (d) KCl, in different concentrations.

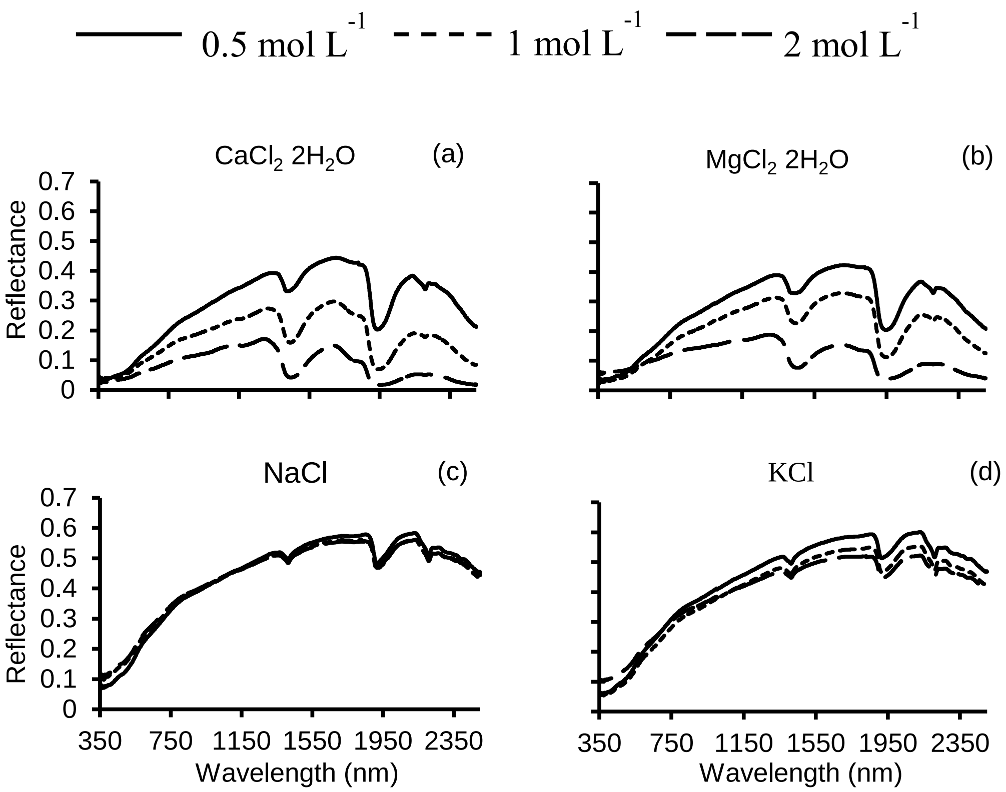

Figure 2.2. Spectral curves of Fluvisol crusts leached with saline solutions of (a) $CaCl_2.2H_2O$, (b) $MgCl_2.2H_2O$, (c) NaCl and, (d) KCl, in different concentrations.

The absorption features related to the presence of water molecules (1400 and 1900 nm) appeared in all crusts, being more intense in the crusts of soils leached with saline solutions of $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$. The presence of water in the composition of these salts contributed to increase in the concavity (width and depth) of the absorption bands centered at 1400 and 1900 nm. According Lindberg and Snyder (1972), this is due to the vibrations of water molecules adsorbed in minerals, which when struck by electromagnetic energy, vibration of these molecules occurs with a consequent decrease in reflectance, promoting the formation of absorption bands.

The soils leached with saline solutions of NaCl and KCl had lower concavities (narrower and less deep) in the absorption bands. Howari et al. (2002) observed water bands in the spectrum of halite crusts, at wavelengths of 1400, 1900, and 2250 nm, saying that these are dominant features of absorption of halite (NaCl). The results of studies from Howari et al. (2002) and Farifteh et al. (2008) agree with those obtained in this work, showing an upward trend in the depth of absorption features with increasing salt concentration.

The reflectance of soils leached with $CaCl_2.2H_2O$ showed reductions in all spectral bands selected as a function of increasing salt concentration applied in both soils (Table 2.3). Thus, increased levels of salt in the soil can result in reductions in their reflectance. Since this salt, present not only hygroscopic but also in deliquescent properties, these characteristics significantly influence the values of its reflectance.

Table 2.3. Average values of salts studied reflectance in selected spectral bands depending on the concentration of saline solution applied

Salt concentration	Spectral band selected (nm)					
	550-770	900-1030	1270-1520	1940-2150	2150-2310	2330-2400
			ARENOSOL			
			$CaCl_2.2H_2O$			
0.5	0.16	0.28	0.35	0.28	0.34	0.29
1.0	0.1	0.19	0.23	0.15	0.2	0.16
2.0	0.07	0.13	0.13	0.05	0.08	0.06
			$MgCl_2.2H_2O$			
0.5	0.13	0.24	0.29	0.2	0.26	0.2
1.0	0.13	0.23	0.26	0.16	0.22	0.17
2.0	0.09	0.15	0.15	0.07	0.10	0.07
			NaCl			
0.5	0.29	0.44	0.55	0.61	0.58	0.56
1.0	0.29	0.42	0.53	0.58	0.56	0.53
2.0	0.29	0.41	0.51	0.56	0.54	0.51
			KCl			
0.5	0.27	0.41	0.53	0.6	0.57	0.54
1.0	0.26	0.39	0.5	0.56	0.53	0.51
2.0	0.25	0.37	0.47	0.53	0.5	0.48
			FLUVISOL			
			$CaCl_2.2H_2O$			
0.5	0.15	0.28	0.37	0.31	0.35	0.3
1.0	0.11	0.2	0.22	0.13	0.18	0.14
2.0	0.07	0.12	0.1	0.03	0.05	0.03
			$MgCl_2.2H_2O$			
0.5	0.14	0.28	0.36	0.29	0.34	0.28
1.0	0.11	0.22	0.27	0.18	0.24	0.19
2.0	0.10	0.15	0.13	0.05	0.08	0.06
			NaCl			
0.5	0.28	0.41	0.52	0.56	0.54	0.51
1.0	0.28	0.41	0.51	0.53	0.51	0.49
2.0	0.29	0.42	0.51	0.53	0.51	0.49
			KCl			
0.5	0.24	0.4	0.52	0.57	0.54	0.52
1.0	0.22	0.36	0.48	0.53	0.5	0.47
2.0	0.25	0.37	0.47	0.5	0.48	0.45

In crusts of soils leached with solutions of $MgCl_2.2H_2O$, despite having similar properties to $CaCl_2.2H_2O$, with respect to hygroscopicity and deliquescence, larger differences were obtained in a more concentrated saline solution (2 mol L^{-1}) for both soils. With the Arenosol,the greatest differences in reflectance in the intervals 1940-2150 and 2150-2310 nm were found, while in the Fluvisol were observed large differences between the concentrations in almost all intervals evaluated (Table 2.3).

With respect to NaCl, increasing the salt concentration of the solution did not promote larger differences in the values of reflectance of the visible region in Arenosol (Table 2.3). However, in other selected intervals larger differences were observed only in soils where it was applied to less saline solution (0.5 mol L^{-1}). With the Fluvisol, only the crust of the soil leached with saline solutions of the highest concentration (2 mol L^{-1}) showed larger reductions in their reflectance values (Table 2.3). The average reflectance of soils leached with KCl showed that the Arenosol presented reductions in their reflectance in all bands selected, while with the Fluvisol these significant reductions occurred most notably in the intervals after the near-infrared (Table 2.3).

The comparison of the spectral response of the different salts used in each concentration measured in each soil is shown in Figure 2.3. It was observed that for almost all concentrations in both soils, the intensity of reflectance was increased in the following sense among the salts studied: NaCl > KCl > $MgCl_2.2H_2O$ > $CaCl_2.2H_2O$. This can be observed in their mean values (Table 2.4).

The crust of the soil leached with saline solutions of NaCl and KCl had significantly more intense reflectance in relation to soils leached with saline solutions of $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$ at all concentrations in both soils. The absence of water in the composition of NaCl and KCl salts causes these salts present in soil will precipitate more intensely in relation to salts containing water in their composition and these salt crusts will become more evident on the surface, giving them greater reflectivity.

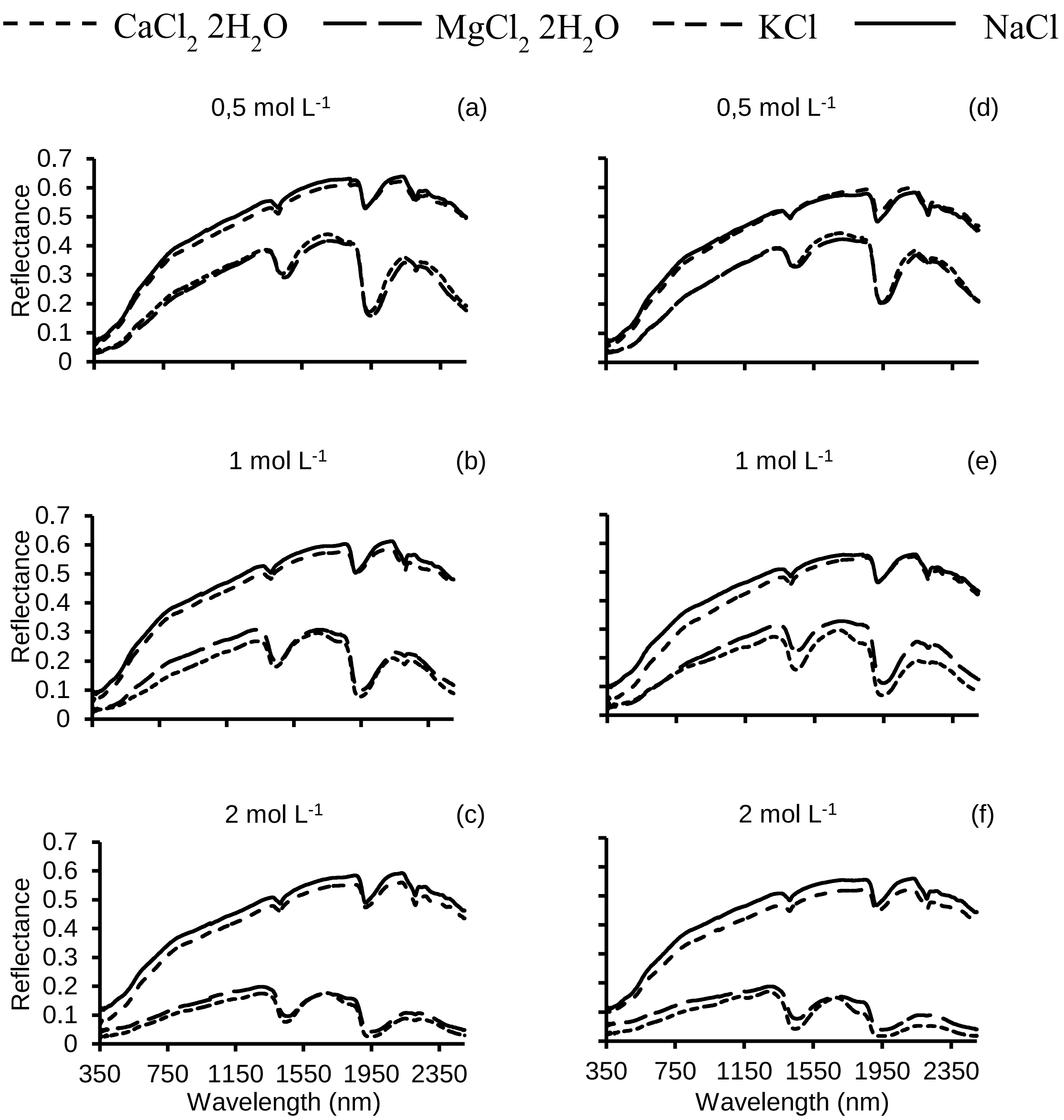

Figure 2.3. Spectral curves of different salts crusts in the three concentrations studied with the Arenosol (a, b, c) and the Fluvisol (d, e, f).

According to Drake (1995) only occasionally the absorption features are slightly different, which may be related to variations in the purity of the mineral, grain size, shape, and structural order. Some researchers argue that these absorption features in the spectrum of most minerals are mainly associated with internal vibrations of anionic groups or water molecules that are trapped or adsorbed in some way associated with the crystal structure (Hunt and Salisbury, 1970; Crowley, 1991).

The absorption features close to 1000, 1200, 1400 and 1900 nm in the spectrum of hydrated minerals, such as $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$ are related to vibrations of those anionic groups, with relatively broad absorption features due to overlapping bands of water molecules, while the less hydrated salts have overlapping narrow bands (Crowley, 1991). Weng et al. (2008) used the reflectance spectroscopy to investigate the level of soil salinity in relation to soil spectra in 95 soil samples from the Yellow River Delta of China and they observed that the overall reflectance decreases between 589 nm and 803 nm.

Table 2.4. Comparison between salts reflectance values for each concentration in both soils studied

Saline solution	Spectral band selected (nm)					
	550-770	900-1030	1270-1520	1940-2150	2150-2310	2330-2400
			ARENOSOL			
			0.5 mol L^{-1}			
NaCl	0.29	0.44	0.55	0.61	0.58	0.56
KCl	0.27	0.41	0.53	0.6	0.57	0.54
$MgCl_2.2H_2O$	0.13	0.24	0.29	0.2	0.26	0.2
$CaCl_2.2H_2O$	0.16	0.28	0.35	0.28	0.34	0.29
			1 mol L^{-1}			
NaCl	0.29	0.42	0.53	0.58	0.56	0.53
KCl	0.26	0.39	0.5	0.56	0.53	0.51
$MgCl_2.2H_2O$	0.13	0.23	0.26	0.16	0.22	0.17
$CaCl_2.2H_2O$	0.10	0.19	0.23	0.15	0.2	0.16
			2 mol L^{-1}			
NaCl	0.29	0.4	0.51	0.56	0.54	0.51
KCl	0.25	0.37	0.47	0.53	0.5	0.48
$MgCl_2.2H_2O$	0.09	0.15	0.15	0.07	0.1	0.07
$CaCl_2.2H_2O$	0.07	0.13	0.13	0.05	0.08	0.06
			FLUVISOL			
			0.5 mol L^{-1}			
NaCl	0.23	0.37	0.47	0.47	0.47	0.43
KCl	0.24	0.4	0.52	0.57	0.54	0.52
$MgCl_2.2H_2O$	0.14	0.28	0.36	0.29	0.34	0.28
$CaCl_2.2H_2O$	0.15	0.28	0.37	0.31	0.35	0.3
			1 mol L^{-1}			
NaCl	0.28	0.41	0.51	0.53	0.51	0.49
KCl	0.22	0.36	0.48	0.53	0.5	0.47
$MgCl_2.2H_2O$	0.11	0.22	0.27	0.18	0.24	0.19
$CaCl_2.2H_2O$	0.11	0.2	0.22	0.13	0.18	0.14
			2 mol L^{-1}			
NaCl	0.29	0.42	0.51	0.53	0.51	0.49
KCl	0.25	0.37	0.47	0.5	0.48	0.45
$MgCl_2.2H_2O$	0.1	0.15	0.13	0.05	0.08	0.06
$CaCl_2.2H_2O$	0.07	0.12	0.1	0.03	0.05	0.03

It was observed that in both soils, the increase in the concentration of salts in saline solutions provided a most obvious difference in reflectance of the crusted soil leachate, where the shapes of the curves of soil crusts bleach with the salts NaCl and KCl was similar in all three concentrations. The same behavior occurred in the crusts of soils leached with salts $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$.

The shapes of the curves followed the same spectral pattern in the three concentrations tested, differing with respect to the intensity of reflectance.

Crusts of the Arenosol (Figures 2.3 a, b, c) leached with $CaCl_2.2H_2O$ showed a slightly higher reflectance than that leached with $MgCl_2.2H_2O$ in the regions of the visible (400-700 nm) and near infrared (700-1100 nm) spectrum. The increased concentration of these salts in the leaching solution provided an inversion in the spectral response of the spectrum in these bands. The same occurred in the infrared region (1900-2500 nm) where in the region 1400 to 1900 nm was found to have virtually no differences in reflectance due to the increase of salt concentration of the leaching solution. The crusts of the soils leached with NaCl showed higher reflectance than the crust of the soils leached with KCl in all bands of the spectrum.

In the Fluvisol, it wasn't practically impossible to differentiate the intensity of reflectance of the crusted soils leached with $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$ salts and leached with the salts NaCl and KCl at a concentration of 0.5 mol L^{-1} (Figure 2.3 c, d, e). At this concentration, a sharper difference in the intensity of reflectance was noticeable only in the regions of the visible and near infrared to the crusts leached with solutions of NaCl and KCl. With increasing concentration of the solutions, the reflectance of the crusts showed more evident differences among themselves than in the crusts of the Arenosol. The greater retention of these salts by the Fluvisol may have contributed to the incident.

With the exception of $MgCl_2.2H_2O$, the Arenosol showed higher reflectance in relation to Fluvisol between the others salts (Figure 2.4 and Table 2.5). Both soils presented similar reflectance when saline solutions of $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$ were applied. The reflectance of the soil, not only at the wavelength of visible light, but also of all other lengths of the optical spectrum band, is a cumulative property that derives from the spectral behavior of the mineral constituents, organic and fluid, which when, combined, make up the soil (Meneses and Madeira Netto, 2001).

According to Resende et al. (2005), the Arenosol by definition is a sandy soil containing low levels of organic matter and iron oxides, mineralogy in sand fraction consists predominantly of quartz. Thus, these authors state that in general, the sandy textured soils tend to have higher reflectance intensity in relation to clay, especially when the sand is dominated by quartz, as well as due to low levels of organic matter and iron oxides. The results of this study agree with the statement of these authors. Table 2.2 indicates that the Arenosol has a greater sand content in relation to Fluvisol. With this the largest fraction of quartz in Arenosol may be the factor that most contributed to the higher reflectance.

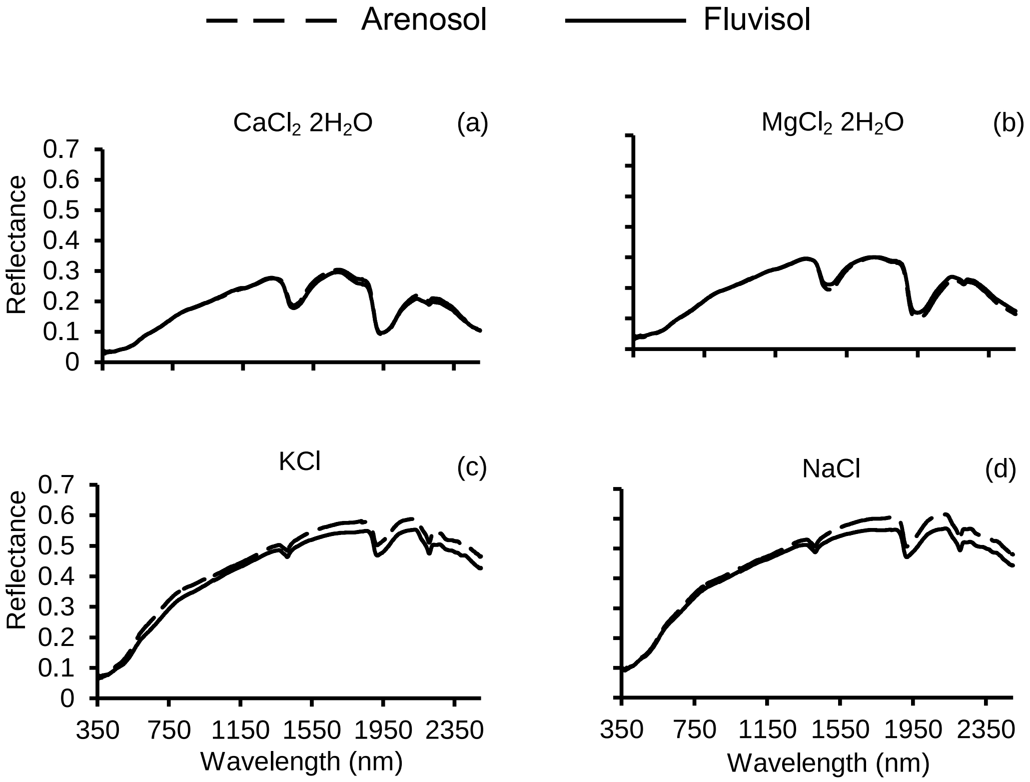

Figure 2.4. Spectral signatures of soils for salts of $CaCl_2.2H_2O$, $MgCl_2.2H_2O$, KCl and NaCl.

Table 2.5. Comparison of mean values of the reflectance of soil in selected ranges for each type of salt

Soil Class	Spectral Band selected (nm)					
	550-770	900-1030	1270-1520	1940-2150	2150-2310	2330-2400
			$CaCl_2.2H_2O$			
Arenosol	0.11	0.2	0.24	0.16	0.21	0.16
Fluvisol	0.11	0.2	0.23	0.16	0.19	0.16
			$MgCl_2.2H_2O$			
Arenosol	0.12	0.21	0.25	0.16	0.22	0.17
Fluvisol	0.12	0.22	0.26	0.18	0.22	0.18
			NaCl			
Arenosol	0.29	0.42	0.53	0.58	0.56	0.53
Fluvisol	0.28	0.41	0.51	0.54	0.52	0.5
			KCl			
Arenosol	0.26	0.39	0.5	0.56	0.54	0.51
Fluvisol	0.23	0.36	0.47	0.5	0.48	0.46

Another factor that contributed to a lower reflectance in the Fluvisol may be relation to a higher content of organic matter in the soil. Organic matter is a constituent which interferes strongly in the color of the soil, making them darker and, therefore; also a close relationship with the soil reflectance. Dalmolin (2002) noted an increase in the spectral response of the soil when there was a decrease in organic matter content; and Demattê et al. (2003) observed that removal of soil organic matter promoted an increase in reflectance intensity across the spectrum for various orders of soil evaluated in their study.

The absorption features related to the presence of water molecules (1400 and 1900 nm) and water molecules versus hydroxyls at 1400 nm (Lindberg and Snyder, 1972) appear in both soils, being more intense in the Fluvisol. The predominance of finer particles (Table 2.1) resulted in greater retention of moisture in these soil crusts, which resulted in lower reflectance and, therefore, this difference in intensity of absorption bands.

The reflectance of the crusted soil salts leached with $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$ at concentrations of 0.5 and 1 mol L^{-1} hardly differed in their intensities. For these salts, only the concentration of 2 mol L^{-1} promoted sharper differences in reflectance of crusts. In contrast, the crusts of the soils leached with KCl and NaCl salts showed noticeable differences at all concentrations tested. For the crust of the soil leached with these two salts showed a weak trend of increasing absorption with increasing concentration of salts. Similar results were also obtained by Farifteh et al. (2008), which stated that the band at about 2204 nm become less developed as it increased the concentration of saline solution.

2.4 Conclusions

Increasing the salt concentration of chlorides in the crust of the two soils resulted in a reduction in reflectance, and a larger decrease when these salts that have water molecules in composition such as $MgCl_2.2H_2O$ and $CaCl_2.2H_2O$. In this study, for the soils leached with salt crusts, the standard reflectance is changed only at a concentration of 2 mol L^{-1}.

In both soils, crusts leached with the salts NaCl and KCl had similar reflectance patterns at all concentrations of the solutions. Crusts leached with the salts $MgCl_2.2H_2O$ and $CaCl_2.2H_2O$ also showed similar reflectance patterns, where the increase in the concentration of salts promoted sharper differences in the intensity of reflectance.

The crust of the Arenosol showed higher reflectance intensity with respect to the Fluvisol at all concentrations for the salts NaCl and KCl. For crusts subjected to leaching salts of $CaCl_2.2H_2O$ and $MgCl_2.2H_2O$, only the concentration of 2 mol L^{-1} promoted the reflectance intensity differences between the soils.

