IUG LOPES

SPATIO-TEMPORAL ANALYSIS OF ENVIRONMENTAL VARIABLES TO SUPPORT WATER RESOURCES MANAGEMENT

RECIFE - PE

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Doctoral thesis presented at Universidade Federal Rural de Pernambuco (Federal Rural University of Pernambuco) in partial fulfilment of the requirements for obtaining the Degree of Doctor of Science: Agricultural Engineering.

Advisor: Prof. Dr. Abelardo Antônio de Assunção Montenegro

Co-Advisor: Prof. Dr. João Luís Mendes Pedroso de Lima

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amor e afeto.

Dedico (in Portuguese)

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“O sucesso é ir de fracasso em
fracasso sem perder entusiasmo”
Winston Churchill

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GENERAL ABSTRACT

Hydrological studies combined with the use of conservation practices are essential for an adequate management of water resources. It is necessary to expand the knowledge about hydrological processes and their seasonal variations, as well as the rainfall patterns of the different hydrographic basins, considering their spatial and temporal distributions. Thus, the objective with this research is to investigate hydrological processes, soil conservation techniques, cultivation conditions and patterns of temporal space variability of water and electrical conductivity available in the semiarid region of Pernambuco, with emphasis on the use of conservationist techniques and cultivation in experimental plots, with the prospect of increasing agricultural resilience and sustainability in the semiarid region. Chapter 1 covers the general and specific introduction, hypotheses and objective and the literature review. Chapter 2 addresses the verification of the accuracy of indirect measurements of the apparent electrical conductivity (ECa) using the EM38®, as well as of physical-hydric parameters of the soil, and their spatial interrelationships. Chapter 3 presents an investigation of the cross variance between soil moisture and soil apparent electrical conductivity (ECa), under different land uses in an alluvial valley in Pernambuco. Chapter 4 presents the investigation of small-scale hydrological processes and the impact of soil conservation techniques in reducing runoff and sediment losses. This study used the textural characterization of the associated transported sediments, using runoff plots with different soil coverings (bare soil, Caatinga, mulch and Palma) under natural rain, in the Caatinga biome of Brazil. Chapter 5 presents the study of the interception process (i.e., water retention and absorption) of rain by different types, sizes and densities of some organic coverings that are commonly found in the Brazilian semiarid region. These results are important for the definition of soil and water conservation practices in these environments. In general, a high covariance between soil moisture and ECa is identified in the fallow area and under cultivation at different depths, under conditions of extreme water scarcity. For alluvial areas, a covariance of soil moisture with ECa is detected, as well as the occurrence of strong spatial dependence. The effect of mulch due to the deciduous characteristics of Caatinga vegetation is important for maintaining soil moisture, contributing to the development and maintenance of plant biomass in riparian forest. The natural cover (Caatinga) produces less runoff and loss of sediment when compared to bare soil and soil conservation practices (mulch and Palma). Adoptions of organic cover dosages from 2 t ha^{-1} already promote significant retention / absorption, contributing to possible delay in the onset of runoff, increased water infiltration and consequent reduction of water and soil losses.

Keywords: mulch size, mulch types, geostatistics, ecosystem services, slope study, Semi-arid Region of Brazil

LOPES, I. **Análise espaço-temporal de variáveis ambientais para suporte à gestão de recursos hídricos.** 2020. 130 f. Tese (Doutorado em Engenharia Agrícola) - Universidade Federal Rural de Pernambuco, Recife, Pernambuco, Brasil.

RESUMO GERAL

Estudos hidrológicos aliados à utilização de práticas conservacionistas são essenciais para um gerenciamento adequado dos recursos hídricos. Faz-se necessário ampliar o conhecimento sobre os processos hidrológicos e suas variações sazonais, assim como os regimes pluviométricos das diversas bacias hidrográficas, considerando as suas distribuições espaciais e temporais. Assim, o objetivo com esta pesquisa é investigar processos hidrológicos, técnicas de conservação do solo, condições de cultivo e padrões de variabilidade espaço temporal de umidade e condutividade elétrica do solo disponíveis no semiárido de Pernambuco, com ênfase no uso de técnicas conservacionistas e cultivos em parcelas experimentais, com a perspectiva de incremento da resiliência e sustentabilidade agrícola em ambiente semiárido. Inicialmente aborda a introdução, hipóteses e objetivo geral e específicos e a revisão de literatura. Posterior aborda a verificação da precisão de medições indiretas da condutividade elétrica aparente (CEa) utilizando o EM38®, bem como de parâmetros físico-hídricos do solo, e suas inter-relações espaciais. Continuando com a apresentação da investigação da variância cruzada entre a umidade do solo e a condutividade elétrica aparente do solo (CEa), sob diferentes usos do solo em um vale aluvial de Pernambuco. Além da investigação de processos hidrológicos de pequena escala e o impacto das técnicas de conservação do solo na redução das perdas de escoamento e sedimentos. Este estudo utilizou a caracterização textural dos sedimentos transportados associados, utilizando parcelas de escoamento superficial com diferentes coberturas de solo (solo descoberto, Caatinga, cobertura morta e Palma) sob chuva natural, no bioma Caatinga do Brasil. Finalizando com o estudo do processo de interceptação (i.e., retenção e absorção de água) da chuva por diferentes tipos, tamanhos e densidades de algumas coberturas orgânicas que são comumente encontradas no semiárido brasileiro. Esses resultados são importantes para a definição de práticas de conservação do solo e da água nesses ambientes. De uma forma geral, alta covariância entre umidade do solo e CEa é identificada na área de pousio e em cultivo em diferentes profundidades, sob condições de extrema escassez de água. Para áreas aluviais, é detectada uma covariância da umidade do solo com CEa, bem como a ocorrência de forte dependência espacial. O efeito da cobertura morta devido às características decíduas da vegetação da Caatinga é importante para a manutenção da umidade do solo, contribuindo para o desenvolvimento e manutenção da biomassa vegetal da mata ciliar. A cobertura natural (Caatinga) produz menos escoamento e perda de sedimentos quando comparado ao solo descoberto e às práticas de conservação do solo (cobertura morta e Palma). As adoções de dosagens de coberturas orgânicas a partir de 2 t ha^{-1} já promovem a retenção/absorção significativa, contribuindo com possível retardamento do início do escoamento superficial, o aumento da infiltração de água e consequentes redução de perdas de água e solo.

Palavras-chave: tamanho de cobertura, tipos de coberturas mortas, geoestatística, serviços ecossistêmicos, estudo em encosta, Região Semiárida do Brasil.

INDEX

CHAPTER I

General Introduction and Lieterature Review

1. INTRODUCTION

Studies related to hydrological experimentation and the impacts of land use changes on water resources have been highlighted in recent years, given the need for better management and protection of water and soil and the coexistence with climate change, whose impacts on water resources are still uncertain.

In general, changes in the soil surface might promote significant impacts on the hydrological processes of a region, such as changes in runoff, greater risk of erosive processes, changes in the catchment budgets due to variations in evaporation rates and the balance between this process and precipitation, interfering to the crops productivity.

For the semi-arid region of Brazil, studies on the consequences of land use changes on hydrological processes, whether in the field or using modeling, are still scarce.

Thus, hydrological studies linked to the use of conservation practices are essential for an adequate management of water resources. It is necessary to expand the knowledge about hydrological processes and their seasonal variations, as well as the rainfall regimes across the region, considering their spatial and temporal distributions.

In the semi-arid region of Pernambuco State, excessive anthropic activities, mainly due to the extraction of timber resources, expansion of agricultural and urban areas culminate with a high degree of degradation in the region. The vegetation of Caatinga, which is a typical brazilian Biome, has already been widely deforested, and on the river banks the vegetation coverage index is nearly zero, with the preservation areas being restricted only to high altitude places.

Studies to analyze land use changes in hydrological processes through in situ measurements for this region are crucial for a better understanding of the impacts caused by such changes, since they might be determinant for the productivity and maintenance of water resources availability in the basin, besides allowing a better understanding of the basin water dynamics. Associated to this, this information is important in implementing conservation practices leading to an increase in soil moisture and techniques for adapting agricultural activities in different scenarios of land use change and water supply.

In the semi-arid basins, water storage is closely related to soil moisture and the presence of shallow groundwater table, and soils usually present low vegetation cover, being susceptible to erosive processes. In addition to the quantity of available water, it is required to investigate the water quality, particularly its salinity and sediments.

Thus, the increasing scarcity of water resources in semi-arid regions, both quantitatively and qualitatively, requires the development of agricultural management procedures and alternatives for the use and management of available water, their efficiency evaluation, as well as the users empowerment.

2. HYPOTHESES

The characterization of the spatial-temporal dynamics of soil moisture and salinity under cultivation conditions, as well as of agro-climatological parameters, is essential for proper management and precision agriculture applications;

The use of different materials, sizes and densities for soil mulch covers provides different retention values and water absorption, as well as conservation practices afficiency;

The natural cover and riparian forests have high relevance in water and soil conservation, and in the dynamics of salts at the subsurface and superficial layers.

The different types of uses/coves of the soil provide different levels of soil and water conservation in the semi-arid region of Pernambuco State;

Conservation practices are determinant for the maintenance of soil moisture and on the control of water and soil losses.

3. OBJECTIVE

3.1. General objective

The objective of the Thesis is to investigate hydrological processes, soil conservation techniques, cultivation conditions and patterns of spatio temporal variability of soil moisture and soil electrical conductivity in the semiarid region of Pernambuco State, Brazil, with emphasis on the use of conservation techniques and cultivation alternatives in experimental plots, with the perspective of increasing agricultural resilience and sustainability in the semiarid region.

3.2. Specific objectives

- Carry out field monitoring with the perspective of soil and water conservation in the semi-arid region of Pernambuco;
- To evaluate the performance of conservation practices in soil moisture maintenance and soil loss control;
- To investigate the spatio temporal dynamics of soil moisture and soil salinity under different cultivation conditions, as well as agro-climatological parameters;
- To characterize water retention and absorption by different materials used as soil cover in conservation practices;
- To investigate the relevance of natural cover and riparian forests in water and soil conservation, and in the dynamics of salts in the surface layer and subsurface.

4. LITERATURE REVIEW

4. 1. Hydrologic processes and movement of salts in riparian regions

There has been a growing demand for spatial soil information in order to enable decision-making related to the environment and land use management (BORRELLI et al., 2014). Knowledge of the variability of soil attributes, which can be achieved through geostatistical techniques, is fundamental for the precise management of agricultural areas (LABORCZI et al., 2015).

With geostatistical analysis it is possible to organize the available data spatially according to the similarity among georeferenced data (GRECO et al., 2014). Geostatistics is a well consolidated methodology for soil studies regardless of the size of the sampled area

(GOOVAERTS, 1997; GREGO and VIEIRA, 2005). Soares (2006) describes the potential for several other applications involving earth and environmental science.

Geostatistical studies, aiming at understanding the spatial variability of soil attributes, have recently gained prominence and importance in Brazil (BOTTEGA et al., 2013; ZONTA et al., 2014). This tool has been widely used in soil science and other sciences to characterize and analyze the spatial variation of soil characteristics (BOTTEGA et al., 2013; GOIS et al., 2015) and allows the production of highly precision maps by means of kriging method (DALCHIAVON et al., 2012).

Spatial information about soil characteristics is essential for making appropriate decisions regarding the environment and land use management, especially in the semi-arid region (e.g. MONTENEGRO and MONTENEGRO, 2006; LOPES and MONTENEGRO, 2019).

Alluvial valleys are of strategic importance for the semiarid region because they regulate runoff and provide water storage in both saturated and unsaturated zones (MONTENEGRO and MONTENEGRO, 2006). From the ecohydrological point of view, such valleys favour the development of riparian vegetation, which in turn promote the interception of precipitation, favouring infiltration. Vidon (2012) presents a detailed study of the riparian vegetation connection with the potentiometric dynamics of alluvial water tables, and with the spatio temporal variability of nutrients, particularly phosphorus and nitrogen.

In the alluvial valleys of the Brazilian semiarid, high potential for agriculture can be observed. However, these areas are susceptible to the processes of salt accumulation, both in the unsaturated and saturated zones (YANG et al., 2019). Salt distribution is influenced, among other factors, by the spatial distribution of soil hydraulic characteristics (MONTENEGRO and MONTENEGRO, 2006; HEIL and SCHMIDHALTER, 2017). Lopes and Montenegro (2019) successfully applied a geostatistical methodology to map soil salinity and soil moisture in an alluvial valley, combining local measurements and EM38® electromagnetic readings.

One of the soil components that has the ability to represent a set of other variables is the apparent electrical conductivity (ECa). The main soil characteristics/conditions of agricultural relevance that influence ECa values are salinity, water content, texture and chemical variables, such as iron content (RHOADES et al., 1989; MOLIN and FAULIN, 2013).

Corwin and Lesch (2003) and Corwin (2005) highlight the potential of using geophysical techniques based on electromagnetic readings (particularly measured with

EM38®) in precision agriculture. However, quality applications can only be achieved if the instrument is accurately calibrated, especially in areas with high spatial heterogeneity, such as alluvial valleys and their riparian zones (THIESSON et al., 2014; MONTENEGRO et al., 2010).

Schlosser et al. (2013) and Heil and Schmidhalter (2017) applied geophysical techniques of electrical resistivity in alluvial valleys, following transects across the main watercourse, to assess the dynamics of unsaturated flows during rainfall events. Such flows are of great relevance to increase ecosystem services associated with riparian vegetation.

Salt content in soils is dependent on physical and water characteristics and, consequently, requires local management, established through mapping (ALARCÓN-JIMÉNEZ et al., 2015). Thus, it is possible to qualitatively identify areas with greater susceptibility to salinization based on the soil physical characteristics and, therefore, allow the application of different management methods with high precision (GAVIOLI et al., 2019).

Geophysical readings can be influenced, among other factors, by the spatial distribution of soil hydraulic characteristics and salt contents (MONTENEGRO and MONTENEGRO, 2006). Apparent electrical conductivity (ECa) can be easily evaluated, being related to the spatial distribution of nutrients and crop productivity, constituting a decision support index to maximize yields and minimize sampling efforts (SANCHES et al., 2019).

Some studies have shown that the spatial patterns of soil ECa remain stable over time, regardless of the magnitude of temporal electrical conductivity, while variables such as soil temperature and soil moisture generally vary widely (MOLIN and RABELLO, 2011).

Yao et al. (2007) stress the importance of obtaining parameters such as soil moisture, texture, density and doil hydraulic conductivity, which are related to electromagnetic induction readings.

The spatial variability of soil attributes interferes on agricultural practices and water availability, affecting the soil moisture and salinity distribution. Montenegro et al. (2010) emphasize the high potential of alluvial valleys for water supply in the semi-arid, and warn about the susceptibility of such areas to degradation processes, due to salt accumulation.

For precision agriculture, a very large quantity of samples is usually required to accurately represent the variability over an area. In some approaches the large sample quantity is used to define the structural variance, spatial distribution and change tendency of soil properties (GUO et al., 2015).

Complementing the results obtained by Lopes and Montenegro (2019a), which were successful for salinity evaluation using different meshes for direct soil salinity measurements and EM38® readings, the results observed by Shaner et al. (2008) highlight the importance of detailed sampling in a first mesh sampling design and afterwards the use of ECa directed at local areas, as an alternative to avoid sampling at the transition zones of soil texture and soil organic matter.

Approximately 80% of the samples at 10 m mesh sites were correctly classified compared to samples <10 m, where only 50-54% were correctly classified. Corwin et al. (2010) described a procedure that served as the basis for the metodology to estimate electrical conductivity from apparent reading. In this model-based sampling approach, a minimum set of calibration samples was selected based on the measured spatial ranges and locations of the ECa readings.

Guimarães et al. (2010), Laborczi et al. (2015) and Lemos Filho et al. (2016) also applied geostatistical analysis in precision agriculture, respectively to investigate the variability of the soil physical and hydro properties of an irrigated plot, for mapping the surface texture and moisture variability of an irrigated sandy plot.

For cultivated soils, changes in their chemical and physical attributes might occur depending on the intensity of use, preparation and management adopted, which might have negative consequences for production. One alternative is the implementation of proper management agricultural techniques and the preservation of areas in rotation systems. Additionally, it is recommended the maintenance of preservation areas and riparian areas, which provides a buffer zone for water retention and soil loss control from cultivated areas (OLIVEIRA JUNIOR et al., 2014; LOPES and MONTENEGRO, 2019).

4. 2. Hydrologic processes and soil cover in experimental plots

The semi-arid region of the Brazilian Northeast presents limited water resources availability, related to an irregular rainfall regime, shallow soils with low water retention capacity, and incipient vegetation cover. Hence, it is required a permanent monitoring of the spatial and temporal dynamics of rainfall, hydrologic processes, groundwater recharge, as well as the protection of springs for sustainable development of the regional, as highlighted by Montenegro et al. (2013)

Impacts caused by the replacement of vegetation cover on the hydrological processes have been highlighted in recent years, mainly due to possible changes in temperature and precipitation regimes projected by the Intergovernmental Panel on Climate Change - IPCC, whose impacts on water resources are still uncertain (ALMEIDA et al., 2007; TUCCI, 2005; IPCC, 2013).

It is well known that strong changes in the distribution and amount of precipitation can occur, and thus knowing the land uses and future perspectives are fundamental for the development of more effective and sustainable strategies in water resources management (NUNES, 2006).

Despite successive scientific efforts to expand the rainfall and streamflow time series available for the semi-arid, such series are still short, and there is a need to expand them in order to better understand natural processes and improve water resources planning.

Studies related to the impacts of land use changes on the streamflow regimes have been widely conducted, as in China (FENG et al., 2011; YANG et al., 2014; HU et al., 2019), and the United States (TU, 2009). In Brazil, similar studies have been carried out for river basins located in different regions (VIOLA et al., 2014; TATSCH, 2011; ZANATA, 2014; NOBRÉGA, 2014; RIBEIRO FILHO et al., 2018), including the Northeast (MONTENEGRO and RAGAB, 2010; RODRIGUES et al., 2013; LOPES and MONTENEGRO, 2019).

In general, surface changes should promote significant negative impacts on hydrologic processes, such as changes in runoff, greater risk of erosive processes, change in basin water productivity due to changes in evaporation rates and on the water budget (ANDRÉSSIAN et al., 2004; BRUIJNZEEL, 2004; TUCCI, 2005).

Observational data have shown that changes in soil cover type tend to promote changes in soil moisture (YANG et al., 2015), at the same time as there is a reduction in the infiltration process due to rapid flow. For evapotranspiration (ET), small scale deforestations might for water availability in the basin by reducing transpiration, while large scale deforestations decrease ET due to reductions on soil water retention capacity, as consequence of degradation processes (LYRA and RIGO, 2019).

Due to the increasing pressure on semi-arid ecosystems, several institutions, including universities at the Pernambuco State have conducted characterization studies, agrometeorological monitoring, and agricultural and hydrological management to increase water and soil conservation. Montenegro and Ragab (2010) and Andrade et al. (2020) have shown that future scenarios of climate change and changes in land use and occupation for the Upper Ipanema Basin are likely to cause a decrease in water availability in the Agreste Region of Pernambuco State, due to changes in rainfall regime and increased evapotranspiration, making it necessary to implement mitigation measures and coexistence with scarcity.

Santos and Montenegro (2012) and Silva et al. (2013) statistically analyzed the time series of rainfall in Agreste, and its hydrological patterns, identifying the frequent occurrence of erosive events, requiring the implementation of conservation actions to subsidize management plans, since for deforestation scenarios, runoff tends to be increased, runoff peaks may be observed and flood occurrences may be favoured (NOBRÉGA, 2014). Among the conservation practices with high implementation potential, straw mulch and fodder palm vegetative cords might be capable of significantly reduce runoff losses and increasing soil water stocks, as detailed in Santos et al. (2011).

Montenegro et al. (2013) investigated the mulch cover performance and verified its relevance for soil moisture and temperature conservation, and for erosion control, considering different hydrological patterns of precipitation, typical of the semi-arid region of Pernambuco State.

Using experimental monitoring at field plots, Santos et al. (2016) verified the relevance of mulch cover for increasing infiltration processes. At experimental basin scale, Silva Júnior et al. (2011), Melo and Montenegro (2015) and Lopes et al. (2019) conducted a broad compilation of soil moisture profile measurements for different vegetation cover conditions, in order to subsidize management plans and enable a more adequate calibration and validation of numerical models at different scales. Among the main results of the latter studies, it is worth mentioning the temporal stability analysis of spatially distributed measurements, capable of optimizing the sampling meshes and process analysis.

In this sense, hydrological monitoring in rural basins and the use of conservation techniques to control erosion on slopes and support crop production of dryland are essential scientific activities for increasing knowledge about hydrological processes, expanding the time series available, and increasing the resilience of rural communities under vulnerable conditions.

Under conditions of limited water supply, practices to improve crop resilience are indicated. One of the most used is the use of adapted species, which are suitable for different scenarios of water availability. Oil palm (Nopalea sp. and Opuntia sp.), sorghum (Sorghum bicolor L. Moench) and millet (Pennisetum glaucum [L.] R. Br.) are indicated in semiarid for animal feed due to their good acceptability and easy digestibility by herds, besides being a relevant source of energy, fibers and, carbohydrates (GALVÃO JÚNIOR et al., 2014).

Consorption among agricultural crops is another highly important practice for optimizing the water use, commonly applied for food crops in the Brazilian semiarid region, and employed by producers to improve the agronomic efficiency. However, the use of consortia should be followed by an agronomic, ecological and socioeconomic assessment, in order to understand their effects on the agricultural system (YILMAZ et al., 2015).

In Brazil, experiments addressing resilient agricultural systems have been largely conducted with the Mexican Elephant Ear, IPA Sertânia and Miúda clones of Palma Cactus. However, other clones with morphological characteristics and growth habits distinct from the latter may emerge in different water regimes. For example, African Elephant Ear, F21 and V19 are cited in literature with different growth conditions and biomass production (SILVA et al., 2014; PEREIRA et al., 2017), and may have different adaptations.