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3 - CHAPTER II

SOIL PROPERTIES AND CORRELATION WITH SPECTRAL REFLECTANCE AT DIFFERENT SALINITY LEVELS

Abstract

Spectral response patterns of saline soil are a function of the quantity and mineralogy of the salt contained. In the semiarid region of Pernambuco state and in semiarid regions of Brazil, studies in relation to spectral responses of soil salinization and their associations with the soil properties are scarce or unavailable. In this study, a field investigation was conducted in which soil samples were collected from four watersheds with varying degrees of salinity and sodicity. The main objectives were: (1) to separate the soil samples into groups based on relation to the criteria for salinity and sodicity through cluster analysis; (2) to obtain the physical, chemical and spectral characterization of these soils groups; (3) to establish the correlation between soil properties and soil reflectance. Each of the four watersheds (Brígida, Terra Nova, Pajeú and Moxotó) had soil samples collected from 10-15 topsoil samples (0-5 cm depth). Cluster analysis was used to investigate the similarity between the levels of salinity and sodicity in the soils for four watersheds resulting in arrangement of six homogeneous groups. The difference found in this study between the groups is likely due to soil chemical properties. Groups 1, 2, and 3 have high levels of EC and SAR indicating the presence a high level of soluble salts which is toxic for plant development. Groups 4, 5 and 6 contain sampling sites most likely to plant development and plant growth conditions due to your low levels presented of EC, SAR and ESP. It was observed that there was an increase in reflectance with increasing wavelength to the spectral response of all groups formed. The ESP obtained the best correlation coefficients followed by percent sand. The variable ESP had good correlation coefficients obtained with the positive spectral reflectance bands in virtually all tested, while the variable fine sand obtained negative coefficients. Then by the cluster analyses associate with the physical and chemical parameters of soil it can be used as a good indicator of degraded areas. This work suggests that high levels of salts in soil can decrease the spectral reflectance related to higher water content in that soils and low carbon content can represent high associations with the reflectance due to soil dispersion.

Keywords: soil salinity and sodicity; spectral reflectance; semiarid region

3.1 Introduction

Soil salinization is considered to be a large impediment lending to environmental degradation in agricultural areas. It adversely affects biological functions in ecosystems and can decrease soil and water resource quality and health. This is a common problem encountered in arid and semiarid regions, where agriculture is confounded with additional growth issues. As a result, a reduction in food production could occur while population growth continues to increase. Thus, the establishment of an efficient land management plan is necessary for better understanding of saline agricultural areas.

Remote sensing techniques are potentially useful for detecting and monitoring soil salinization. Soil salinity can be detected from remotely sensed data on bare soils, with salt crust, or through the biophysical properties of vegetation (Abd-Elwahed, 2005). These techniques have been widely used to identify and map saline areas at various scales like 1:100.000 or 1:2.5 M, (e.g., Everitt et al., 1988; De Jong, 1992; Ben-Dor et al., 2002; Dehaan and Taylor, 2003; Metternicht and Zinck, 2003; Farifteh et al., 2006). Identification of saline areas with varying degrees of salt affected soils can be increased if the spectral characteristics of the salt-affected soils and the underlying factors are given more attention including the analysis of spectra reflectance (Farifteh et al., 2008).

Soil spectral reflectance is determined by the inherent physical–chemical properties of a soil, including parent materials, soil texture, organic matter, type of clay minerals, and soil moisture content (Csillag et al., 1993; Metternicht and Zinck, 1997, Shrestha et al., 2005; Brown et al., 2006). Spectral response patterns of saline soil are a function of the quantity and mineralogy of the salt it contains. In addition, hyperspectral remote sensing is an advanced technique that often provides ample spectral information to delineate material characteristics. This capability allows for the identification of targets based on their established spectral absorption features (Goetz et al., 1985). The spectral information enables quantitative assessment and research of salt-affected soil (Ben-Dor et al., 2002).

In addition to being applied to identify the mineral composition, the reflectance spectroscopy has been used for predicting soil physical, chemical and biological characteristics. Howari et al. (2002) observed bands in the spectrum of water halite crusts, for wavelengths of 1400, 1900, and 2250 nm, arguing that these are dominant absorption characteristics halite (NaCl). Dehaan and Taylor (2002) evaluated the spectrum derived from field samples of saline soil and spectral analysis indicated that these saline soils have significant absorption features at 505, 920, 1415, 1915, and 2205 nm and hydroxyl features at approximately 2200 nm, which are less developed for the more saline soil. Metternicht and Zinck (2003) claim that sodic soils are generally dark on the surface because the excess sodium causes dispersion of organic matter when soils are moist. Farifteh et al. (2008) used laboratory spectroscopy to recognize the presence and abundance of salts in soils and they found that the Continuum-Removed (CR) spectra indicate a strong negative correlation between increase of soil EC and changes in absorption bands parameters (depth, width, and area).

In the semiarid region within the state of Pernambuco and in other semiarid regions withinBrazil, studies in relation to spectral responses of soil salinization and their associations with the soil properties are scarce or unavailable. In this study, a field investigation was conducted in which soil samples were collected from four watersheds with varying degrees of salinity and sodicity from Pernambuco. Physical and chemical characterization and laboratory spectral measurements were performed on the soils collected. The main objectives were to: (1) separate the soil samples into groups based on relation to the criteria for salinity and sodicity through cluster analysis; (2) obtain the physical, chemical, and spectral characterization of these soils groups; (3) establish the correlation between soil properties and soil reflectance.

3.2 Material and methods

3.2.1 Study areas

The four selected watersheds are located in the Pernambuco semiarid region, Brazil. The Brígida watershed is located between coordinates 7° 30' - 9° 00' south latitude and 39° 30' - 41° 00' west longitude, with an area of 14,366 km^2. Terra Nova watershed is located between 7° 40' 20"and 8º 36' 57" south latitude and 38º 47' 04" and 39º 35' 58" west longitude, with an area of 4,887.71 km^2. The Pajeú watershed is geographically between latitudes 9° 27' and 11° 30' south and between longitudes 40° 22 'and 41° 30' west, occupying an area of 16,760 km^2. The Moxotó watershed is located between 07º 52' 21" and 09º 19' 03" south latitude and between 36º 57' 49 "and 38º 14' 41" west longitude, occupying a total area of 9,744.01 km^2 (Figure 3.1).

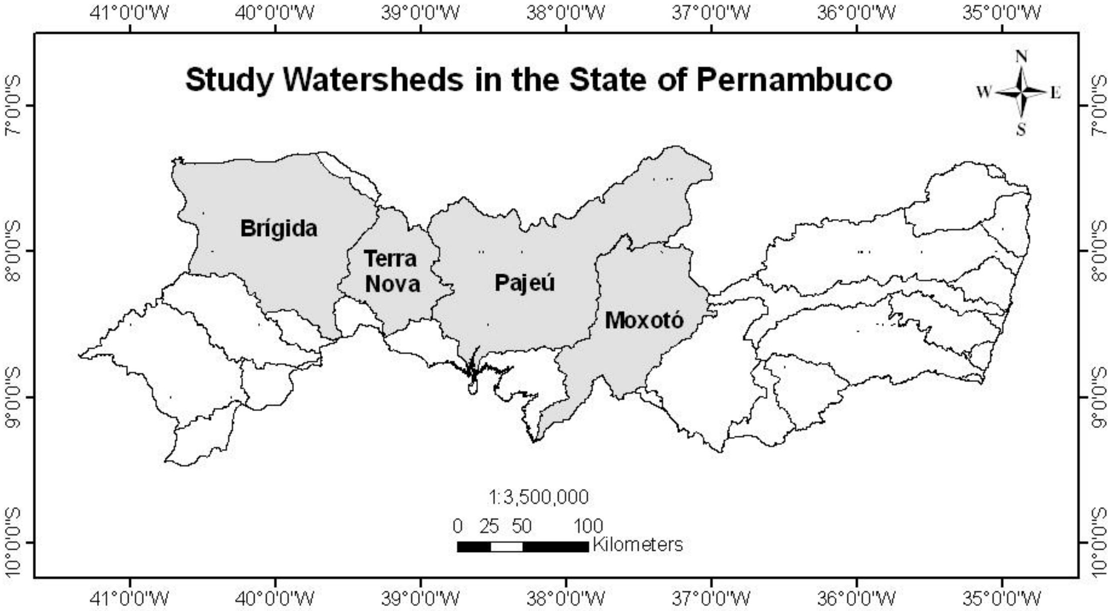

Figure 3.1. Study watersheds map in state of Pernambuco, Brazil.

This region is characterized by low rainfall, with annual averages of about 600 mm, with the prevalent vegetation being from Caatinga biome (Galvíncio and Moura, 2005). The soils range from undeveloped soils to soils with a high degree of weathering. Besides climatic factors, which may contribute to the natural emergence of these degraded areas, anthropogenic factors contribute strongly to soil and water resource quality resulting in low quality irrigation water.

3.2.2. Soil sampling

Each of the four watersheds (Brígida, Terra Nova, Pajeú and Moxotó) had soil samples collected from 10-15 topsoil (0-5 cm depth) sites which were composited into one mixed sample representing each 400 m^2 watershed, respectively. Additional individual soil samples were collected for further physical analysis.

The collected soil composite samples were air-dried and passed through a 2 mm sieve to remove large debris, stones, and sere stubbles. Each composite sample was split into three sub-samples. One was used for spectroscopic measurements; one was used for physical analysis; and, the other was used for chemical analysis to characterize saline soil properties.

3.2.3 Physical analysis

The physical characterization determined the sand, silt, and clay content, and water dispersible clay, by sieving and sedimentation (EMBRAPA, 1997). The sand content was determined by thick sand (diameter size particles between 2 and 0.2 mm) and fine sand (diameter size particles between 0.2 and 0.05 mm). The bulk density was analyzed on an unmixed sample and soil particle density was analyzed by volumetric flask (include methods here). The saturated hydraulic conductivity was determined in medium saturation with vertical column and constant load permeameter by unmixed samples.

Total porosity was calculated with bulk density and particle density soil data. The degree of flocculation and degree of dispersion were calculated with total clay and water dispersible clay data.

3.2.4 Chemical Analysis

For the evaluation of the chemical attributes, soil samples were submitted for analysis of the soluble elements (Richards, 1954). Electrical conductivity (EC_e at 25 °C) and soluble cations: Ca^{2+} and Mg^{2+} by Atomic Absorption Spectrophotometry – Inductively Coupled Plasma and Na and K by flame emission photometry.

On the soil, was measured pH (1:2.5) and determined the exchangeable cations Ca^{2+}, Mg^{2+}, K^+ and Na^+, extracted with ammonium acetate solution 1 mol L^{-1}. Calcium and Mg^{2+} were determined by spectrophotometry atomic absorption and Na^+ and $K^+$by flame emission photometry. The cation exchange capacity (CEC) was determined by the method of sodium acetate and ammonium acetate 1 mol L^{-1} (Richards, 1954). With the results of analyzes, were calculated the sum of bases (S), the percentage of base saturation (BS), the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP), the last two according to Richards (1954).

3.2.5 Soil spectral data acquisition in laboratory

To collect spectral data from the laboratory, the hyperspectral sensor, FieldSpec Spectroradiometer with fiber optic cable, which covers the spectral range between 450 and 2500 nm with spectral resolution of 1 nm and between 1100 and 2500 nm with spectral resolution 2 nm, was used.

A standard white plate was used as a baseline with 100% reflectance for the soil spectral readings. The ratio of spectral radiant flux reflected by a sample by the radiant flux reflected by the reference material generates the bidirectional spectral reflectance factor, from which the curve is fitted reflectance (Nicodemus et al., 1977). The procedure used was to measure the radiance from the target and compare it with the white reference plate pattern maximum of reflection. A 600 W halogen lamp was used as the source of illumination.

3.2.6 Statistical analysis

A cluster analysis was applied to the soil salinity and sodicity characteristics (EC, pH, ESP, and SAR) to distinguish whether sampling sites were similar to each other. The dissimilarity measure used was the Euclidean distance and the Ward algorithm was used as a method of agglomeration. A dendrogram was utilized to find 20% dissimilarity between the soil samples. The variables of soil groups from the cluster by salinity and sodicity classes were evaluated using the following descriptive measures: mean and standard deviation.

Six spectral readings were performed on each soil sample to generate an average representative curve per soil sample. For recognizing the soil salinity status, some key spectral ranges in part of the visible (550–770 nm), near-infrared (900–1030 nm, 1270–1520 nm), and middle infrared (1940–2150 nm, 2150–2310 nm, 2330–2400 nm) were identified according to Csillag et al. (1993).

For this study, nine representative spectral bands from the continuum of wavelengths were selected to characterize the chemical and physical properties of the saline soils: 488, 530, 670, 880, 940, 1400, 1900, 2200, and 2300 nm because the correlation between these properties were more important for soil reflectance and the corresponding reflectance (Leone and Sommer, 2000). Thus, Pearson correlation analysis was applied to find the relationship between those nine bands representing and the properties of saline soil, as well as between texture and organic carbon content which also exert great influence on the spectral reflectance of soils.

3.3 Results and discussion

3.3.1 Cluster analysis

Cluster analysis is used to investigate the similarity between the levels of salinity and sodicity in the soils for four watersheds resulting in the arrangement of six homogeneous groups (Fig. 3.2). The number of similar groups was defined by the partition dendrogram at 20% similarity. These results demonstrate more internal (within groups) similarities than external (between groups) similarities. These findings indicated the application of cluster analysis for separation of groups of soils at different salinity and sodicity levels.

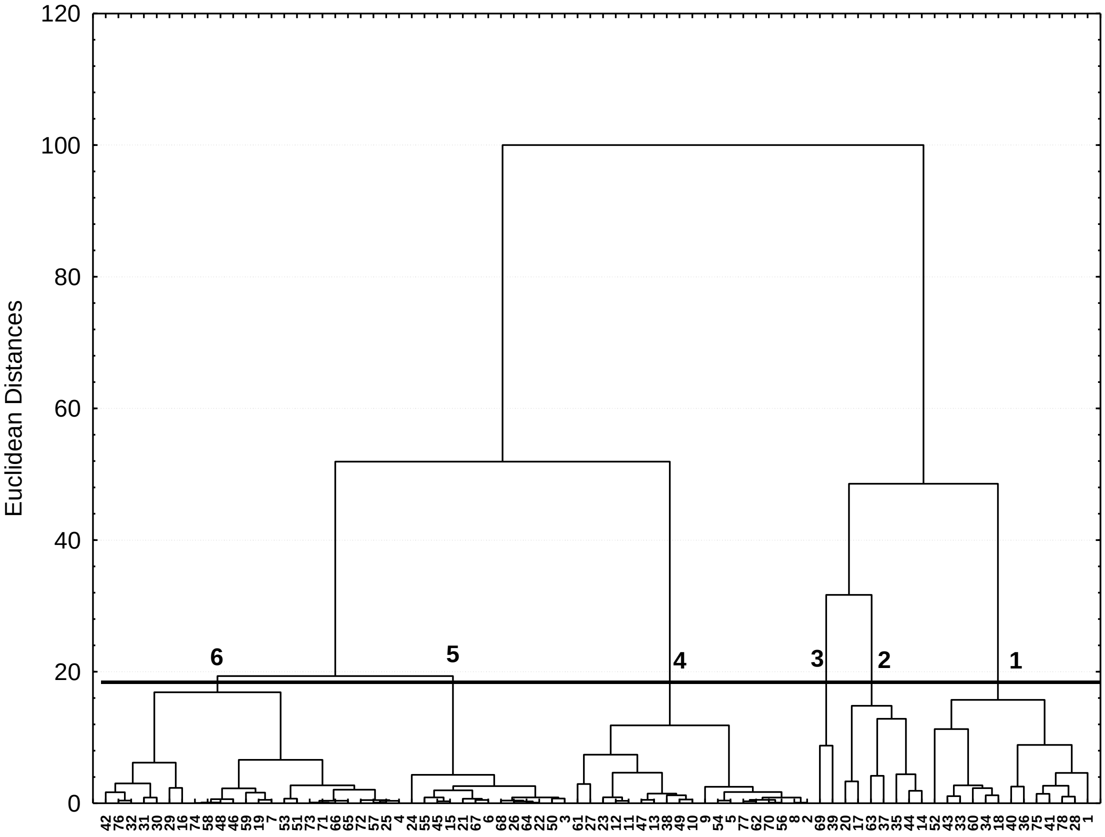

Figure 3.2. Dendrogram obtained from cluster analysis of the saline and sodic variables (pH, EC, ESP, and SAR) from soil samples collected in the watersheds of Brígida, Terra Nova, Pajeú and Moxotó, Pernambuco, Brazil.

One study that has used cluster analysis with semiarid soils specifically in irrigated perimeter is Andrade et al. (2011). These authors evaluated the application of multivariate analysis and cluster analysis to identify similarities in the concentrations of salts in irrigated fields in State of Ceará, Brazil. They observed that the cluster analysis proved appropriate to define similarities between the studied attributes, identifying areas with higher or lower risks salinity.

Thus, separation of classes of salinity and sodicity through soil grouping is pertinent due to the definition of these classes and it can define management strategies more appropriate in accordance with the status of each soil salt formed grouping. However, other studies differ on this in relation to salt levels found here (Shresta, 2006; Elnaggar and Noller, 2010) and in relation to the criteria for partition of the dendrogram (Andrade et al., 2011).

3.3.2 Physical properties of the soils

The results indicate that there was a predominance of the coarse sand fraction in relation to clay and silt fractions in all the groups formed. The highest average levels of sand were found in the soils of Group 3, which also received the greatest levels of coarse sand fraction. The highest average levels of fine sand fraction were observed in soils from Group 4, while soils in Group 2 had a predominance of silt and clay fractions (Table 3.1).

It was observed that samples of soil had considerable amounts of clay dispersed in water, influencing the high dispersive index values (Table 3.1). It was noted that the soil samples from Group 4 demonstrated mean values of dispersive index higher than the rate of flocculation, explaining that clays of the soil samples of this group are in a near constant state of dispersion with respect to flocculation.

The average density of the particles varied from 2.67 g cm^{-3} (for the mean value obtained in Group 6), 2.73 g cm^{-3} (for the average obtained in Group 4) with bulk densities ranging from 1.35 to 1.44 g cm^{-3}. Thus, from this data it was observed that the mean values of total porosity were similar among the groups formed and they can be considered as soil with good surface porosity. Other authors have found an increase in density and decrease in soil porosity with increasing depth (Cooke et al., 2010, Figueiredo et al., 2009), attributing this fact to different soil management.

Table 3.1. Cluster analysis formed salinity and sodicity group physical properties as a function of salinity and sodicity variables (pH, EC, SAR and ESP) for soil samples from Pernambuco, Brazil

Atribute	Salinity and Sodicity group											
	1		2		3		4		5		6	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Thick sand (%)	31.0	18.0	19.0	25.0	56.0	4.0	31.0	18.0	29.0	16.0	36.0	19.0
Fine sand (%)	30.0	18.0	26.0	18.0	29.0	4.0	32.0	12.0	26.0	14.0	31.0	14.0
Clay (%)	15.0	14.0	17.0	22.0	5.0	1.0	15.0	8.0	17.0	13.0	15.0	10.0
Silt (%)	24.0	21.0	37.0	26.0	10.0	1.0	22.0	14.0	28.0	27.0	18.0	17.0
WDC (%)	5.0	3.0	4.0	1.0	2.0	2.0	7.0	3.0	8.0	6.0	7.0	5.0
PD (g cm^{-3})	2.7	0.08	2.68	0.19	2.72	0.08	2.73	0.1	2.69	0.09	2.67	0.12
BD (g cm^{-3})	1.4	0.04	1.4	0.19	1.35	0.21	1.44	0.11	1.43	0.15	1.42	0.18
Pt (cm^3 cm^{-3})	0.48	0.27	0.48	0.05	0.51	0.07	0.47	0.05	0.47	0.05	0.47	0.06
DI	0.48	0.27	0.46	0.29	0.45	0.28	0.53	0.14	0.49	0.17	0.49	0.18
FI	0.52	7.28	0.54	0.29	0.55	0.28	0.47	0.14	0.51	0.17	0.51	0.18
K_0 (cm h^{-1})	4.08	0.19	3.01	6.09	3.58	3.41	5.97	7.91	14.73	29.55	15.54	20.6

SD – Standard deviation; WDC – Water dispersible clay; PD – Soil particle density; BD – Soil bulk density; Pt – Porosity total; DI – Dispersion index; FI – Flocculation index; K_0 – Saturated hydraulic condutivity.

The average saturated hydraulic conductivity in Groups 5 and 6 was extremely high when compared with the values of the other groups. Additional studies (Araújo et al., 2004; Silva et al., 2005) have emphasized the influence of soil management as one of the most important factors modifying their physical properties. However, the difference found in this study between the groups is likely due to soil chemical properties being dominated by salinity levels. Thus, it is likely that within the same group are found different management systems, which is not responsible for the variations found in the differences between the groups.

3.3.3 Chemical properties of the soils

The pH values were higher in the soil samples of Group 3 due to higher levels of carbonates and bicarbonates present in these soils (Table 3.2). The average pH values for Groups 2 and 4 had high alkalinity and other groups had average pH values more suitable for plant growth.

In general, all groups had high levels of exchangeable cations and soluble Ca^{2+}, Mg^{2+}, Na^+ and K^+, high values of sum of bases, base saturation and levels of organic carbon, ranging from 7 to 16 g kg^{-1} (Table 3.2). Groups 2 and 3 had high levels of ESP, which resulted in high values of ESP, over 15%, which is the threshold for classifying soils as sodic according to Richards (1954). It is observed that high values of ESP in sampling sites of the Groups 2 and 3 (Table 3.2) may have contributed to the low hydraulic conductivity values presented in the sites of these groups (Table 3.1).

Groups 1, 2, and 3 have high levels of EC and SAR indicating the presence of high levels of soluble salts which is toxic for plant development. These high levels of salts include high levels of soluble sodium, which is the predominant ion in relation to other cations evaluated in the saturation extract (Table 3.2). Only a few plant cultures tolerant to excess salts would be able to grow under these degraded conditions (Richards, 1954).

Table 3.2. Chemical properties for the groups formed by cluster analysis as a function of salinity and sodicity variables (pH, EC, SAR and ESP) for the soil samples from Pernambuco, Brazil

Atribute	Salinity / Sodicity group											
	1		2		3		4		5		6	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Exchangeable cations												
pH	7.2	0.56	8.3	0.9	10.2	0.64	8.2	0.43	6.5	0.29	7.2	0.2
Ca^{2+} (cmol$_c$ kg^{-1})	14.0	12.8	6.1	4.7	8.9	3.22	5.6	3.62	3.2	2.98	6.4	6.72
Mg^{2+} (cmol$_c$ kg^{-1})	3.3	2.85	2.7	2.34	1.8	0.84	1.7	1.35	1.7	1.59	1.8	2.0
Na^{+} (cmol$_c$ kg^{-1})	1.5	1.79	4.1	3.12	2.0	0.93	0.3	0.52	0.2	0.17	0.4	0.39
K^{+} (cmol$_c$ kg^{-1})	0.5	0.33	0.3	0.21	0.5	0.29	0.6	0.75	0.4	0.23	0.5	0.68
CEC (cmol$_c$ kg^{-1})	19.9	16.28	16.1	12.5	13.3	2.86	11.3	5.73	10.0	8.53	9.7	8.7
S (cmol$_c$ kg^{-1})	19.3	16.4	13.2	09.99	13.2	2.83	8.4	4.81	5.5	4.31	8.9	8.63
BS (%)	90.4	18.65	83.5	18.14	99.4	0.13	73.9	24.09	60.4	21.1	87.4	18.87
ESP (%)	5.8	3.23	31.8	10.44	16.4	10.57	3.2	2.68	2.8	1.69	6.3	5.71
OC (dag k^{-1})	1.4	7.9	0.8	4.1	0.7	1.5	1.4	6.5	1.6	11.7	1.1	6.1
Saturation extract												
EC (dS m^{-1})	64.5	21.33	28.4	23.14	66.1	43.88	3.7	7.1	0.8	1.0	2.1	4.1
Ca^{2+} (mmol$_c$ L^{-1})	205.6	189.53	58.5	71.72	14.3	9.08	20.4	53.0	1.9	2.48	6.6	13.33
Mg^{2+} (mmol$_c$ L^{-1})	265.3	161.96	106.3	146.37	5.8	6.06	26.6	54.7	3.8	3.64	7.5	10.64
Na^{+} (mmol$_c$ L^{-1})	937.4	755.54	779.8	671.09	1856.1	1099.78	108.2	306.9	5.0	8.35	8.0	20.58
K^{+} (mmol$_c$ L^{-1})	12.4	16.45	1.9	1.47	143.6	90.2	1.6	2.9	0.5	0.35	0.8	1.26
SAR (mmol$_c$ L^{-1})^{0,5}	90.6	79.9	97.4	102.92	585.1	122.3	10.3	27.2	3.7	6.57	2.6	4.56

SD – Standard deviation; CEC – Cation exchange capacity; S – Bases sum; BS – Percent base saturation; ESP – Exchangeable sodium percentage; OC – Organic carbon; EC – Electrical condutivity; SAR – Sodium adsorption ratio.

Groups 4, 5 and 6 contain sampling sites most likely to plant development and plant growth conditions due to your low levels presented of EC, SAR and ESP. The sites that comprised the Groups 1, 2 and 3 have degraded by soil salinity and sodicity The cluster analysis obtained allows the observation of three different situations with respect to the sampling sites included in the groups with one finding: the sampling sites included in Groups 1, 2 and 3 are not suitable for farming and indicate that these areas are in need of being reclaimed. The sampling sites included in Group 4 are at high risk of degradation by salinization (EC = 3.7 dS m^{-1}). Areas not currently determined to be at high risk for salinization andor sodicity should adopt management practices that minimize any contribution toward soil and water degradation. Finally, the soil sample sites included in Groups 5 and 6 could be utilized designed for agricultural purposes since they does not present any risk of degradation by salt (especially sodium).

Fernandes (2007) evaluated the same parameters of salinity in soils of an irrigation perimeter from municipality of Serra Talhada, Pernambuco, Brazil, in three layers (0-20, 20-40 and 40-60 cm), from June 2006 to March 2007, utilizing four soil samples distributed in time in each perimeter site. At the surface layer (0-20 cm), the soil had a mean pH ranging from 7.9 to 8.5, but the maximum value was 9.6 and the minimum value was 6.5. At the same layer, the average EC ranged from 2.25 to 3.13 dS m^{-1}, and the maximum value was 44.70 dS m^{-1} and the minimum value was 0.16 dS m^{-1}. This demonstrates the high variability of salt affected soils, and the author still got different values in deeper layers of the soils evaluated.

ESP mean values also ranged from 5.6% to 10.1%, with the maximum value of 64.28% and the minimum of 0.00%; and SAR mean values varying from 1.3 to 9.0 ($mmol_c$ $L^{-1})^{0.5}$, and maximum of 125.07 ($mmol_c$ $L^{-1})^{0.5}$ and minimum of 0.04 ($mmol_c$ $L^{-1})^{0.5}$.

3.3.4 Hyperspectral Measurements of the Soils

The complex nature of soils soil presents itself in the spectral identification of mineral soils (Csillag et al., 1993). Figure 3.3 shows the reflectance curves for each group consisting of cluster analysis. In each group was calculated the average reflectance between the sampling sites to represent the six saline groups.

It was observed that the more evident absorption bands were found at 1400, 1900, and 2200 nm. According to Lindberg and Snyder (1972), these absorption bands at 1400 and 1900 nm are due to the vibration of water molecules in clay minerals, and at 2200 nm are due to the presence of kaolinite. According to these authors when the water molecules adsorbed on the minerals are affected by electromagnetic energy, the vibration of these molecules occurs with a consequent decrease in reflectance, promoting the formation of absorption bands.

The shape of the curves did not change between the different groups formed. What changed the most was the level of reflectance due to differences between the levels of salinity and sodicity and the other soil properties of the groups formed.

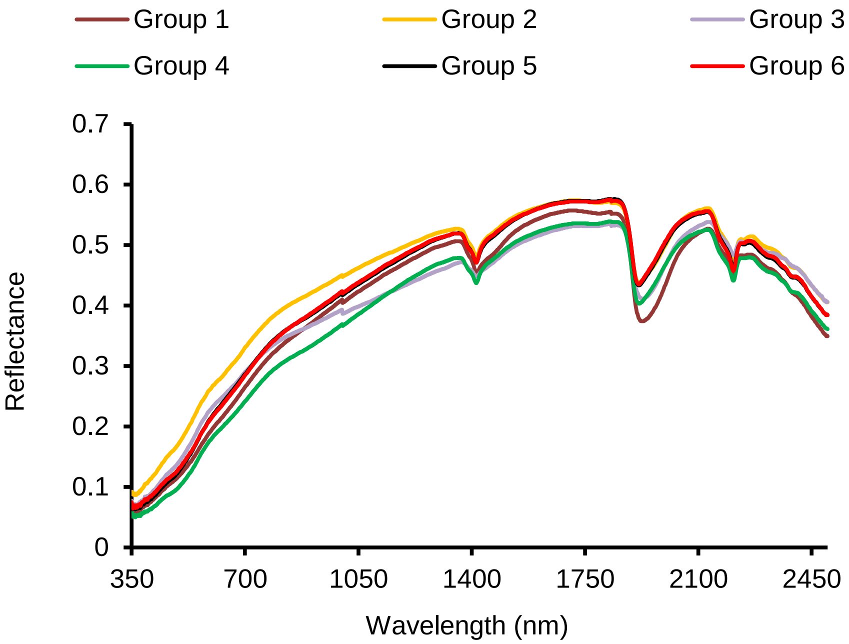

Figure 3.3. Average spectral reflectance curves of the six groups formed by cluster analysis on soils sampled from Pernambuco, Brazil.

It is observed that there was an increase in reflectance with increasing wavelength to the spectral response of all groups formed. The average reflectance formed by all groups demonstrated a low reflectance in the visible region which according to Demattê et al. (2005) can be assigned to strong absorptions that occur due to the effect of the presence of Fe $^{3+}$ in the wavelengths shorter than 540 nm.

Several studies indicate that the reflectance is increased with an increasing amount of salt in the surface (Rao et al., 1995; Metternicht and Zinck, 2003). In this study, Groups 1, 2 and 3, which had high levels of salt and sodicity (Table 3.2), also had reflectance values higher than those groups with lesser amounts of salts and sodium (Table 3.3).

Table 3.3. Mean values of the reflectance of soil groups formed by cluster analysis, on the selected spectral intervals.

Soil group	Wavelength (nm)					
	550 - 770	900 - 1030	1270 - 1520	1940 - 2150	2150 - 2310	2330 - 2400
1	0.24	0.39	0.49	0.47	0.48	0.44
2	0.3	0.44	0.52	0.52	0.51	0.48
3	0.26	0.38	0.47	0.49	0.5	0.48
4	0.22	0.35	0.47	0.49	0.47	0.44
5	0.26	0.41	0.51	0.52	0.5	0.46
6	0.26	0.41	0.51	0.52	0.5	0.46

The average reflectance from Group 2 indicated values higher than the other groups over the entire spectrum (Table 3.3). However, it was observed that the Groups 5 and 6 had reflectance values that were identical at each interval. These two groups didn’t demonstrate any degradation by salinization or sodification (Table 3.2). Groups 5 and 6 also have similar physical characteristics (Table 3.1). Therefore, it is reasonable to deduce that the similarity of the properties of soils contributed to the similarity of the reflectance values between the groups.

The Pearson correlation coefficient results are presented in Table 3.4. The ESP obtained the best correlation coefficients followed by percent sand. The variable ESP had good correlation coefficients obtained with the positive spectral reflectance bands in virtually all tested, while the variable fine sand obtained negative coefficients (Table 3.4).

In this study, other saline and sodic variables (pH, EC and SAR) had low correlation coefficients, indicating minimal influence on the spectral reflectance of soils. Some studies in the literature (Rao et al., 1995; Metternicht and Zinck, 2003) claim that the EC has a good correlation with the spectral reflectance. Probably due to the high concentration of salts present mainly in Groups 1 and 3, the low correlation coefficients were obtained in realtion to EC likely becaue of an increase soil moisture.

Table 3.4. The R correlation coefficients between spectral bands and the properties of soils sampled in Pernambuco, Brazil

Properties of Soil	Wavelength (nm)								
	488	530	670	880	940	1400	1900	2200	2300
pH	0.29	0.31	0.17	-0.14	-0.24	-0.56	-0.11	0.51	0.23
EC	0.23	0.2	0.11	0.01	-0.02	-0.3	-0.45	0.38	0.2
SAR	0.3	0.32	0.22	-0.05	-0.14	-0.45	-0.07	0.66	0.32
ESP	0.92	0.92	0.85	0.71	0.65	0.34	0.42	0.74	0.7
OC	-0.66	-0.66	-0.57	-0.36	-0.29	0.0	-0.36	-0.73	-0.66
Thick sand (0.2-2 mm)	-0.16	-0.14	-0.2	-0.4	-0.46	-0.61	-0.15	0.3	0.05
Fine sand (0.05-0.2 mm)	-0.7	-0.71	-0.78	-0.76	-0.74	-0.64	-0.6	-0.66	-0.66
Clay	-0.05	-0.07	0.03	0.29	0.37	0.62	0.17	-0.46	-0.15
Silt	0.4	0.38	0.43	0.43	0.61	0.67	0.27	-0.02	0.16

As ESP was the saline variable that best correlated with reflectance, this was most influential in the larger reflectance values in Group 2 (Table 3.4); this group indicated the highest values of ESP compared to the others (Table 3.2). The findings herein suggest that soils where the organic matter contents are low, ESP can help to increase the reflectance of the soil due to dispersion of the colloidal material. In this study, samples of Groups 2 and 3 had the lowest levels of organic carbon compared to the other groups (Table 3.2), as determined by chemical analysis.

The organic carbon content obtained negative correlations in the bands 488, 530, 670, 2200, and 2300 nm. The organic matter, which influences many physical and chemical characteristics of soil, is a primary constituent of the color of soil, therefore it has a close relationship with the soil reflectance (Dalmolin et al., 2005). The studies found in the literature claim that there is a decrease in reflectance with increasing organic matter content, agreeing with the results found in this study, in which samples of Groups 2 and 3 had lower organic carbon content (Table 3.2) and higher reflectance values in the ranges 550-770 nm and 2150-2310 nm (Table 3.3).

The negative correlation between the reflectance and the fine sand fraction also contributed to a higher reflectance in Group 2 compared to the others groups (Table 3.4). This group had lower levels of this fraction (Table 3.1), which also contributed to its higher reflectance. According to Stoner (1979), in sandy soils the decrease in particle size, in other words, increasing the proportion of fine sand and very fine sand causes an increase in reflectance, disagreeing with the results obtained in this work and in agreement with those obtained by Shi and Huang (2007) that claim this may not be as likely to sandy soils with high salt content, as was found in this work.

3.4 Conclusions

The study was developed from sampling sites at different levels of salinity and sodicity. Cluster analysis proved to be an efficient tool for identification of greater similarity within each group and between disparities among the groups. This work is important in determining available resources to minimize soil and water degradation in agricultural areas and to ultimately improve soil management practices.

This study evaluated the relationship of saline and sodic variables on the soil samples taken from four watersheds in a semiarid region in Northeastern Brazil. The 0 to 5-cm depth soil sample findings indicated that based on a Euclidean distance dendrogram, three out of the six groups had levels of salt considered toxic for plant growth. The existence of salt crusts prevalent in the 0 to 5 cm portion of the soil profile explains the high similarity between Groups 1, 2, and 3.

The average values of the data obtained from the physical and chemical analyses values were compared between groups relative to sodic and saline variables. It is important to understand the influence of seasonal cycles on saline and sodic soils. According to the chemical analysis, the sites with several degradation by salinity and sodicity are these included on Groups 1, 2 and 3. It indicates that all the sites included in those groups should be implanted remediation strategies. While the Groups 5 and 6 presented good chemical characteristics the site included in those two groups can be indicated for use in agriculture as well. Moreover, these Groups 5 and 6 presented good physical characteristics by their good permeability that is important for leacheate the salts.

The vast majority of studies indicate that the increase in soil salinity causes an increase in its spectral reflectance. The levels of salts in this study are higher than the level of salinity reported in references cited in this research. Thus, only in extreme cases could increased salinity occur with greater absorption of water molecules in these soils, especially when hygroscopic salts predominate, thereby helping to reduce the reflectance of these soils. Therefore, , those soils can get more humid due the presence of those hygroscopic salts, and then, it can get darker contributing to lower reflectance values.

Exchangeable sodium percentage values found in this study presented strong correlations with the spectral reflectance of the samples. Although the literature mostly point the ESP as a parameter that causes a reduction in reflectance, the data presented during the research indicate that this will be governed by the content of organic matter present in the soil. For cases of low organic matter content, the ESP can contribute to increase the reflectance of the soil.

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4 - CHAPTER III

SPATIAL DISTRIBUTION AND CHARACTERIZATION OF SOIL SALINITY IN A SEMIARID REGION OF NORTHEASTERN BRAZIL

Abstract

An understanding of the processes involved in the development of soil salinization and identification of appropriate management practices contribute to the ability to develop defectiveve and efficient methods of obtaining information on the spatial distribution of salinity. The Identification of salts in soils is essential to develop sustainable agricultural management techniques. This study was conducted in a semiarid region of the Pernambuco state within Brazil, with the objectives to characterize the chemical properties of soils for four watersheds and to demonstrate the spatial distribution of the levels of salinity ions in those respective watersheds. The average levels of soluble and exchangeable anions and cations were high in the four watersheds studied. The anions SO_4^{2-}, HCO_3^- and Cl^- indicated high levels in the saturation extract. The speciation analysis revealed that the strongest association between cations and anions was the formation of sulfate and chlorides species. The Pearson correlation analysis revealed that Na^+ ions (exchangeable and soluble), HCO_3^- and Cl^- ions are those that contribute most to increase the salinity and sodicity in soils. The area most affected by sodium exchangeable and soluble sodium is located in the east portion, in the south, especially in the Moxotó watershed, as represented by the Exchangeable Sodium Percentage (ESP) and Sodium Adsorption Ratio (SAR) levels. The Moxotó watershed had the highest level of degradation by salinity and sodicity among the watersheds, where cations and anions contribute the most to salinity and sodicity of soils are Na^+ soluble and exchangeable, Cl^-, and to a lesser extent, HCO_3^-. The spatial distribution of salinity and sodicity levels allowed the establishment, in the watersheds of the study: non-degraded areas, areas that need special management systems, and areas that need to be recovered in the semiarid region from Pernambuco state, Brazil.

Keywords: saline and sodic soils, salt speciation, spatial distribution

4.1 Introduction

Soil salinity in arid and semiarid regions where crop water requirements are augmented by irrigation is a major concern for the sustainability of irrigated agricultural systems. It causes severe environmental degradation and leads to reduced crop growth and regional production (Abbas et al., 2011). According to the Food Agriculture Organization (FAO, 2000), the global area affected by salts is approximately 831 million hectares, of which 48% is affected by saline soils and 52% by sodic soils.

In order to understand the processes involved in development of soil salinization and planning appropriate management practices to control its speed and development, rapid and reliable methods of obtaining information on the spatial distribution of salinity are required. This can be achieved by the use of tools like geographical information systems (GIS) and global positioning systems (GPS) which provide ways to investigate and display areas spatially (Grunstra and Auken, 2007). Therefore, digital mapping of salt-affected soils is useful to monitor spatial and temporal changes in soil salinity status for the purpose of managingland use and reclamation.

Soil mapping or soil surveying is a process in which the spatial distribution of physical, chemical, and descriptive soil properties are evaluated and presented in a form that can be understood and interpreted by several users (Dent and Young, 1981) from many disciplines. Spatial representation of the distribution of underlying soil properties is a useful foundation for any tool or manager that relies on soil resource management. For example, evaluating the spatial variability of basic soil properties in saline soils, and mapping the spatial distributions of these soil properties, can help farmers and agricultural managers make effective site-specific management decisions (Zheng et al., 2009).

Soils in the world vary spatially and are heterogeneous physically and chemically and continue to vary with time. Variability is one of the intrinsic characteristics of soil quality and many studies indicate that there were strong spatial variations in soil properties and they may vary significantly within a given ecosystem (Robinson and Metternicht, 2006). These variations can arise from factors and processes of pedogenesis and land use. Hence, geostatistical methods can be used for better understanding of spatial variations of the soil characteristics. Many studies of soil salinity have incorporated GIS into their analysis or presentation of their data. GIS interpolations have been used to determine the spatial dynamics of soil salinity in arid and semiarid conditions (Jordan et al., 2004) as well as to determine the spatial variability of soil salinity in a coastal saline field (Shi et al., 2005), and evaluate and analyze spatial variability of soil EC as an aspect of soil degradation (Ashraf and Abbaspour, 2011).

Salinity parameters like electrical conductivity (EC), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR) and pH also are influenced strongly by a variety of soil properties for which the spatial variability of each could be potentially established. Thus, salinity interpretation is fundamental to understand the spatial patterns of salinization. Then, the knowledge of the soil properties and mapping their spatial distribution using geo-statistical techniques provide a set of information that can contribute beneficially for farmers and stake holders to take appropriate decisions in adopting management practices more efficiently. The Identification of salt sources in these areas is, therefore, essential to develop direct sustainable agricultural management techniques (Costa et al., 2011).

This research was conducted with the following objectives: (1) characterize the chemical properties of soils for different watersheds in the semiarid region from Pernambuco state, Brazil; (2) evaluate the salt species dominants within each watershed; (3) evaluate which ions better correlate with the salinity parameters (EC, pH, ESP, and SAR); and (4) characterize spatially the levels of thealinity parameters.

4.2 Material and methods

4.2.1 Study areas

The study watersheds are located in the semiarid region of the state of Pernambuco, Northeastern from Brazil. Brígida Watershed is located between coordinates 7°30' - 9°00' south latitude and 39°30' - 41°00' west longitude, with an area of 14,366 km^2. Terra Nova Watershed is located between 7°40'20"and 8º36'57" south latitude and 38º47'04" and 39º35'58" west longitude, with an area of 4,887.71 km^2. Pajeú Watershed is geographically between latitudes 9°27' and 11°30' south and between longitudes 40°22' and 41°30' west, occupying an area of 16,760 km^2. Moxotó Watershed is located between 07º52'21" and 09º19'03" south latitude and between 36º57'49" and 38º14'41" west longitude, occupying a total area of 9,744.01 km^2 (Figure 4.1).

This semiarid region from Pernambuco state has a typical semiarid climate, characterized by low rainfall, with annual averages about 600 mm, where the predominant vegetation is the Caatinga. The soils in the region range from undeveloped soils to soils with a high degree of weathering. Besides climatic factors, which may contribute to the degradation of the soils in this area naturally, the humans also have a major role in the soil salinization through the use of low quality water in irrigated areas. These waters generally have a large concentration of salts and when applied in the soils contribute to their salinization.

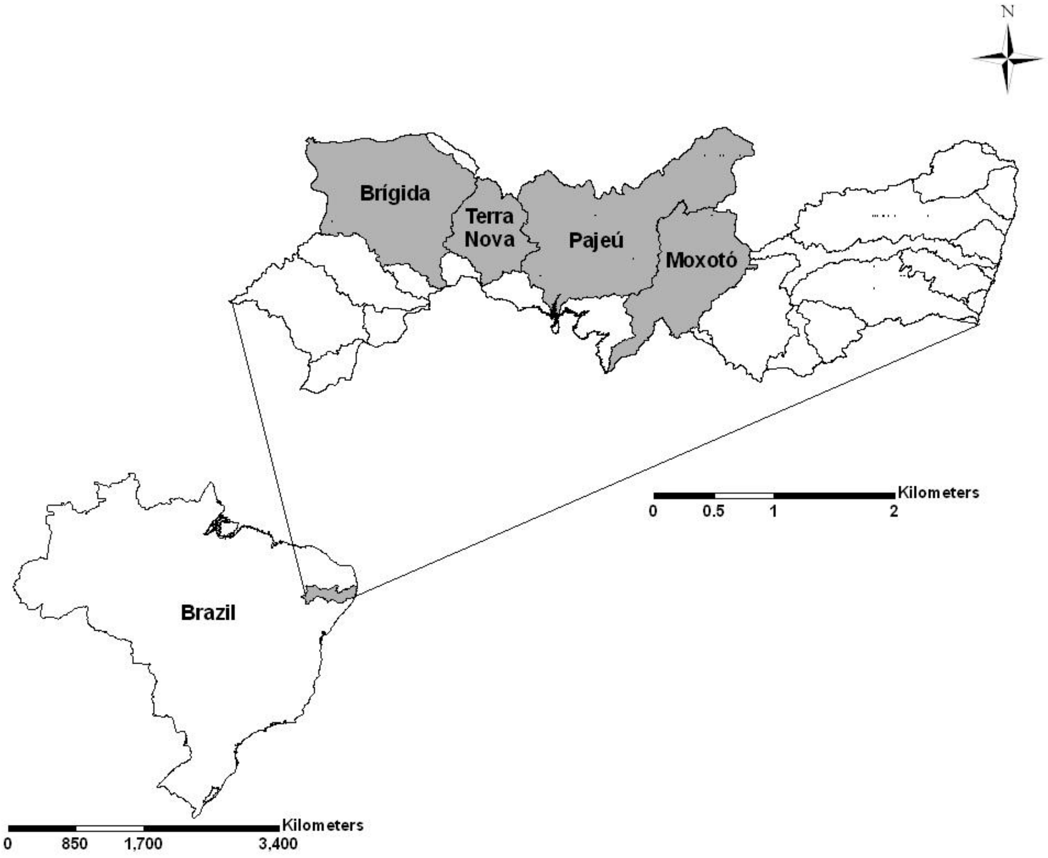

Figure 4.1. Study watersheds map from the state of Pernambuco, Brazil.

4.2.2 Topsoil Sampling

Soil samples were collected in a total of 78 sampling sites in the four watersheds (Brígida, Terra Nova, Pajeú and Moxotó) from Pernambuco semiarid region, Brazil. Each sampling site covered an area of approximately 400 m^2. In each sampling site, 10 - 15 topsoil single samples (depth 0 – 5 cm) were collected and were mixed into one composite soil sample.

The collected soil composite samples were air-dried and passed through a 2 mm sieve to remove large debris, stones, and sere stubbles. Each composite sample was used for chemical analysis to characterize the saline properties of soils.

4.2.3 Chemical analysis

Soil chemical attributes of the collected composite soil samples collected at the 78 sampling site were evaluated by analyzing soluble elements from the saturation extract using the methods described by Richards (1954). From the saturation extract, EC (25 °C) and pH was measured. Other parameters that were also measured are soluble anions and cations: Ca^{2+} and Mg^{2+} by atomic absorption spectrophotometry; Na^{+} and K^{+} by flame emission photometry. The anions measured were Cl^{-}, CO_3^{2-} and HCO_3^{-} by titration and SO_4^{2-} by colorimetry.

In the exchangeable fraction of soil, was measured pH (1:2.5) in water and the total organic carbon (TOC) was determined by Walkley-Black method. The exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) also were determinated according to Richards (1954), extracted with ammonium acetate solution 1 mol L^{-1}. The cation exchange capacity was determinate by the method of sodium acetate and ammonium acetate 1 mol L^{-1}. Based on the results of the analysis, SAR and ESP were calculated according to Richards (1954), through the equations 4.1 and 4.2:

$$SAR\ \left(mmolc\ L^{-1}\right)^{0.5} = \frac{Na^{+}}{\sqrt{\frac{\left(Ca^{2+}+Mg^{2+}\right)}{2}}} \quad (4.1)$$

$$ESP = 100 \times \frac{Na^{+}}{CEC} \quad (4.2)$$

4.2.4 Statistical analysis

For the data obtained by the analyses soil in each watershed, the soil characteristics were evaluated using the following descriptive measures: mean, minimum and maximum values, standard deviation and coefficient of variation. Descriptive analyzes were performed with the aim of observing the general behavior of the data. This type of analysis considers the data spatially independents, and it is important for allowing the identification of outliers that can exert some influence on the type of geostatistical analyzes, as well as to compare results obtained in other studies.

Pearson's correlation analyses were established among the variables of salinity (pH, EC, ESP and SAR) and the levels of cations and anions in the soil and saturation extract and the cations in the exchangeable fraction. The correlation analysis assesses the degree of association between two variables, with the strongest degree of relationship the closer to 1 or -1. In this study, correlation analysis was performed in order to determine what or which ions are more positively or negatively associated with variable salinity.

With the average values of pH, cations and anions in the saturation extract of soil in each basin, was performed chemical speciation of ions with the Visual Minteq 3.0 software. Chemical speciation describes the composition of an aqueous solution. The significance of chemical speciation for the studies in soils is its usefulness as a tool for the interpretation of toxicity of chemical compounds. Thus, through this analysis is possible to have a knowledge of which species dominate the chemical composition of soil solution among the watersheds studied.

4.2.5 GIS and map preparation

To display and manipulate the spatial data of soil characteristics, GIS was used in this study. All spatial data were entered into the GIS environment using commercial GIS software: ArcView 9.3. Maps of saline properties (pH, EC, ESP and SAR) were prepared using ordinary Inverse-Distance-Weighting (IDW) interpolation. This interpolation procedure is suitable for use in an exploratory spatial assessment (Weber and Englund, 1992; Gotway et al., 1996; Corwin et al., 2006).