These crop studies allied to conservation practices are essential to control environmental degradation, and guide management plans in basins. The watershed is a well-defined physical, social and political unit, and according to the National and State Water Resources Policy it is the territorial unit for the implementation of the State Water Resources Policy and for the operation of the State Water Resources Management System.

Thus, an adequate water resources management plan should be based on the knowledge of rivers behavior, their flows seasonality, as well as the pluviometric regimes, considering their spatial and temporal distributions, which requires a permanent program of hydrological monitoring and data interpretation, whose reliability becomes greater as their historical series become more extensive. This information is essential for local and sustainable economic development of a region (SILVA et al., 2012).

For the semi-arid region, where surface water courses present high intermittence, groundwater is a strategic resource (MONTENEGRO et al., 2010), requiring an adequate assessment of its potential. Moreover, the soil water stock (moisture) present is critical for environmental maintenance and agricultural production (MONTENEGRO et al., 2013). Such studies depend on regular monitoring, field experimentation and hydrologic modeling support.

The current study gives continuity to previous experimental assessments at plot scale, in the Ipanema River Basin, Brazil. Initially, Santos et al. (2008) and Santos et al. (2009) conducted studies on experimental plots at multiple locations. The former evaluated the performance of water and soil conservation techniques in controlling erosion rates and organic carbon losses in the transported sediment, under simulated rainfall conditions, in cultivated soil with beans (Phaseolus vulgaris L.), in the early growth phase. The latter study evaluated the influence of conservation practices on soil and water losses by water erosion in a Fluvic Neosol, with simulated rainfall. However, it should be highlighted that the current study has been developed at the same plots adopted by Santos et al. (2009), hence some coverings of such study continued to be adopted, and under similar pedological condition.

With results in 2010, Santos et al. (2010), already with the fixed installation of the plots, aimed to evaluate the water profile of an abrupt eutrophic Yellow Argisol in the semi-arid region of the Pernambuco State. Different surface conditions and their effects on the variation of water content in the soil, as well as on bean yields have been investigated.

In the following year, Santos et al. (2011) presented results from research on the temporal variability of water content in the soil under different types of topsoil, using time domain reflectometry (TDR), considering the precipitation characteristics that occurred in the semiarid region of Pernambuco.

In 2012, Silva et al. (2012) presented the results of a more detailed physical and water characterization of the predominant soil profiles in the Upper Ipanema Basin, in the semiarid region of Pernambuco, in order to broaden the knowledge of the hydrological potential of experimental river basins in these regions and to generate a database to subsidize the hydrologic modeling in the basins studied, also verifying the influence of conservationist treatments on the hydraulic conductivity in subsurface.

Menezes et al. (2013) investigated the behavior of water content in the soil under two surface conditions, Caatinga and bare soil, in the Ipanema Representative Basin, located in the semiarid region of Pernambuco.

Borges et al. (2014) evaluated the influence of different conservation techniques on the maintenance of soil moisture, as well as on the agronomic characteristics of corn (Zea mays L.), in the semiarid region of Pernambuco, under natural rain conditions.

Lopes and Montenegro (2017) investigated hydrologic processes and soil moisture dynamics through conceptual modeling on intensely monitored experimental plots under natural fall with different soil cover conditions in the semi-arid region of Brazil.

Montenegro et al. (2019) conducted field evaluations of the spatio-temporal distribution of soil surface moisture and assessed the impact of natural baseline soil conservation techniques on the reduction of runoff compared to the natural condition of Caatinga, using runoff plots and a network of access pipes for the soil. moisture monitoring in an experimental ephemeral basin in the State of Pernambuco, Brazil.

Carvalho et al. (2019) investigated the soil moisture content and productivity of green corn in a dryland field in semi-arid northeastern Brazil, assessing the impact of mulch on these variables and considering spatial variability at a small scale.

More recently, this Thesis research contributed to an understanding of the importance of mulch cover on water and soil loss. Lopes et al. (2019) investigated small-scale hydrological processes and the impact of soil conservation techniques in reducing runoff and sediment losses. This study used the textural characterization of the associated transported sediments, using surface runoff plots with different soil cover (bare, Caatinga, mulch and palm) under natural rainfall in the Caatinga biome of Brazil.

4. 3. Water retention by different covers for applications on the soil

The water loss, due to the run-off process, in addition of causing problems for arable land, with loss of soil nutrients, limits rainfed farming. These erosion losses remain high, since most farmers do not use appropriate management and conservation techniques (OLIVEIRA et al., 2010).

In particular, cultivation downhill is still a widely adopted technique, causing adverse environmental impacts in watersheds (SANTOS et al., 2010). Conservation preparations and management systems related to the different types of cover and soil preparation provide higher efficiency in controlling water erosion, by reducing water losses from runoff (SILVA JÚNIOR et al., 2011).

A cover condition that minimizes the impacts of rain drops on soil surface is mulch cover (SILVA et al., 2019), which can contribute to improve soil fertility, increase water availability by improving infiltration and reducing evaporation, minimizing nutrient losses and also controlling soil temperature variations (SILVA et al., 2014; RIBEIRO FILHO et al., 2018; QIN et al., 2015)

Soil cover is a highly recommended practice for semi-arid regions as it contributes to crop development, reduces water loss, decreases surface erosion and increases moisture.

Montenegro et al. (2013) found that straw based mulch, with application rates of 2 and 4 t ha^{-1}, was efficient in controlling runoff and soil temperature, in addition to promoting higher soil moisture during different simulated rainfall events.

Shen et al. (2012) evaluated the effect of different wheat straw mulch cover rates (0.6 and 12 t ha^{-1}) on the soil under dry farming conditions during 2009 and 2010 in northern China, with two maize varieties, noting that the cover contributed to increase soil moisture at a depth of 20-80 cm during the spigot-anthesis phase. These authors also noted that grain productivity was higher with the presence of mulch at the highest rate of application (12 t ha-1), compared to other treatments.

Santos et al. (2010) also observed an increase in bean yield with the adoption of conservative treatments, verifying that beans grown in contour with mulch and stone barriers showed productivity (1.782 t ha^{-1}) that was higher than beans in consortium with fodder Palm and black beans below, with values of around 1.140 and 0.692 t ha^{-1}, respectively. The use of plants to form a vegetative cord is a conservation technique in which the plants must be grown along rows and arranged in contour lines.

Due to its adaptation to the climate of the semi-arid Northeast, forage Palm (Opuntia ficus-indica Mill.) is an alternative and can be used for human and animal food (SILVA and SANTOS, 2006; WANDERLEY et al., 2012). When cultivated in vegetative cords, this crop increases water storage in the soil, thus contributing to erosion control and degraded areas reclamation, mitigating water and soil losses by functioning as a natural barrier (LE HOUÉROU, 1996; LOPES et al., 2019). In addition, shrub roots can contribute to the increase of soil moisture, since they increase water infiltration during the rainy season.

The quantification of water required for plant development maximizes the efficiency of water use in regions with irregular rainfall distribution. Santos et al. (2010) found that the soil surface condition significantly influences the variation in soil moisture during both the dry and rainy seasons.

Rolsolem et al. (2003) highlighted that the use of straw mulch can promote improvements in soil water storage, as well as release nutrients gradually. Triticale, black oat, sorghum, millet, crotalaria and brachiaria coverings were used. Among these coverings, it was verified that rainfall events of 10 mm or higher practically stabilized the water retention.

Soil coverings can provide variations in the initial abstraction value of a runoff, and greater abstraction can occur for higher cover densities. Lopes and Montenegro (2017) observed different initial abstractions with the SMAP Model model, with varying levels of ground cover in the semi-arid.

Dijk et al. (2015) observed that the fractions of rainfall reaching the ground vary according to the total rainfall event and the characteristics of the ground cover; the water storage capacity of the cover, the duration of rainfall and the evaporation rate of water retained in the cover during rainfall are the important variables to determine the interception depth; the interception process can be conceptualized as consisting of two components: evaporation of the wet canopy during rain, followed by drying the canopy when the rainfall stops; and the wind can spill ground cover water, but may also increase evaporation.

5. STRUCTURE OF THE THESIS CHAPTERS (ARTICLES)

Chapter 2 presents an article published in the Caatinga Journal, addressing the verification of the accuracy of indirect measurements of apparent electrical conductivity (CEa) using EM38®, as well as soil physical and hydro parameters, and their spatial relationships (LOPES and MONTENEGRO, 2019a).

Chapter 3 presents an article published in the Irriga Journal, investigating the cross variance between soil moisture and apparent electrical conductivity of the soil (CEa), under different soil uses in an alluvial valley of Pernambuco (LOPES and MONTENEGRO, 2019b).

Chapter 4 presents an article published in Water Journal, with the investigation of small-scale hydrological processes and the impact of soil conservation techniques in reducing runoff and sediment losses. This study used the textural characterization of the associated transported sediments, using surface runoff plots with different soil cover (open soil, Caatinga, mulch and Palm) under natural rainfall, in the Caatinga biome (LOPES et al., 2019).

Chapter 5 presents an article, with the objective of studying the interception process (i.e., water retention and absorption) of rainfall by different types, sizes and densities of some organic coverings that are commonly found in the Brazilian semiarid region. These results are important in defining soil and water conservation practices in these environments.

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CHAPTER II -

LOPES, I.; MONTENEGRO, A. A. A. Spatialization of electrical conductivity and physical hydraulic parameters of soils under different uses in an alluvial valley. **Caatinga Journal**, v.32, n.1, p.222 –233, 2020. http://dx.doi.org/10.1590/1983-21252019v32n122rc

SPATIALIZATION OF ELECTRICAL CONDUCTIVITY AND PHYSICAL HYDRAULIC PARAMETERS OF SOILS UNDER DIFFERENT USES IN AN ALLUVIAL VALLEY

1. ABSTRACT

Evaluating spatial variability of hydraulic properties and salinity of soils is important for an adequate agricultural management of alluvial soils, and protection of riparian vegetation. Thus, the objective of this work was to evaluate the accuracy of geophysical techniques for indirect measurements of apparent electrical conductivity (ECa), using an electromagnetic induction equipment (EM38®), and soil physical hydraulic parameters and their spatial interrelations. The study was carried out at the Advanced Research Unit of the UFRPE, in the Brígida River Basin, in Panamirim, state of Pernambuco, Brazil, in the second half of 2016. This river had a 100 m wide riparian forest strip transversely to the river bank on both sides of the river. A regular 20×10 m grid with 80 points was used to evaluate the soil hydraulic conductivity and ECa. The geostatistics showed the spatial dependence and the dependence of the soil attributes, their spatialization, and precise mapping through indirect readings. Most of the variability (86%) in soil electrical conductivity was explained by indirect readings using the EM38®. Ranges of 80 m, 380 m, and 134 m were found for soil moisture, ECa, and hydraulic conductivity, respectively, presenting strong spatial dependence. The results showed the importance of riparian forests to the maintenance of soil moisture and porosity to the improvement of soil water infiltration capacity even under severe water deficit conditions and soil subsurface layers.

Key words: EM38, ecosystem services, soil use, Beerkan, geostatistics

ESPACIALIZAÇÃO DA CONDUTIVIDADE ELÉTRICA E PARÂMETROS FÍSICO-HÍDRICOS SOB DIFERENTES USOS EM REGIÃO ALUVIAL

RESUMO

A caracterização da estrutura de variabilidade espacial de propriedades hidráulicas e da salinidade do solo é de grande importância para um adequado manejo agrícola de vales aluviais e para proteção da vegetação ciliar. Dessa forma, o objetivo deste trabalho foi a verificação da precisão de medições indiretas da condutividade elétrica aparente (CEa) utilizando o EM38®, bem como de parâmetros físico-hídricos do solo, e suas inter-relações espaciais. O estudo foi desenvolvido na Unidade Avançada de Pesquisa da UFRPE, localizada na Bacia do Rio Brígida, município de Panamirim-PE, no período do segundo semestre de 2016, possuindo uma faixa de mata ciliar de 100 m de largura, transversalmente a cada margem do rio. Adotou-se uma área com malha regular 20 x 10 m, totalizando 80 pontos, onde foram feitas avaliações da condutividade hidráulica e a calibração da CEa. A utilização da geoestatística permitiu identificar a dependência espacial e a dependência de todos atributos estudados, possibilitando sua espacialização e a utilização das leituras indiretas no mapeamento de precisão. Verificou-se que 86% da variabilidade da condutividade elétrica do solo pode ser explicada pelas leituras indiretas com o equipamento de indução eletromagnética (EM38®). Os valores de alcance foram de 80 m, 380 m e 134 m foram obtidas para a umidade do solo, CEa e condutividade hidráulica, respectivamente, as quais apresentaram forte dependência espacial. Verificou-se a relevância da mata ciliar na manutenção de umidade e porosidade do solo e, principalmente, contribuição para uma maior capacidade de infiltração do solo, mesmo para condições severas de escassez, e para as camadas sub-superficiais do mesmo.

Palavras-chave: EM38, serviços ecossistêmicos, uso de solo, Beerkan, geoestatística

2. INTRODUCTION

Soil spatial information has been increasingly required for decision-making regarding the environment, and land use managements (BORRELLI et al., 2014). The spatial variability of soil attributes, which can be evaluated by geostatistics techniques, is important for the management of agricultural areas (LABORCZI et al., 2015).

Alluvial valleys have strategic importance for the Brazilian semiarid region; they determine water flow and soil water storage capacity in both saturated and unsaturated zones (MONTENEGRO; MONTENEGRO, 2006). From the ecohydrological point of view, these valleys favor the development of riparian vegetation, which intercepts precipitation, favoring water infiltration into the soil. Vidon (2013) described the connection between riparian vegetation and the potentiometric dynamics of the alluvial water table, and spatial and temporal variabilities of nutrients (phosphorus and nitrogen).

The apparent electrical conductivity (ECa) is a soil property that can represent a set of other properties. The main soil properties of agricultural importance that influence the ECa are salinity, water content, texture, and chemical attributes (RHOADES et al., 1989; MOLIN; FAULIN, 2013).

Corwin and Lesch (2003), and Corwin (2005) reported the efficiency of geophysical techniques based on electromagnetic readings with an electromagnetic induction equipment (EM38®) in precision agriculture. However, their quality is dependent on accurately calibration of this tool, especially in areas with high spatial heterogeneities, such as alluvial valleys and riparian zones (THIESSON et al., 2014; MONTENEGRO et al., 2010). Schlosser et al. (2013) applied geophysical techniques of electrical resistivity in an alluvial valley, following transects transverse to the main water course, to evaluate the dynamics of unsaturated flows during rainfall events. Such flows are important to increase the ecosystem services associated with riparian vegetation.

Geophysical readings can vary according to the spatial distribution of soil hydraulic properties and salinity (MONTENEGRO; MONTENEGRO, 2006). Precision agriculture requires a very large number of samples to accurately represent variabilities. Some approaches are used to define structural variance, distribution, and trends in soil properties (GUO et al., 2015). According to Yao et al. (2007), obtaining moisture, texture, and density parameters, and indirectly, hydraulic conductivity is important because they are related to the electromagnetic induction data.

Chemical and physical attributes of cultivated soils may change depending on the use intensity, preparation, and cultural practices used, and may have negative consequences for the crop production. Thus, using favorable agricultural techniques, and preservation of areas in rotation systems are important. Maintenance of preservation and riparian areas can improve water retention and decrease soil loss of agricultural areas (OLIVEIRA JUNIOR et al., 2014).

In this context, the objective of this work was to evaluate the accuracy of geophysical techniques for indirect measurements of apparent electrical conductivity (ECa) using an electromagnetic induction equipment (EM38®), characterize the spatial variability of soil moisture and salinity, and evaluate soil variables of a riparian zone of the Brígida River Basin (for ecosystem services purposes), and physical hydraulic parameters of soils with different uses under severe water deficit in its alluvial valley (semiarid region of the state of Pernambuco, Brazil).

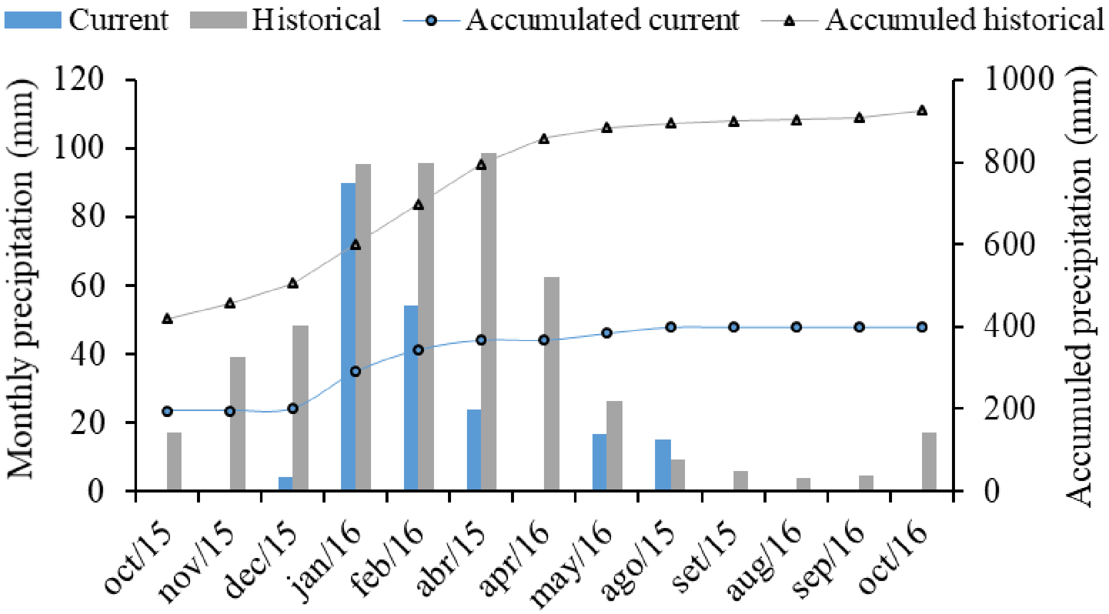
3. MATERIAL AND METHODS

Area description

Hydraulic parameters, electrical conductivity, and soil texture were evaluated in an area in Parnamirim, semiarid region of Pernambuco, Brazil. An area of an alluvial valley (08°05'08"S; 39°34'27"W) of the Area of Advanced Research Unit of the Rural Federal University of Pernambuco (UFRPE) was studied. This area is in the Brígida River Basin, downstream the Fomento Dam.

Field sampling was carried out in the second half of 2016, a period of extreme water deficit in the region, which can be confirmed by the precipitation of the previous year and by the historical data series of 1990-2016 (Figure 1).

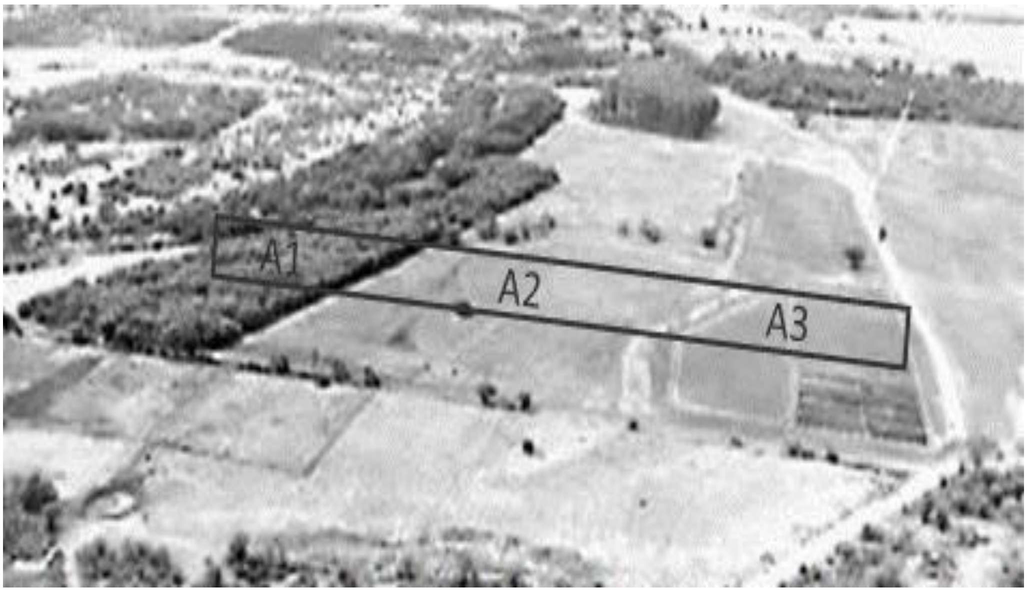
Figure 1. Monthly and accumulated precipitation for the historical data series of 1961 to 2016, and for 2016.



Sampling and analysis

The study area had 2.8 ha (Figure 2), with three different uses (coverages) - preservation area (arboreous Caatinga vegetation) (A1); fallow area (A2); and soil preparation area (A3).

Figure 2. Aerial depiction of the studied areas with preservation area (arboreous Caatinga vegetation) (A1); fallow area (A2); and soil preparation area (A3).



The soil use, vegetation cover, and agricultural use of the areas were different. A regular grid of 20×10 m (80 points) was used to sample soil moisture and soil hydraulic conductivity; and a regular grid of 10×10 m (152 points) was used to sample the soil apparent electrical conductivity (ECa) using electromagnetic inductions, with four horizontal points.

The soil of the area was classified as Fluvic Neossolo of clayey loam texture in the 0-0.3 m layer, with means of 46% of sand, 28.9 of silt, and 25% of clay. The 0.3-0.6 m layer presented means of 31.89% of sand, 44.51% of silt, and 23.60% of clay; and the 0.6-0.9 m layer presented means of 30.32% of sand, 42.35% of silt, and 27.33% of clay.