In interpolation with IDW method, a weight is attributed to the point to be measured. The amount of this weight is dependent on the distance of the point to another unknown point. These weights are controlled on the bases of power of ten. With increase of power of ten, the effect of the points that are farther apart diminishes. Lesser power distributes the weights more uniformly between neighboring points. In this method the distance between the points count, so the points of equal distance have equal weights (Burrough and McDonnell, 1998); in this method the weight factor was calculated with (Eq. 4.3):

$$\lambda i = \frac{D_i^{-\alpha}}{\sum_{i=1}^{n} D_i^{-\alpha}} \qquad (4.3)$$

Where: λ*i* is the weight of point; *Di* denotes the distance between point *i* and the unknown point; and *α* is the power ten of weight.

The Inverse Distance Weighted (IDW) method is a widely used method for spatial interpolation and is based on local deterministic interpolation technique (ESRI, 1999; Ormsby and Alvi, 1999; Johnston et al., 2001). A local technique calculates the estimated values for the entire study area based on small spatial areas or neighborhoods. The IDW method is an exact interpolator which predicts a value at a sample location that is equal to the measured value in the dataset (ESRI, 1999; Johnston et al., 2001).

The calculations used with this procedure are based on the principle that each data point has a local influence that is reduced with distance (ESRI, 1999; Ormsby and Alvi, 1999; Johnston et al., 2001). The IDW method produces accurate surface interpolation as long as a regularly distributed sampling pattern is used in data collection (ESRI, 1999, 2000; Ormsby and Alvi, 1999; Johnston et al., 2001). Low concentration or an uneven distribution in the sampling points often produces sharp peaks or troughs in the output surface (Ormsby and Alvi, 1999; ESRI, 2000; Johnston et al., 2001).

4.3 Results and discussion

4.3.1 Soil characterization

Tables 4.1 – 4.4 provide descriptive statistics of the topsoil properties in watersheds of Brígida, Moxotó, Pajeú and Terra Nova. In the saturation extract, the average pH values were neutral, ranging from 7.7 to 7.74, being higher in Pajeú watershed (Table 4.3). The average values of electrical conductivity were high and ranged from 9.96 to 22.31 dS m^{-1}, evidencing the presence of salt affected soils in the four study watersheds, with maximum values reaching 100.18 dS m^{-1} in Moxotó watershed (Table 4.2). Areas with a degree of degradation in the critical level, which was observed for the maximum values of electrical conductivity (Tables 4.1 – 4.4). Only a few cultures tolerant to salts survive, forming desertified areas or in desertification processes due to toxic levels of salts in the soil.

Table 4.1. Descriptive statistics of topsoil properties in Brígida watershed

Soil Property	Mean	Min.	Max.	SD	CV (%)
			Saturation Extract		
pH	7.07	5.8	7.9	0.5	7.13
EC (dS m^{-1})	9.96	0.12	87.68	22.44	225.4
Ca^{2+} ($mmol_c$ L^{-1})	12.31	0.09	70.76	21.44	172.25
Mg^{2+} ($mmol_c$ L^{-1})	63.02	1.7	430.67	135.2	214.54
Na^{+} ($mmol_c$ L^{-1})	109.02	1.02	1059.67	316.46	289.17
K^{+} ($mmol_c$ L^{-1})	1.89	0.17	11.49	3.24	171.23
CO_3^{2-} ($mmol_c$ L^{-1})	ND	ND	ND	ND	ND
HCO_3^{-} ($mmol_c$ L^{-1})	7.14	1.33	20.67	6.09	85.27
SO_4^{2-} ($mmol_c$ L^{-1})	13.79	0.1	195.56	43.07	312.43
Cl^{-} ($mmol_c$ L^{-1})	107.26	5.0	1095.0	273.74	255.21
SAR ($mmol_c$ L^{-1})$^{0.5}$	8.41	0.6	70.25	20.39	242.5
			Change Complex		
pH	7.6	5.7	9.1	0.95	12.46
Ca^{2+} ($cmol_c$ kg^{-1})	3.74	0.14	9.62	2.74	73.43
Mg^{2+} ($cmol_c$ kg^{-1})	1.71	0.02	8.13	1.99	116.06
Na^{+} ($cmol_c$ kg^{-1})	0.52	0.14	3.87	0.86	164.22
K^{+} ($cmol_c$ kg^{-1})	0.51	0.11	3.5	0.73	143.35
CEC ($cmol_c$ kg^{-1})	8.51	1.29	20.24	5.56	65.26
OC (%)	1.52	0.48	2.9	0.64	42.38
ESP (%)	6.7	1.84	42.32	9.01	134.23

EC: electrical conductivity; SAR: sodium adsorption ratio; CEC: cation exchange capacity; OC: organic carbon; ESP: exchangeable sodium percent; ND: not detected.

The average levels of soluble cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) in soil saturation extracts were high in the four watersheds studied. The watershed Moxotó had levels of soluble cations higher than the other watersheds (Table 4.2). Among the cations evaluated in the saturation extract, the Na^{+} ion was that higher concentrations. Once the SAR is a function of levels of sodium in the saturation extract, these high levels of soluble sodium contributed to the high values scanned in the Moxotó and Pajeú watersheds (Tables 4.1 – 4.4). The Moxotó watershed also had higher values of SAR in comparison to other watersheds of the study, reaching mean concentration of 60.25 ($mmol_c$ L^{-1})$^{0.5}$ (Table 4.2).

Table 4.2. Descriptive statistics of topsoil properties in Moxotó watershed

Soil Property	Mean	Min.	Max.	SD	CV (%)
			Saturation Extract		
pH	7.47	6.3	9.0	0.52	6.91
EC (dS m^{-1})	22.31	0.27	100.18	31.86	142.81
Ca^{2+} ($mmol_c$ L^{-1})	94.1	0.07	625.21	155.87	165.65
Mg^{2+} ($mmol_c$ L^{-1})	75.29	0.14	414.67	124.91	165.92
Na^{+} ($mmol_c$ L^{-1})	473.11	0.64	2633.75	786.68	166.28
K^{+} ($mmol_c$ L^{-1})	6.88	0.01	79.82	17.43	253.33
CO_3^{2-} ($mmol_c$ L^{-1})	ND	ND	ND	ND	ND
HCO_3^{-} ($mmol_c$ L^{-1})	7.16	0.67	28.67	6.12	85.51
SO_4^{2-} ($mmol_c$ L^{-1})	13.87	0.04	152.17	29.25	210.86
Cl^{-} ($mmol_c$ L^{-1})	430.58	0.5	1775.0	568.16	131.95
SAR ($mmol_c$ $L^{-1})^{0.5}$	60.25	0.16	671.57	130.28	216.25
			Change Complex		
pH	7.4	6.2	9.8	0.86	11.56
Ca^{2+} ($cmol_c$ kg^{-1})	10.13	0.22	50.0	9.84	97.18
Mg^{2+} ($cmol_c$ kg^{-1})	2.67	0.1	8.87	2.22	83.2
Na^{+} ($cmol_c$ kg^{-1})	1.37	0.05	7.98	2.12	155.2
K^{+} ($cmol_c$ kg^{-1})	0.5	0.11	1.2	0.28	58.82
CEC ($cmol_c$ kg^{-1})	17.2	1.62	64.71	13.02	75.7
OC (%)	1.03	0.26	2.44	0.55	53.77
ESP (%)	7.91	0.76	34.48	8.34	105.43

EC: electrical conductivity; SAR: sodium adsorption ratio; CEC: cation exchange capacity; OC: organic carbon; ESP: exchangeable sodium percent; ND: not detected.

With respect to anions evaluated, carbonates were detected only in the topsoil sample of the Pajeú watershed, the same that were found the highest values of pH, reaching a maximum of 10.70 (Table 4.3). This indicates that the majority of soils of the study area have low levels of this element. The other anions (SO_4^{2-}, HCO_3^{-} and Cl^{-}) had high levels in the saturation extract (Tables 4.1 – 4.4). These high levels of HCO_3^{-} in the extract saturation of the soil in all watersheds are responsible for the neutral pH, since these ions along with CO_3^{2-} are responsible for the alkalinity (Yaalon, 1997). The concentration of Cl^{-} ranged from 107.3 to 430.6 $mmol_c$ L^{-1} (Tables 1 - 4) and was much higher compared to other anions in all watersheds, and its highest levels found in the watershed of Moxotó.

Table 4.3. Descriptive statistics of topsoil properties in Pajeú watershed

Soil Property	Mean	Min.	Max.	SD	CV (%)
			Saturation Extract		
pH	7.74	6.6	10.2	0.72	9.3
EC (dS m^{-1})	12.03	0.1	75.97	21.81	181.29
Ca^{2+} ($mmol_c$ L^{-1})	13.44	0.03	87.38	25.05	186.43
Mg^{2+} ($mmol_c$ L^{-1})	35.92	0.1	420.0	99.23	276.26
Na^{+} ($mmol_c$ L^{-1})	246.56	0.03	1078.43	443.46	179.86
K^{+} ($mmol_c$ L^{-1})	12.62	0.01	207.38	47.24	374.17
CO_3^{2-} ($mmol_c$ L^{-1})	0.71	0.0	13.57	3.11	435.89
HCO_3^{-} ($mmol_c$ L^{-1})	11.03	1.33	93.0	20.71	187.67
SO_4^{2-} ($mmol_c$ L^{-1})	6.03	0.04	51.27	12.94	201.25
Cl^{-} ($mmol_c$ L^{-1})	173.42	2.5	1097.5	343.14	197.87
SAR ($mmol_c$ $L^{-1})^{0.5}$	53.06	0.01	498.61	125.6	236.69
			Change Complex		
pH	7.54	6.4	10.7	0.99	13.14
Ca^{2+} ($cmol_c$ kg^{-1})	5.15	0.17	15.48	4.47	86.7
Mg^{2+} ($cmol_c$ kg^{-1})	1.21	0.04	4.47	1.18	97.62
Na^{+} ($cmol_c$ kg^{-1})	0.4	0.02	2.55	0.61	154.88
K^{+} ($cmol_c$ kg^{-1})	0.34	0.08	0.7	0.15	44.28
CEC ($cmol_c$ kg^{-1})	8.23	0.6	22.41	6.07	73.75
OC (%)	1.26	0.39	2.83	0.72	57.37
ESP (%)	5.42	0.8	35.44	7.87	145.04

EC: electrical conductivity; SAR: sodium adsorption ratio; CEC: cation exchange capacity; OC: organic carbon; ESP: exchangeable sodium percent; ND: not detected.

Assessing the soil saturation extract and soluble elements, the Moxotó watershed had more severe conditions of degradation among the watersheds studied, not only in quantitative terms, but also about the qualitative aspects. However, the dominant ions in the soil solution to all watersheds are Na^{+} and Cl^{-}, that when present in high concentrations even be toxic to plant development. Also, when in high concentrations in soil solution, the soluble Na^{+} might move to the exchangeable phase, further aggravating the degradation due to the damage it has on the physical properties of soils.

Table 4.4. Descriptive statistics of topsoil properties in Terra Nova watershed

Soil Property	Mean	Min.	Max.	SD	CV (%)
		Saturation Extract			
pH	7.26	6.6	7.7	0.41	5.65
EC (dS m^{-1})	12.53	0.1	61.68	27.48	219.37
Ca^{2+} ($mmol_c$ L^{-1})	12.7	0.11	53.68	23.16	182.35
Mg^{2+} ($mmol_c$ L^{-1})	89.76	6.03	414.67	181.64	202.35
Na^{+} ($mmol_c$c L^{-1})	215.3	0.81	1059.66	472.03	219.24
K^{+} ($mmol_c$ L^{-1})	2.22	0.07	9.94	4.32	194.47
CO_3^{2-} ($mmol_c$ L^{-1})	ND	ND	ND	ND	ND
HCO_3^{-} ($mmol_c$ L^{-1})	13.53	2.33	33.33	11.73	86.67
SO_4^{2-} ($mmol_c$ L^{-1})	30.47	0.15	130.48	56.6	185.76
Cl^{-} ($mmol_c$ L^{-1})	251.5	5.0	1227.5	545.62	216.94
SAR ($mmol_c$ $L^{-1})^{0.5}$	15.11	0.46	69.25	30.28	200.34
		Change Complex			
pH	7.7	6.7	8.3	0.6	7.79
Ca^{2+} ($cmol_c$ kg^{-1})	3.76	0.97	12.32	4.85	128.75
Mg^{2+} ($cmol_c$ kg^{-1})	2.36	0.28	4.53	1.9	80.5
Na^{+} ($cmol_c$ kg^{-1})	0.36	0.17	0.69	0.23	63.93
K^{+} ($cmol_c$ kg^{-1})	0.19	0.07	0.44	0.16	83.48
CEC (cmolc kg^{-1})	9.44	2.13	17.13	7.02	74.38
OC (dag kg^{-1})	2.09	0.37	04.51	1.72	82.34
ESP (%)	9.88	1.08	23.71	11.42	115.56

EC: electrical conductivity; SAR: sodium adsorption ratio; CEC: cation exchange capacity; OC: organic carbon; ESP: exchangeable sodium percent; ND: not detected.

In the exchange complex the mean values of pH for the topsoil sample had around neutrality, ranging from 7.4 to 7.7 (Tables 4.1 – 4.4), indicating that the semiarid soils from the state of Pernambuco have reaction from basic to alkaline mostly in surface. However, these are average values, when evaluating the maximum values were observed pH values of 9.1 in Brígida watershed (Table 4.1), 9.8 in Moxotó watershed (Table 4.2), 10.7 in Pajeú watershed (Table 4.3) and 8.3 in Terra Nova watershed (Table 4.4). Soil pH is affected by three factors (Brady and Weil, 2001): i) the percentage of base saturation, ii) the kind of absorbed bases, and iii) nature of the colloids present. Thus, it is observed that the first two factors have contributed greatly to the pH values encountered in the areas sampled.

The average levels of exchangeable cations were high in all watersheds, however, the highest levels were observed in the Moxotó watershed (Tables 4.1 –

4.4). In the topsoil sample of all watersheds under study, the mean levels of exchangeable cations followed the order: Ca^{2+} > Mg^{2+} > Na^+ > K^+. Thus, it is observed that the average content of Na^+ were higher than K^+, as a result of competition between these elements in the soil soluble phase, where Na^+ levels greatly exceed K^+ levels.

These results indicate that the soils of the semiarid region of Pernambuco have high levels of Na^+, where the data from this study indicate that these soils are not only susceptible to degradation processes by salts, but also sodium, since this element at high levels in soil physical effects brings undesirable soils under agricultural cultivation. These data resemble those reported by Oliveira et al. (2009), who evaluated twelve soil profiles in semiarid region of Pernambuco and Paraíba. This may be associated with large amounts of primary minerals present in sand and silt fractions Planosols and Luvisols, mainly plagioclase and micas (Oliveira, 2007).

There weren't determined the concentrations of Al, as in soils of semiarid climates this cation is not significant, especially at pH above 5.5, as seen in this study (Richards, 1954).

Despite high levels of exchangeable sodium, the mean values of ESP in soils of the four watersheds studied ranged from 5.4% to 9.9% (Tables 4.1 – 4.4), and have not reached the limit of 15% which classifies soils as sodic, according to Richards (1954). However, depending on the type of soil, this limit may not be appropriate because ESP values well below the 15% set by Richards (1954) were enough to reduce the hydraulic conductivity of soils of Pernambuco, making them unfit for irrigation (Freire et al., 2003).

The Terra Nova watershed had the highest average value of ESP among the other study watersheds. Noting the maximum values of ESP, it appears that in all watersheds were found ESP values well above this limit of 15%, evidencing the presence of severely degraded soils by sodification (Tables 4.1, 4.2, 4.3, 4.4). This indicates that these areas require remediation strategies. However, based on the values of ESP, it is noted that the soil management systems require special soil correction since they are susceptible to degradation by the sodification.

The mean values of cation exchange capacity (CEC) were elevated in the soils of all watersheds, ranging from 8.23 to 17.20 $cmol_c\ kg^{-1}$. Despite low average levels of organic carbon found in these soils, which ranged 1.0% to 2.1%% (Tables 4.1 – 4.4), this fact should be associated with the predominant type of clay in these soils. According to Darwish et al. (2005), an increase in organic matter content improves the buffering capacity of the soil against rapid changes in salinity.

The maximum levels of ions and the maximum values of the parameters of salinity (pH, EC, SAR and ESP) found from Pernambuco semiarid are considered very high compared with soils from other parts of Brazil. For example, Andrade et al. (2011) evaluated the status of salinity in soils from Ceará, northeastern Brazil, and observed maximum values of EC ranged from 0.45 to 4.9 dS m^{-1}, Na^+ soluble ranging from 0.72 to 26 mmolc L^{-1}, Cl^- ranging from 5.4 to 36.0 $mmol_c$ L^{-1}, and SAR varying from 1.1 to 5.2 $(mmol_c\ L^{-1})^{0.5}$. Mendes et al. (2008) evaluated the temporal variability of different soils from Paraíba, Northeast Brazil, and found maximum values of EC ranged from 4.49 to 10.88 dS m^{-1}, ESP ranging from 14.13 to 22.70% and pH ranging from 8.85 to 8.37, in the dry season.

Variations in the data field level are determined by the coefficient of variation (CV) (Corwin et al., 2006). The coefficients of variation had a number of spatial variability to some general trends (Tables 4.1 - 4.4). Only the pH values exhibited low CV in all study watersheds, but the low variability is a characteristic of pH. In general, high CV values for all parameters were obtained in this study, except for CEC and TOC, which indicated CVs values ranging from moderate to high. These results indicate that there is a great variability on a local scale, within each watershed.

4.3.2 Geochemical speciation of cations and anions species

Dominant cations were the various forms of Ca^{2+}, Mg^{2+}, K^+, and Na^+ in the saturation extract of the soil samples (Table 4.5). Nevertheless, the chloride and sulfate species of calcium, magnesium, sodium and potassium contributed significantly to the total contents in the soils from all watersheds. Calcium coordinated with Cl^- constituted 6%, 20%, 9% and 11% of total Ca contents in soil solutions extracted in Brígida, Moxotó, Pajeú and Terra Nova watersheds respectively (Table 4.5).

Table 4.5. Mass distribution of the cation and anion in different species

Component	Specie Name	% of total concentration in each watershed			
		Brígida	Moxotó	Pajeú	Terra Nova
		Cations in Saturation Extract			
Calcium	Ca^{2+}	83.65	74.52	85.45	72.38
	$CaCl^{+}$	6.12	20.4	9.76	11.53
	$CaSO_4$	10.23	5.08	4.57	16.09
	$CaHCO_3^{+}$	-	-	0.18	-
	$CaCO_3$	-	-	0.04	-
Magnesium	Mg^{2+}	82.43	67.21	81.6	69.98
	$MgCl^{+}$	9.56	29.15	14.77	17.66
	$MgSO_4$	8.01	3.64	3.46	12.36
	$MgCO_3$	-	-	0.03	-
	$MgHCO_3^{+}$	-	-	0.14	-
Sodium	Na^{+}	96.55	91.71	95.74	93.02
	$NaCl$	2.44	7.72	3.79	5.06
	$NaSO_4^{-}$	1.01	0.57	0.45	1.92
	$NaHCO_3$	-	-	0.02	-
Potassium	K^{+}	96.27	91.56	95.63	92.51
	KCl	2.44	7.71	3.78	5.04
	KSO_4^{-}	1.29	0.73	0.59	2.45
		Anions in Saturation Extract			
Carbonate and Bicarbonate	CO_3^{2-}	0.1	0.2	0.52	0.16
	$Mg_2CO_3^{2+}$	0.09	0.19	0.15	0.2
	$MgCO_3$	0.36	0.7	0.99	0.63
	$CaCO_3$	0.14	1.93	0.78	0.18
	$NaCO_3^{-}$	0.06	0.51	0.66	0.17
	H_2CO_3	9.77	2.96	2.23	6.03
	HCO_3^{-}	73.04	60.7	79.63	73.22
	$NaHCO_3$	1.99	6.3	4.74	3.58
	$MgHCO_3^{+}$	11.59	9.75	6.93	13.4
	$CaHCO_3^{+}$	2.86	16.76	3.37	2.43
Sulfate	SO_4^{2-}	46.14	26.15	49.4	43.2
	$MgSO_4$	36.6	19.75	20.64	36.4
	$CaSO_4$	9.13	34.46	10.18	6.71
	$NaSO_4^{-}$	7.95	19.28	18.55	13.51
	KSO_4^{-}	0.18	0.36	1.23	0.18
Chloride	Cl^{-}	91.16	81.83	90.52	88.73
	$CaCl^{+}$	0.7	4.46	0.76	0.58
	$MgCl^{+}$	5.62	5.1	3.06	6.3
	KCl	0.04	0.12	0.27	0.05
	$NaCl$	2.48	8.49	5.39	4.34

The speciation analysis revealed that the strongest association between cations and anions was the formation of sulfate and chlorides species. However, due to the high solubility of chloride compounds, the single Cl^{-} was the major contributor (> 90%) of the total concentration of chloride in the soil solution. Nevertheless, as their association with Na^+ and Mg^{2+} was the largest this suggests that NaCl and $MgCl^+$ must be the dominant salts formed.

The $CaSO_4$ species constituted 4% - 16% of the total dissolved Ca^{2+} in the solution extracted from soils in all watersheds of study. While the $MgCl^+$ and $MgSO_4$ species constituted respectively 9% – 29% and 3% - 12% of the total dissolved Mg in the solution extracted from soils in all watersheds of study (Table 4.5).

Species of sodium and potassium sulfates and chlorides also were present in extract saturation of the soil samples in all watersheds. It was observed that the NaCl species constituted 2% – 7% while the $NaSO_4^-$ species constituted 0.45% – 1.92% of the total dissolved Na^+. The KCl and KSO_4^- species constituted respectively 2% – 7% and 0.5% – 2% of the total dissolved K in the extract saturation of the soil samples (Table 4.5). We observed high associations of the HCO_3^- ions with Ca^{2+}, Mg^{2+} and Na^+ ions and these revealed formations of bicarbonate species like $NaHCO_3$, $MgHCO_3^+$ and $CaHCO_3^+$, which ranged 1.99% – 6%, 6% – 13% and 2% – 16% respectively among the watersheds.

Acosta et al. (2011) evaluated the salinity status of a highly productive agricultural area, under a semiarid climate in Murcia, SE Spain and founded similar results to this study, where they founded stronger correlations among the concentration of Cl^- and Ca^{2+}, Mg^{2+} and Na^+, suggesting its presence in the form of NaCl, $MgCl_2$ and $CaCl_2$. Thus, according to the data founded in this research, the chloride species and the sulfate species dominated the soil solution.

4.3.3 Correlation between salinity parameters and the levels of the ions

The Pearson correlation coefficients between the parameters of salinity (ESP, pH, SAR and EC) and the ions in the saturation extract and in the exchange complex are presented in Table 4.6. It was observed that the ESP had low correlations with Na^+ and SO_4^{2-} in the saturation extract, however, high correlations with the exchangeable Na^+, due to its value being directly related to the contents of this element in the exchange complex.

Soil pH obtained low correlations with the ions Na^+, SO_4^{2-} and Cl^- in the saturation extract and with Ca^{2+} and Na^+ in the exchange complex. The highest correlation coefficients of pH were obtained with K^+, CO_3^{2-} and HCO_3^- in the saturation extract. These last two are primarily responsible for variation in soil pH, which explains its high correlation with this parameter.

Table 4.6. Correlation coefficients between salinity parameters (ESP, pH, SAR and EC) and levels of cations and anions in saturation extract and exchangeable cations

Component	Salinity parameters			
	ESP	pH	SAR	EC
	Cations in extract saturation			
Ca^{2+}	0.11	0.17	0.2	0.88**
Mg^{2+}	0.16	0.89	0.12	0.81**
Na^{+}	0.36*	0.41**	0.72**	0.72**
K^{+}	0.06	0.55**	0.86**	0.24
	Anions in extract saturation			
CO_3^{2-}	0.06	0.53**	0.85**	0.18
HCO_3^{-}	0.16	0.69**	0.89**	0.4 **
SO_4^{2-}	0.31**	0.35*	0.31*	0.49**
Cl^{-}	0.31*	0.29*	0.62**	0.6 **
	Exchangeable cations			
Ca^{2+}	-0.16	0.27*	0.34*	0.41**
Mg^{2+}	0.07	0.23	0.1	0.49**
Na^{+}	0.57**	0.41**	0.49**	0.63**
K^{+}	-0.16	0.14	-0.06	-0.02

ESP: exchangeable sodium percent; SAR: sodium adsorption ratio; EC: electrical conductivity; *$P < 0.05$; **$P < 0.01$.

The SAR had strong correlations with the Na^+, K^+, CO_3^{2-}, HCO_3^- and Cl^- in the saturation extract and with the ion Na^+ in the exchange complex. These data suggest that the predominance of K^+ ion in soil saturation extract implies lower levels of divalent ions such as Ca^{2+} and Mg^{2+}, thus reducing the values of SAR.

The EC presented higher correlation with Ca^{2+}, Mg^{2+}, Na^+ and Cl^- in the saturation extract, and with the exchangeable Na^+. This demonstrates that the Ca^{2+} and Mg^{2+} soluble they are most related to degradation processes by salt, since increased levels of these elements tend to reduce the degradation of the soil by the sodification.

The Pearson correlation analysis revealed that Na^+ ions (exchangeable and soluble), HCO_3^- and Cl^- ions are those that contribute most to the increase of salinity and sodicity in these soils. These ions had higher correlation coefficients with the parameters related to soil salinity and sodicity in relation to the other.

Thus, high levels of these ions in soils may indicate degradation by salinization and/or sodification.

As support for the correlation data found in this study, it was observed in the Table 4.5 that the soluble Na^+ presented association with chloride and bicarbonate anions, resulting in the formation of species of sodium chloride and sodium bicarbonate. So, this suggests that these two species were the more associated species with the parameters of salinity and sodicity of soils. In addition, soil samples have higher mean levels of Na^+ forms exchangeable and soluble, as well as high average levels of Cl^- (Tables 4.1 - 4.4), which indicates these ions as the main contributors to soil degradation by salinization and sodification in the semiarid of Pernambuco. The HCO_3^- ion would also be a contributor to a lesser extent compared to Cl^-.

4.3.4 Spatial distribution of salinity parameters

The spatial distribution of salinity parameters in the soil is very useful for predicting where the highest fluctuations in salinity or sodicity may take place. This allows the identification of vulnerable areas (Yan et al., 2007) and thus to take cost-efficient implementation of mitigation measures. In addition, distribution maps can be used to delimit areas, according to their management and reclamation requirements (Ardahanlioglu et al., 2003) in order to decrease the risk for sensitive crops.

Figure 4.2 presents the spatial distribution of salinity parameters (pH, EC, ESP and SAR) linked to soils salinization or sodification. Problems of soil alkalinity were detected only in the eastern portion, at the north of the Pajeú watershed (Figure 4.2 a). Thus, it is observed that the pH of the soils from semiarid of Pernambuco have a high pH range for growth of most cultures. The highest levels of EC were observed on the eastern and central portion, to the north. This increased salinity levels reflected by higher EC can reduce crop yields in these areas due to toxic ion (e.g., Na toxicity) and osmotic effects.

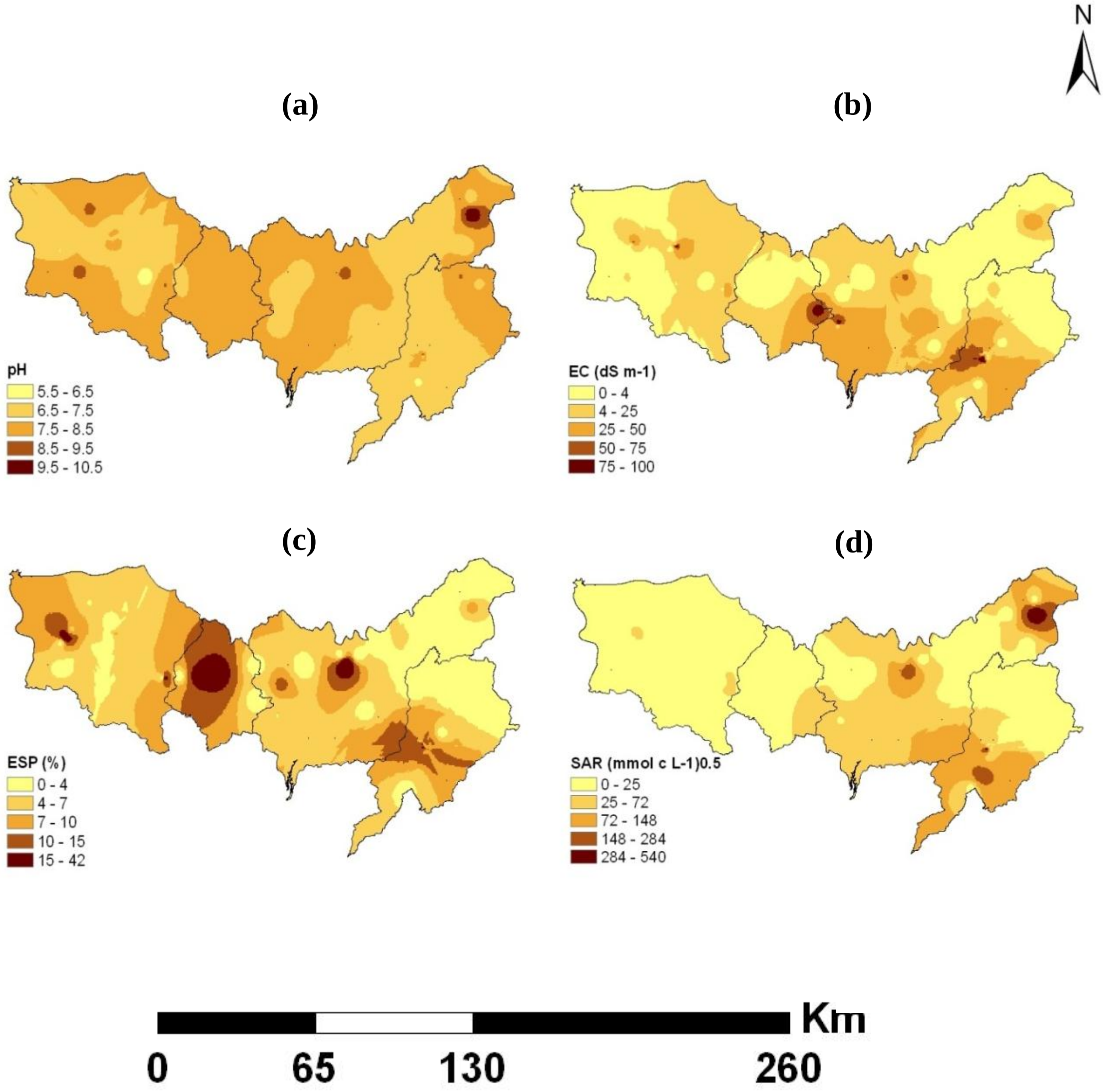

Figure 4.2. Spatial distribution of the salinity parameters levels for the four study watersheds in semiarid region from the state of Pernambuco: (a) pH, (b) EC, (c) ESP and (d) SAR.

The most area affected by soluble and exchangeable sodium is located in the east portion, toward the south, especially on Moxotó watershed as determined by the ESP and SAR levels (Figure 4.2 c and 4.2 d). It can be seen in some spatial patterns similar among areas inside to the watersheds of study. These patterns are related to areas which present high levels of EC, ESP and SAR. This means that those areas present similar degradation by the high levels of EC, ESP and SAR.

Thus, these areas present restriction to crop cultivation where special management practices should be taken or in some cases these areas should be recovered.

Zheng et al. (2009) conducted a study to characterize the spatio-temporal variability of the soil salinity irrigated and cultivated with cotton, and to determine the main factors influencing the variability of soil spatiotemporal salinity. Among these factors, the authors cite: climate, farming practices, level of soil organic matter (SOM), irrigation system used and increased inputs of chemical fertilizers. Is this study, the same factors can have contributed for the difference in the spatial distribution among the study watersheds, according with these authors.

Salinity levels and spatial distribution are also important to consider when choosing crop types. The salinity-tolerance thresholds are different among the crops. For example, corn EC is 170 mS m^{-1}, and studies have generally stated that EC values between 70 and 300 mS m^{-1} and higher may cause abnormal crop growth (Beltran, 1999; Murtaza et al., 2006; Li et al., 2007). If corn is to be planted in this region, especially in the eastern part of the study site, special management procedures would have to be implemented to reduce the salinity level and achieve high economic returns.

4.4 Conclusions

Assessing the chemical properties of soils had that the Moxotó watershed had the worst levels of degradation by salinity and sodicity among the others. However, all watersheds studied had degraded areas, which could be observed for the maximum values. Thus, these data indicate that the soils of semiarid area from Pernambuco state require appropriate management practices, if subject to agricultural use.

The cations and anions that contribute most to the salinity and sodicity of soils in the semiarid region of Pernambuco are Na^+ soluble and exchangeable, Cl^- and to a lesser extent, the HCO_3^-. Through high levels of these elements found in analyzes of soil and of associations formed between them, this work suggests that the forms of NaCl and $NaHCO_3$ are more damaging to the semiarid soils of Pernambuco.

The spatial distribution analysis allowed detecting spatially areas most affected by salinization/sodification through the levels of pH, EC, ESP and SAR, in the four watersheds studied. This allowed us to establish, in the watersheds of the study: non-degraded areas, areas that need special management systems and areas that need to be recovered in the semiarid region from the state of Pernambuco. This enables the selection of plants that can be grown according to their tolerance to a particular level of salinity or sodicity on those soils.

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5 - CHAPTER IV

PREDICTION OF CORN YIELD AND SOIL SALINITY STATUS WITH VARYING IRRIGATION SCENARIOS IN SEMIARID NORTHEASTERN, BRAZIL

Abstract

The main stress factors able to restrain potential crop growth in semiarid conditions include water and salt stress, an appropriate strategy for management of irrigation should be developed especially in semiarid regions aimed at removal of salts from the soil and providing good conditions for the plant development. With the objective to make realistic predictions about the influence of different irrigation managements on the salts dynamic in soils and corn yield using the EPIC model, were collected three different soil profiles into the Moxotó watershed. In each soil profile were collected 5 soil samples until 1 m in depth (each soil sample was collected every 20 cm). Soil characteristics, crop parameters as well as daily weather parameters were included as input to the simulation model. Two different kinds of irrigation (drip and furrow) and two trigger irrigation (0.1 and 1) were used for the generation of the scenarios: drip irrigation with trigger irrigation 0.1; drip irrigation with trigger irrigation 1; furrow irrigation with trigger irrigation 0.1; and furrow irrigation with trigger irrigation 1. Were simulated amount of water of 25, 50, 75, 100 and 150% for each scenario. In both types of irrigation and the type of trigger, the EC levels were reduced by increasing the amount of water used in the simulation, on the three soils under study. The increase in the amount of water simulated on irrigation indicated a reduction in salt stress, in which the amount of water applied to supply 100% of stress water, was observed as the adequate amount that not to promote stress salt. The simulated data indicate that the use of irrigation with good quality water promoted the leaching of salts, by increasing the salt content with depth, indicating removing these salts along the profile of the soil. The study found that the best irrigation strategy for the corn crop grown was the drip irrigation, and the trigger irrigation 0.1. However, for the low water content applied, the trigger irrigation value of 1 should be used.

Keywords: semiarid, irrigation, saline soils, EPIC model

5.1 Introduction

A solution to water shortages for plants is irrigation, which has made agriculture possible in many unproductive areas predominantly in semiarid regions where the rates of evapotranspiration exceeds the precipitation rates. In these areas the irrigation becomes essential to get greats crop yields. Since the main stress factors able to restrain potential crop growth in semiarid conditions include water and salt stress, an appropriate strategy for management of irrigation should be developed especially in semiarid regions aimed at removal of salts from the soil and providing good conditions for the plant development.

Soil salinity has been predicted as a function of the salinity of the irrigation water and the leaching fraction in the traditional steady-state model described in FAO 29 (Ayers and Westcot, 1985; Rhoades et al., 1992). While this model is a good first approximation, it does not account for soil properties, rainfall patterns or various climates where ET changes throughout the year. These factors will have a profound influence on soil salinity throughout the crop season (Ayers and Westcot, 1985). The irrigation method is only considered in FAO 29 by assigning different root-water uptake patterns in relation to high frequency and conventional irrigation and by assuming that the electrical conductivity (EC) of the soil solution must be weighted to account for root-water uptake in high frequency irrigation systems (Ayers and Westcot, 1985).

At present, a multitude of simulation models for one or several field crops is available. Studies demonstrate that crop simulation models can be used to determine irrigation requirements at farm, county, and state levels (Hoogenboom et al., 1991; Alexandrov and Hoogenboom, 1999; Heinemann et al., 2002; Guerra et al., 2007; Liu et al., 2007). Other studies report that crop models can be employed to optimize the allocation of irrigation water during the growing season and among crops (Bryant et al., 1992; Cabelguenne et al., 1997; Minacapilli et al., 2008) as well as to evaluate efficient irrigation scheduling strategies (Fortson et al., 1989; Epperson et al., 1993; Santos et al., 2000).

Nevertheless, several crop models do not take into account the toxic effects of high saline and/or aluminum soil contents on crop production. These parameters are considered in the most recent of the Erosion Productivity Impact Calculator (EPIC) versions. None of the most common crop models simulate the degradation of the physical behavior of soils affected by high sodium levels and its impact on the crop performance (Barros et al., 2004).

Thus, from all available models, the EPIC model seems the most appropriate for being adjusted to simulate agricultural production under the conditions of the semiarid northeast of Brazil, since this model not only consider several of the determining processes of crop development in this region (i.e. climatic factors, hydrological processes, crop management practices, N and P cycling in the soil-plant system and the effects of salinity and aluminum toxicity on crop development) but also the competition for water and nutrients in mixed cropping systems (Williams, 1995).

The assessment of appropriate management strategies requires the previous analysis of a lot of factors such as the existing irrigation and drainage systems, environmental conditions and as well as prediction of the potential consequences of changes to various hydrological factors and cropping system. According to Man Singh et al. (2002), to enable such assessment in a quick and efficient way, computer aided analytical tools and models are needed. These authors claim that the models help in evaluation of different development strategies, to suggest solutions and to predict medium to long-term consequences of adopting such strategies.

Then, with the intent to assess the ability of EPIC in simulate the salt balance, were collected different types of soil in different textures and salinity levels, in the Moxotó watershed, semiarid region from state of Pernambuco, Brazil. The objective of this study was to make realistic predictions about the influence of different irrigation managements on the salts dynamic and corn yield in that three site at the Moxotó watershed using the EPIC model.

5.2 Material and methods

5.2.1 Study area and soil sampling

The Moxotó Watershed is located in the semiarid region from state of Pernambuco, Northeast of Brazil, between 07º 52' 21"and 09º 19' 03" south latitude and between 36º 57' 49 "and 38º 14' 41" west longitude, occupying a total area of 9,744.01 km² (Figure 5.1) in all state of Pernambuco.

Were studied three sites into the Moxotó watershed. In each site were collected soil samples in a total of 3 soil profiles, being one soil profile per site. In each soil profile were collected 5 soil samples until 1 m in depth (each soil sample was collected every 20 cm).

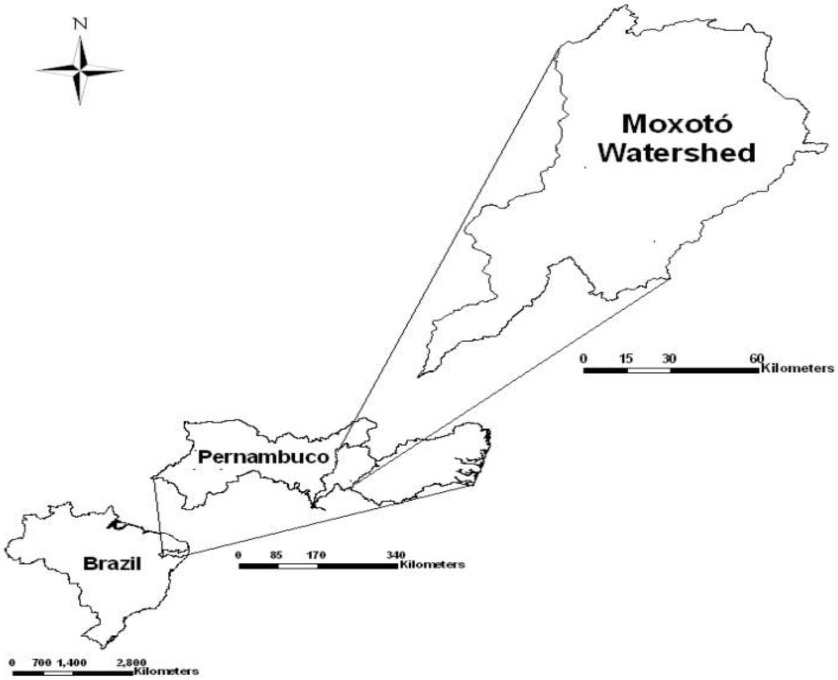


Figure 5.1. Location of Moxotó Watershed from state of Pernambuco, Brazil.

5.2.2 Soil data

The soil data were input according to the soil profile data for each site of study. For each site one described soil profile with relevant physical and chemical parameters was studied. The collected soil samples on sites were air-dried and passed through a 2 mm sieve to remove large debris, stones, and sere stubbles. Each soil sample was split into two sub-samples. One was used for physical analysis and the other was used for chemical analysis to characterize saline soil properties. The physical and chemical properties of the soils are described in Table 5.1.

According to the soil characterization, the soil profiles of the study site presented different textures and salinity levels. As observed on the earlier chapters, this region from Pernambuco semiarid is adversely affected by soil salinization. Thus, each soil profile was used for simulate the yield of corn and the salts dynamic by the use of irrigation with good quality water. Our intent was try to determine adequate ways for irrigation management, for great reductions on salt levels of soils and increases on corn yields.

Table 5.1. Soil chemical and physical parameters of the soil profiles collected on Moxotó watershed, Pernambuco – Brazil

	Soil depth				
	0 – 20 cm	20 – 40 cm	40 – 60 cm	60 – 80 cm	80 – 100 cm
Silty Loam (saline soil)					
Sand thick (%)	7.0	6.0	5.0	7.0	6.0
Sand thin (%)	20.0	24.0	24.0	27.0	28.0
Clay (%)	18.0	9.0	24.0	22.0	22.0
Silt (%)	55.0	61.0	47.0	46.0	44.0
Particle density (g cm^{-3})	2.67	2.53	2.7	2.47	2.78
Bulk density (g cm^{-3})	1.32	1.44	1.39	1.5	1.45
θ_{fc} (%)	15.2	16.5	21.4	20.5	20.5
θ_{pwp} (%)	9.3	10.6	14.7	13.5	13.2
K_{sat} (cm h^{-1})	1.5	0.2	0.1	0.1	0.1
pH	7.1	7.2	7.7	9.5	8.9
EC (dS m^{-1})	13.2	17.9	15.5	14.1	12.9
Organic carbon (g kg^{-1})	7.8	8.2	6.1	4.3	4.5
Silty Clay (saline soil)					
Sand thick (%)	3.0	2.0	2.0	3.0	2.0
Sand thin (%)	1.0	2.0	2.0	2.0	2.0
Clay (%)	45.0	43.0	45.0	46.0	49.0
Silt (%)	51.0	53.0	51.0	49.0	47.0
Particle density (g cm^{-3})	2.5	2.67	2.35	2.63	2.56
Bulk density (g cm^{-3})	1.21	1.38	1.45	1.23	1.35
θ_{fc} (%)	33.5	36.8	34.2	36.1	35.5
θ_{pwp} (%)	3.9	6.0	4.8	4.8	5.6
K_{sat} (cm h^{-1})	0.0	0.3	0.0	0.0	1.7
pH	6.6	7.8	7.0	7.3	6.9
EC (dS m^{-1})	39.7	21.5	20.4	21.4	17.7
Organic carbon (g kg^{-1})	18.1	10.6	12.1	12.7	10.3
Sandy Loam (non-saline soil)					
Sand thick (%)	29.0	31.0	24.0	22.0	25.0
Sand thin (%)	35.0	34.0	34.0	35.0	32.0
Clay (%)	17.0	18.0	24.0	23.0	23.0
Silt (%)	19.0	17.0	18.0	20.0	20.0
Particle density (g cm^{-3})	2.78	2.74	2.63	2.63	2.78
Bulk density (g cm^{-3})	1.46	1.54	1.61	1.62	1.71
θ_{fc} (%)	14.0	13.1	16.1	16.8	15.8
θ_{pwp} (%)	1.5	1.6	1.9	1.9	1.8
K_{sat} (cm h^{-1})	1.8	3.6	0.1	0.3	1.1
pH	7.9	7.8	7.3	7.5	7.9
EC (dS m^{-1})	0.7	0.5	0.5	0.4	0.6
Organic carbon (g kg^{-1})	12.8	6.3	5.7	3.1	3.9

Sand thick: diameter > 0.2 and < 2 mm; Sand thin: diameter > 0.05 and < 0.2 mm; θ_{fc}: soil moisture on field capacity; θ_{pwp}: soil moisture on permanent wilting point; K_{sat}: hydraulic conductivity saturated; EC: electrical conductivity.

5.2.3 EPIC model

The EPIC model was developed by a USDA modeling team in the early 1980s to address this technology gap and was designed to evaluate water quality and other agricultural environmental problems at the field scale and watershed scale, respectively (Williams et al., 1984; Jones et al., 1991). Your simulations can examine one year or hundreds of years and results can be summarized and examined daily, monthly, yearly or with multi-year analyses.

Since 1985, an interactive data entry system, extensive soil, weather, crop and tillage generation databases, and alternative methods to simulate erosion, weather, irrigation, fertilization, and tillage have been added (Jones et al., 1991). A general plant growth model is used in EPIC to simulate light interception, energy conversion to biomass, water, and nutrient uptake (Williams et al., 1989).

There are few crop growth models that are able to simulate maize growth under the strongly contrasting environmental conditions observed in the tropics, considering temperature stress, nutrient deficiencies of nitrogen, phosphorous and potassium, as well as the toxic effects of salts, oxygen deficiency and aluminum toxicity in the rhizosphere which may affect root growth, water uptake and crop development (Gaiser et al., 2010).

The EPIC model (Williams, 1990) potentially takes into account all relevant soil processes (soil water dynamics, availability of nitrogen, phosphorous and potassium, soil salinity, aluminum toxicity) and is considered therefore to be suitable for application in the tropics. Because of its ability to simulate a variety of important agricultural practices, EPIC has been chosen to estimate the effects of crop management strategies on crop productivity and soil quality in the semiarid region of NE of Brazil (Barros et al., 2004).

5.2.4 Weather data

The monthly maximum and minimum air temperatures and the total precipitation were collected from the data of National Institute of Spatial Researches (Instituto Nacional de Pesquisas Espaciais – INPE). Table 5.2 gives mean monthly maximum and minimum air temperatures, solar radiation, and total precipitation for the Moxotó watershed for 2001–2011 and historical means for the last 30 years. The solar radiation was calculated by the software Weather Import. With all this data was created a weather station for WINEPIC and used for the simulations.