Apparent electrical conductivity (ECa)

The electromagnetic induction was used in vertical and horizontal modes with an electromagnetic induction equipment (EM38®) positioned at different heights in relation to the ground level (0, 0.3, 0.6, 0.9, 1.2, and 1.5 m), as recommended by Rhoades and Corwin (1981) and Montenegro et al. (2010).

This procedure provided a system of equations that can be used to evaluate the soil ECa profile through regression functions.

The following regression functions were used to evaluate the soil electrical conductivity, and electromagnetic induction readings:

1. Functions of Rhoades and Corwin (1981):

The equations proposed by Rhoades and Corwin (1981) (Table 1) involve five heights of the EM38® (0, 0.3, 0.6, 0.9, and 1.2 m represented by the indexes 0, 1, 2, 3, and 4, respectively).

Table 1. Equations used in the methodology.

Soil layer (m)	Equation for electrical conductivity - Rhoades e Corwin (1981)			Equation
0-0.3	$-0.1285EM_0+0.1446EM_1+5.3878EM_2-17.4476EM_3+15.0549EM_4-0.1309$			(1a)
0.3-0.6	$-1.3259EM_1+4.8938EM_2+55.8250EM_3-94.0405EM_4+47.4196EM_4-0.9169$			(1b)
0.6-0.9	$9.1705EM_0-8.4116EM_1-18.3090EM_2+50.6298EM_3-42.5033EM_4-0.1224$			(1c)
0.9-1.2	$1.1090EM_0+0.2352EM_1-23.3536EM_2+221.0100EM_3-266.8789EM_4-3.5012$			(1d)
Soil layer (m)	Equation for electrical conductivity - Rhoades et al. (1989)	N	R^2	Equation
	$EM_H \leq EM_V$			
0-0.3	$ECr0.25 = 2.539EM_{H0.25} - 1.413EM_{V0.25} - 0.068$	759	0.810	(2a)
0.3-0.6	$ECr0.25 = 2.092EM_{H0.25} - 0.81EM_{V0.25} - 0.179$	761	0.895	(2b)
0.6-0.9	$ECr0.25 = 1.894EM_{H0.25} - 0.407EM_{V0.25} - 0.292$	758	0.840	(2c)
	Para $EM_H > EM_V$			
0-0.3	$ECr0.25 = 1.164EM_{H0.25} - 0.078EM_{V0.25}$	165	0.922	(2d)
0.3-0.6	$ECr0.25 = 0.640EM_{H0.25} + 0.568EM_{V0.25} - 0.114$	163	0.969	(2e)
0.6-0.9	$ECr0.25 = 1.367EM_{V0.25} - 0.209$	162	0.919	(2f)
Soil layer (m)	Equation for electrical conductivity - Rhoades et al. (1999)			Equation
0-0.3; 0.3-0.6 and 0.6-0.9	$\ln(EM_H)-\ln(EM_V)\ 0.04334+0.03058\ \ln(EM_H)+0.00836(EM_H)^2$			(3)
	Equation for hydraulic conductivity - Beerkan			Equation
	$Ks=b1/\{0.67*[(2.92/(r*\alpha))+1]\}$			(4)

2. Functions of Rhoades et al. (1989):

The equations 2a, 2b, 2c, 2d, 2e, and 2f (Figure 1) are based on the fourth root transformation of the horizontal and vertical readings, considering the equipment positioned only at the soil surface level.

3. Functions of Rhoades et al. (1999):

Rhoades et al. (1999) developed linear relationships between the Napierian logarithm of EM_H (horizontal EM38$^{®}$) and the difference between $\ln(EM_H)-\ln(EM_V)$ (EM_V-vertical EM38$^{®}$) to remove the collinearity between the horizontal and vertical readings of the EM38$^{®}$, as found by Lesch et al. (1992). The relation $\ln(EM_H)-\ln(EM_V)$ of the measures was established for regular profiles, less than 5% of the theoretical $\ln(EM_H)-\ln(EM_V)$.

The mathematical models, relating the type of profile and the logarithm of apparent conductivities, were developed for the 0-0.3, 0.3-0.6, and 0.6-0.9 m soil layers, positioning the equipment on the soil surface.

Beerkan Methodology

The Beerkan methodology was used with simple rings of radius of 0.075 (HAVERKAMP et al., 1998; LASSABATÈRE et al., 2006) to evaluate physical hydraulic parameters, in 78 points. It has advantage over other experimental methods because of the reduced time, and high efficiency of its application (HAVERKAMP et al., 1998).

This method is applied to represent the water infiltration into the soil on a local scale, allowing the adjust of soil water infiltration curves to determine hydraulic conductivity of the saturated soil (Ks) (Table 1, Equation 4). The equation is composed of an angular parameter of the linearized equation of the line (*b1*); and four values (0.036, 0.012, 0.004, and 0.001 mm) corresponding to soils ranging from coarse sand to compacted clays (α). An α of 0.004 mm was taken as the first approximation for most clayey loam soils, thus, it was applied for such verification.

Determination of soil moisture

Disturbed soil samples (78 samples) of the layers described in Table 1 were collected with an auger, placed in hermetically sealed containers, and taken to a laboratory to measure their moisture by the gravimetric method (EMBRAPA, 2011).

Determination of texture and electrical conductivity of the saturated soil

Soil texture was determined in 30 samples (10 of each area) collected near the points used to measure hydraulic conductivity.

Soil sand, clay, and silt fractions were determined by the Boyoucus densimeter method, following the methodology proposed by Embrapa (2011). Salinity was determined using the saturated soil paste method (RICHARDS, 1954), and moisture was corrected based on the gravimetric method. The sand and clay fractions were used to show the texture composition of the three evaluated areas.

Statistics and Spatial variability

The data was subjected to descriptive statistics, determining mean, median, amplitude, quartiles, standard deviation, and coefficient of variation, which showed the dispersion and distribution of the variables. Data normality test was performed using the Kolmogorov-Smirnov test (K-S) at 5% probability.

The spatial dependence was then analyzed through geostatistics and semivariograms. The classical function for the semivariogram allows spatial autocorrelation between neighboring sites.

Semivariograms were developed using the Geoeas® program. Then, gaussian, spherical, exponential, and linear models were tested. The fitting of the data to the experimental models showed the coefficients of the best theoretical model for the semivariogram, which were described as nugget effect (C_0), sill (C_0+C1), and range (a).

Cross-validation process was used; it consists of using an estimator to reevaluate the known sample values by calculating them one by one as if they were unknown (VAUCLIN et al., 1983).

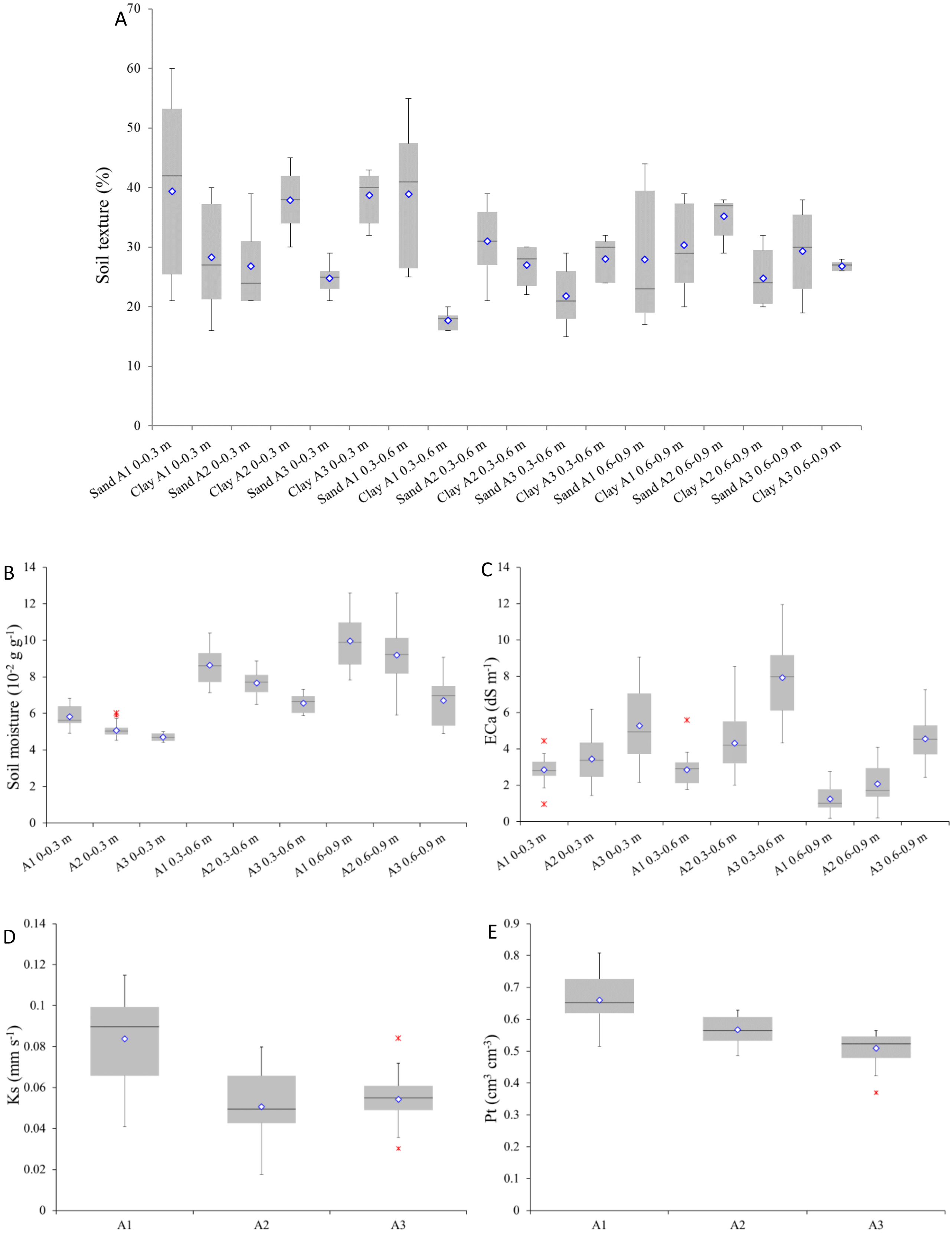
The magnitude of spatial dependence (SD) in the semivariograms was classified as strong, moderate, or weak, according to the criteria proposed by Cambardella et al. (1994).

Data spatialization and map development were carried out using kriging interpolation algorithm for the individual variables, and cokriging for previous verification of the correlation between soil ECa and moisture, using the Surfer 7.0 program (Golden Software, 1999).

4. RESULTS AND DISCUSSION

The box-plot of the soil texture (represented by sand and clay), moisture, apparent electrical conductivity, hydraulic conductivity (Ks), and total porosity (Pt) for the preservation area (A1), fallow area (A2), and soil preparation area (A3) at the 0-0.3, 0.3-0.6, and 0.6-0.9 m soil layers is presented in Figure 3.

Figure 3. Box-plot of soil texture (A), moisture (B), apparent electrical conductivity (C), hydraulic conductivity (Ks) (D), and total porosity (Pt) (E) for the preservation area (A1), fallow area (A2), and soil preparation area (A3) at the 0-0.3, 0.3-0.6, and 0.6-0.9 m soil layers.


A
Soil texture (%)
0
10
20
30
40
50
60
70
Sand A1 0-0.3 m
Clay A1 0-0.3 m
Sand A2 0-0.3 m
Clay A2 0-0.3 m
Sand A3 0-0.3 m
Clay A3 0-0.3 m
Sand A1 0.3-0.6 m
Clay A1 0.3-0.6 m
Sand A2 0.3-0.6 m
Clay A2 0.3-0.6 m
Sand A3 0.3-0.6 m
Clay A3 0.3-0.6 m
Sand A1 0.6-0.9 m
Clay A1 0.6-0.9 m
Sand A2 0.6-0.9 m
Clay A2 0.6-0.9 m
Sand A3 0.6-0.9 m
Clay A3 0.6-0.9 m
B
Soil moisture (10^{-2} g g^{-1})
0
2
4
6
8
10
12
14
A1 0-0.3 m
A2 0-0.3 m
A3 0-0.3 m
A1 0.3-0.6 m
A2 0.3-0.6 m
A3 0.3-0.6 m
A1 0.6-0.9 m
A2 0.6-0.9 m
A3 0.6-0.9 m
C
ECa (dS m^{-1})
0
2
4
6
8
10
12
14
A1 0-0.3 m
A2 0-0.3 m
A3 0-0.3 m
A1 0.3-0.6 m
A2 0.3-0.6 m
A3 0.3-0.6 m
A1 0.6-0.9 m
A2 0.6-0.9 m
A3 0.6-0.9 m
D
Ks (mm s^{-1})
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
A1
A2
A3
E
Pt (cm^3 cm^{-3})
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
A1
A2
A3

Regarding the soil texture, more sandy profiles were found in A1 than in A2 and A3, although the A2 and A3 had varied values in the evaluated soil layers. Heterogeneous soils at surface and subsurface layers are common in alluvial valleys (MONTENEGRO; MONTENEGRO, 2006).

Greater soil moisture was found in A1, in the three evaluated layers. A3 presented the lowest moisture in all evaluated soil layers. The difference between areas was smaller in upper layers; deeper soil layers of the areas without soil coverage had very low moistures. Campos et al. (2013) found similar results, with statistically similar means to the Caatinga vegetation area and bare areas in the soil surface layer (0-0.30 m), denoting the great evapotranspiration of the Brazilian semiarid region.

A3 had discrepancies, with high ECa, and the ECa of A2 was lower than that of A1. The high soil salinity found is explained by external sources, since the natural environment does not have high soil salinity as the other areas that have been used for crops and had soil preparation with the use of fertilizers and irrigation.

A1 presented higher Ks than the other areas; it was associated with the natural vegetation, which favors water infiltration. Similarly, A1 had the highest total soil porosity (Figure 3E), followed by A2 and A3, favoring ECa. Campos et al. (2013) found favorable microporosity, total porosity, and particle density in a natural forest area, which favors soil water dynamics.

According to Lima et al. (2015), river basins in the semiarid region of Pernambuco have reduced soil thicknesses and limited Ks, which tend to affect negatively natural drainage and lead to accumulation of salts in the soil profile.

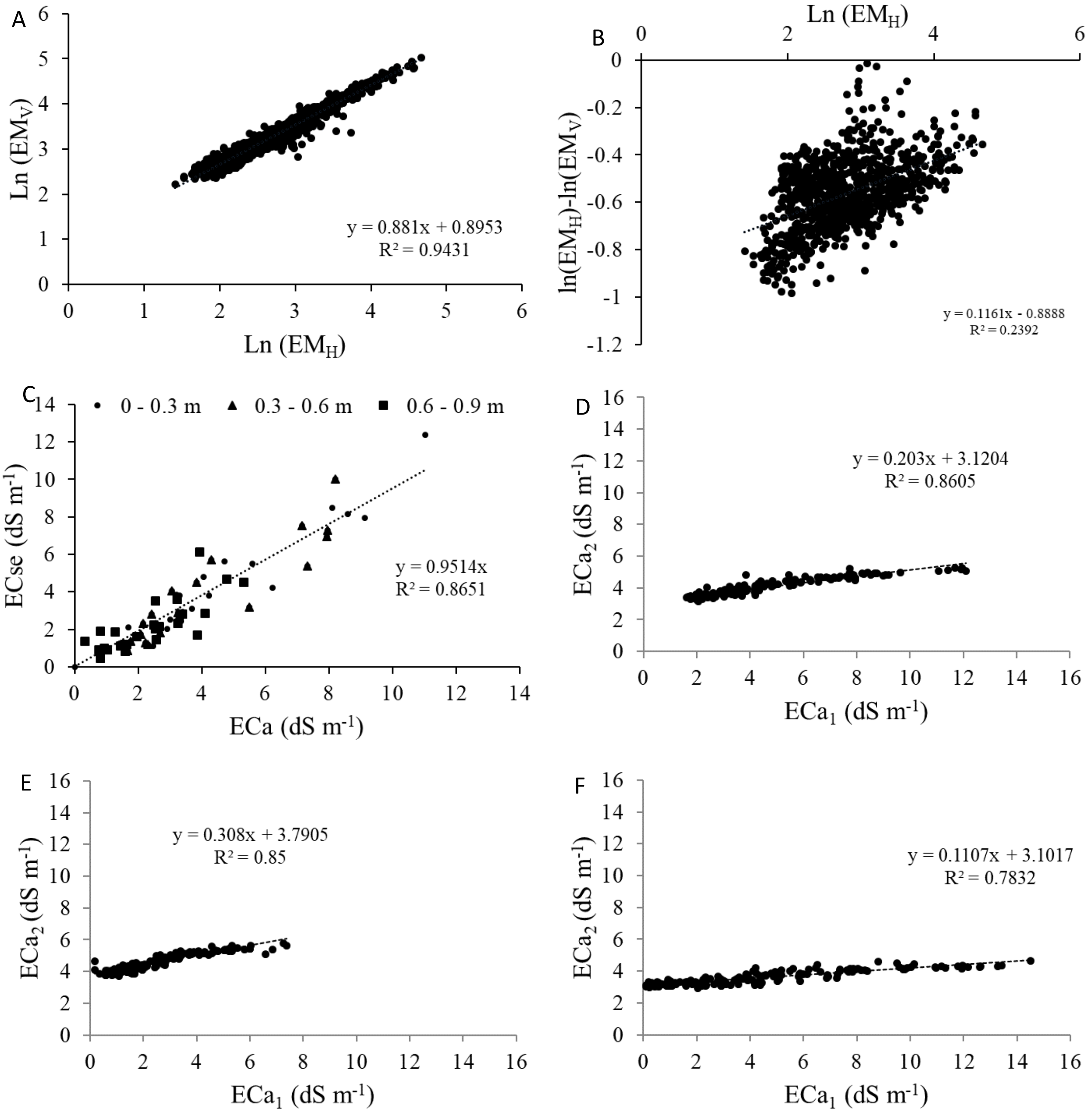
Oliveira Júnior et al. (2014) evaluate the Ks of a preservation area in the Brazilian semiarid region, which resembles A2, and found a negative effect of pastures on hydrodynamic parameters, especially in Ks; the area with Caatinga vegetation presented twice the Ks of the soil with crops.

Soil texture, moisture, and total porosity data showed that area A1 had, in general, good structure, better particle size arrangement, and greater moisture. According to Parente et al. (2010), these characteristics combined with the soil organic matter content improve soil hydraulic conductivity and water retention, allowing greater dispersion and leaching of salts.

Areas of alluvial valleys present heterogeneous soils, thus, the regressions for the EM38® values provided important and accurate information that shows qualitative and quantitative variations of physical and chemical attributes of the soil profiles, mainly for soil management, as also pointed out by Montenegro et al. (2010).

Lesch et al. (1992) evaluated the same models used in the present study and found satisfactory results, thus, these models can be used for areas with different sizes and high salinity amplitude. Figure 4A shows the ECa transformed by the logarithm, and the high horizontal and vertical collinearities in the readings. The use of the difference ln(EM_H)-ln (EM_V) was efficient in removing such dependence (Figure 4B); this verification is part of the data validation process.

Figure 4. Relation of ln(EM$_H$) with ln(EM$_V$) (A); withdrawal of collinearity between ln(EM$_H$)-ln(EM$_V$) and ln(EM$_H$) (B); relation between ECa (estimated by Rhoades and Corwin, 1981) and ECse (electrical conductivity of the saturated extract) (C); and relation between ECa$_1$ (estimated by Rhoades and Corwin, 1981) and ECa$_2$ (estimated by Corwin, 1999) for the 0-0.3 m (D), 0.3-0.6 m (E), and 0.6-0.9 m (F) soil layers.



The Rhoades and Corwin (1981) model presented good accuracy for all layers (Figure 4C), with ECse (electrical conductivity of the saturated extract) and ECa data evaluated together, and a coefficient of determination of 0.86. Thus, the measured and estimated data can be applied to the total depth, not requiring stratification. These results presented better fit when compared to those of Montenegro et al. (2010), and can be explained by the difference in texture, chemical composition, moisture, and calibration, as observed by Triantafilis et al. (2002) and Thiesson et al. (2014).

Since the application of the Rhoades and Corwin (1981) model was validated for the studied area, a correlation with the Rhoades et al. (1999) model was performed. The values obtained by Rhoades et al. (1999) were underestimated when compared to Rhoades and Corwin (1981), as showed in Figures 4D, 4E, and 4F, corresponding to the 0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m soil layers, respectively. However, this methodology was also validated, with coefficients of determination above 0.78. This shows a low sensitivity of the Rhoades et al. (1999) model because this methodology uses mean values and presents a logarithmic conversion to obtain ECa values.

The descriptive statistical analysis (mean, median, variance, coefficient of variation (%), asymmetry coefficient, kurtosis coefficient, largest error, and Kolmogorov-Smirnov validation at 5%) are presented in Table 2.

Table 2. Results of descriptive statistical analysis.

Variable	Mean	Median	Variance	Coef. of variation (%)	Coef. of asymmetry	Coef. of kurtosis	Largest error	KS 5%
EC 0-0.3 m	3.7350	3.2966	2.7859	44.6881	1.1966	1.5541	0.1331	0.1870
EC 0.3-0.6 m	4.7989	4.1824	6.5144	53.1861	1.0358	0.3761	0.1582	0.1870
EC 0.6-0.9 m	2.4650	2.0252	2.5532	64.8234	0.8006	-0.0656	0.1404	0.1870
EC 0-0.3 m	0.0521	0.0521	0.0000	11.4909	1.0128	0.3474	0.1454	0.1870
EC 0.3-0.6 m	0.0768	0.0763	0.0001	13.6365	0.4660	0.0241	0.0496	0.1870
EC 0.6-0.9 m	0.0878	0.0880	0.0004	21.3106	-0.1004	-0.3762	0.0494	0.1870
Ks	0.0603	0.0551	0.0006	40.4810	0.1744	-0.5949	0.1159	0.1870

All variables presented normality at 5% probability, allowing to obtain parameters of theoretical semivariograms with the experimental data (Table 3), showing the values of nugget effect (C_0), sill (C_0+C), range (A), and spatial dependence level (SD) of the tested models (exponential, spherical, and Gaussian).

Table 3. Parameters of the theoretical models for the semivariance of the soil variables measured, and the Jack-Knifing test.

						Cross validation			
	Model	C_0	C+C_0	C	A	MR*	SDR*	R²	SD*
Moisture 0-0.3 m	Spherical	0.004	0.318	0.314	86.0	0.001	1.237	0.834	0.012
Moisture 0.3-0.6 m	Spherical	0.008	0.876	0.868	72.3	0.093	0.749	0.745	0.009
Moisture 0.6-0.9 m	Spherical	0.1	3.215	3.115	72.1	0.026	0.998	0.809	0.031
ECa 0-0.3 m	Spherical	1.173	3.992	2.819	410.9	0.016	1.163	0.847	0.291
ECa0.3-0.6 m	Spherical	1.4	9.809	8.409	377.9	0.007	1.151	0.898	0.142
ECa0.6-0.9 m	Spherical	0.46	3.93	3.47	359.9	0.005	0.812	0.95	0.117
Ks	Gaussian	0.0002	0.00057	0.00037	134	0.016	0.996	0.972	0.351
Moisture x EC 0-0.3 m	Gaussian	-0.001	-2.003	-2.002	711.7	---	---	0.895	0.001
Moisture x EC 0.3-0.6 m	Gaussian	-0.001	-2.011	-2.01	293.9	---	---	0.96	0.001
Moisture x EC 0.6-0.9 m	Gaussian	-0.001	-1.922	-1.922	184.3	---	---	0.962	0.001

MR = Mean of Residues; SDR = Standard Deviation of Residues; SD = Spatial dependence.

Although some attributes had R² lower than 0.90, the semivariograms had cross-validation through the Jack-Knifing methodology (VAUCLIN et al., 1983), yielding residues with averages between 0.001 and 0.093, and standard deviations between 0.749 and 1.237. Silva et al. (2010) applied this methodology for mapping sand in the 0-0.2 m layer of an alluvial soil in the Agreste region of Pernambuco, and estimated, by interpolation, values of the variables for non-sampled sites, allowing the development of maps of greater precision.

ECa parameters were estimated using the EM38® values, by applying Rhoades and Corwin (1981) model, validated by the correlations with the ECse. The ECa of A1 (natural preservation area) may be associated with the silt fraction (SOUZA et al., 2008), however, the variances of the other two areas were associated with the possible presence of fertilizers, especially in the area that was again being prepared for irrigated crops.

Ks presented a Gaussian model, with a range of 134 m. Montenegro and Montenegro (2006), and Santos et al. (2012) found that the Gaussian model had best fit to semivariance when evaluating Ks. These two studies had similar spacing, and different scale to those of the present study.

Considering information on the Ks spatial distribution and soil texture variation, Alarcón-Jiménez et al. (2015) stated that the soil salinity variability can present the same variance and, consequently, can be dependent on management.

The cross-variance between moisture and ECa showed an atypical result, because the moisture increases EM38® values; ECa is the response of several parameters that affect the flow of electrons in porous media, such as moisture (GEONICS, 1999).

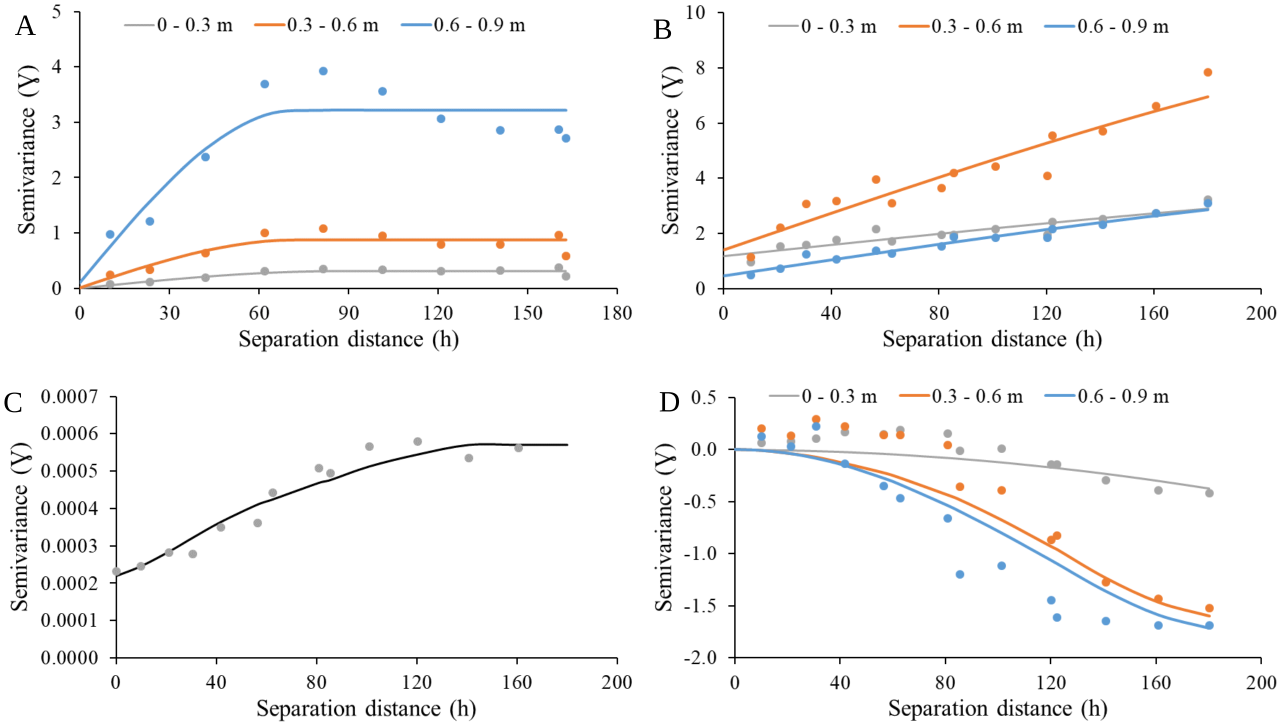
An inverse relation of moisture and ECa was found, i.e., the greater the variance of one the smaller variance of the other. However, a high range value was found, with good coefficients of correlation for all evaluated soil layers.

The studied area had a high ECa variation. Thus, the effect of moisture is low and presents an inverse correlation. Therefore, the evaluation of moisture through ECa is not compromised, making it possible to obtain moisture values through ECa for points that were not sampled.

The savings in resources that occurred was also observed by Bottega et al. (2014) for the estimation of soil parameters by EC in soils altered by agriculture. Molin and Faulin (2013) found variation in electrical conductivity as a function of soil moisture in areas with more homogeneous ECa, thus, suggesting that moisture is a good indicator of soil quality.

The parameters of the theoretical semivariograms fitted to the experimental data allowed the elaboration of semivariance graphs (Figures 5A, 5B, 5C, and 5D). The semivariograms were generated for the entire area and individualized for the three evaluated soil layers, except Ks, which was evaluated in the surface layer.

Figure 5. Semivariograms of the moisture of the 0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m soil layer (A), ECa of the 0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m soil layer (B), Ks (C), and moisture × ECa of the 0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m soil layer (D).



According to the semivariograms, the sill of the ECa (0-0.3 m, 0.3-0.6 m, and 0.6-0.9 m) (Figure 5B), and moisture × ECa (0-0.3 m, and 0.3-0.6 m) (Figure 5D) are not noticed. Thus, the minimum amount of 40 pairs of points was extrapolated and they are still within the greatest distance between points in the area, and others have extrapolated both. The ECa (0-0.3 m) and moisture × ECa (0-0.3 m) extrapolated the limits of the area, thus, it would be more convenient to evaluate them in a grid that covers a larger area.

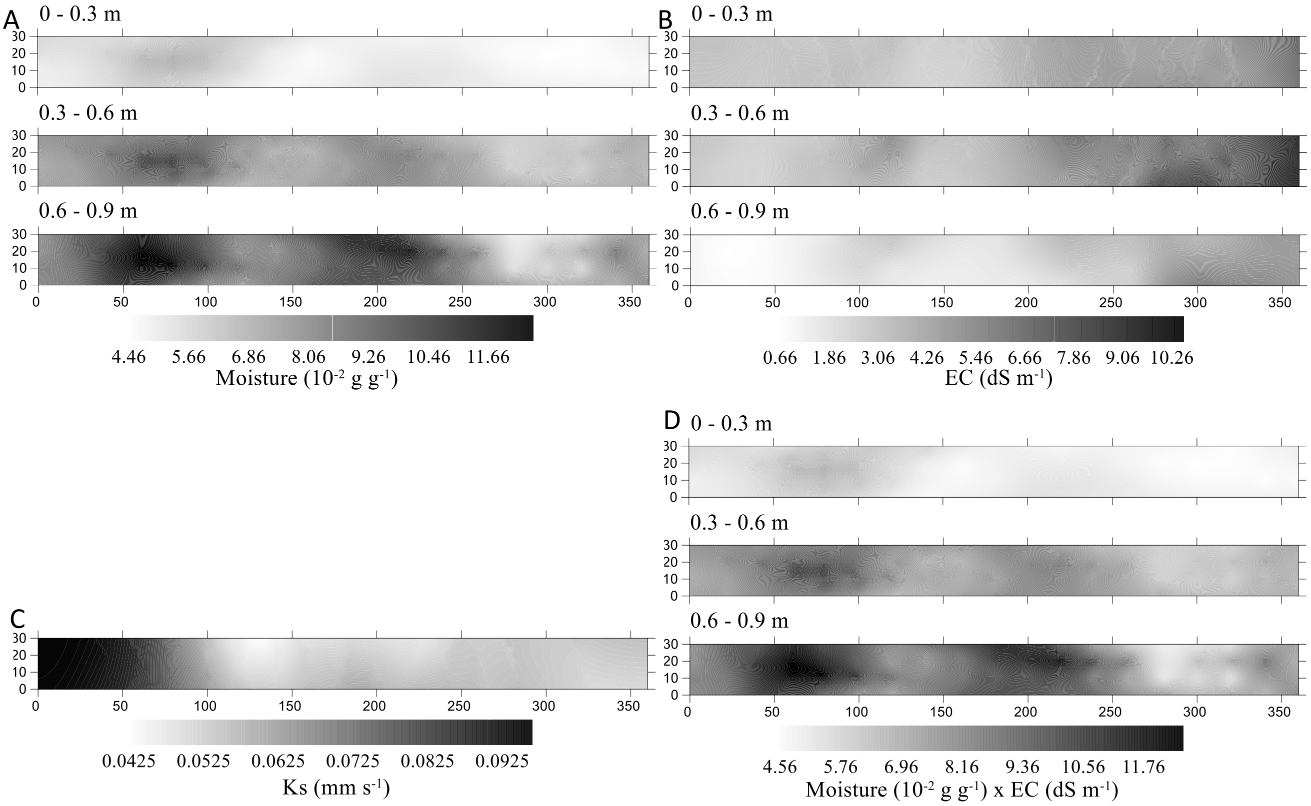
Considering the high coefficients of determination of the theoretical models fitted to the cross-semivariance, the moisture × ECa maps were developed using the cokriging technique. They presented greater similarity to moisture spatial distribution than those developed with kriging.

Despite the different variances, the semivariograms for soil moisture had similar results, thus, the surveying must be carried out with equal grids and spacing of smaller range value in soils with different uses or coverages, denoting the textural variation and, consequently, variation in water storage of alluvial soils.

The three soil layers had similar ECa, and did not present sill; thus, the correlation lengths were larger than the size of the study area. The increases in the semivariances (0.3-0.6 m) were high, probably because this region is strongly affected by combined infiltration and capillary processes. This causes greater variability in the results, as seen in the ECa box-plots.

The maps for soil moisture, salinity (ECa), and Ks, and moisture × ECa covariance (Figure 6) showed higher moisture and Ks gradients at first distances, and higher salinity in the region near the northeast end.

Figure 6. Kriging maps for moisture (A), apparent electrical conductivity (B), hydraulic conductivity (C), and moisture × ECa (D).



A1 presented the highest moistures, especially in the 0-0.3 m soil layer. This may be associated with the mulching effect of the Caatinga vegetation due to the deciduous vegetation. Monte-Mor et al. (2012) observed a mulching effect in northern Minas Gerais (semiarid region), Brazil, due to the formation of a leaf layer on the soil, which improved the seed germination process of Caatinga species. In addition, the 0-0.3 m (sandy soil layer) acts as an extinguishing zone of ascending capillary flows, contributing to the maintenance of water in the profile.

Montenegro et al. (2013) evaluated the reduction of soil and water losses due to natural mulching and found a significant and rapid increase in soil moisture due to the mulching.

The Ks in A1 was also favored by the mulching effect. This vegetation causes a constant rearrangement of the soil, making its structure more porous, with an infiltration speed that slows runoff when compared with the other areas.

The maps developed with parameters of cross-semivariograms and fitted to theoretical models showed moisture for points where measurements were not performed, thus, the moisture evaluations for precision agriculture can be performed by reading electromagnetic induction. This methodology is similar to that described by Costa et al. (2014), who mapped soil attributes with precise interpretation and recommendation of managements that can generate economic savings.

5. CONCLUSIONS

The electromagnetic induction equipment (EM38®) used was efficient to verify the presence of salts in the alluvial soil of the Brígida River valley, in Panamirim, state of Pernambuco, Brazil. The equipment was properly calibrated and the results were validated.

The area evaluated has high texture heterogeneity, typical of alluvial soils, with increasing clay contents with increasing soil depth.

The soil cover promoted the maintenance of soil moisture, contributing to the development and maintenance of the vegetal biomass of the riparian forest.

The mulching effect due to the deciduous characteristic of the Caatinga vegetation was important to the maintenance of soil moisture.

Caatinga vegetation contributes to the maintenance of soil structure, favoring surface infiltration speed, and ecosystem services of riparian vegetations.

The indirect methodology used allows the accurate measurement of soil moisture of non-sampled sites from the ECa, reducing uncertainties in spatial estimates.

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CHAPTER III -

LOPES, I.; MONTENEGRO, A. A. A. Space dependence of soil moisture and soil electrical conductivity in aluvial region. **IRRIGA**, v.24, n.1 p.1-15, 2019. DOI: https://doi.org/10.15809/irriga.2019v24n1p1-15

SPACE DEPENDENCE OF SOIL MOISTURE AND SOIL ELECTRICAL CONDUCTIVITY IN ALUVIAL REGION

1. ABSTRACT

Spatial information on soil characteristics is essential to proper decision-making regarding to the environment and land use management. The objective of this work was the investigation of the cross - variance between soil moisture and apparent soil electrical conductivity (CEa), under different land uses in an alluvial valley of Pernambuco. The study was developed at the Advanced Research Unit of Universidade Federal Rural de Pernambuco (UFRPE), located at the Brígida River Basin, municipality of Panamirim-PE. Soil samples were collected in a regular mesh of 20 x 10 m, for soil moisture by gravimetric method and, following a regular 10 x 10 m mesh, CEa measurements were performed using the EM38® device. The cross-semivariograms were assessed and the spatial dependence was verified by geostatistical procedures. It was verified geostatistical procedures a low variation for soil moisture and intermediate variation for CEa. The use of geostatistics allowed identification of the covariance between soil moisture and ECa, as well as the spatial dependence for both variables, for agricultural areas. It was verified that soil moisture, even at levels close to the residual, constitutes a relevant secondary component for increasing soil salinity maps precision, and hence to precision agriculture.

Key words: geostatistics, semi-arid, precision agriculture.

DEPENDÊNCIA ESPACIAL DA UMIDADE DO SOLO E CONDUTIVIDADE ELÉTRICA EM REGIÃO ALUVIAL

RESUMO

Informações espaciais sobre as características do solo são essenciais para uma tomada de decisão adequada em relação ao meio ambiente e ao gerenciamento do uso do solo. O objetivo deste trabalho foi investigar a variância cruzada entre a umidade do solo e a condutividade elétrica aparente do solo (CEa), sob diferentes usos do solo em um vale aluvial de Pernambuco. O estudo foi desenvolvido na Unidade de Pesquisa Avançada da Universidade Federal Rural de Pernambuco (UFRPE), localizada na bacia do rio Brígida, município de Panamirim-PE. As amostras de solo foram coletadas em uma malha regular de 20 x 10 m, para a umidade do solo pelo método gravimétrico e, seguindo uma malha regular de 10 x 10 m, as medidas de CEa foram realizadas usando o dispositivo EM38®. Os semivariogramas cruzados foram avaliados e a dependência espacial foi verificada por procedimentos geoestatísticos. Verificou-se procedimentos geoestatísticos, uma baixa variação da umidade do solo e variação intermediária para CEa. O uso da geoestatística permitiu identificar a covariância entre a umidade do solo e o CEa, bem como a dependência espacial para ambas as variáveis, para as áreas agrícolas. Verificou-se que a umidade do solo, mesmo em níveis próximos ao residual, constitui um componente secundário relevante para o aumento da precisão do mapeamento da salinidade do solo e, consequentemente, para a agricultura de precisão.

Palavras-chave: geoestatística, semiárido, agricultura de precisão

2. INTRODUCTION

Spatial information on soil characteristics is essential to proper decision-making regarding to the environment and land use management, especially in the semi-arid (MONTENEGRO; MONTENEGRO, 2006; LOPES; MONTENEGRO, 2019).

Salt content in soils is dependent on the physical-hydric characteristics, and consequently requires management by zones, established through mapping (ALARCÓN-JIMÉNEZ et al., 2015). Hence, it is possible to qualitatively identify areas with higher susceptibility to salinization based on the soil physical characteristics and, therefore, allowing application of different management methods with higher precision (GAVIOLI et al., 2019).

In alluvial valleys of the Brazilian semiarid region, high potential for communal agriculture can be observed. However, these areas are susceptible to salt accumulation processes, both at the unsaturated and the saturated zone. Salt distribution is influenced, among other factors, by the hydraulic characteristics spatial distribution (MONTENEGRO; MONTENEGRO, 2006).

It was observed by Lima et al. (2015) that soils of the Pernambuco State semi-arid valley present reduced thickness and low hydraulic conductivity, limiting infiltration and drainage, and then enhancing salt accumulation.

The apparent electrical conductivity (ECa) can be easily evaluated, being related to nutrients spatial distribution and crop productivity, thus constituting a support tool for the decision making to maximize yields and minimize sampling efforts (SANCHES et al., 2019).

Studies have found that the spatial patterns of soil ECa have high temporal stability, being independent of the order of magnitude of electrical conductivity, whereas, variables such as soil temperature and soil moisture usually vary largely (MOLIN; RABELLO, 2011).

Thus, electromagnetic measuring instruments have been largely used to assess soil characteristics, with a wide applicability for several studies. However, such applications can only be adequately carried out if the instrument is properly calibrated (THIESSON et al., 2014; MONTENEGRO et al., 2010).

For precision farming, it is usually required a quantitatively large number of soil samples to reliably represent the variability structure, and the experimental semivariograms, for a geostatistical mapping (MONTENEGRO; MONTENEGRO, 2006).

Corwin and Lesch (2003) and Corwin (2005) highlight the potential use of the soil apparent electrical conductivity (CEa) (in particular measured with the EM38® equipment) in precision agriculture, emphasizing its representativeness in applications oriented to studies of the spatial variability of salinity and soil moisture. Lopes and Montenegro (2019) successfully applied a geostatistical methodology for mapping soil salinity and soil moisture, combining local measuraments and EM38 readings.

Guimarães et al. (2010), Laborczi et al. (2015) and Lemos Filho et al. (2016) also applied geostatistical analysis in precision agriculture, respectively for physical-hydric soil proprieties variability of an irrigated plot, for mapping topsoil texture, and for soil moisture variability of an irrigated sandy plot.

Despite several studies, field applications of the EM38® for the Brazilian semi-arid region and under conditions of severe water scarcity are still rare. Thus, the objective of this work was to verify the performance of EM38®, and the potential spatial covariance between CEa and soil moisture, under different uses in an alluvial valley of Pernambuco State.

3. MATERIAL AND METHODS

The investigation of CEa and soil moisture spatial variability was carried out at the Advanced Research Unit of Universidade Federal Rural de Pernambuco (UFRPE), located at an alluvial valley in the semi-arid region of Pernambuco State, with a BSh climate by Köppen methodology (1948), in the municipality of Parnamirim. Field activities were carried out from September to October 2016, in a period of extreme water scarcity in the region (LOPES et al., 2017).