Table 5.2. Mean monthly maximum and minimum air temperatures (TMX, TMN (˚C)), solar radiation (RAD (MJ m^{-2})) and total precipitation (RAIN (mm)) at the Moxotó watershed in 2001-2011 and historical 11 years average

	Month												Year
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
							2001						
TMX	34.47	35.36	34.18	33.08	34.83	29.21	29.08	29.49	33.56	34.62	36.42	35.56	33.32
TMN	18.4	20.36	20.21	18.93	19.2	18.18	17.98	16.02	16.4	19.67	20.11	20.57	18.84
RAIN	2.8	13.1	106.9	12.3	10.5	28.0	12.5	5.4	0.5	31.4	7.9	41.2	272.5
							2002						
TMX	31.34	32.98	33.86	33.15	31.92	29.63	28.95	31.38	33.86	34.8	35.79	35.64	32.78
TMN	20.84	19.23	19.54	18.99	19.08	18.41	15.98	18.17	19.19	20.4	21.15	21.92	19.41
RAIN	172.2	78.0	24.8	18.6	21.9	9.0	0.7	1.0	0.9	24.8	1.3	63.9	417.1
							2003						
TMX	34.8	31.22	31.41	33.49	33.14	31.1	30.24	32.66	33.28	34.74	35.91	36.52	33.21
TMN	21.4	20.36	20.07	19.13	19.11	16.93	16.53	16.62	17.38	18.14	20.18	21.37	18.94
RAIN	41.6	17.7	86.3	13.7	24.2	0.0	5.0	2.9	1.6	2.0	8.6	5.2	208.8
							2004						
TMX	34.72	30.85	32.23	32.56	31.62	29.29	29.75	30.90	32.34	35.03	35.48	35.75	32.54
TMN	21.51	20.39	20.42	20.78	20.24	18.33	18.13	18.21	19.11	20.35	20.82	21.4	19.97
RAIN	410.2	212.8	06.2	50.2	33.2	26.2	12.2	12.2	2.0	7.9	14.1	23.3	810.5
							2005						
TMX	34.12	34.34	25.33	23.86	30.31	30.86	30.51	31.57	34.18	36.12	36.42	33.14	31.73
TMN	21.76	21.67	21.5	18.04	20.91	19.85	18.93	19.33	20.62	22.27	23.28	21.61	20.81
RAIN	27.7	18.7	27.1	11.2	37.0	30.1	6.8	14.4	7.7	8.8	4.7	115.0	309.2
							2006						
TMX	35.74	36.89	35.11	33.44	31.43	29.17	29.47	31.26	33.55	36.32	37.12	37.66	33.93
TMN	18.95	22.29	21.93	21.25	19.77	18.42	17.25	16.37	17.83	19.48	20.55	20.91	19.58
RAIN	20.5	76.8	70.4	85.6	19.3	13.4	16.3	7.1	8.2	12.5	52.4	11.3	393.8
							2007						
TMX	38.09	35.89	32.59	33.69	31.13	30.05	30.78	29.98	31.99	35.37	37.31	36.23	33.59
TMN	21.34	21.73	20.3	19.53	19.23	17.95	16.21	16.86	16.56	17.61	19.74	20.35	18.95
RAIN	21.6	139.7	73.4	19.2	26.3	12.5	3.0	11.2	14.8	2.3	11.6	20.2	355.8
							2008						
TMX	35.78	34.45	32.68	31.84	29.41	28.87	28.17	30.06	33.15	35.01	37.62	36.65	32.81
TMN	20.56	20.69	21.08	20.33	19.69	16.73	17.16	16.99	16.74	17.91	19.58	20.83	19.02
RAIN	35.0	49.2	116.5	68.8	34.1	53.0	18.5	9.7	0.8	218.8	9.3	25.8	639.5
							2009						
TMX	36.47	34.39	35.71	33.33	30.09	29.06	30.27	30.7	34.18	36.43	37.24	36.4	33.69
TMN	20.99	21.27	21.2	21.54	21.24	18.91	17.37	17.32	17.22	20.21	19.39	21.27	19.83
RAIN	25.9	51.4	49.9	122.8	107.9	22.2	14.7	10.0	24.4	18.6	13.5	30.6	491.9
							2010						
TMX	34.92	35.69	36.67	36.4	33.52	29.13	29.26	29.93	32.28	35.34	37.04	36.14	33.86
TMN	20.42	20.62	21.29	20.6	19.37	19.05	16.95	16.4	17.16	19.47	20.13	20.45	19.33
RAIN	87.4	39.3	39.8	59.3	21.8	19.1	17.7	4.5	12.2	42.7	13.8	63.6	421.2
							2011						
TMX	34.9	34.99	34.96	32.98	30.37	30.92	29.39	31.51	31.52	35.06	34.57	36.98	33.18
TMN	20.08	20.45	20.78	20.26	20.15	18.04	17.27	16.33	17.26	18.92	20.07	20.34	19.16
RAIN	54.9	32.9	24.8	62.2	45.0	12.7	6.0	12.4	11.7	30.9	26.1	38.0	357.6
							Average (11 years)						
TMX	35.03	34.27	33.15	32.52	31.61	29.75	29.62	30.85	33.08	35.34	36.44	36.06	33.15
TMN	20.57	20.82	20.76	19.94	19.82	18.25	17.25	17.15	17.77	19.49	20.45	21.0	19.44
RAIN	81.8	66.33	56.92	47.63	34.65	20.56	10.31	8.25	7.71	36.43	14.85	39.83	425.26

5.2.5 Input data

Soil characteristics, crop parameters as well as daily weather parameters were included as input to the simulation model. Table 5.3 gives the crop parameters used for simulations. Differences from previous parameters of the crop file of EPIC, in order to be more accurate to the local varieties used in the Northeast region from Brazil, were taken from the literature and are mainly concerned to maximum root depth of the crops, which was measured in field experiments (Barros et al., 2005)

Table 5.3. Pertinent Crop Parameters used in the simulations, according to Barros et al. (2005)

	Parameter	
wa	Biomass energy ratio (kg MJ^{-1})	40.0
hi	Maximum harvest index (Mg Mg^{-1})	0.5
tb	Optimum air temperature (°C)	25.0
tg	Base temperature (°C)	8.0
dmla	Maximum leaf area index (m^2 m^{-2})	6.0
dlai	Fraction of season when LAI declines	0.70
dlapl	Crop lea/development parameter	15.15
dlapl2	Crop leaf development parameter	70.95
rlad	LAI senescence parameter	1.0
alt	Aluminum tolerance índex	1.0
rdmx	Maximum root depth (m)	0.6
cny	Normal fraction of N in grain (kg kg^{-1})	0.019
cpy	Normal fraction of P in grain (kg kg^{-1})	0.003
cky	Normal fraction of K in grain (kg kg^{-1})	0.004
wsyf	Lower limit of harvest index (Mg Mg^{-1})	0.1
bnl	Normal crop N concentration, emergence (kg kg^{-1})	0.044
bn2	Normal crop N concentration, mid-season (kg kg^{-1})	0.022
bn3	Normal crop N concentration, maturity (kg kg^{-1})	0.016
bp1	Normal crop P concentration, emergence (kg kg^{-1})	0.0036
bp2	Normal crop P concentration, mid-season (kg kg^{-1})	0.0015
bp3	Normal crop P concentration, maturity (kg kg^{-1})	0.0012
bk1	Normal crop K concentration, emergence (kg kg^{-1})	0.021
bk2	Normal crop K concentration, mid-season (kg kg^{-1})	0.012
bk3	Normal crop K concentration, maturity (kg kg^{-1})	0.007

5.2.6 Crop management scenarios

Two different kinds of irrigation (drip and furrow) and two trigger irrigation (0.1 and 1) were used for the generation of the scenarios: drip irrigation with trigger irrigation 0.1; drip irrigation with trigger irrigation 1; furrow irrigation with trigger irrigation 0.1; and furrow irrigation with trigger irrigation 1. The model output variables evaluated were: corn yield, electrical conductivity (EC) levels, salt content and salt stress. The Table 5.4 indicate the schedule management operations.

According to Andrade et al. (2006) taking in count the approximated value of the water consumption by the plant, considering a high demand for evaporation, as occur in semiarid regions, the amount of water applied to the corn should be 640 mm. Thus this amount of water was considered as 100% of the amount of water used on simulation to the corn, in this study. Then based in this amount were simulated amount of water of 25, 50, 75, 100 and 150% for each scenario above described.

Table 5.4. Schedule management operations

Type operation	Year	Month	Day	Description
		1 Cycle		
Tillage	1	January	4	Plow
Tillage	1	January	4	Harrow
Planting	1	January	5	Hand sowing
Fertilizer application	1	January	15	28-10-10, 700 kg ha^{-1}
Fertilizer application	1	February	15	Urea 45%, 100 kg ha^{-1}
Harvest	1	May	4	Hand harvest
Kill	1	May	5	
		2 Cycle		
Tillage	1	August	29	Plow
Tillage	1	August	29	Harrow
Planting	1	August	30	Hand sowing
Fertilizer application	1	September	10	28-10-10, 700 kg ha^{-1}
Fertilizer application	1	October	10	Urea 45%, 100 kg ha^{-1}
Haverst	1	December	29	Hand harvest
Kill	1	December	30	

The amount of fertilizer used on simulation was according to recommend for the state of Pernambuco, described on Fertilizer Manual for the State of Pernambuco (IPA, 2008), which consider to apply just nitrogen on second fertilizer, 30 days after the first application.

5.3 Results and discussion

5.3.1 Simulations of corn yield x electrical conductivity x stress water relations

Studies reported that EPIC can be one of the recommendable models for simulating long-term average crops (Bryant et al., 1992; Kiniry et al., 1995; Moulin and Beckie, 1993; Williams et al., 1989). In order to simulate a relationship between corn yield, electrical conductivity levels and water stress, we obtained an average value of these variables over the eleven years under study, for the soil depth of 30 cm. Figures 5.2 and 5.3 show the results of this simulation for the four scenarios studied in three soils of the Moxotó watershed. These figures simulate the performance that can be obtained at a given level of CE for each stress in the study.

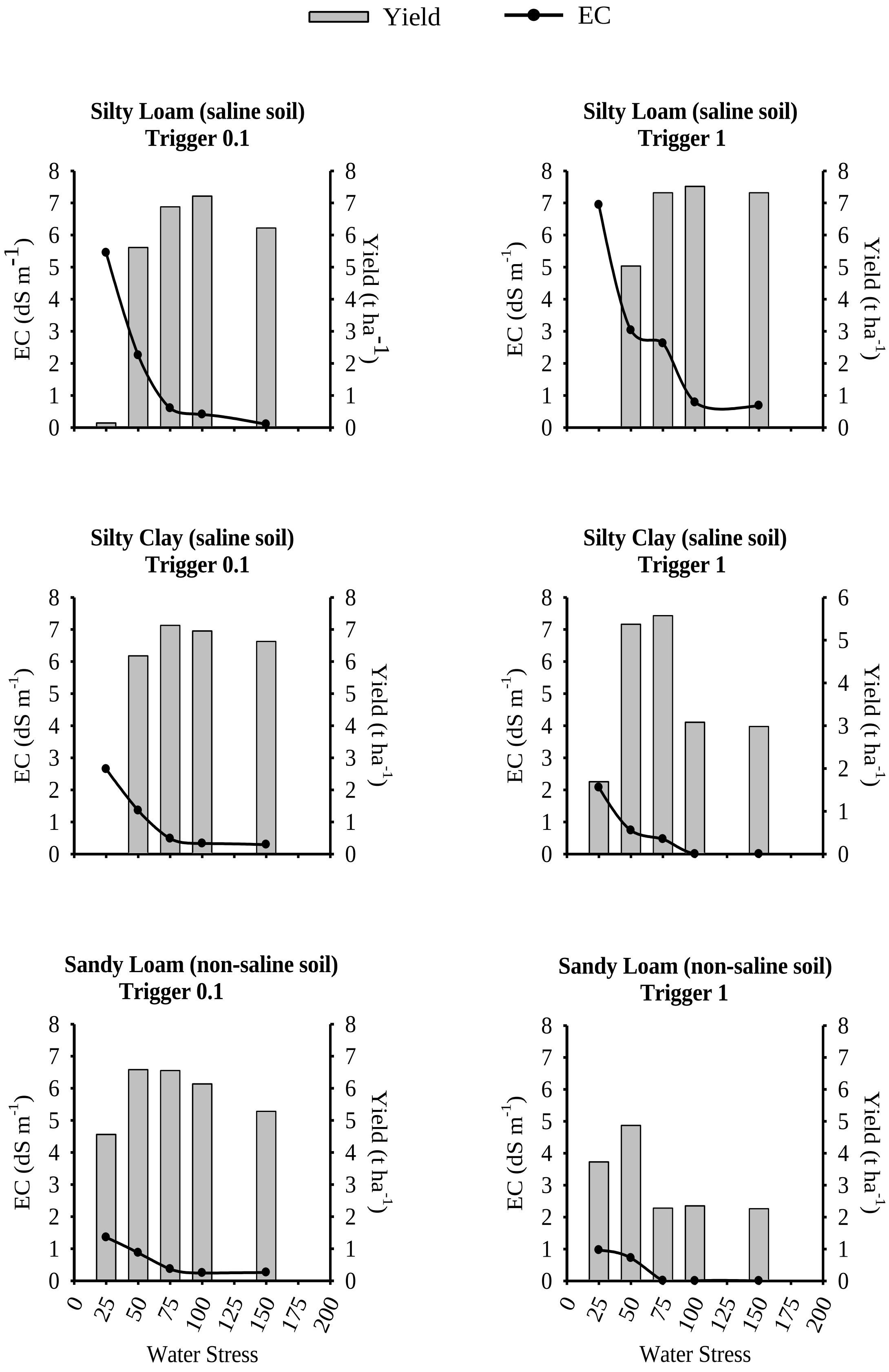


Figure 5.2. Simulation of EC x water stress x yield relations for the drip irrigation.

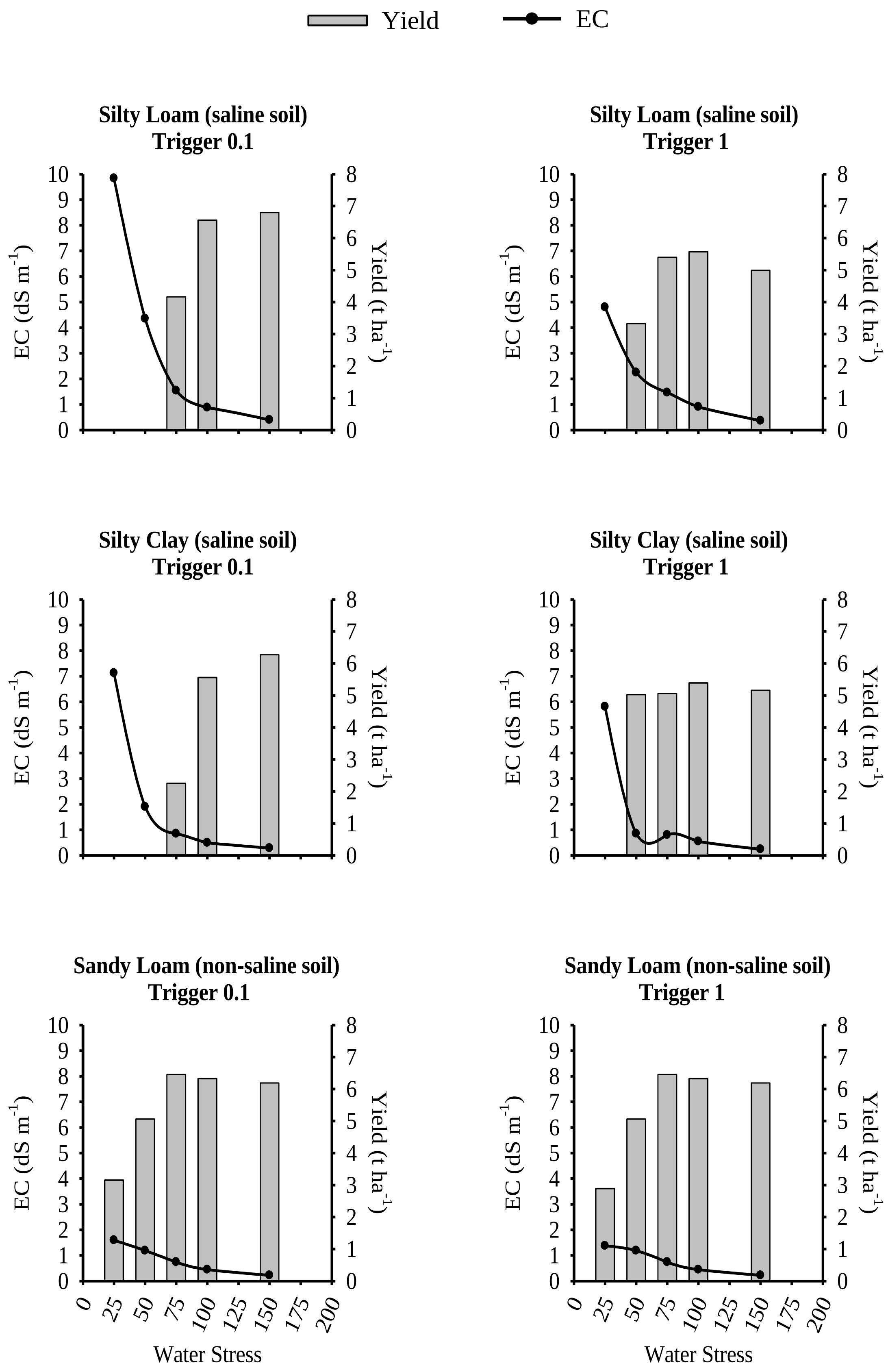


Figure 5.3. Simulation of EC x water stress x yield relations for the furrow irrigation.

In both types of irrigation and the type of trigger, the EC levels were reduced by increasing the amount of water used in the simulation, on the three soils under study. In silt loam soil, the quantity of simulated water equivalent to 100% had better yields to the corn both to 0.1 and to a trigger 1, in the two types of irrigation. This result indicated that although promoting a greater reduction in EC levels, the yield of corn begins to be impaired because of excess water applied to the soil.

With the silty clay soil, the quantity of water equivalent to 75% presented the best performances for the corn, on drip irrigation. This did not occur in the furrow irrigation, indicating that this type of irrigation may be less efficient for this type of soil. In the sandy loam soil, in 50% of the quantity of water to be applied in maize promoted to higher yields in drip irrigation, while for the furrow irrigation the best yield was obtained in 75% of water to be applied.

For the three soils under study, the drip irrigation was more efficient to remove salts from the topsoil, which could be observed by lower levels of EC compared to furrow irrigation. This factor may have contributed to the higher yields observed in this system of irrigation compared to furrow irrigation.

The irrigation trigger 1 also proved to be more efficient in the removal of salts at this 30 cm depth, in relation to the irrigation trigger 0.1. With the exception of the silty loam soil in drip irrigation, all other scenarios indicated the best performance for an irrigation trigger 1 for this 30 cm depth. However, the simulated data indicated that the irrigation trigger 0.1 presented improved yields with respect to irrigation trigger 1 between different scenarios tested. However, for smaller amounts of water simulated, the data indicated better yields of the corn for the irrigation trigger 1. This probably may have occurred due to lower levels of EC presented for the irrigation trigger 1 in relation to irrigation trigger 0.1, for the smallest amount of water simulated.

5.3.2 Salts stress simulations for the corn crop

The relationship between the salt stress and the irrigation trigger was also obtained from the average values for the eleven-year period of simulation and is shown in Figure 5.4. The sandy loam soil had no salt stress for the simulated period by virtue of being a non-saline soil, so their results are not presented.

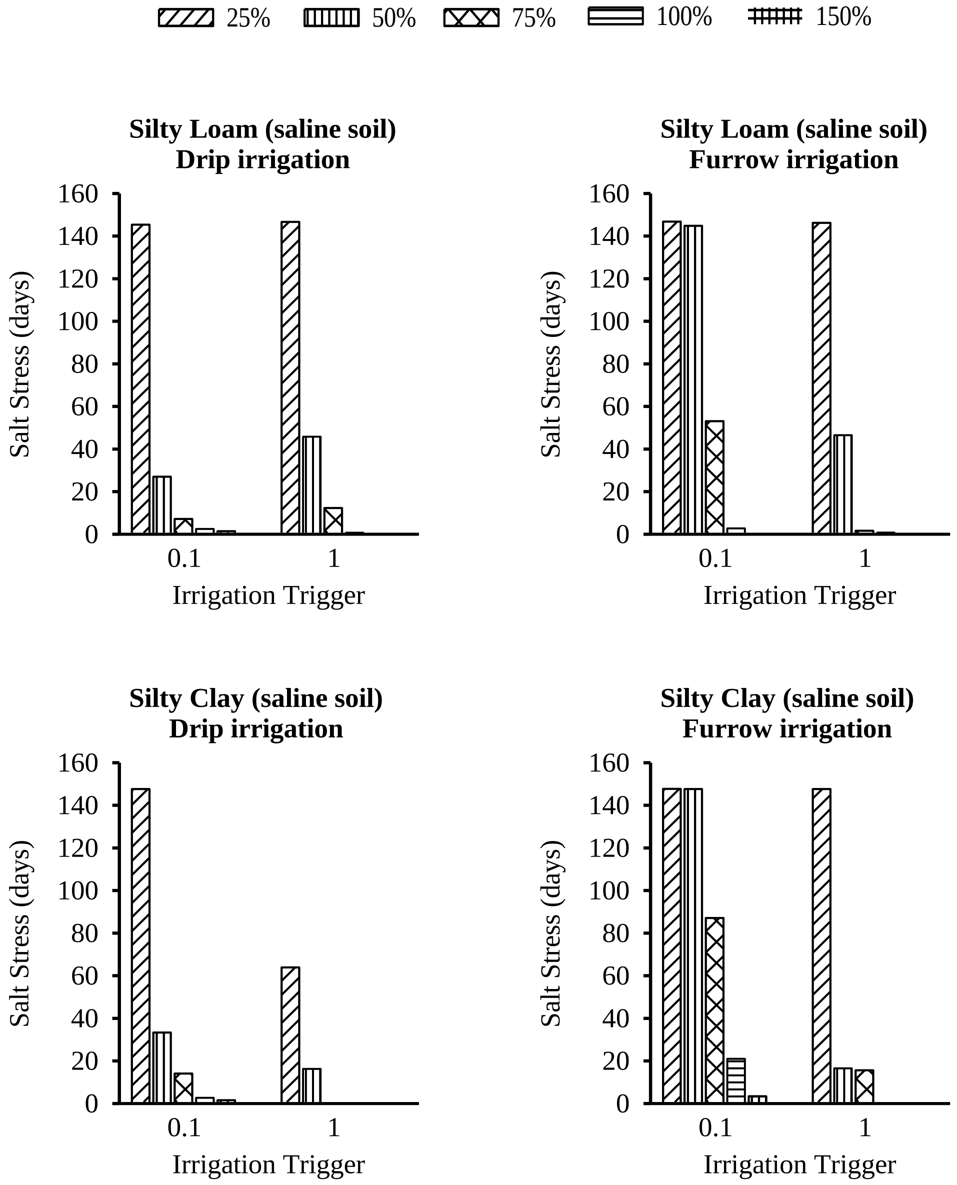


Figure 5.4. Simulation of the salt stress for the corn as function of the kind of irrigation and irrigation trigger.

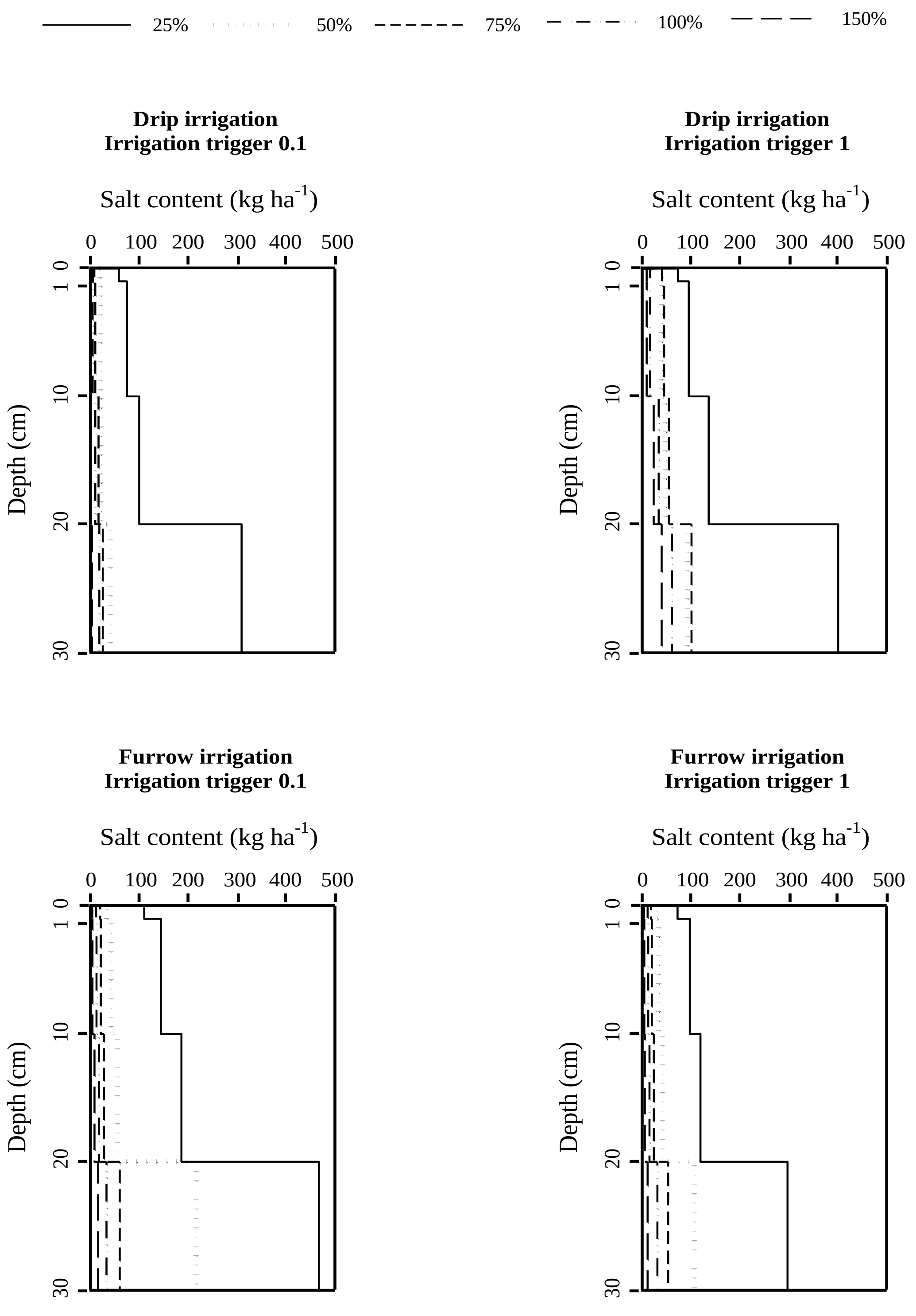
The increase of the amount of water simulated on irrigation indicated a reduction in salt promoted stress, in which from 100% of stress water was observed as the adequate amount that not to promote stress salt. The furrow irrigation and the irrigation trigger 0.1 indicated higher salt stress for maize in relation to drip irrigation and irrigation trigger 1, respectively, in the two salt affected soils.