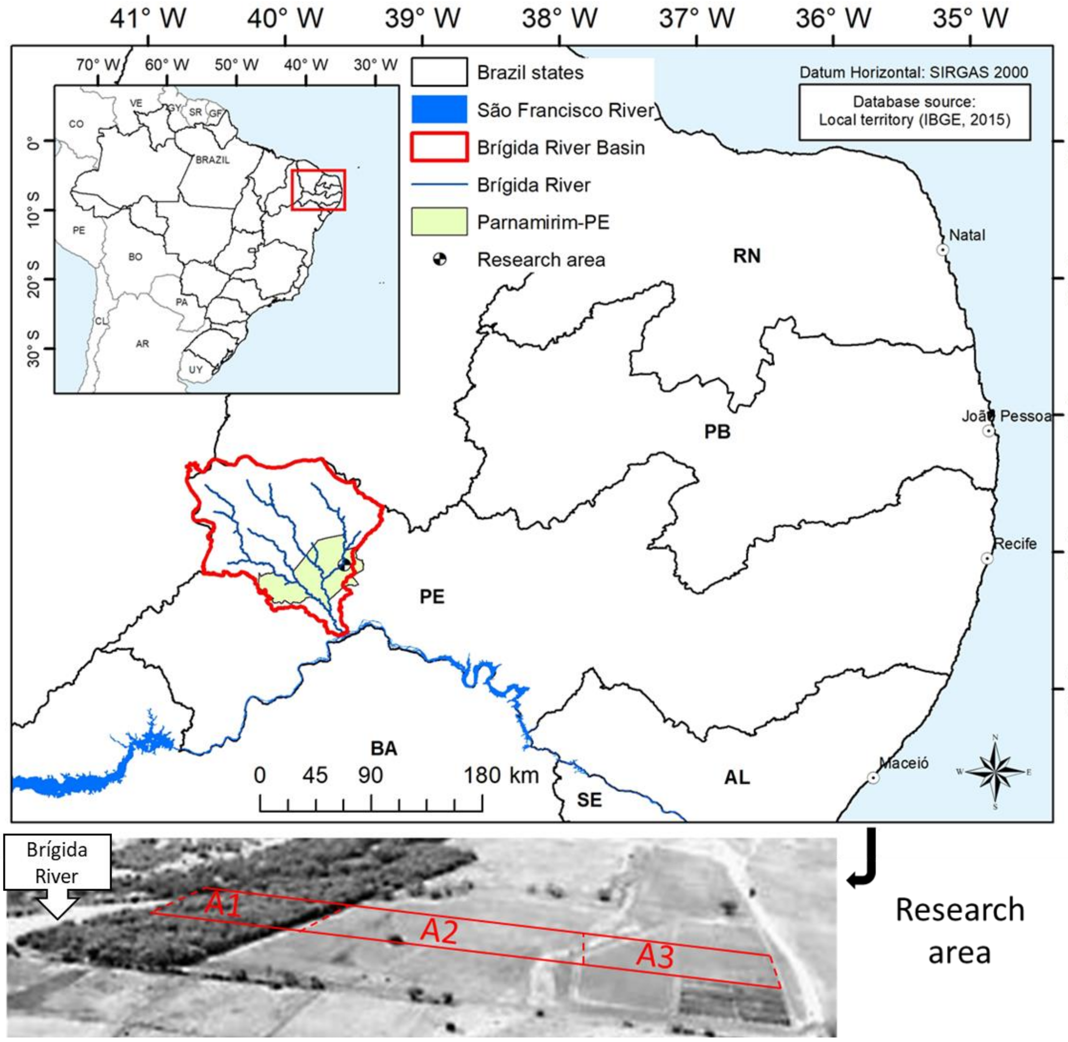
The study area is located in the Brígida River Basin, downstream of the Fomento Dam. Geographic coordinates are 08° 05' 08" south latitude and 39° 34' 27" west longitude, and elevation is approximately 654 m.

The selected area of 2.8 ha presented three different land uses / coverages, classified as:

- A1- Reserve area (Dense Caatinga);
- A2- Fallow area;
- A3- Plowing Area.

Such areas presented differences regarding the soil use and vegetation cover. Aerial view of the experimental area is shown in Figure 1.

Figure 1. Location and aerial view of the areas, in October 2016, with A1 being the reserve area, A2 the fallow area and A3 the plowing area.



Source: Adapted from IBGE (2018).

The soil of the study area is classified as a Fluvic Neosol of mean texture, for the 0-0.3 m layer, with a mean texture of 46.10, 28.90 and 25.00% sand, silt and clay, respectively. The 0.3-0.6 m and 0.6-0.9 m layers present, respectively, of 31.89; 44.51 and 23.60%, and 30.32; 42.35 and 27.33% of sand, silt and clay, for the same textural class sequence.

The near surface hydraulic conductivity surface (Ks) is 0.08 mm s^{-1}, assessed by the Beerkan method (HAVERKAMP et al., 1998), while the saturation soil moisture (USAT) is 0.694 g g^{-1}, the field capacity soil moisture (UCC) is 0.483 g g^{-1}, and the residual moisture (RH) is 0.085 g g^{-1}.

A regular mesh of 20 x 10 m was adopted for soil sampling (32, 44 and 36 points for areas A1 (0.8 ha), A2 (1.1 ha) and A3 (0.9 ha), respectively) and a regular 10 x 10 m mesh (64, 88 e 72 points for areas A1 (0.8 ha), A2 (1.1 ha) and A3 (0.9 ha), respectively) for CEa measurements, using the EM38® equipment, which has electromagnetic induction as its operating principle.

The soil texture, determination for the sand, clay and silt fractions, was by the Bouyoucos densimeter method, according to the methodology proposed by Embrapa (2013). The soil samples were collected at the same locations adopted for CEa measurements.

For the soil moisture determination, disturbed soil samples were collected at the 0-0.3; 0.3-0.6 and 0.6-0.9 m layers and placed in hermetically sealed containers, for further measurements by the gravimetric method.

CEa measurements were performed both in vertical and horizontal modes with the EM38®, as recommended by Rhoades and Corwin (1981), positioned at different heights from the ground level (0, 0.3, 0.6, 0.9, 1.2 m). From the of vertical and horizontal readings at different heights, it is possible to obtain an equations system that allows evaluation of electrical conductivity profile by regression functions.

In this study, the following regression functions were adopted among CEa and the electromagnetic induction readings (EM38) according to Rhoades and Corwin (1981), as presented in Eqs 1, 2, 3 and 4.

$$\mathrm{EC}_{0.0-0.3m} = -0.1285\mathrm{EM}_0 + 0.1446\mathrm{EM}_1 + 5.3878\mathrm{EM}_2 - 17.4476\mathrm{EM}_3 + 15.0549\mathrm{EM}_4 - 0.1309 \quad (1)$$

$$\mathrm{EC}_{0.3-0.6m} = -1.3259\mathrm{EM}_0 + 4.8938\mathrm{EM}_1 + 55.8250\mathrm{EM}_2 - 94.0405\mathrm{EM}_3 + 47.4196\mathrm{EM}_4 - 0.9169 \quad (2)$$

$$\mathrm{EC}_{0.6-0.9m} = 9.1705\mathrm{EM}_0 - 8.4116\mathrm{EM}_1 - 18.3090\mathrm{EM}_2 - 94.0405\mathrm{EM}_3 - 42.5033\mathrm{EM}_4 - 0.1224 \quad (3)$$

$$\mathrm{EC}_{0.9-1.2m} = 1.1090\mathrm{EM}_0 + 0.2352\mathrm{EM}_1 - 23.3536\mathrm{EM}_2 + 221.0100\mathrm{EM}_3 - 266.8789\mathrm{EM}_4 - 3.5012 \quad (4)$$

Eqs. 1, 2, 3 and 4 proposed by Rhoades and Corwin (1981) involved 5 heights of EM38 above the soil surface: 0; 0.3; 0.6; 0.9 and 1.2 m, represented by the indexes 0, 1, 2, 3 and 4, respectively.

The descriptive statistics were applied to the data of CEa and soil moisture, evaluating the mean, median, quartiles, minimum and maximum values. For information about the dispersion, the amplitude, the variance and the standard deviation were obtained. Data normality test was performed by the Kolmogorov-Smirnov test (K-S), being:

$$\begin{cases} H0: The\ data\ follow\ a\ Normal\ distribution \\ H1: The\ data\ do\ not\ follow\ a\ Normal\ distribution \end{cases} \quad (5)$$

The CEa and soil moisture data were normal to 5% probability level.

In order to obtain the theoretical and experimental semivariograms, and the validation of the theoretical models, the GEO-EAS® software (ENGLUND; SPARKS, 1991) was applied. The cross-semivariograms were adjusted and the spatial dependence was then analyzed through geostatistics.

The classical function for the semivariance, according to Eq. 6 presented by Vieira, Nielsen and Biggar (1981), allows to analyze the spatial variability of the variables Z_1 and Z_2 between neighboring sites. For the cross variogram the range (a) represents the maximum spatial dependence distance between the two variables.

$$\gamma_{12}(\mathrm{h}) = \frac{1}{2\mathrm{N(h)}} \sum_{\mathrm{i}=1}^{\mathrm{N(h)}} [\mathrm{Z}_1(\mathrm{X}_\mathrm{i}) - \mathrm{Z}_1(\mathrm{X}_{\mathrm{i+h}})][\mathrm{Z}_2(\mathrm{X}_\mathrm{i}) - \mathrm{Z}_2(\mathrm{X}_{\mathrm{i+h}})] \quad (6)$$

Being:

$\gamma_{12}(h)$ - Semivariogram between the primary and secondary variables;

$Z_1(X_i)$ - Value of the primary variable at point Xi;

$Z_1(X_{i+h})$ - Value of the primary variable at point Xi, adding a distance h;

$Z_2(X_i)$ - Value of the secondary variable at point Xi;

$Z_2(Xi+h)$ - Value of the secondary variable at point Xi, adding a distance h;

N is the number of pairs of points formed for a given distance h.

The cross-linked semivariograms and their respective adjustment parameters were also obtained through the GEO-EAS® software (ENGLUND; SPARKS, 1991). After the construction of the experimental cross-linked semivariograms, the gaussian, spherical and exponential models were tested. For the adjustment process of the theoretical models to the experimental values, the following parameters were estimated: the nugget effect (C_0); the threshold ($C_0 + C_1$); the range (a). The degree of spatial dependence (GD) was calculated using equation (7) (CAMBARDELLA et al., 1994).

$$GD = \left[\frac{C_0}{C_0+C_1}\right] x100 \tag{7}$$

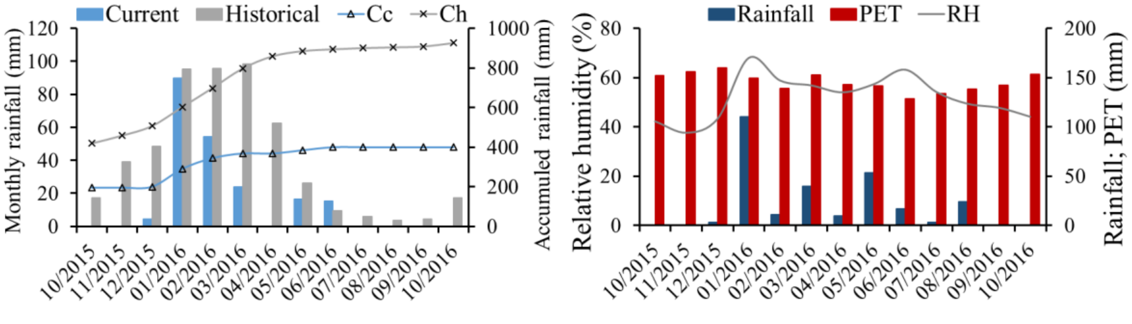
GD can be classified into strong (GD < 25 %), moderate (26 % < GD < 75 %), and weak spatial dependence (GD > 75 %), according to Cambardella et al. (1994).

4. RESULTS AND DISCUSSION

The region was undergoing a period of high water deficit, which can be observed in Figure 2, which shows the monthly and accumulated rainfall from October 2015 to the studied period and also data from the 1990-2016 historical series are presented. For the 2014 to 2016 years, a water scarcity period was also detected by Lopes et al. (2018).

The water budget can also be observed in Figure 2, by comparing rainfall alongside the potential evapotranspiration (PET).

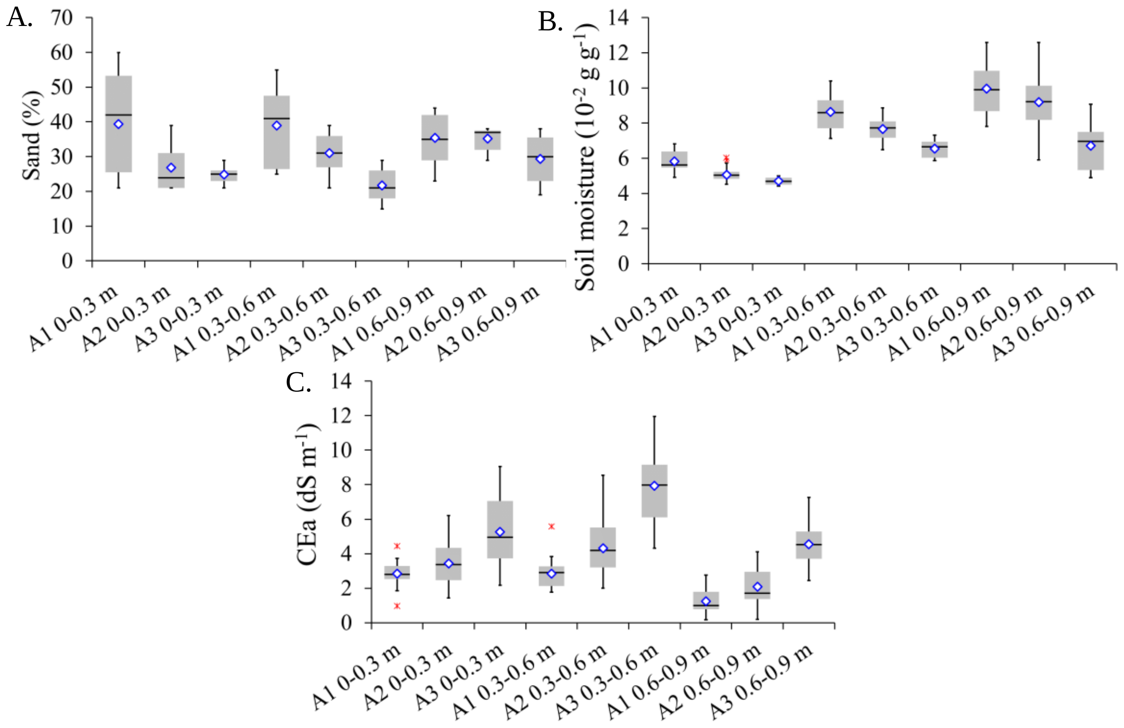
Figure 2. Precipitation for the 2015 year up to the measurements period. Water budget represented by PET and rainfall. Being: Current - the current month's rainfall; Historical - The historic rainfall for the month; Cc - Cumulative current rainfall; Ch - Cumulative historical rainfall; PET - potential evapotranspiration; RH - Relative Air Humidity.



Source: INMET (2018).

In Fig. 3A, 3B and 3C the Box-Plot for the texture (represented by sand), soil moisture and apparent electrical conductivity (CEa), are presented respectively, for the reserve areas (A1), fallow (A2) and Plowing (A3), and at 0-0,3; 0.3-0.6 and 0.6-0.9 m layers.

Figure 3. Box-Plot of the variable (A) Sand, (B) soil moisture and (C) CEa. Being (A1) reserve area, (A2) in fallow and (A3) Plowing area.



Source: Own authorship.

For texture, differences in soil profiles are observed for the three areas, which helps to understand the soil water movement processes and consequently the salts distribution. In area A1, there is a higher percentage of sand than in areas 2 and 3, although these areas presented high variability among layers of soils studied. As an alluvial valley area, it is expected to observe a high variation in soil texture, and the sand content decreases with increasing distance from the riverbed, that is, from A1 to A3.

In general, it can be observed that the land uses exhibit different patterns of soil moisture and CEa, that are influenced directly by the soil texture. In the areas of lower agricultural activity, higher soil moisture and lower salinity were observed, and the higher the use of the area, the lower the soil moisture, and the higher the salinity.

The outlier's values, which were observed for moisture at A2 in the 0-0.3 m layer and CEa at A1 in the 0-0.3 and 0.3-0.6 m layers, were not removed for the semivariogram construction.

There were higher values of soil moisture at the three depths of area A1 and lower ones in area A3 (Figure 1A). For the upper layers, the difference was lower among the areas, and for the lower layers, the areas without cover (A2 and A3) presented residual values. A similar result was observed by Campos et al. (2013), with the difference between the vegetation area with caatinga and the bare areas being small, which was associated to the high evapotranspiration of the semi-arid zone (0.00-0.30 m).

It could be observed that the area A3 presented higher values of CEa than the other areas. It is also noted that the salinity of A2 is lower than at A1. The higher observation values for salt contents can be linked to external sources, like fertilizers. In addition, the A1 area is closer to the Brígida River bed, where the percolation and washing processes are more intense, and the texture is more sandy.

Table 1 shows the minimum (min), mean, median and maximum (max), besides the variance, standard deviation (sd), coefficient of variation (CV), asymmetry coefficient (A), kurtosis coefficient (K) and Kolmogorov-Smirnov (KS at 1%).

Table 1. Descriptive statistics for soil moisture and apparent electrical conductivity (CEa), for 0-0.3, 0.3-0.6 and 0.6-0.9 m layers, for (A1) reserve area, (A2) in fallow and (A3) Plowing

Variables	Mean	Median	Min	Max	Sd	CV	A	K	KS
A1									
Soil moisture (0.0-0.3 m)	5.81	5.61	4.91	6.82	0.56	9.71	0.28	-0.93	0.15
Soil moisture (0.3-0.6 m)	8.62	8.60	7.13	10.38	0.94	10.96	0.26	-0.91	0.08
Soil moisture (0.6-0.9 m)	9.96	9.89	7.81	12.57	1.48	14.88	0.19	-0.95	0.06
CEa (0.0-0.3 m)	2.75	2.82	0.97	4.43	0.73	26.73	-0.62	0.68	0.11
CEa (0.3-0.6 m)	2.65	2.41	1.61	5.57	0.78	29.19	1.21	2.54	0.14
CEa (0.6-0.9 m)	1.14	0.99	0.17	2.75	0.58	50.85	1.04	0.82	0.12
A2									
Soil moiture (0.0-0.3 m)	5.06	5.03	4.53	6.01	0.36	7.13	1.08	0.90	0.12
Soil moisture (0.3-0.6 m)	7.67	7.71	6.48	8.86	0.56	7.31	-0.15	-0.66	0.1
Soil moisture (0.6-0.9 m)	9.19	9.22	5.90	12.58	1.37	14.94	0.01	0.38	0.04
CEa (0.0-0.3 m)	3.33	3.28	1.01	6.21	1.31	39.36	0.18	-0.59	0.06
CEa (0.3-0.6 m)	4.26	4.19	1.96	8.54	1.52	35.36	0.70	0.17	0.09
CEa (0.6-0.9 m)	2.18	2.01	0.18	4.28	0.87	40.06	0.43	-0.31	0.12
A3									
Soil moisture (0.0-0.3 m)	4.69	4.68	4.41	5.01	0.19	4.24	0.09	-1.48	0.12
Soil moisture (0.3-0.6 m)	6.55	6.65	5.87	7.32	0.49	7.51	-0.01	-1.44	0.17
Soil moisture (0.6-0.9 m)	6.70	6.96	4.89	9.07	1.22	18.22	-0.01	-1.04	0.16
CEa (0.0-0.3 m)	5.12	4.88	1.19	10.50	2.09	40.84	0.49	0.18	0.06
CEa (0.3-0.6 m)	7.87	7.74	3.83	12.10	2.14	27.16	0.28	-0.14	0.09
CEa (0.6-0.9 m)	4.61	4.55	2.42	7.36	1.25	27.33	0.36	-0.34	0.07

Source: Own authorship.

All variables presented normality at 1% probability, thus, allowing non biased parameters of theoretical the semivariograms being obtained. The theoretical cross-linked semivariograms adjusted to the experimental data are shown in Table 2. The values of the nugget effect (C_0), sill (C_0 + C), range (A) and spatial dependency (GD) for the tested models (Gaussian, spherical and exponential) are presented.

Table 2. Parameters of theoretical models for cross-linked semivariograms of the soil variables measured. Being: C0 - nugget effect, C0 + C - sill, A - range and GD - spatial dependency

	Model	C_0	C_0+C	C	A	GD*
			A1			
Soil moisture x CEa 0.0-0.3	EPP	---	---	---	---	---
Soil moisture x CEa 0.3-0.6	EPP	---	---	---	---	---
Soil moisture x CEa 0.6-0.9	EPP	---	---	---	---	---
			A2			
Soil moisture x CEa 0.0-0.3	Gaussian	0.0001	0.1542	0.1541	50.40	0.01
Soil moisture x CEa 0.3-0.6	Gaussian	0.0010	0.3680	0.3670	49.01	0.01
Soil moisture x CEa 0.6-0.9	Spherical	0.1000	0.2800	0.1801	34.04	0.35
			A3			
Soil moisture x CEa 0.0-0.3	Gaussian	0.0620	0.4200	0.3580	89.81	0.15
Soil moisture x CEa 0.3-0.6	Gaussian	0.1710	2.4520	2.2810	88.64	0.06
Soil moisture x CEa 0.6-0.9	Gaussian	0.0010	2.0110	2.0100	63.40	0.01

Source: Own authorship.

In the area A1 it was not possible to identify cross dependence between soil moisture and salinity. This fact may be related to variation of plant types, causing differences for the vegetation cover indexes, at their root zones, and consequently higher or lower evapotranspiration within the area.

When studied physico-hydraulic components, Lima et al. (2015) and Sabino Junior et al. (2014) observed that there is spatial dependence for the Caatinga area. However, when the seasonal factor is inserted, spatial dependence is affected, as observed in this study.

A condition that may explain the non-dependence between soil moisture and CEa in the area A1 was presented by Lopes and Montenegro (2017), being the sensitivity of soil moisture in response to rainfall events influenced by the soil cover condition. Indeed, interception/absorption processes by the trees or due to higher humidity contribute to the spatial independence among the points.

The semivariograms for the areas A2 and A3 presented spatial dependence (Table 2). It is noteworthy that, for the areas and depths modified by agriculture, it was possible to adjust covariance equations between soil moisture and ECa, due to the strong spatial dependencies.

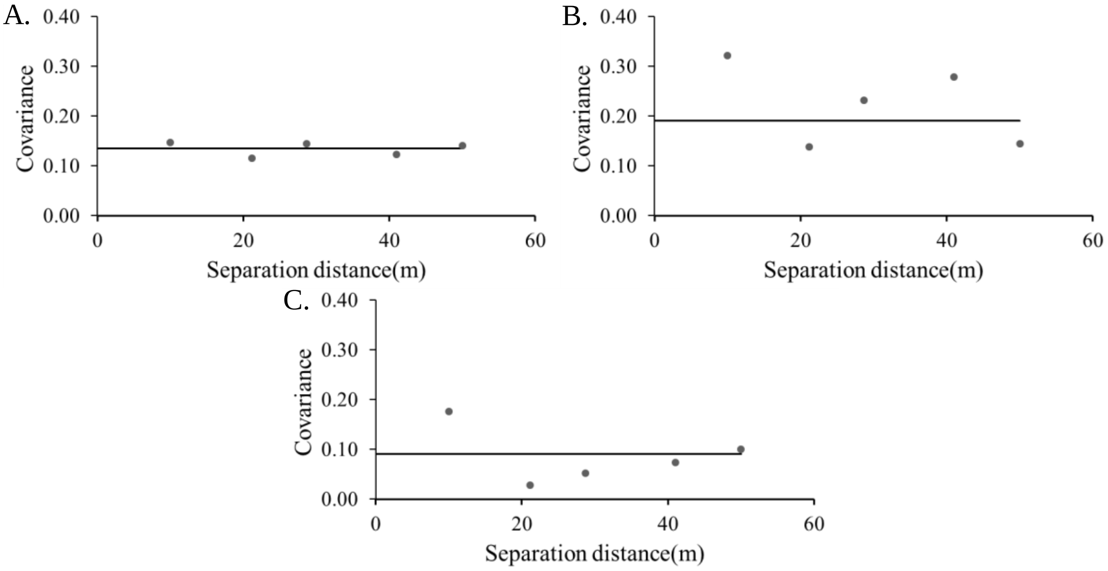
The obtained values of spatial dependence were classified as strong for soil moisture x CEa for A2, for 0.0-0.3, 0.3-0.6 m layers and for A3, for 0.0-0.3, 0.3-0.6 and 0.6-0.9 m layers. Only for A2 at the 0.6-0.9 m the dependence was classified as moderate.

For the areas A2 and A3, and studied depths, a high ECa variation is observed, and the effect of humidity is low, but it has a positive relation. The evaluation of the soil moisture through the ECa is not compromised (it presents high spatial dependence), allowing to obtain soil moisture values from the ECa measurements for points that were not sampled. The soil moisture estimation by ECa for sites that were not sampled was also obtained by Lopes and Montenegro (2019), for an alluvial region in the Pernambuco State.

It is worth mentioning the covariance of the soil moisture of the A3 for the three depths, with a range greater than 63 m, especially for the upper layers, showing the occurrence of spatial dependence even for at long distances (Table 2). This behavior, in which farmed areas presented high spatial dependence, is interesting, so that the information obtained quickly and easily (EM38®) can be used for managing zones (through differentiation), as also observed by Van Meirvenne et al. (2013), Tagarakis et al. (2012) and Valente et al. (2012), for other areas and parameters.

In Figures 4, 5 and 6 the experimental cross-linked semivariograms are presented.

Figure 4. Cross-linked semivariograms of the variables of area A1, being (A) Soil moisture x CEa 0-0.3 m, (B) Soil moisture x CEa 0.3-0.6 m and (C) Soil moisture x CEa 0.6-0.9 m.

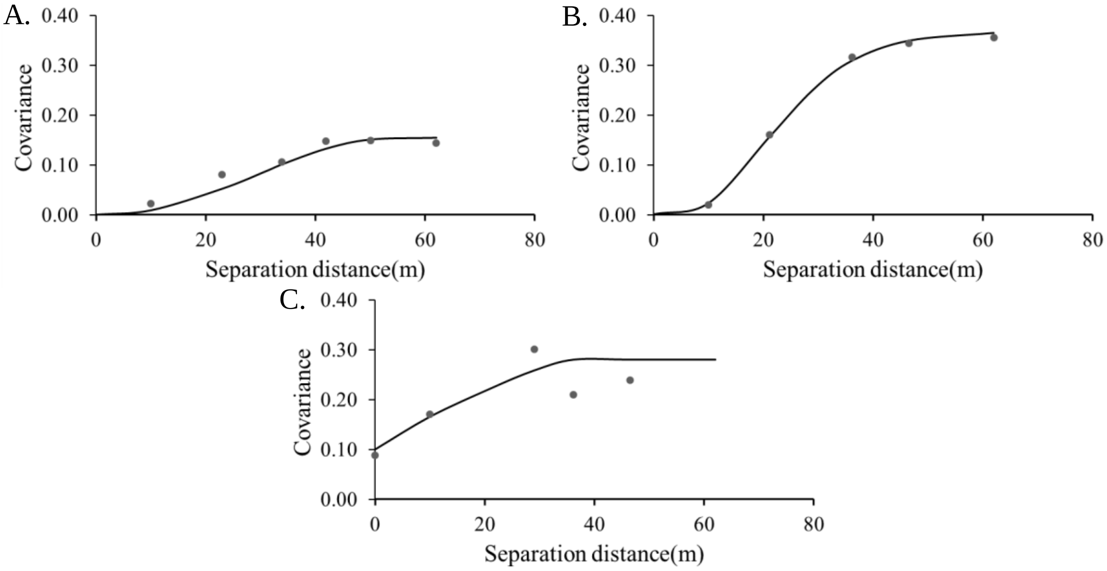


Source: Own authorship.

The cross-inference of soil moisture through CEa is affected for A1, due to the low dependence between them. Bottega et al. (2014) observed similar behavior for the estimation of soil parameters through CEa in soils altered by agriculture. This can occur due to the low variability of the soil moisture data of the first layer (Figure 3B), regardless of its use.

Thus, for A2, the data spatial dependence for the three initial layers was observed, but with lower dependence on the third layer. In this way, it is inferred that at deeper soil layers, the precision of the soil moisture estimation by CEa can be reduced from the electromagnetic induction reader (EM38®).

Figure 5. Cross-linked semivariograms of the variables of area A2, being (A) Soil moisture x CEa 0-0.3 m, (B) Soil moisture x CEa 0.3-0.6 m and (C) Soil moisture x CEa 0.6-0.9 m.

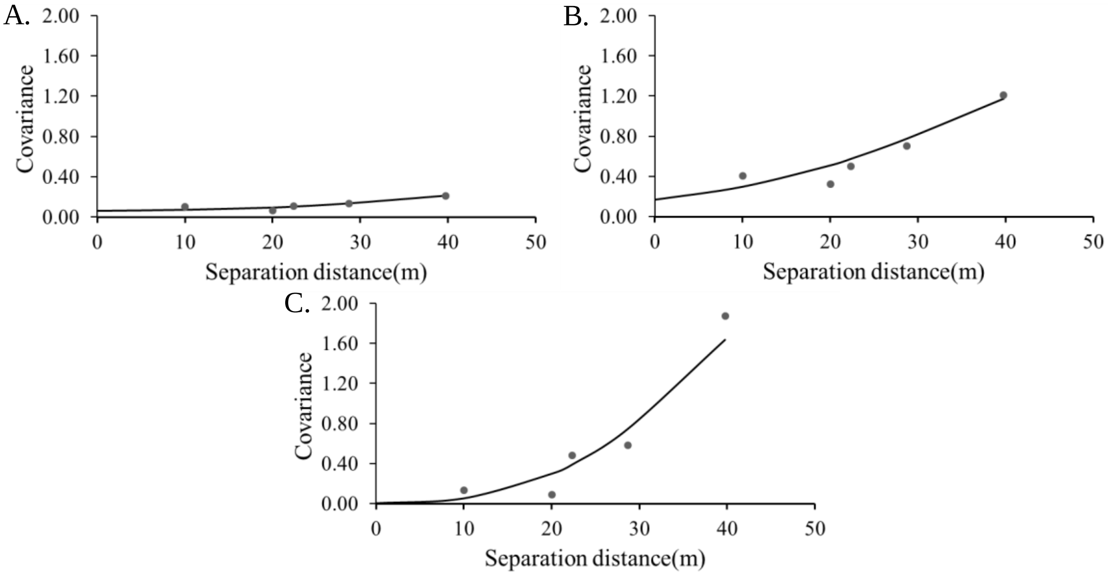


Source: Own authorship.

It can be observed that the Gaussian model was the one that best fitted the soil moisture covariance data set, with the CEa at all depths evaluated (Figure 5A and 5B). With this result of the Gaussian adjustment for the areas and depths, it can be inferred that the covariance between moisture and CEa is also Normal.

Observing the crossed semivariograms of the area A3 in Figure 6, it can be emphasized that for the three layers of soil, the sill for the semivariograms was not established.

Figure 6. Cross-linked semivariograms of the variables of area A3, being (A) Soil moisture x CEa 0-0.3 m, (B) Soil moisture x CEa 0.3-0.6 m and (C) Soil moisture x CEa 0.6-0.9 m.



Source: Own authorship.

The increase in covariance for the cross-semivariograms is more visible for the deepest layer, in the plowing area. The covariance values for 0-0.3 m were 0.1; For 0.3-0.6 m of 1 and for 0.6-0.9 m of 1.8, all values for the same separation distance. Thus, this result corroborates with the Box-Plots in which in A3 occurs higher variation of the data and thus the increase in dispersion for the soil moisture values and CEa.

Areas A2 and A3 presented high values and variations for CEa, but did not prevent mapping for soil moisture from the data obtained with the EM38®. For agricultural areas, Molin and Faulin (2013) and Lopes and Montenegro (2019) identified soil moisture variation as a function ECa, being a good alternative for soil monitoring, applicable to precision agriculture.

This is due to the existence of covariance, which was obtained computing the variation of the electromagnetic induction reading as a function of the variation of the soil moisture values. In this way, it is possible to subsidize precision agriculture, similar to Sousa et al. (2016), which verified the relevance of the soil attributes mapping to obtain higher accuracy in the interpretation and management recommendations, thus providing higher efficiency.

Future studies should be performed to verify the performance of the cross-variance between moisture and CEa for the rainy periods or with higher soil moisture.

5. CONCLUSIONS

The data obtained with EM38® present adequate resolutions for irrigated areas and precision agriculture in alluvial soils, especially in relation to the application of cross-geostatistics between moisture and CEa variables, for periods of strong water restriction, thus allowing a more precise mapping produce.

High covariance between soil moisture and CEa are identified in the fallow area (A2) and in the plowing area (A3) for the three depths, under conditions of extreme water scarcity. For alluvial areas, a covariance of soil moisture with CEa is detected as well as the occurrence of strong spatial dependence.

The method allows improvements for future sampling plans, particularly for analyzing soil moisture and salinity non-sampled locations, at distances no higher than the correlation lengths.

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CHAPTER IV -

LOPES, I.; MONTENEGRO, A. A. A.; DE LIMA, JOÃO L. M. P. Performance of Conservation Techniques for Semiarid Environments: Field Observations with Caatinga, Mulch, and Cactus Forage Palma. **Water**, v. 11, p. 792, 2019. DOI: https://doi.org/10.3390/w11040792

PERFORMANCE OF CONSERVATION TECHNIQUES FOR SEMIARID ENVIRONMENTS: FIELD OBSERVATIONS WITH CAATINGA, MULCH, AND CACTUS FORAGE PALMA

1. ABSTRACT

Understanding small-scale hydrologic processes and the impact of soil conservation techniques are crucial in reducing runoff and sediment losses in semi-arid regions. This study was conducted in the Alto Ipanema River Basin, in Pernambuco State (Brazil). Soil and water dynamics were intensely monitored in twelve experimental plots with different coverage conditions (plot with bare soil—Bare; plot with natural vegetation—Natur; plot with mulch—Mulch; plot with Cactus Palma—Palma). By far, bare soil conditions produced higher runoff and soil losses. Mulch cover was close to natural vegetation cover, but still presented higher runoff and sediment losses. Palma, which is a very popular spineless cactus for animal feed in the Brazilian semi-arid region, presented an intermediate hydrologic impact in controlling runoff, enhancing soil moisture, and also reducing soil losses. Experiments were conducted in one hydrologic year (2016/2017) at three different sites. They were intensely monitored and had the same number of plots. This enabled us to carry out a robust performance assessment of the two soil conservation practices adopted (Mulch and Palma), compared to natural vegetation cover and bare soil conditions. Such low-cost alternatives could be easily adopted by local farms in the region, and, hence, improve soil reclamation and regional resiliency in a water-scarce environment.

Palavras-chave: hillslope; mulch; Caatinga; Cactus Palma; soil; runoff generation.

DESEMPENHO DAS TÉCNICAS DE CONSERVAÇÃO PARA AMBIENTES SEMIÁRIDOS: OBSERVAÇÕES EM CAMPO COM FORMAÇÃO DE CAATINGA, MULCH E PALMA

RESUMO

A compreensão dos processos hidrológicos de pequena escala e o impacto das técnicas de conservação do solo são cruciais na redução das perdas de escoamento e sedimentos em regiões semi-áridas. Este estudo foi realizado na Bacia do Alto Ipanema, no Estado de Pernambuco (Brasil). A dinâmica do solo e da água foi monitorada intensamente em doze parcelas experimentais com diferentes condições de cobertura (parcela com solo descoberto - Bare; parcela com vegetação natural - Natur; parcela com cobertura morta - Mulch; parcela com Cactus Palma - Palma). De longe, as condições de solo nu produziram maiores escoamentos e perdas de solo. A cobertura vegetal foi próxima da cobertura natural da vegetação, mas ainda apresentou maiores perdas de escoamento e sedimentos. Palma, que é um cacto muito popular para alimentação animal no semiárido brasileiro, apresentou um impacto hidrológico intermediário no controle do escoamento, melhorando a umidade do solo e também reduzindo as perdas do solo. As experiências foram realizadas em um ano hidrológico (2016/2017) em três locais diferentes. Eles foram intensamente monitorados e tiveram o mesmo número de parcelas. Isso nos permitiu realizar uma avaliação robusta do desempenho das duas práticas de conservação do solo adotadas (Palha e Palma), em comparação com a cobertura natural da vegetação e as condições do solo descoberto. Tais alternativas de baixo custo poderiam ser facilmente adotadas pelas fazendas locais da região e, portanto, melhorar a recuperação do solo e a resiliência regional em um ambiente escasso de água.

Key words: encosta; cobertura morta; Caatinga; Palma; solo; geração de escoamento.

2. INTRODUCTION

Erosion is a natural process, leading to serious environmental consequences, reducing agricultural productivity, and increasing the sediment amount for the water bodies downstream. Soil erosion is probably one of the most relevant environmental degradation challenges, especially in hilly shallow soils typical in arid and semi-arid regions (BROCA et al., 2012; SERENGIL et al., 2007; ALKHARABSHEH et al., 2013; MONTENEGRO et al., 2013).

Reliable local-scale measurements of runoff and erosion under natural rainfall for different soil cover conditions are still limited, especially in semiarid environments, with sparse vegetation cover (OSTOVARI et al., 2017; BRASIL, et al., 2013).

Mulch minimizes the impact rain has on soil surfaces (ABRANTES et al., 2018), which might contribute to improved soil fertility, increase water availability through enhancing infiltration, and reduce evaporation, thus minimizing nutrient losses and also controlling soil temperature variations (MONTENEGRO et al., 2013; RIBEIRO FILHO et al., 2017; QIN et al., 2015).

Another potential alternative largely adopted in Brazilian semiarid areas is the cultivation of forage Palma, a cactus crop that presents a modified stem a with thin, flat vertical structure. Although it has limited rainfall interception, it has a high leaf area index (PINHEIRO et al., 2015), and if cropped along contour lines, then it tends to reduce surface runoff (SANTOS et al., 2010).

The use of field erosion plots under natural rainfall allows the study of many hydrological processes at on local scale. Well-designed experimental plots provide an opportunity to improve understanding of the local-scale water budget and plant cover effects on runoff. The knowledge to be acquired on these experimental small plots is valuable for some specific issues, such as evaluation of soil and water conservation practices, water retention, infiltration, and soil water dynamics (HOLKO et al., 2015).

Small-scale plots both in laboratory and in natural watersheds can also successfully contribute to the understanding of major hydrological processes during extreme rainfall events (PRATS et al., 2018; ZHOU et al., 2018). In semiarid environments it is very challenging to collect runoff and soil loss data of a reasonable quality under natural conditions, as the number of rainfall runoff events is very limited; therefore, each event might have an important role in evaluating the impact of soil and water conservation alternatives (PLAN-HA et al., 2012).

Santos and Montenegro (2012) analyzed high intensity rainfall events and their contributions to soil disaggregation, transport, and deposition in the Pernambuco semiarid environment. Based on a time series of 29 years, the authors verified that the first half of the year was characterized by rainfall events with high erosive potential, and complex rainfall patterns were observed with a higher occurrence where the peak level fell at the beginning of each rainfall event. Previously, Santos et al. (2010) verified the potential use of mulching and Palma cactus in increasing soil moisture, over a 301-day study period, during a wet year. This was conducted in the same area as in our investigation, although no attempt was made regarding rainfall runoff analysis.

In studies of water and soil conservation in watersheds in Africa, Wenninger et al. (2008) highlighted that hydrological processes in semi-arid regions usually presented high spatio-temporal variability. Hence, it is important to obtain local rainfall and runoff measurements, for soil moisture dynamics, in order to properly understand runoff generation.

Northeastern Brazil, particularly the semi-arid region of Pernambuco State, is usually subject to high intensity local rainfall events, known as thunderstorms (SILVA et al., 2012). Such events cause high runoff rates and sediment losses, requiring conservation alternatives to be adopted in order to prevent irreversible degradation of the topsoil.

The objective of this study was to investigate small-scale hydrologic processes and the impact of soil conservation techniques on reducing runoff and sediment losses. This study used textural characterization of the associated transported sediments, using runoff plots with different soil covers (Bare, Natur, Mulch, and Palma) under natural rainfall, in the Caatinga biome of Brazil.

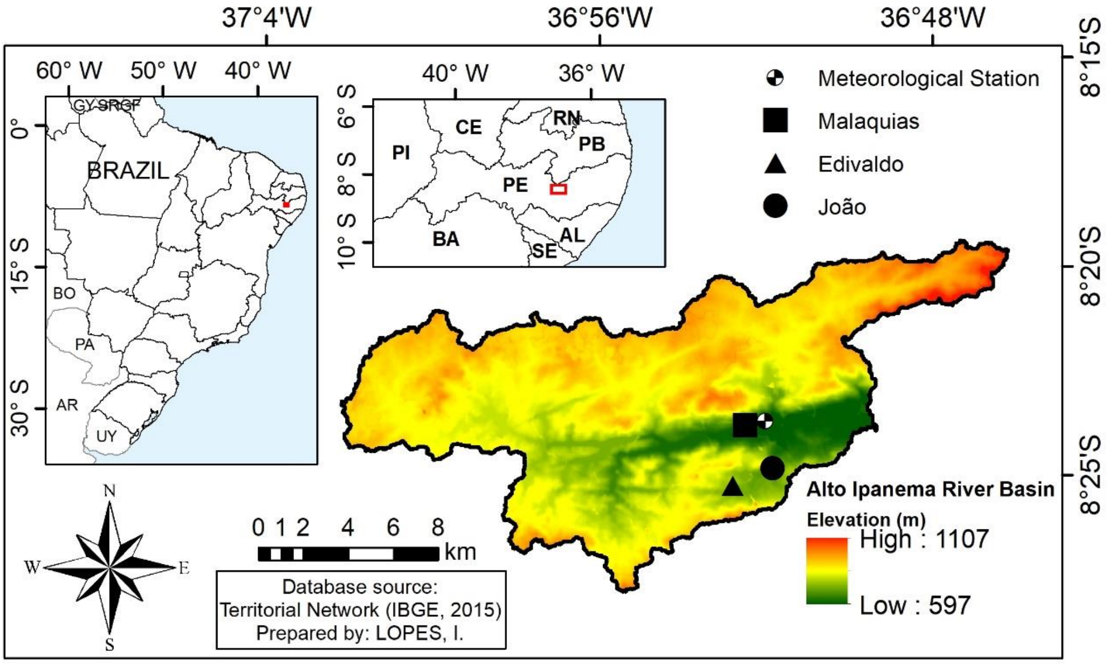
3. MATERIAL AND METHODS

Study Sites

The study area (Figure 1) was located at the Alto Ipanema River Basin (AIRB), a sub-basin of Ipanema River, one of the sub-basins monitored by the Hydrology Network of the Semi-Arid Region (REHISA). It is part of the municipalities of Arcoverde and Pesqueira, in the Pernambuco State (Brazil). The area has a complex landscape, characterized by a high spatial variability of elevation and climate, and deciduous vegetation, which constitutes the Caatinga Biome.

The vegetation presents strong seasonality over time, characteristic of the Caatinga Biome. In the dry period, the native forest area presents loss of foliage (deciduous behaviour) and, in areas of sparse vegetation, large areas exhibit exposed soils. However, the cover conditions change considerably during the rainy season, which is characteristic of semi-arid regions, with rapid foliage regeneration (BRASIL, et al., 2013; SANTOS et al., 2016).

Figure 1. Location of the study sites of Malaquias, Edivaldo, and João in Alto Ipanema River Basin, Pernambuco State, Brazil.



Previous field investigations were adopted (SANTOS et al., 2016; SANTOS et al., 2010) as sources of information for the physical and chemical characteristics of soil in the experimental plots. These studies were located in the same pedological unit, and the soil properties were very similar among the three studied sites. The mean values from the data are presented in Table 1. The soil classification was Ultisol Eutrophic Typical and the infiltration capacity was 0.134 m h−1.

Table 1. Soil physical and chemical characteristics for the experimental plots. Alto Ipanema River Basin, Pernambuco State, Brazil. Source: SANTOS et al. (2016); SANTOS et al., (2010).