As observed in the Figures 5.2 and 5.3, the furrow irrigation and the irrigation trigger 0.1 were less efficient in the removal of salts according to the data simulated, which contributed to provide higher salt stress. However, it was observed that for the lowest amount of water applied, the irrigation trigger 0.1 simulated better yields for maize (Figures 5.2 and 5.3). This can be explained by the fact that while the irrigation trigger 1 was more effective in reducing the values of EC (Figures 5.2 and 5.3), under these conditions the stress salt is equivalent (Figure 5.4). In other words, this indicates that the removal of salts that occurred, although it was higher in the irrigation trigger 1, still has not been sufficient to promote reductions in salt stress and consequently didn’t promotes an increase in crop yield. This was verified only at the lowest quantity of water simulated, in other words, under the greatest stress condition of the plant or 25% of the total water simulated.

5.3.3 Salts leaching simulations

Figures 5.5, 5.6 and 5.7 show simulations of the leaching of the salt content to a depth of 30 cm in the soils silt loam, clay silty and sandy loam, respectively, between the different scenarios studied. The higher contents of salts to a depth of 30 cm were observed with the simulation of small amounts of water application, supporting the highest values of EC found for the same quantities of water in Figures 5.2 and 5.3.

According to the simulated data and presented in Figures 5.5, 5.6 and 5.7, it can be seen that the use of irrigation with good quality water promoted leaching salts, which is perceived by increasing the salt content in depth, indicating removing these salts along the profile of the soil. These simulated data also help explain the stress conditions simulated in Figure 5.4 and corn yields in Figure 5.5. The scenarios that simulated a greater removal of salts also simulated lesser stress conditions and higher yields conditions. The drip irrigation and irrigation trigger 1 were the most efficient to simulate salts leaching at 30 cm deep, also agreeing with the simulations obtained for the values of EC in Figures 5.2 and 5.3, for the three simulated soil.



Drip irrigation
Irrigation trigger 0.1

Drip irrigation
Irrigation trigger 1

Furrow irrigation
Irrigation trigger 0.1

Furrow irrigation
Irrigation trigger 1

Figure 5.5. Salt content leaching at 30 cm in depth for the Silty Loam soil in the scenarios evaluated.

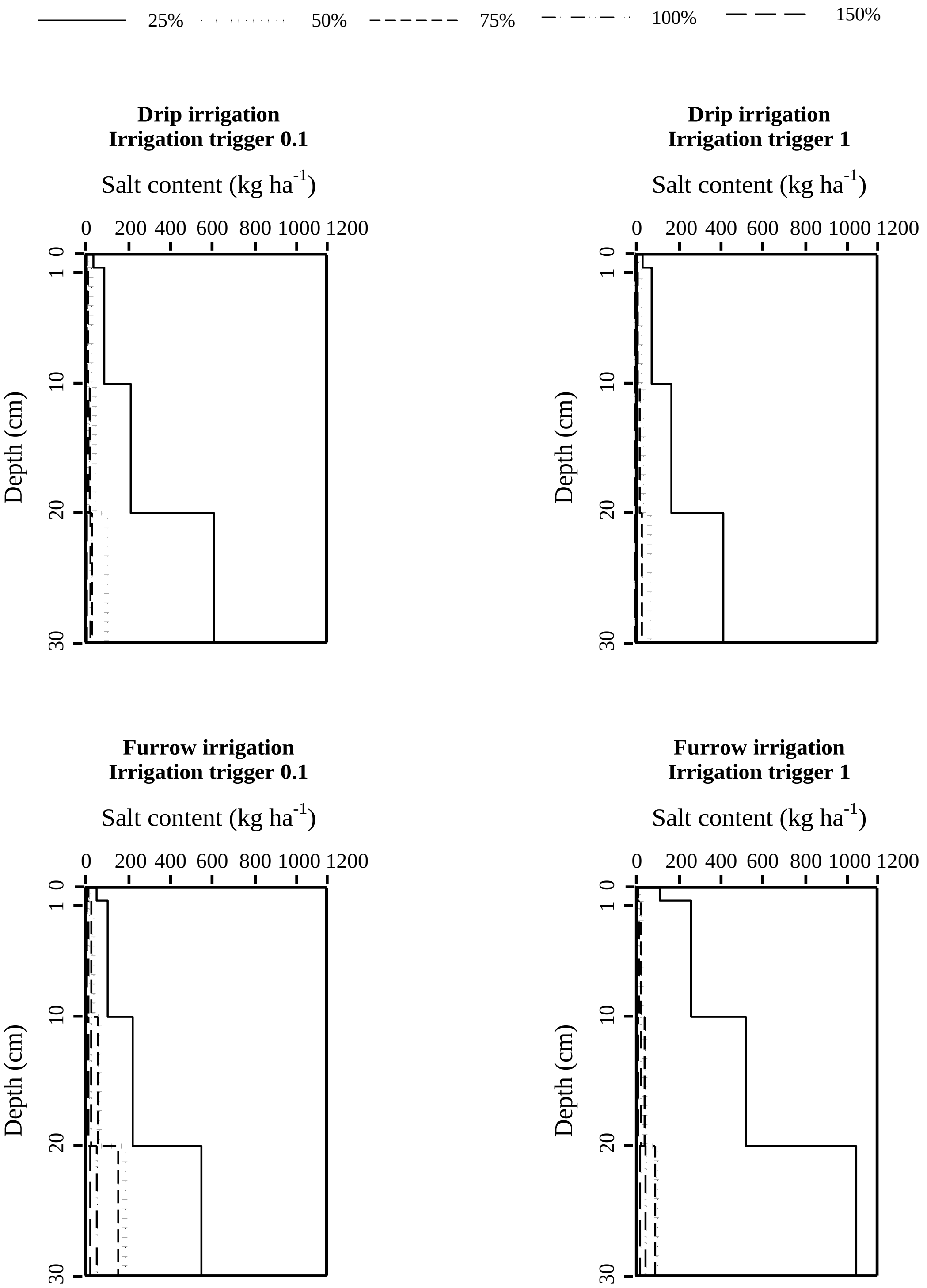


Figure 5.6. Salt content leaching at 30 cm in depth for the Silty Clay soil in the scenarios evaluated.

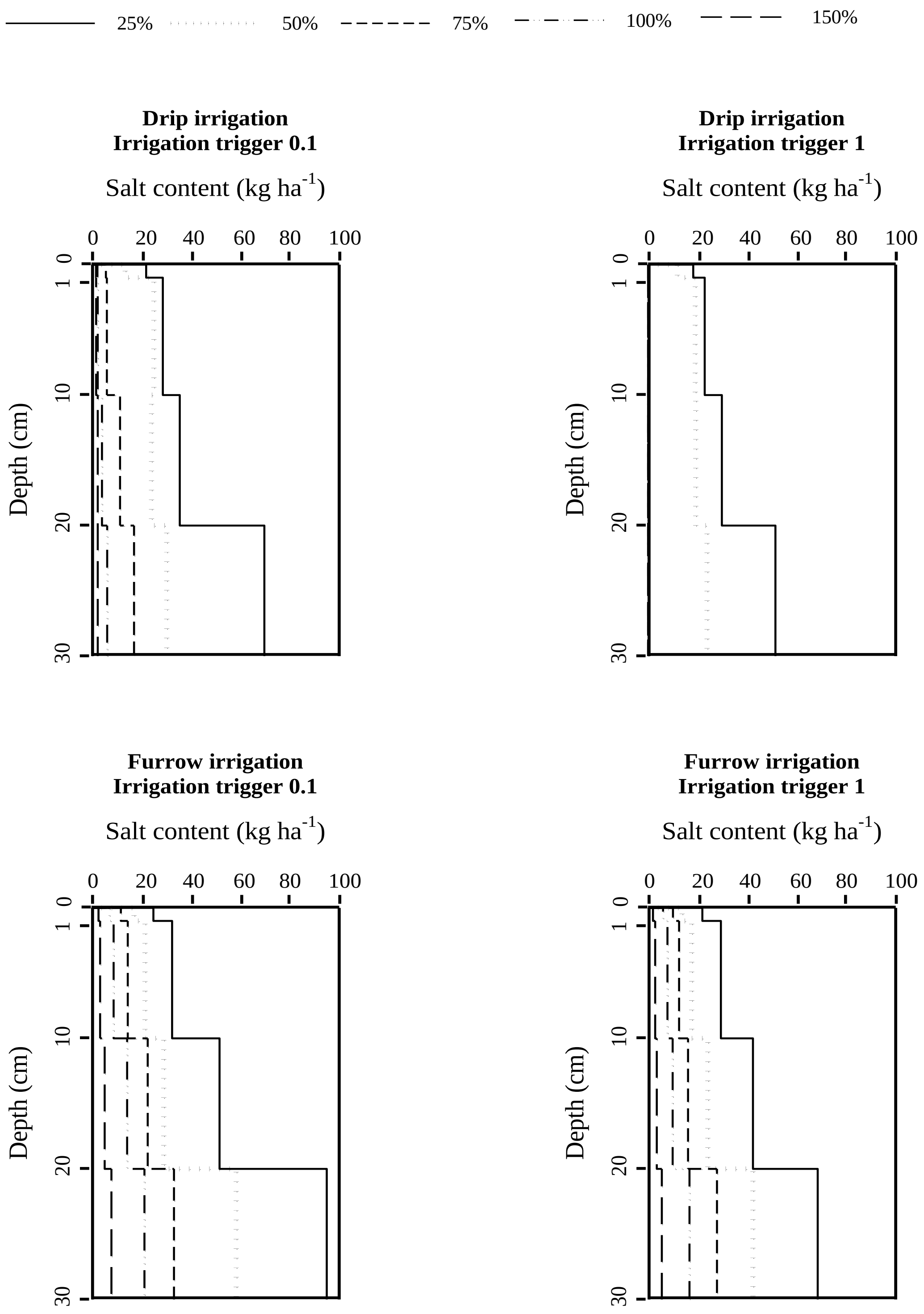


Figure 5.7. Salt content leaching at 30 cm in depth for the Sandy Loam soil in the scenarios evaluated.

5.4 Conclusions

Four different irrigation management scenarios were tested over an 11 years simulated period in the Moxotó watershed, in Northeastern Brazil using the EPIC model. The scenarios were drip and furrow irrigation, and irrigation trigger 0.1 and 1. These results found in this research suggest that the use of quality water with low concentrations of salts promotes the leaching of salts in the soil surface layer and provides good conditions for development of corn in the soils simulated.

The data of irrigation water prediction indicated that increasing the amount of water applied was more efficient in the removal of salts in the soil surface, however, reductions were observed in yields differently for each soil. This research found that the quantity of water applied to the need to 100% of corn, according to the amount of water suggested by Andrade et al. (2006), was ideal only for silt loam soil. Thus, this study suggests that the amounts of water applied that can vary between types of irrigation and trigger irrigation are pertinent per simulation result.

This study found that the best irrigation strategy for the corn crop grown was the drip irrigation, and the trigger irrigation 0.1. However, for the low water content applied, the trigger irrigation 1 should be used.

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6 - CHAPTER V

CLASSIFICATION OF SOILS AFFECTED BY SALTS IN PERNAMBUCO SEMIARID, BRAZIL - A CASE STUDY

Abstract

Among thirteen orders of soil in the Brazilian System of Soil Classification, ten orders are prone to problems of salinization and sodification, which portrays the importance of this issue for soil scientists in Brazil. This chapter aims to describe soil profiles in critical areas found in the previous chapter. Were collected four soil profile, in the municipalities of Ibirimim, Parnamirim and Serra Talhada, Pernambuco semiarid, Brazil. The soils studied have profiles with characteristic features of orders of Fluvisols and Cambisols, which may indicate a strong relationship with these orders salinity problems in the semiarid region of Pernambuco. All soil profiles studied presented an alkaline reaction, for both pH values measured in water and pH values measured in KCl. The highest levels of Ca^{2+}, Mg^{2+}, Na^{+} and K^{+} were found in NEOSSOLO FLÚVICO Sódico sálico. However, all other profiles also had high levels of these elements, especially Na^{+}, which resulted in high values of ESP found. The content of soluble cations and anions were extremely high in profile surface with large decreases in depth in the profiles 1, 2 and 3. This reduction of the levels of soluble cations and anions in these profiles, confirm the values obtained from the EC, which were also reduced over the soil profile. The granulometric composition of soil samples consisted predominantly of fine particles, with high levels of silt and clay fractions in the whole profile. The profiles in the study had high levels of salts and sodium in depth. Furthermore, the predominance of fine particles in the studied soils is a factor which tends to complicate the recovery of these soils.

Keywords: salt-affected soils; salinity and sodicity of soils; Fluvisols; Cambisols

6.1 Introduction

Globally, over 800 million hectares of land are estimated to be salt-affected areas, accounting for over 6% of arable land (Muns and Tester, 2008). Despite technological advances, millions of acres remain salinized, contributing heavily to the reduction of global agricultural production (Khan and Abdullah, 2003).

Regarding the problem of salinity in Brazil highlights the semiarid region of the Northeast, however, other areas are also affected, as some sites in the Amazon Region and Minas Gerais Northern, despite the most representative of salinized soils are found in Brazilian Northeast. By the Surveys of the “National Service of Survey and Soil Conservation” (Serviço Nacional de Levantamento e Conservação de Solos – SNLCS) (Pereira et al., 1982), in Brazil have been related areas over 9.1 million hectares of salt affected soils in the Northeast alone.

Several factors may contribute to the formation of salt affected soils, since all these factors are always related to climatic conditions where rates of evapotranspiration exceed precipitation (typical condition in regions of arid and semiarid) and drainage conditions deficient. Under such conditions, some soils tend to be more prone to the phenomenon of salinization, and this susceptibility more or less, by some soils, will rely heavily on their physical, chemical and mineralogical properties.

Under natural conditions, the presence and concentration of salts in the soil are controlled by factors like: geological, climatic, geomorphological and hydrological. The primary minerals of igneous and metamorphic rocks, mainly silicates and aluminosilicates, are the original sources of salts found in nature. Through the primary mineral weathering release cations and anions that combine to form a variety of salts, such as chlorides, sulfates, carbonates and bicarbonates of sodium, calcium, magnesium and potassium, among others (Zinck and Metternicht, 2008).

Humansalso contributes significantly to the process of soil salinization, both through the use of saline waters, such as the adoption of irrigation practices and inadequate soil management. Around 76.3 million hectares have been salinized as a consequence of human activities in accordance with the Global Assessment of Human - induced Soil Degradation (GLASOD) project led by GLASOD in the 80s. According to study data, this represents 3.9% of 1,964.4 billion hectares affected by anthropogenic soil degradation. This is much lower values when compared with the degradation of soil erosion by wind and laminate, for example (46.8% and 23.1%, respectively), but these values become quite significant when compared to other types of degradation anthropogenic soil, such as acidification, pollution and compression, corresponding to 0.3, 1.1 and 3.5%, respectively (Oldeman et al. 1991).

Some soil orders, by the very nature of pedogenetic processes involved in their formation, marked by intense chemical weathering and leaching, don’t present salinity or sodicity in normal conditions, these being among the orders Luvisols, Ferralsols and Podzols. Problems of high levels of salinity and sodicity are closely related to the formation of soil that has suborders and great groups formed under conditions of deficient drainage in semiarid, as Fluvisols, Vertisols, Cambisols, Planosols and Gleysols. The remaining orders of the Brazilian System of Soil Classification, as Regosols and Arenosols, Chernozems, Planosols, Nitisols and Plinthosols as well as large groups of Fluvisols, Vertisols, Cambisols, Gleysols and Histosols present salinity and sodicity in moderate degree (Ribeiro et al., 2003).

Thus, we note that of the thirteen orders of soil in the Brazilian System of Soil Classification, ten orders are prone to problems of salinization and sodification, which portrays the importance of this issue for soil scientists in Brazil. This chapter aims to describe four soil profiles in critical areas found in the previous chapters.

6.2 Material and methods

6.2.1 Selection and collection of profiles

The choice of the areas where the soil profiles were collected was made during the sampling field. Later, in possession of the soil analyzes results and the map generated in Chapter IV was observed stains critical in terms of salinity and sodicity in the four watersheds studied. Therefore, the selection criteria for opening the soil profiles was based on data analyzed with regard to levels of salinity and sodicity, as well as areas with critical patches observed on the maps created.

Profile 1 (P1) was collected in the municipality of Ibimirim, located in Moxotó watershed, in coordinates Lat: -8°32’10’’; Long: -37°40’11’’, to 431 m of altitude. The soil had been discovered and little local vegetation present consisted exclusively of halophytes, which are indicative of saline environments (Figure 6.1).

Figure 6.1. Selected area for the collection of Profile 1.

Profile 2 (P2) was collected in the municipality of Parnamirim, situated in Brígida watershed, in coordinates Lat: -8°5'41''; Long: -39°34'21'', to 392 m of altitude. The soil was also discovered and presented with local vegetation consists predominantly of halophytes (Figure 6.2).

Figure 6.2. Selected area for the collection of Profile 2.

Profile 3 (P3) was also collected in the municipality of Parnamirim, at coordinates Lat: -8°10'9''; Long: -39°40'21''. The soil was nearly discovered and presented a local vegetation consists predominantly of halophytes and some vegetation sized tree (Figure 6.3).

Figure 6.3. Selected area for the collection of Profile 3.

The Profile 4 (P4) was collected in Serra Talhada, located in the Pajeú watershed, in coordinates Lat: -7˚55’4’’; Long: -38˚19’10’’, to 429 m of altitude. As in the other, the ground had also discovered and with local vegetation consisting solely of halophytes (Figure 6.4).

Figure 6.4. Selected area for the collection of Profile 4.

The descriptions of the profiles and sample collection were performed according to the recommendations of the Handbook of Soil Description and Soil Collection Field (Santos et al., 2005). Disturbed samples were collected from all soil profiles and soil samples were collected from the horizons in each soil profile.

6.2.2 Physical analysis

The physical characterization determined the sand, silt and clay content, and water dispersible clay, by sieving and sedimentation (EMBRAPA, 1997). The sand content was determined by thick sand (diameter size particles between 2 and 0.2 mm) and fine sand (diameter size particles between 0.2 and 0.05 mm). The bulk density was analyzed on an unmixed sample and soil particle density was analyzed by volumetric flask (EMBRAPA, 1997).

Total porosity was calculated with bulk density and particle density soil data. And the degree of flocculation was calculated with total clay and water dispersible clay data. The silt/clay relation was obtained by the division among the silt and clay contents.

6.2.3 Chemical analysis

For the evaluation of the chemical attributes, soil samples were submitted for analysis of the soluble elements according to Richards (1954). On the saturation extract were obtained the electrical conductivity (EC_e at 25°C) and the pH. Soluble cations: Ca^{2+} and Mg^{2+} were obtained by atomic absorption spectrophotometry and Na^+ and K^+ by flame emission photometry. The anions Cl^-, CO_3^{2-} and HCO_3^- were obtained by titration and SO_4^{2-} by colorimetry.

On the soil, was measured pH (1:2.5 – water and KCl 1mol L^{-1}) and determined the exchangeable cations Ca^{2+}, Mg^{2+}, K^+ and Na^+, extracted with ammonium acetate solution 1 mol L^{-1}. The ΔpH was obtained by the difference between pH (KCl 1mol L^{-1}) – pH (water). Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry and Na^+ and K^+ by flame emission photometry. The cation exchange capacity was determined by the method of sodium acetate and ammonium acetate 1 mol L^{-1} (Richards, 1954). The organic carbon content was obtained according to Walkley-Black method, modified by Tedesco et al. (1995).

With the results of analyzes, were calculated the sodium adsorption ratio (SAR) and exchangeable sodium percentage (ESP), according to Richards (1954).

6.3 Results and discussion

6.3.1 Morphology and classification of soils

Morphological characterization full soil profile is presented in summary form in Table 6.1. The soils studied have profiles with characteristic features of orders of Fluvisols and Cambisols, which may indicate a strong relationship with these orders salinity problems in the semiarid region of Pernambuco.

Generally, the Fluvisols gathered presented little color variation. The same could be observed for the Cambisols. The speckles were absent or barely present in the soil samples.

Profile 1 presented the sequence of horizons Apz1 – Apz2 – 2Cz1 – 2Cz2 – 2Cvz1 – 2Cvz2 (Figure 6.5). This profile was classified, according to the Brazilian System of Soil Classification – SiBCS (EMBRAPA, 2006), as NEOSSOLO FLÚVICO Sódico sálico.

Profile 2 presents the sequence of horizons: Ap1 – 2Ap2 – 2Bi – 2BC – 2C1 – 3C2 (Figure 6.5), being classified as CAMBISSOLO FLÚVICO Sódico sálico.

The Profile 3 presents the sequence of horizons: Ap – Cv – 2C – 3Cg1 – 4Cg2 (Figure 6.5), being classified as NEOSSOLO FLÚVICO Sódico sálico (EMBRAPA, 2006).

The Profile 4 has the sequence of horizons: Ap – BA – Bi – C1 – C2 – 2C3 (Figure 6.5), also being classified as CAMBISSOLO FLÚVICO Sódico sálico (EMBRAPA, 2006).

It was observed that boths Fluvisols resemble in relation to the depth, consistency and structure. The two Cambisols also have similarities between them with respect to these parameters.