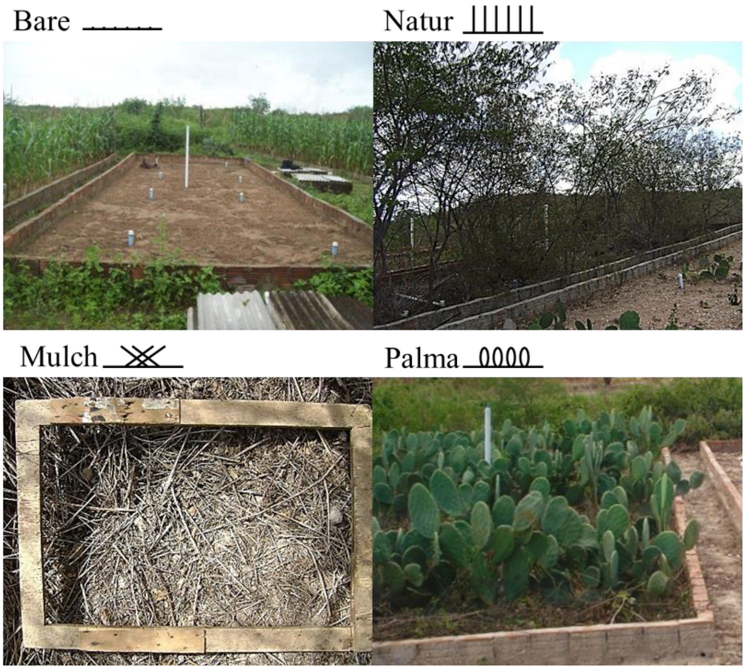
Depth	**Hor.**	**Sand**	**Clay**	**Silt**	**Dp**	**Ds**	**P**	**pH**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**Na^{+}**	**H+Al**	**OC**
m		----------%----------			--g cm^{-3}--		%		---------------cmol$_c$ kg^{-1}---------------					g kg^{-1}
0.00 – 0.12	Ap	44.9	23.2	32.0	2.64	1.48	43.9	6.07	2.08	0.65	0.43	0.27	2.39	20.80
0.13 – 0.27	A1	44.2	26.5	29.3	2.72	1.51	44.5	5.20	1.57	0.41	0.16	0.24	2.15	15.70
0.28 – 0.46	A2	31.5	32.5	36.0	2.64	1.45	45.1	5.43	0.81	0.29	0.18	0.23	2.12	8.10
0.47 – 0.69	AB	28.9	33.8	37.3	2.67	1.68	37.1	5.47	0.73	0.36	0.21	0.30	1.71	7.30
0.70 – 0.86	Bt	15.2	69.2	29.3	2.66	1.88	29.3	6.10	1.44	1.32	0.10	1.58	1.43	14.40

(where: Hor. = soil horizon; Dp = particle density; Ds = soil bulk density; P = porosity; and OC = organic carbon).

Four experimental plots with different cover conditions were considered at each of the three sites (corresponding to 12 plots in total). Soil and water monitoring was performed in experimental plots with different cover conditions (plot with bare soil—Bare; plot with natural cover—Natur; plot with mulch—Mulch; plot with Cactus Palma—Palma). Maintenance was carried out on the experimental plots before the beginning of the experiment, and minimal reworking was performed only to allow proper representativeness of the soil cover conditions (e.g., weed control procedures).

Figure 2 shows a general view of the investigated cover conditions (Bare, Natur, Mulch, and Palma): Bare—soil without any of natural or artificial cover on the plot; Natur—predominantly natural and/or spontaneous vegetation composed of small and medium-sized shallow caatinga, with predominant quince (Croton sonderianus) and jurema-preta (Mimosa hostilis Benth.); Mulch—dry grass mulch (Brachiaria decumbens) with a density of 8 t ha−1; Palm—presence of forage spineless Palma (Opuntia cochenillifera) planted in regular spacing of 0.5 × 1.5 m, forming a vegetation contour ridge.

Figure 2. Photographs of the experimental plots for the different cover conditions (plot with bare soil—Bare; plot with natural cover—Natur; plot with mulch—Mulch; and plot with Cactus Palma—Palma).



4. RESULTS AND DISCUSSION

Rainfall Event Analyses

The studied hydrologic year of 2016/2017 can be classified as water-scarce. During the study period there were 76 daily rainfall events, which totaled 404.20 mm (corresponding to 60% of the mean rainfall depth in the 2017 hydrological year).

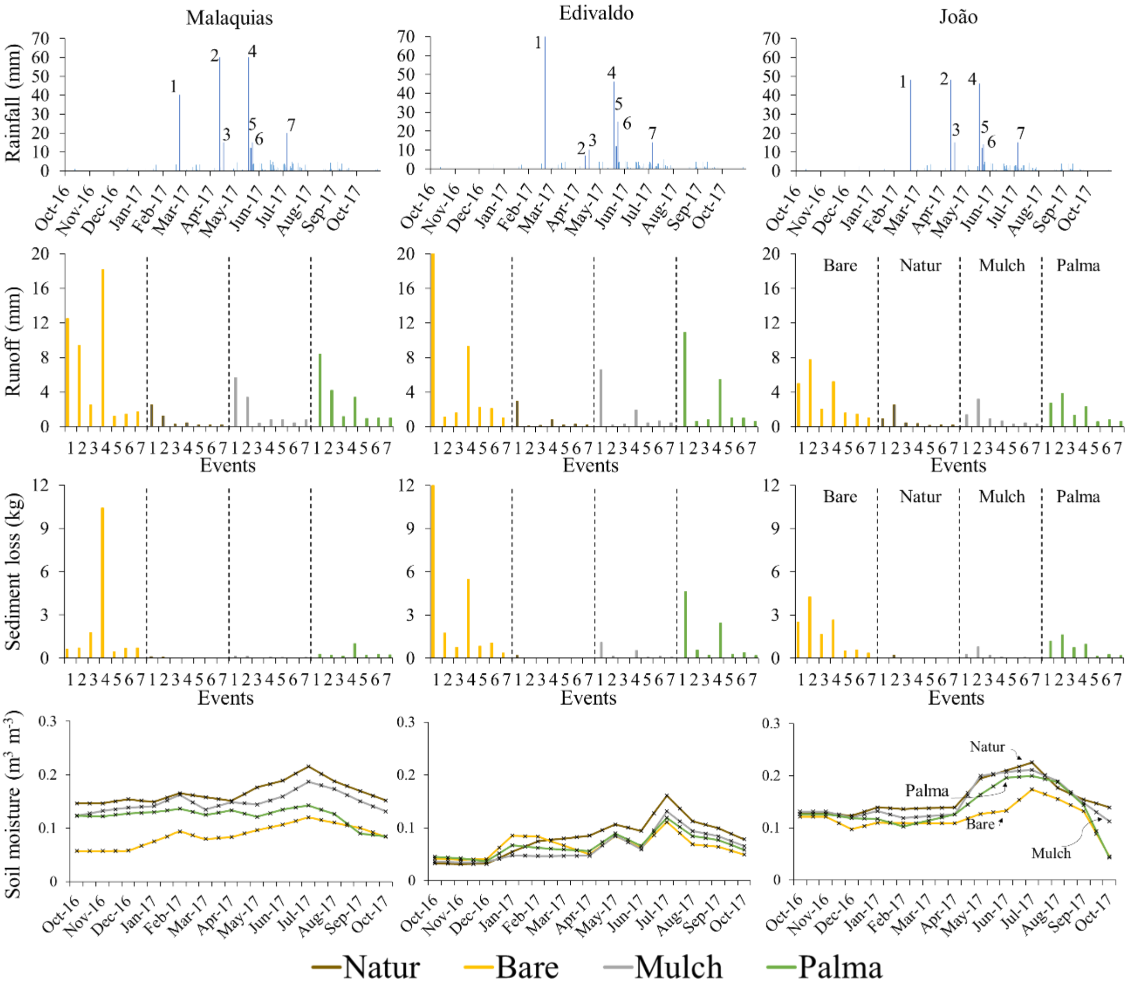
Figure 4 presents the observed rainfall, runoff, soil losses, and soil moisture temporal behaviors occurring from October 2016 to October 2017, for rainfall higher than 5 mm.

Only seven events produced runoff. The highest precipitation intensity occurred on 4 March 2017, with a value of 70 mm during 0.5 hours, corresponding to a return period of 300 years, according to Silva et al. (2012).

The water and sediment production characteristics for each rainfall event are presented in Figure 4, as well as the mean soil moisture for the 0 to 0.6 m layer, as a function of time.

Runoff generation and soil losses were very limited for the Natur soil cover condition, and the conservation practices of Mulch and Palma efficiently reduced water and soil losses, as expected. More detailed rainfall runoff and rainfall soil loss analyses have been carried out in next section, exploring the correlations between the variables and also their statistical behaviors.

Figure 4. Time series of rainfall, runoff, sediment loss, and soil moisture during the study period. The cover condition identification was inserted in the charts of João, thus representing all the other sites.



The main variations observed for the moisture values could be explained by semi-arid characteristics, with precipitation events of high intensity and small duration, followed by high evapotranspiration rates. Lopes et al. (2016), studying the rainfall spatial distribution for a region of the Brazilian semi-arid region, observed that there was a high spatio-temporal variation caused by the previously mentioned rainfall characteristics.

The different surface covers influenced soil moisture dynamics. At the beginning of the hydrological year, soil moisture was below the soil water content at the permanent wilting point

(0.071 m^3 m^{-3}). Soil moisture for bare soil was the lowest among the studied soil cover conditions.

Table 2 gives an overview of the different sites and plots, namely the relative position of the different cover plots in each site. Although there were differences, plot characteristics were approximately the same, and rainfall had the same magnitude order. In addition, Table 2 also presents the statistical analysis results for runoff, soil losses, and soil moisture for the different sites and soil cover conditions.

Table 2. General characteristics (mean values and Tukey test for all seven events in each site) for the plots with surface covers: n—Natural; b—Bare soil; m—Mulch; and p—Palma.

Site	**Soil**	**Slope**	**Exposition**	**Position of plots (from left to right)**
Malaquias	Red Yellow Argisol	~6%	Northwest	m; p; b; n
Edivaldo			Northwest	b; n; p; m
João			Northeast	m; b; p; n

Site	**Maximum/Mean total rainfall (mm)**	**Maximum/Mean rainfall intensity in 30 min (mm h^{-1})**	**Mean soil losses (kg)**	**Mean Runoff (mm)**	**Soil moisture (m^3 m^{-3})**
Malaquias	60/31	48/24.5	n- 0.03 (c);	0.6 (d);	0.16 (a);
			b- 1.91 (a);	5.9 (a);	0.11 (d);
			m- 0.06 (c);	1.5 (c);	0.15 (b);
			p- 0.28 (b)	2.5 (b)	0.13 (c)
Edivaldo	70/26	90/33.6	n- 0.03 (c);	0.6 (d);	0.08 (a);
			b- 3.31 (a);	5.4 (a);	0.06 (c);
			m- 0.26 (c);	1.3 (c);	0.07 (b);
			p- 1.03 (b)	2.5 (b)	0.06 (c)
João	48/28	60/24.4	n- 0.04 (c);	0.6 (d);	0.16 (a);
			b- 1.56 (a);	3.0 (a);	0.08 (d);
			m- 0.18(c);	0.9 (c);	0.14 (b);
			p- 0.63 (b)	1.5 (b)	0.12 (c)

Mean values followed by the same letter do not significantly differ in the same column, according to the Tukey test ($p < 0.05$).

Statistical differences occurred between the distinct cover conditions and bare soil for the three studied sites (Malaquias, Edivaldo and João—Table 2). Higher soil loss was observed for the bare soil condition, followed by Palma. Natural Caatinga cover and mulch presented lower soil erosions.

Runoff had different behavior, with natural cover generating the smallest runoff depth and bare soil conditions producing the highest runoff. Mulch reduced soil loss because small barriers of accumulated mulch material formed, approximately following the elevation contours. These barriers (Figure 5) promoted the deposition of soil particles upslope.

Figure 5. Photograph detailing the soil surface after a rainfall event (plot with mulch cover).

Statistical differences were also detected for the mean soil moisture for the whole period, being more evident for the João Site. Araújo et al. (2018) studied the spatial distribution of soil moisture for the Ipanema River Basin, where the experimental plots were inserted, and also observed low water availability conditions for the whole area in the same period.

Observing Figure 4, it can be verified that some moisture differences were more evident for periods with rainfall spells as a result of the rainfall pattern, evapotranspiration, and the limited soil water holding capacity at the plots.

According to Table 2, mulch was the most suitable conservation practice for maintaining the highest soil moisture values. The observed soil moisture contents varied over time during the experimental period, and variations were related to the different cover types.

Santos et al. (2010), studying the same soil cover conditions for a wet hydrologic year in the same region, observed that soil surface conditions had a high influence on soil moisture variation, both in the dry and the rainy periods. It was verified that natural vegetation cover (Caatinga biome) presented the largest water content in soil compared to the other treatments for the entire rainy period. Bezerra et al. (2014) highlighted the importance of monitoring soil water dynamics for different cover conditions in semi-arid Brazil, especially in the Caatinga biome, aiming to improve soil water storage and to provide experimental in situ data for soil losses resulting from rainfall events.

Runoff and Soil Loss Correlations

Figures 6 and 7 verify the relationships between the runoff coefficient (defined as the ratio between runoff depth and total rainfall) and soil loss as a function of rainfall depth and intensity. Rainfall intensity explains better the observed variations in the runoff coefficient than rainfall depth. It was shown that mulching successfully protected the soil surface for all three sites, which allowed a higher infiltration rate and, thus, greater soil moisture storage. For Palma, a similar behavior was observed both for runoff and soil loss.

These results can be explained by the following mechanisms and surface characteristics, presented by Montenegro et al. (2013): (1) soil cover protection from direct impact of rain drops; (2) higher hydraulic roughness based on mulch cover, retarding surface flow, and enhancing infiltration; and (3) water retention of the mulch cover. In addition, contour barriers provided by the Palma reduced overland flow velocities, favoring sediment deposition.

Figure 6. Runoff coefficient as a function of rainfall volume and intensity, for all sites and plots.

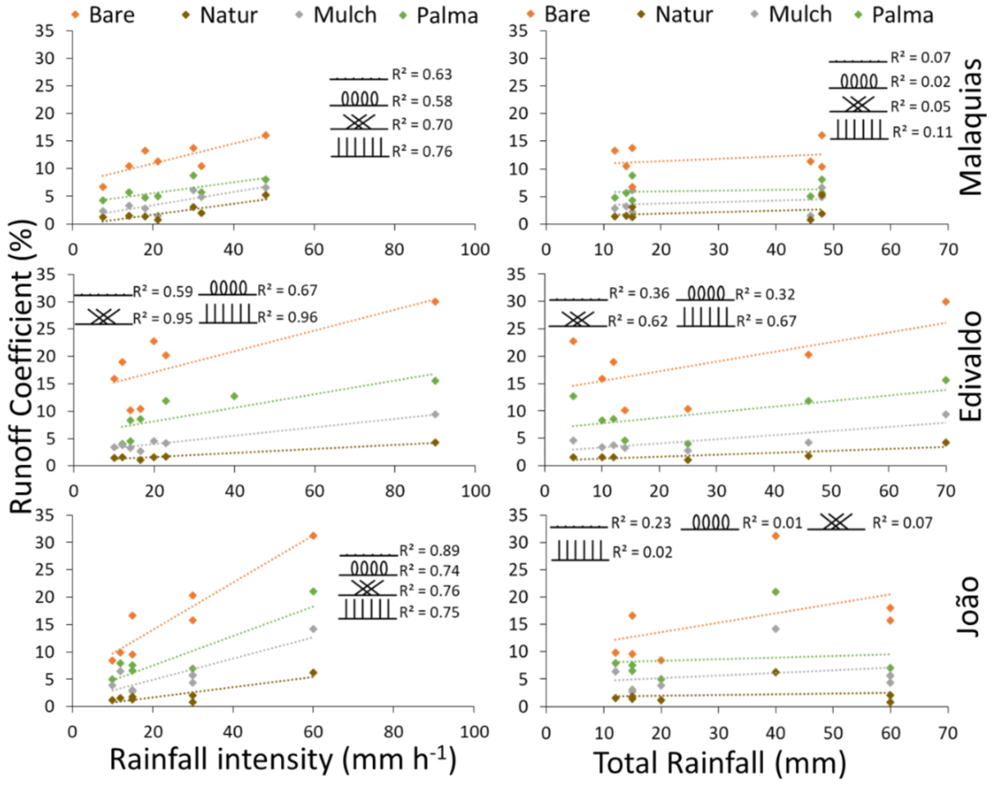
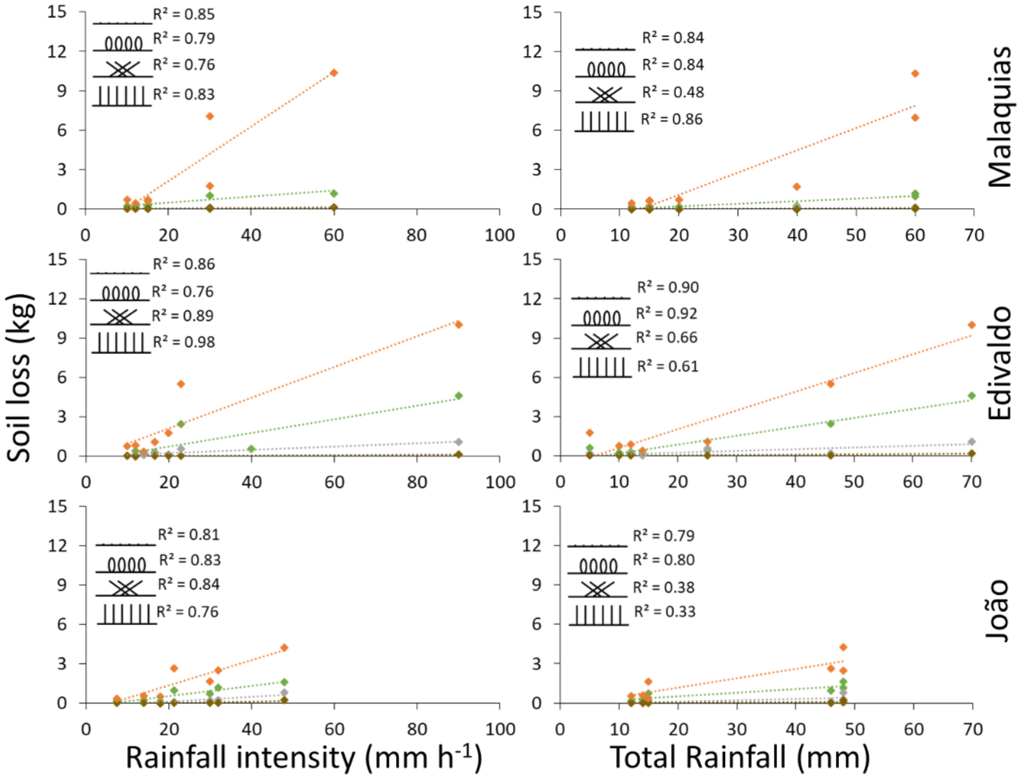
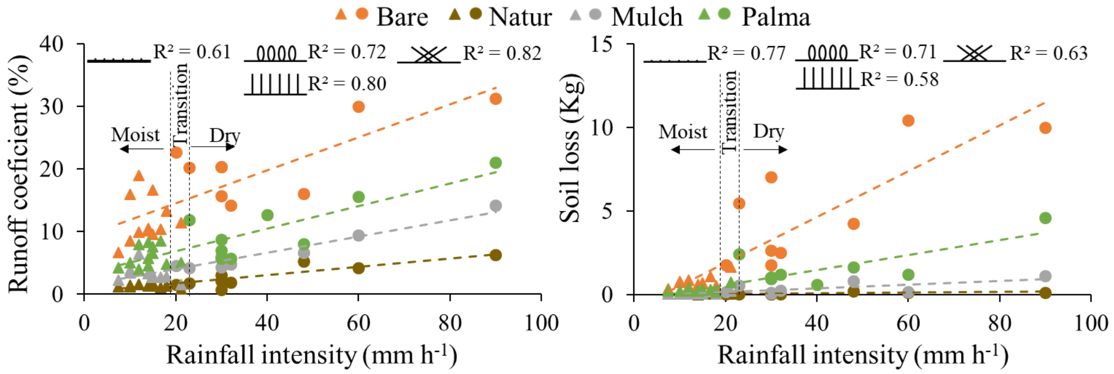


Figure 7. Soil loss as a function of rainfall volume and intensity, for all sites and plots.



Runoff generation was strongly related to antecedent moisture conditions of a specific event, as observed in Figure 8 (a). Soil loss, however, was more correlated to rainfall intensity (Figure 8 – b). Characteristic rainfall temporal regimes in the Brazilian semi-arid region, where higher intensities were verified at the beginning of the event, were also observed.

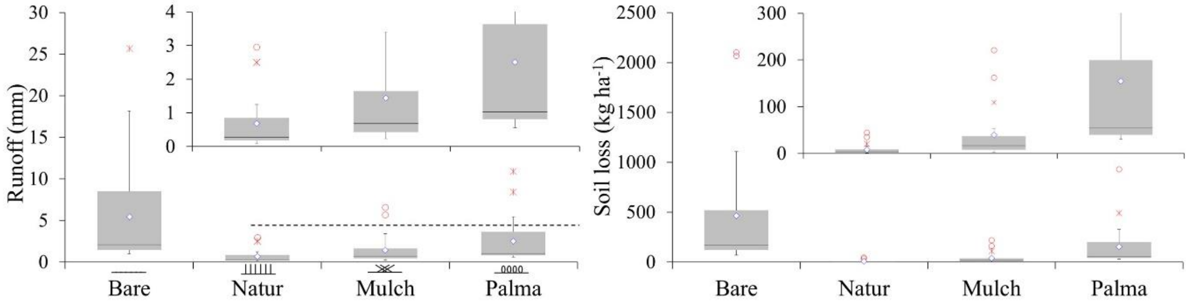
Figure 8. Runoff coefficient (a) and soil loss (b) for all sites and all rainfall events. Antecedent soil moisture conditions are indicated by triangles, representing high antecedent soil moisture (moist conditions), and circles, representing low antecedent soil moisture (dry conditions).