Table 6.1. Morphological attributes of the soil profiles studied

Horizon	Depth (cm)	Color			Structure	Consistency			Transition
		Dry	Humid	Mottled		Dry	Humid	Wet	
					P1 – NEOSSOLO FLÚVICO Sódico sálico				
Apz1	0 – 10		10YR 4/2	2,5YR 8/1	Weak to moderate; very fine to medium; platy		Firm	Plastic and sticky	Plane and clear
Apz2	10 – 28		10YR 5/3		Weak, fine to medium, subangular blocky		Firm	Plastic and sticky	Plane and abrupt
2Cz1	28 – 52		10YR 5/2		Weak, fine to medium, subangular blocky		Firm	Very plastic and very sticky	Plane and gradual
2Cz2	52 – 82		10YR 4/2		Weak, very fine to medium, subangular blocky and angular blocky		Firm	Very plastic and very sticky	Plane and diffuse
2Cvz1	82 – 130		10YR 4/1		Weak, very fine to medium, subangular blocky and angular blocky		Firm	Very plastic and very sticky	Plane and diffuse
2Cvz2	130 – 160+		10YR 4/1		Weak, very fine to medium, subangular blocky and angular blocky		Firm	Plastic and sticky	
					P2 – CAMBISSOLO FLÚVICO Sódico sálico				
Ap1	0 – 5	10YR 6/4	10YR 5/4		Weak, fine to medium, platy	Slightly hard	Very friable	Slightly plastic and non-sticky	
2Ap2	5 – 20	7,5YR 6/4	7,5YR 4/4		Weak, fine to medium, subangular blocky	Hard	Friable to firm	Slightly plastic and slightly sticky	
2Bi	20 – 48	7,5YR 5/4	7,5YR 4/4		Weak to moderate, fine to medium, subangular and angular blocky		Friable to firm	Plastic and sticky	
2BC	48 – 85	7,5YR 4/3	7,5YR 3/3		Weak to moderate, fine to medium, subangular blocky		Friable to firm	Plastic and sticky	
2C1	85 – 120		7,5YR 3/2		Weak to moderate, fine to medium, subangular blocky		Friable	Slightly plastic and slightly sticky	
3C2	120 – 190		10YR 3/2		Weak to moderate, fine to medium, subangular and angular blocky		Friable to firm	Plastic and sticky	
					P3 – NEOSSOLO FLÚVICO Sódico sálico				
Ap	0 – 10	10YR5/3	10YR4/3		Weak to moderate, medium to coarse, subangular and angular blocky, very fine and platy	Hard to extremely hard	Friable to firm	Plastic and sticky	
Cv	10 – 40	10YR5/3	10YR4/3		Weak to moderate, medium to coarse, prismatic with medium, big angular blocky	Hard to extremely hard	Friable to firm	Very plastic and sticky	
2C	40 – 75		10YR4/3	10YR3/2	Weak, fine to medium, subangular blocky	Hard to extremely hard	Friable	Plastic and sticky	
3Cg1	75 – 120		10YR4/2	7,5YR4/3	Weak, fine to medium, subangular blocky	Hard to extremely hard	Friable	Slightly plastic and slightly sticky	
4Cg2	120 – 150		10YR6/3	10YR7/3	Grain single	Hard to extremely hard	Very friable	Non-plastic and non-sticky	
					P4 – CAMBISSOLO FLÚVICO Sódico sálico				
Ap	0 – 12	10YR5/3	10YR3/3		Weak, fine to coarse, subangular blocky, and medium to coarse, prismatic	Very hard to extremely hard	Frible	Slightly plastic and slightly sticky	Plane and clear
BA	12 – 26	7,5YR6/4	7,5YR5/4		Weak, fine to coarse, subangular blocky, and medium to coarse, prismatic	Very hard to extremely hard	Friable to firm	Plastic and slightly sticky	Plane and gradual
Bi	26 – 60	7,5YR6/4	7,5YR5/4		Weak, fine to medium, subangular Blocky and parts massive	Very hard to extremely hard	Friable to firm	Plastic and sticky	Plane and gradual
C1	60 – 100		7,5YR5/3	10YR4/3	Weak, fine to medium, subangular blocky		Friable to firm	Plastic and sticky	Plane and gradual
C2	100 – 160		7,5YR4/3		Weak, fine to medium, subangular blocky		Friable to firm	Plastic and sticky	Plane and gradual
2C3	160 – 200+		10YR5/3	10YR6/2	Weak, fine to medium, subangular blocky		Friable to firm	Plastic and sticky	

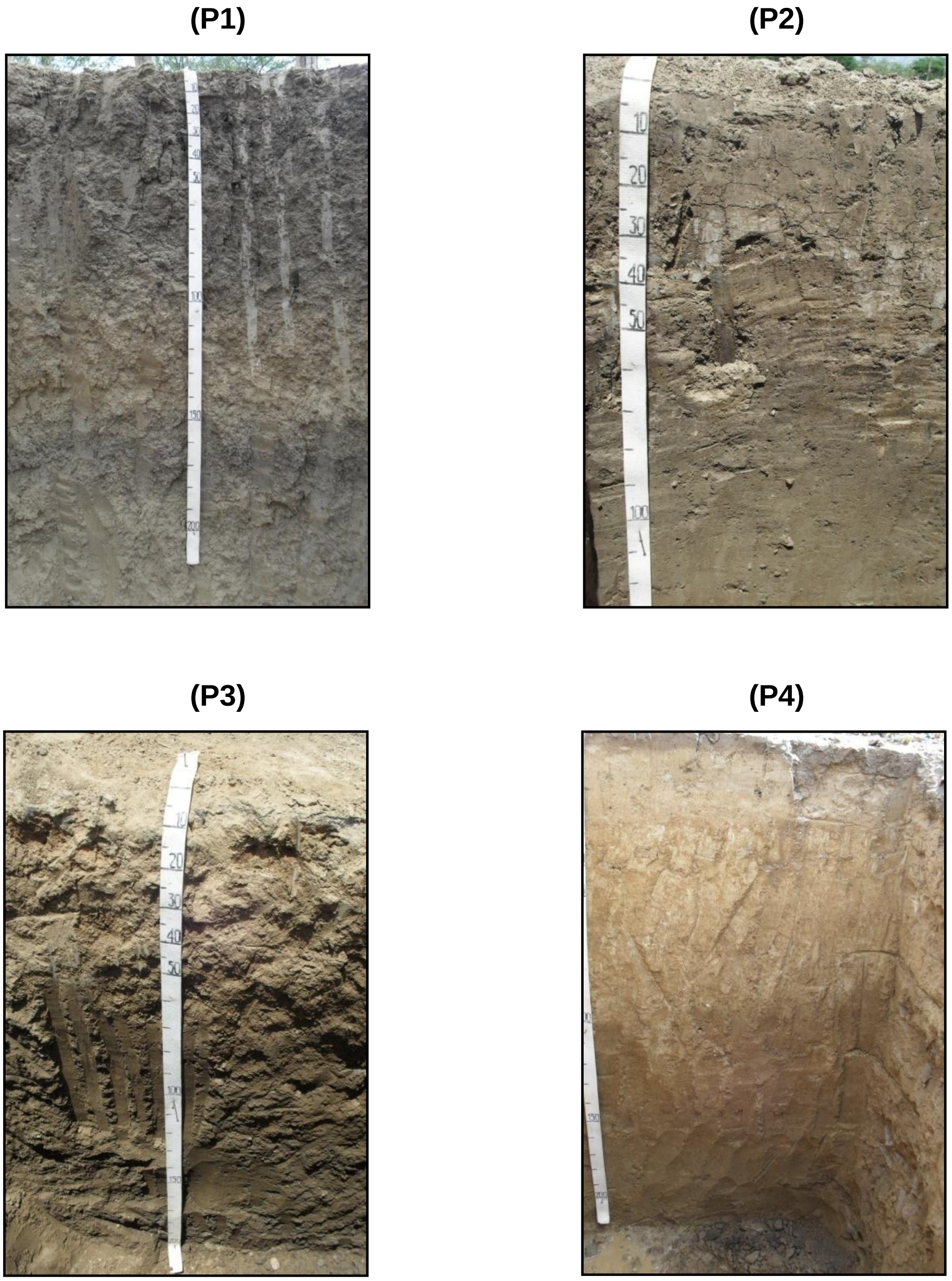

Figure 6.5. Soil profiles collected: (P1) NEOSSOLO FLÚVICO Sódico sálico, collected in Ibimirim; (P2) CAMBISSOLO FLÚVICO Sódico sálico, collected in Parnamirim; (P3) NEOSSOLO FLÚVICO Sódico sálico, collected in of Parnamirim; and (P4) CAMBISSOLO FLÚVICO Sódico sálico, collected in Serra Talhada. Classification according to EMBRAPA (2006).

6.3.2 Chemical attributes

All soil profiles studied presented an alkaline reaction, for both pH values measured in water and pH values measured in KCl (Table 6.2). The pH values were high, with increases of pH values at depth. The pH ranges noted may be considered unsuitable for the development of most cultures. Negative values of ΔpH found in the soil samples characterize these soils as being predominantly electronegative.

The highest levels of Ca^{2+}, Mg^{2+}, Na^+ and K^+ were found in P1. However, all other profiles also had high levels of these elements, especially Na^2, which resulted in high values of ESP found (Table 6.2). With the exception of P2, all other soils showed an increase in the values of ESP in depth. This may be an indication of the source material contribution to the high levels of Na^+ in depth. In P3 and P4, the levels of exchangeable sodium outweigh the Ca^{2+} and Mg^{2+} levels in depth. These data indicate that these soils are difficult to recover because the sodium has dispersive effect over clays, which hinders the permeability of water.

The K^+ presented similar dynamics in all studied profiles, with reduced levels with increasing depth. The Mg^{2+} levels decreased in depth in the P2, P3 and P4. The element Ca^{2+} presented a particular dynamic, differentiated from other exchangeable cations. This cation had reductions in their levels in depth only on P3, however, in the other it was distributed over the profiles.

Despite the low levels of total organic carbon (Table 6.2), the CEC values were high in all soil samples. This indicates that these high values of CEC found should be more likely to predominant minerals in these soils.

In saturation extract, pH values were also high, and the values of EC (Table 6.3). In the profiles 1, 2 and 3, the values of EC were reduced in depth, indicating a higher concentration of salts on the surface. Only on the P4, the salts were evenly distributed throughout the profile.

Table 6.2. Chemical attributes of the soil profiles studied - exchange complex

Horizon	Depth (cm)	pH		ΔpH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CEC	ESP	OC
		KCl	water		$cmol_c\ kg^{-1}$					%	
P1 – NEOSSOLO FLÚVICO Sódico sálico											
Apz1	0 – 10	6.85	7.70	-0.85	37.77	8.82	5.52	0.63	52.75	10.46	1.29
Apz2	10 – 28	6.88	8.10	-1.22	16.36	6.75	5.71	0.29	29.11	19.61	0.58
2Cz1	28 – 52	6.51	8.00	-1.49	22.93	12.17	7.63	0.29	43.01	17.73	0.71
2Cz2	52 – 82	6.51	8.20	-1.69	20.30	9.62	8.77	0.35	39.04	22.46	0.77
2Cgvz1	82 – 130	6.40	8.00	-1.60	19.59	11.23	9.84	0.35	41.01	24.00	0.70
2Cgvz2	130 – 160+	6.40	8.20	-1.80	21.92	11.29	10.19	0.23	43.65	23.37	0.75
P2 – CAMBISSOLO FLÚVICO Sódico sálico											
Ap1	0 – 5	7.9	8.2	-0.3	11.74	8.53	5.13	0.18	25.58	20.07	0.65
2Ap2	5 – 20	6.97	8.1	-1.13	10.5	9.89	5.71	0.18	26.28	21.72	0.4
2Bi	20 – 48	6.44	8.4	-1.96	13.13	8.82	5.52	0.16	27.63	19.97	0.44
2BC	48 – 85	6.38	8.5	-2.12	15.45	7.08	4.85	0.08	27.46	17.65	0.35
2C1	85 – 120	6.53	8.7	-2.17	8.38	7.28	4.27	0.08	20.02	21.33	0.25
3C2	120 - 190	6.29	8.8	-2.51	11.21	9.56	5.33	0.09	26.19	20.33	0.28
P3 – NEOSSOLO FLÚVICO Sódico sálico											
Ap	0 – 10	6.13	6.8	-0.67	13.84	7.95	3.22	0.19	25.2	12.76	0.88
Cv	10 – 40	6.88	8.9	-2.02	9.69	7.82	11.27	0.14	28.93	38.96	0.36
2C	40 – 75	6.82	8.8	-1.98	8.18	7.95	11.99	0.13	28.25	42.43	0.43
3Cg1	75 – 120	6.94	9.1	-2.16	4.04	5.15	8.87	0.11	18.18	48.83	0.19
4Cg2	120 – 150	7.34	9.5	-2.16	0.39	0.49	1.87	0.06	2.81	66.54	0.14
P4 – CAMBISSOLO FLÚVICO Sódico sálico											
Ap	0 – 12	6.25	7.0	-0.75	8.08	1.27	1.87	0.41	11.63	16.11	1.51
BA	12 – 26	7.97	9.7	-1.73	10.0	1.54	6.67	0.18	18.74	35.59	0.44
Bi	26 – 60	8.3	10.0	-1.7	9.29	0.67	13.41	0.46	23.84	56.27	0.19
C1	60 – 100	8.66	10.3	-1.64	11.41	2.8	14.13	0.41	28.76	49.14	0.17
C2	100 – 160	8.6	10.4	-1.8	4.34	0.25	14.13	0.35	19.08	74.08	0.15
2C3	160 – 200+	8.67	10.4	-1.73	2.22	0.52	9.84	0.23	12.82	76.76	0.14

CEC – Cation exchange capacity; ESP – Exchangeable sodium percentage; OC – Organic carbon.

Table 6.3. Chemical attributes of the soil profiles studied – saturation extract

Horizon	Depth (cm)	pH	EC (dS m^{-1})	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	CO$_3^{2-}$	HCO$_3^{-}$	SO$_4^{-}$	SAR (mmol$_c$ L^{-1})$^{0.5}$
				mmol$_c$ L^{-1}								
P1 – NEOSSOLO FLÚVICO Sódico sálico												
Apz1	0 – 10	7.05	59.63	621.74	36.27	471.1	3.11	1180.0	ND	6.6	14.81	25.97
Apz2	10 – 28	7.3	17.25	35.58	2.1	187.28	0.28	185.0	ND	5.8	12.87	43.15
2Cz1	28 – 52	7.57	13.35	28.34	1.6	153.83	0.24	113.0	ND	5.4	176.15	39.76
2Cz2	52 – 82	7.98	9.08	11.82	0.59	95.47	0.17	78.0	ND	8.6	7.51	38.33
2Cgvz1	82 – 130	7.52	8.28	9.24	0.51	80.02	0.15	70.0	ND	4.6	7.17	36.25
2Cgvz2	130 – 160+	7.31	6.16	6.87	0.34	59.42	0.11	49.0	ND	4.2	5.6	31.31
P2 – CAMBISSOLO FLÚVICO Sódico sálico												
Ap1	0 – 5	7.1	65.97	21.65	92.52	471.10	4.79	2520.0	ND	25.4	150.62	62.35
2Ap2	5 – 20	7.77	20.11	44.51	4.68	248.99	0.34	183.0	ND	11.0	42.04	50.21
2Bi	20 – 48	7.68	7.44	18.84	1.52	74.87	0.09	30.0	ND	6.6	189.98	23.47
2BC	48 – 85	7.37	5.83	11.51	0.76	57.71	0.08	26.0	ND	4.6	12.37	23.3
2C1	85 – 120	7.47	4.89	6.67	0.51	43.98	0.07	28.0	ND	6.2	8.99	23.22
3C2	120 - 190	7.68	3.92	6.46	0.42	38.83	0.06	22.0	ND	6.6	7.54	20.93
P3 – NEOSSOLO FLÚVICO Sódico sálico												
Ap	0 – 10	7.56	39.87	424.12	25.17	414.46	1.74	640.0	ND	9.0	156.14	27.65
Cv	10 – 40	8.03	12.59	4.9	0.76	146.97	0.08	127.0	ND	9.8	5.38	87.39
2C	40 – 75	8.06	12.38	2.67	0.76	129.8	0.06	125.0	ND	9.4	4.49	99.23
3Cg1	75 – 120	7.95	10.88	2.83	0.51	119.5	0.06	106.0	ND	8.6	2.83	92.56
4Cg2	120 – 150	7.67	8.8	2.19	0.25	93.76	0.07	80.0	ND	5.8	2.11	84.78
P4 – CAMBISSOLO FLÚVICO Sódico sálico												
Ap	0 – 12	8.32	8.6	12.12	0.67	93.76	0.91	82.0	ND	19.4	1.5	37.07
BA	12 – 26	8.35	12.72	7.02	0.17	150.4	0.13	124.0	ND	25.4	7.17	79.34
Bi	26 – 60	8.43	21.42	6.67	0.06	317.57	0.49	263.0	ND	21.0	10.64	173.15
C1	60 – 100	9.2	19.53	4.44	0.04	276.42	0.39	212.0	3.0	26.2	7.96	184.59
C2	100 – 160	9.43	16.32	10.81	0.05	207.85	0.18	157.0	2.8	27.4	5.44	89.2
2C3	160 – 200+	9.29	13.39	5.0	0.04	155.55	0.24	127.0	2.33	34.33	4.25	98.02

EC – Electrical condutivity; SAR – Sodium adsorption ratio.

The content of soluble cations and anions were extremely high in profile surface with large decreases in depth in the profiles 1, 2 and 3. This reduction of the levels of soluble cations and anions in these profiles, confirm the values obtained from the EC, which were also reduced over the soil profile. The P4 had levels of soluble cations and anions well distributed along the profile, also corroborating the EC values recorded in this profile.

With the exception of the upper horizons, it is observed that in all other subsurface horizons in all profiles studied, the soluble Na^+ presents higher levels than the other cations. This reflects the high SAR values observed in this study, indicating the predominance of soluble Na^+ in relation to Ca^{2+} and Mg^{2+}. Note that all profiles and all horizons have SAR values much higher than the limit of 13 $(mmol_c\ L^{-1})^{0.5}$ proposed by Richads (1954), indicating a high degree of degradation by this element. Similarly to exchange complex, the K^+ cation was detected at lower levels than the other.

With respect to anions, Cl^- was found in higher concentrations. This element at high concentrations is toxic to most crops and remediation practices require the removal of this element. The high levels of this element along with the high levels of Na^+ checked may indicate a predominance of salts NaCl, which as seen in Chapter III, was the main salt predominant in soils in the semiarid of Pernambuco.

The concentration of CO_3^{2-} were absent in profiles 1, 2 and 3. This element was detected only in the lower horizons of profile 4, but at levels much lower compared to other anions. Probably these low levels observed in these profiles may have been derived from source material. However, the data in this study indicate that the CO_3^{2-} has no restriction on soils. These data suggest that high pH values observed are more associated with HCO_3^-, which was found in considerable amounts in all profiles analyzed. In profile 4, where the levels of HCO_3^- were higher than the other, it were observed pH values both in saturation extract (Table 6.3), as in the exchange complex (Table 6.2). Just on the P3 the HCO_3^- levels were higher than SO_4^{2-}.

6.3.3 Physical attributes

The granulometric composition of soil samples consisted predominantly of fine particles, with high levels of silt and clay fractions (Table 6.4) in the whole profile.

This may be indicative of low permeability of the soils, in addition to high levels of exchangeable sodium (Table 6.2) and soluble (Table 6.3), which contribute to the dispersion of clay, further hindering the percolation of water along the profile. The P1 had very low levels of the sand fraction in relation to the profiles P2, P3 and P4, which showed levels of fine sand fraction higher than those of coarse sand fraction.

The clay dispersed in water had high up on the profiles P1, P2 and P3, reflecting the high levels of exchangeable sodium and soluble. The P4 had uniform levels of clay dispersed in water along the profile. In the upper horizons, the high content of salts contributed to lower levels of water dispersible clay, mainly in P1 and P3. These high levels of clay dispersed in water corroborate the low values of flocculation of clay, which were low in the profiles under study. Higher values of flocculation of clay was found in upper horizons of Fluvisols P1 (86.21%) and P3 (61.47%).

The lowest values of silt/clay ratio were observed in P1, indicating that this profile appears more weathered than the other, which had a predominance of silt over clay, indicating they are less weathered soils.

The values of soil density decreased in depth in all profiles. The upper horizons had higher values of soil density. Regarding porosity, note that the soils had high values, however, considering the high levels of silt and clay fractions found in these profiles, this suggests that the pore space of the soil profile is predominantly composed of micropores.

Table 6.4. Physical attributes of the soil profiles studied

Horizon	Depth (cm)	Sand		Silt	Clay	WDC	FI (%)	Silt / Clay	Soil bulk density	Soil particle density	Porosity (%)
		Coarse	Fine								
		g kg^{-1}							g cm^{-3}		
				P1 – NEOSSOLO FLÚVICO Sódico sálico							
Apz1	0 – 10	25.6	41.4	248.6	684.4	94.4	86.21	0.36	1.65	2.55	35.29
Apz2	10 – 28	6.6	99.8	139.2	754.4	384.4	49.05	0.18	1.59	2.45	35.1
2Cz1	28 – 52	17.6	30.6	277.4	674.4	574.4	14.83	0.41	1.63	2.6	37.31
2Cz2	52 – 82	17.4	18.6	269.6	694.4	634.4	8.64	0.39	1.57	2.44	35.66
2Cgvz1	82 – 130	7.6	13.6	204.4	774.4	644.4	16.79	0.26	1.55	2.62	40.84
2Cgvz2	130 – 160+	7.6	18.6	239.4	734.4	614.4	16.34	0.33	1.56	2.68	41.79
				P2 – CAMBISSOLO FLÚVICO Sódico sálico							
Ap1	0 – 5	27.4	406.4	351.8	214.4	194.4	9.33	1.64	1.65	2.66	37.97
2Ap2	5 – 20	17.6	380.6	287.4	314.4	274.4	12.72	0.91	1.69	2.68	36.94
2Bi	20 – 48	6.0	235.6	424.0	334.4	260.8	22.01	1.27	1.53	2.78	44.96
2BC	48 – 85	7.4	263.8	404.4	324.4	267.2	17.63	1.25	1.57	2.82	44.33
2C1	85 – 120	8.4	316.0	391.2	284.4	147.2	48.24	1.38	1.6	2.44	34.43
3C2	120 - 190	26.0	242.6	407.0	324.4	267.2	17.63	1.25	1.65	2.49	33.73
				P3 – NEOSSOLO FLÚVICO Sódico sálico							
Ap	0 – 10	25.8	186.2	613.6	174.4	67.2	61.47	3.52	1.65	2.73	39.56
Cv	10 – 40	21.4	126.6	397.6	454.4	363.6	19.98	0.87	1.67	2.89	42.21
2C	40 – 75	9.8	119.4	456.4	414.4	353.6	14.67	1.1	1.66	2.46	32.52
3Cg1	75 – 120	6.0	270.0	429.6	294.4	240.0	18.48	1.46	1.61	2.74	41.24
4Cg2	120 – 150	31.8	801.0	72.8	94.4	60.o	36.44	0.77	1.59	2.74	41.97
				P4 – CAMBISSOLO FLÚVICO Sódico sálico							
Ap	0 – 12	65.2	252.2	428.2	254.4	216.4	14.94	1.68	1.56	2.44	36.07
BA	12 – 26	50.4	229.6	445.6	274.4	240.0	12.54	1.62	1.56	2.63	40.68
Bi	26 – 60	98.0	261.2	306.4	334.4	280.0	16.27	0.92	1.6	2.74	41.61
C1	60 – 100	70.2	267.0	368.4	294.4	247.2	16.03	1.25	1.55	2.41	35.68
C2	100 – 160	41.4	250.0	374.2	334.4	290.0	13.28	1.12	1.6	2.67	40.07
2C3	160 – 200+	167.6	264.8	243.2	324.4	260.0	19.85	0.75	1.55	2.67	41.95

WDC – Water dispersible clay; FI – Flocculation indice.

6.4 Conclusions

The profiles in the study had high levels of salts and sodium in depth. Furthermore, the predominance of fine particles in a particle size is factors which tend to complicate the recovery of these soils.

The soils selected in critical spots were classified as Neossolos and Cambissolos. Thus, these soils may be strongly associated with the presence of high levels of soil degradation by salinization and sodification in the semiarid of Pernambuco. Under the conditions evaluated, these soils were unfit for agriculture, and require remedial action.

The data obtained in this study indicated that the exchangeable sodium, soluble chloride and soluble cations were present in higher concentrations. Thus, the removal of these elements is essential for recovery of these soils, since in high concentrations they come to be toxic to plants.

6.5 References

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7 - FINAL CONSIDERATIONS AND RECOMMENDATIONS

7.1 Final considerations

The research presented here, highlights some of possibilities that can be achieved in detecting, predicting, and monitoring soil salinity and sodicity. However, the application of the developed methods can be extended to focus predominantly on research areas that were not covered in this study.

The integration of techniques such as remote sensing and GIS can be successfully used for the identification and monitoring of areas degraded by salinization and sodification. However, it is difficult to extract information using remote sensing and GIS from the soil profile, while salinization and sodification occur both at the surface and the near-surface.

Identification and spatial distribution of areas affected by salts and sodium in the semiarid region of Pernambuco indicated that all watersheds had degraded areas; however, salinity is the main type of degradation compared to sodification.

The data obtained in this research indicate that the semiarid region from the state of Pernambuco presents levels of degradation by salinity and sodicity very high compared to other regions of Brazil. In addition, the sodium and chloride ions were found at high levels and were highly correlated with parameters of salinity and sodicity. Furthermore, these ions in high concentrations are toxic to plants. Thus, recovery strategies in these areas should include the removal of these ions, which includes leaching to a deeper depth.

Studies of environmental modeling can be used for monitoring and developing strategies for cultivation and soil management. In this study, by EPIC model it was possible to determine the best strategy for production irrigation of corn and remove salts from the upper layers. However, once calibrated and validated, these models can be very useful in simulating the balance of salts in degraded areas.

7.2 Recommendations

- Using mixtures of salts to obtain radiometric measurements in laboratory tests;

- Evaluate the dynamics of salinity and sodicity, and the cations and anions levels as well both spatially and temporally, at different depths;
- Include the vegetation indicator of degraded areas in studies identifying areas affected by salts;
- Conduct studies to help identify sources of salinity in these areas to prevent the expansion of the problem;
- Create and evaluate the efficiency of algorithms and indices to estimate soil salinization in laboratory testing and field samples;
- Improve simulations of soil salinity through field measurements with subsequent calibration and validation of the model;
- Using models able to simulate the salt movement, in order to understand its dynamics in the study areas, as an aid in the identification of these areas;
- Carry out field experiments with corn or other crops, in order to calibrate, validate and make predictions of crop yields studied, according to local conditions;
- Conduct research with the intent to recover these degraded areas existing.