(**a**) (**b**)

Figure 9 describes the basic statistics for runoff and soil loss by comparing the different surface covers. By far, the bare soil plots produced more total runoff and sediments. Mulch cover was close to natural vegetation cover, but still had a higher runoff and sediment loss. Palma presented an intermediate hydrologic response (see also Figures 6 and 7).

Figure 9. Box plot runoff and soil loss for all plot covers. The superimposed graphs are enlarged in order to visualize details for Caatinga, Mulch, and Palma plots. Key: '◊' average; '-' median; '□' 25% to 75% probability; '┬' maximum; '┴'minimum; '*' outlier; and '○' extreme.



According to the box plot in Figure 9, the natural Caatinga cover was efficient at increasing soil water storage; this result was also reported by Caloiero et al. (2016). Although the presence of native forest increased water consumption as a result of transpiration, it was also verified that soil moisture of nearby soil surfaces increased in comparison to areas where vegetation was removed.

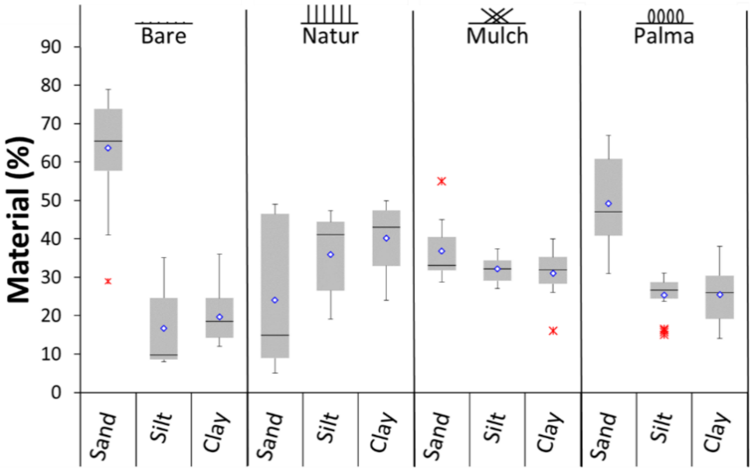
Brasil et al. (2017) studied the importance of the Caatinga canopy in reducing rainfall kinetic energy and increasing soil water storage. In addition to the aforementioned contributions, natural cover enhances infiltration (MCLAUGHLIN et al., 2013) and reduces evapotranspiration (SERENGIL et al., 2013).

The study by Kiani-Harchegani et al. (2017) might explain the presence of outliers and extremes for runoff and soil loss data, which also occurred in their study when rain intensity and surface slope were varied. Such values were associated with rainfall intensities that were outside of the 99% probability of occurrence for the studied dataset (SILVA et al., 2012).

Aspects Related to Granulometry

Erosion in the bare soil plot provided the highest sand percentage (Figure 10), and the highest percentages of silt and clay were observed for the natural vegetation cover plot. Palma cover crop presented similar behavior to bare soil, since the soil was largely unprotected from direct drop impact, with sand percentage clearly above the silt and clay percentages for the transported sediments.

Figure 10. Boxplot of the percentages of sand, silt, and clay for sediments transported in runoff, for all plot covers. Key: '◊' average; '-' median; '□' 25% to 75% probability; '┬' maximum; '┴'minimum; '*' outlier; and '○' extreme.



In general, runoff carried more sand fraction for the earlier events of the year, as noted by the maximum discharges that were observed. Later, more intermediate and finer materials were observed. Sand components in the eroded sediment resulted from both raindrop impact and the higher surface runoff, which resulted in higher velocity and, hence, in higher transportation capacity, observed mainly for bare soil cover conditions.

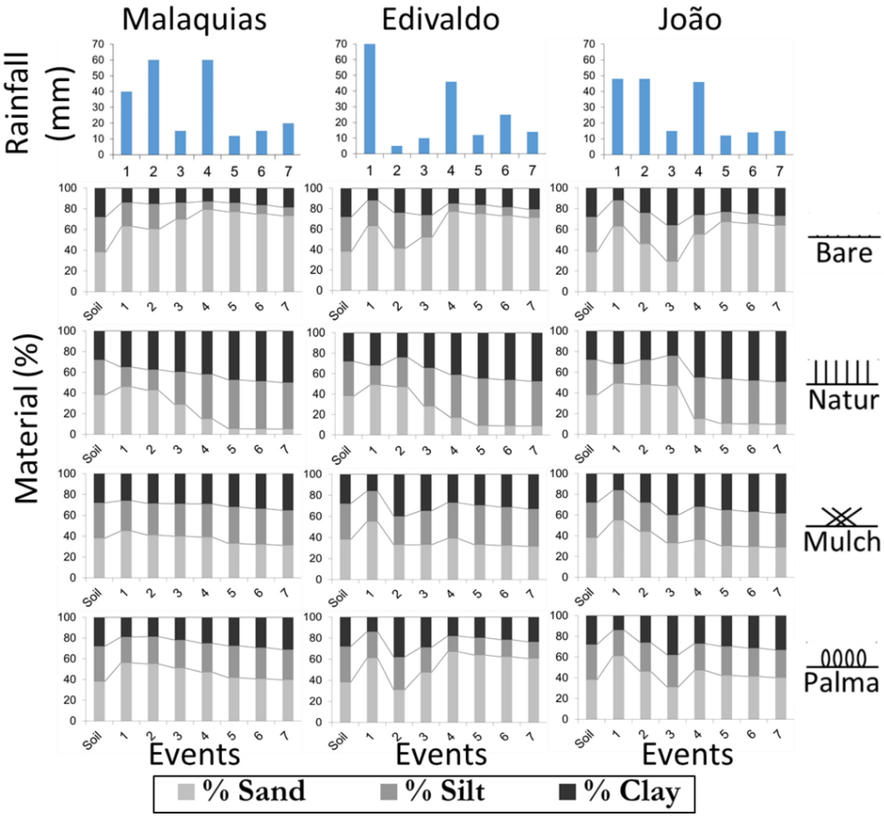
An experiment to help understand sediment loss was performed by Silveira et al. (2016). In spite of the fact that the study was conducted in urban environment, the authors observed that the nature of sediment accumulation was complex, and it depended on the type of soil cover, such as green cover, compacted soil, construction, and slope activities. In addition, combinations of bare soil and steeper slopes have greater contributions to sediment loss.

Sediments for the natural cover (Caatinga) treatment consisted mainly of fine particles, because interception prevented the direct impact of raindrops reaching the soil surface. Observations by Kiani-Harchegani et al. (2017) under laboratory conditions highlighted the relevance in considering all the key variables involved in sediment transport processes for a better understanding of grain size dynamics.

Bashari et al. (2013), studying the effects of soil textures on soil losses, verified that erosion in soils is complex, and more research is still needed to fully understand the erosion mechanism.

Sediment evolution, in terms of percent of clay, silt, and sand in our study, can be observed for the sequence of rainfall events in Figure 11. Lines show the behavior of the textural displacement in the United States Department of Agriculture (USDA) textural chart. According to Figure 11, there were common textural displacement patterns for each soil cover (Bare, Natur, Mulch, and Palma).

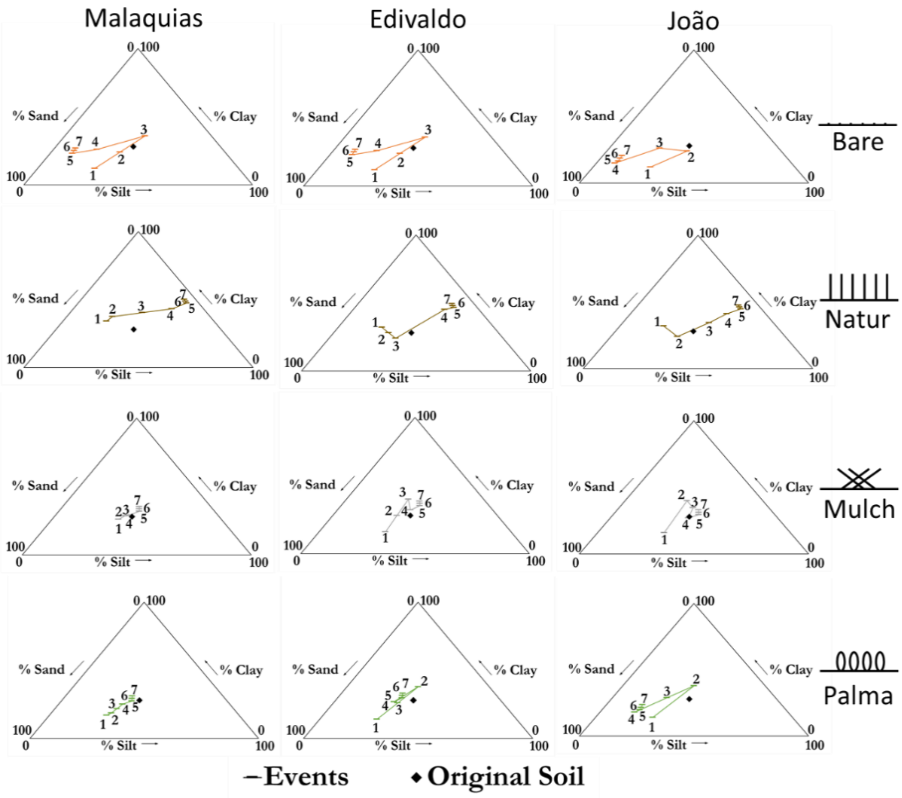
Figure 11. Tracking percentages of sand, silt, and clay for the three sites in all soil covers, together with the seven rainfall events that produced erosion in the plots.



The flow takes thick material first, and when the soil loses the loose particles, as well as increasing wetness, the finer particles begin to be carried off. The more unprotected soil, the greater the amount of coarse material in the transported material. Bare soil plots, because of their unprotected soil surfaces and higher observed runoffs, are subjected to more energy and sediment transport capacity, especially for heavier sand particles. Such behavior was observed for all events and sites in our study.

The USDA textural charts (Figure 12) highlight the variation of the granulometric composition of the original soil and for runoff composition. For the bare soil, it was possible to observe that initially there was a loss of finer sediment, and later a predominance of sand fraction loss occurred.

Figure 12. Evolution of sand, silt, and clay percentages during the hydrology year 2016/2017, for all runoff events and studied plot covers.



The paths (position sequence, illustrating the evolution in time) in the USDA textural classification chart (triangle) associated with the rainfall events for the bare soil plots have different paths associated with the other coverages. Natural cover presented an unmodified pattern, with coarser grain sizes at the beginning of the runoff evolving to a finer size when soils had a higher water content.

For natural cover conditions, the transported sediment texture was always thinner than for the original soil. For Mulch cover, however, rainfall events produced dynamic soil texture losses around the original soil composition.

Few studies were found focusing on the granulometric variation of the transported sediments. De Lima et al. (2008) studied soil texture variation under laboratory conditions in various plot sizes and slopes, and observed that an increase in the plot length, and, hence, in the peak discharge, had a greater erosive capacity. Thus, surface water was mainly composed of thicker material, independent of the slope.

Experimental data for flow and sediment losses can contribute to improving the performance of hydrological models in predicting runoff and sediment transport for varied soil cover conditions. Such experimental observations are required, not only for model calibration/validation, but mainly for better parameterization. For instance, when applied to hydro-sedimentological models such as Water Erosion Prediction Project (WEPP) (described by Brooks et al. 2016) and Soil & Water Assessment Tool (SWAT)for simulating extreme processes on a basin scale (ARNOLD et al. 1998), including drastic coverage withdrawal, texture dynamics might aid the model's ability to predict the impact of land use changes in runoff and soil conservation conditions

5. CONCLUSIONS

Based on field experiments conducted during the 2016/2017 hydrologic year, after a five-year drought in the studied region, the experimental data from three sites with 12 plots and four surface covers successfully enabled us to assess the performance of two low-cost soil conservation practices (Mulch and Palma), compared to natural cover conditions and to bare soil conditions.

By using experimental plots to compare natural cover conditions (Caatinga) with the applied soil conservation practices, the following conclusions can be drawn:

- Mulch was more efficient as a soil conservation technique than Cactus Palma, although Palma significantly increased soil moisture compared to bare soil.
- Natural Cover (Caatinga) yielded less mulch runoff and sediment loss when compared to bare soil and to soil conservation practices (Mulch and Palma).
- Rainfall intensity was the single most important factor in runoff generation and soil losses.

When mulch is not available, Cactus Palma appears to be an attractive solution for reducing sediment losses and increasing infiltration. Moreover, being rooted, they are not easily transported away by wind, and they can be used as relevant livestock food alternatives during severe drought situations.

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CHAPTER V -

WATER RETENTION AND ABSORPTION EVALUATION OF ORGANIC MULCHING COVERS UNDER SIMULATED RAINFALL FOR SOIL AND WATER CONSERVATION PRACTICES IN SEMIARID BRAZIL

1. ABSTRACT

The understanding of the amount of water stored by rainfall events in vegetation cover has become relevant for the understanding of effective rainfall on soil. There are still few studies that analyze rainfall interception for different organic mulch densities, sizes and types of cut. The aim of this study was to investigate the process of interception, retention and absorption of rainwater by different types, sizes and densities of some organic coverings were used, Six organic coverings were used, being coconut leaf and (cc), cashew leaf (ca), elephant grass (el), corn leaf (co), brachiaria grass (br) and sugar cane leaf (su), under simulated rainfall condition. It was possible to construct the curve and determine the water retention and absorption capacity for the vegetation materials. The experimental scheme was factorial of 6 types of coverings, with 3 sizes (50, 100 and 200 mm) and 4 densities (1, 2, 4 and 8 t ha^{-1}), with application of analysis of variance, Tukey Test and Regression polynomial. It is observed that the increase in application density systematically leads to an increase in water retention and absorption. For 8 t ha^{-1} the values were 11-23% and 7 to 16% of the gross rainfall depth, respectively, became effective for the studied conditions. When comparing 8 t ha^{-1} with 2 t ha^{-1} densities, rainfall retention and absorption increases greater than 100% were obtained for the former density. Higher values were obtained for cashew and brachiaria grass, promoting better water retention and cashew leaves for absorption. Coconut leaves promoted only 83% retention and 67% water absorption, when compared to the two largest (cashew leaf and brachiaria grass).

Key words: interception; storage capacity; mulching densities; canopy storage

AVALIAÇÃO DA RETENÇÃO E ABSORÇÃO DE ÁGUA POR COBERTURAS ORGÂNICAS SOB CHUVA SIMULADA PARA PRÁTICAS DE CONSERVAÇÃO DE SOLO E ÁGUA NO SEMIÁRIDO DO BRASIL

RESUMO

A compreensão dos quantitativos armazenados de água por eventos de chuva em coberturas vegetais tem se tornado relevantes para a compreensão da chuva efetiva sobre solo. Há poucos estudos que analisem a interceptação de chuva para diferentes densidades, tamanhos e tipos de cobertura morta orgânicas. O objetivo deste estudo foi investigar o processo de interceptação, retenção e absorção de água de chuva por diferentes por diferentes tipos, tamanhos e densidades de algumas coberturas orgânicas que são comumente encontradas no semiárido brasileiro. Foram utilizadas seis coberturas orgânicas, sendo folha do milho (Zea mays), do Capim Elefante e da Braquiária, folhas de cajueiro, folha de coqueiro e palhada de cana de açúcar, sob condição de chuva simulada. Foi possível construir a curva e determinar a capacidade de retenção e absorção de água pelas coberturas. O esquema experimental foi fatorial de 6 tipos de coberturas, com 3 tamanhos (50, 100 e 200 mm) e 4 densidades (1, 2, 4 e 8 t ha^{-1}), com aplicação de análise de variância, Teste Tukey e Regressão polinomial. Observa-se que o aumento da densidade de aplicação leva sistematicamente a um aumento da retenção e absorção de água. Para 8 t ha^{-1} os valores foram de 11-23% e 7 a 16% da chuva, respectivamente, precipitada para as condições estudadas. Quando comparado 8 t ha^{-1} com 2 t ha^{-1} obteve-se valores superiores a 100% de incremento na retenção e absorção da chuva. Obteve-se maiores valores a caju e capim Braquiária promoveram melhor retenção de água e as folhas de caju para absorção. As folhas de coco promoveram apenas 83% de retenção e 67% de absorção de água, quando comparado com as duas maiores (folha de caju e capim Braquiária).

Palavras-Chave: interceptação; capacidade de armazenamento; densidades de cobertura morta; armazenamento no dossel

2. INTRODUCTION

Canopy interception plays an important role on hydrological budgets, controlling runoff generation and soil erosion, particularly in semiarid areas, where soil cover is usually limited. Investigations aiming at the canopy storage capacity at organic mulching surfaces have been increasingly carried out, focusing on the rainfall net contribution to soil moisture (DUNKERLEY, 2000; VALENTE et al., 2020; SMETS et al., 2019).

In order to evaluate net rainfall reaching soil surface, Geddes and Dunkerley (1999) point out the relevance of vegetation residues which might cover 50% or more of the soil surface, hence intercepting significant part of rainfall depth (PUTUHENA and CORDERY, 1996). Thus, quantifying storage capacity of mulch surfaces is essential for a proper understanding of water infiltration processes through soil surfaces.

Mulch cover usually reduces raindrops impact on soil surfaces (reducing soil desagregation), minimizing soil nutrient losses, thus contributing to enhance soil fertility. Moreover, mulching contributes to increase soil water availability and infiltration. On the other hand, mulch surfaces tend to reduce soil evaporation and to buffer soil temperature dynamics (SILVA JÚNIOR et al., 2011; MONTENEGRO et al., 2013; QIN et al., 2015; RIBEIRO FILHO et al., 2017; SILVA et al., 2019).

In areas with limited natural soil cover and where soil and water conservation practices are not adopted, high runoff rates and sediment transport are expected to occur, leading to nutrient losses and limiting crop production. Such losses are still high around the world, due to the lack of conservation practices adoption (e.g., KODZWA et al., 2020; SILVA et al., 2019; ZRIBI et al., 2015; IBRAHIM et al., 2020).

Mulching is highly recommended for semiarid areas. Borges et al. (2014), Karuku (2018), Silva et al. (2019) and Montenegro et al. (2019) have verified that straw mulching with densities of 2 and 4 t ha^{-1} not only successfully reduced runoff and soil temperature, but also resulted in higher soil moisture and thus higher crop production. Experimental plots have been considered in an experimental basin in the Brazilian semiarid, Pernambuco State, and organic mulching from beans and coconut powder were adopted. Moreover, mulching reduces soil evaporation, thus increasing water availability for crops transpiration (Valente et al., 2020). However, it should be highlighted that too high cover densities might reduce water amounts reaching soil surface due to interception, then limiting soil water availability (Dabney et al., 2001)

Organic mulching use might contribute to increase crop production and also to enhance soil and crop quality, particularly in areas under water scarcity and subject to adverse climate change scenarios. Ranjan et al. (2017) have evaluated the advantages of organic mulching for increase the production of fruits and vegetables. For the brazilian semiarid, climate changes are expected to increase temperatures and reduce rainfall amounts (MARENGO et al., 2017; CARVALHO et al., 2020). Hence, conservation practices in rural lands are required for such areas.

Regional studies have revealed the high potential of organic mulching for soil and water conservation, based on vegetation types usually available on their respective locations. Cerdà et al. (2017) have studied the long-term performance of 1.25 t ha-1 oat straw being applied yearly in Spain, verifying its strong impact on runoff and soil losses reduction in rainfed agriculture and pasture areas. Keesstra et al. (2016) used vegetative cover and pruning residues from the apricot culture itself, being managed for 20 years, in the river Albaida basin, in the north of the province of Valencia, in the east of Spain. Lucas-Borja et al. (2019) carried out experimentation with the use of straw, at a density of 2 t ha-1 in southwestern Spain. Borges et al. (2014) used elephant grass straw, with an application rate of 7 t ha-1 and applied to corn planting in the semiarid region of Pernambuco, Brazil. In the same region and agricultural cultivation, Carvalho et al. (2019) used coconut straw, with an application rate of 8 t ha-1, for rainfed cultivation of corn.

Shen et al. (2012) evaluated the effect of different rates of wheat straw mulch (0.6 and 12 t ha-1) on the soil, under rainfed conditions, during the years 2009 and 2010, in northern China, with two varieties of corn, verifying that the adopted cover contributed to the increase of soil moisture to a depth of 20-80 cm, during the ear-anthesis phase. These authors also noted that grain yield was higher with the presence of mulch at the highest application rate (12 t ha-1), compared to other treatments.

In the assessment of surface hydrological processes, it is understood that soil cover with mulch initially retains part of the gross rainfall through the interception and absorption processes, and then, under conditions close to saturation, release water excess to the soil surface. This process is similar to throughfall, which occurs after natural vegetation begins to allow rain drops to pass through the soil (STUART et al., 2006; SILVA et al., 2019).

The initial water storage capacity for a mulch cover is important due to the delay in the beginning of the flow of the drainage process, and represents the amount of water close to that required to completely saturate the cover (DAVID et al., 2005). Depending upon cover architecture and density, high variations for the initial flow abstraction might be observed, and a larger abstraction may occur for greater coverage densities. Lopes and Montenegro (2017) observed different initial abstractions by modelling overland flow at experimental plots using the SMAP Model, under varying levels of soil cover in the semiarid.

De Lima et al. (2019) addressed the effect of the size of rice straw mulch applied on the soil surface on runoff and soil loss conducting experiments using a soil flume and a rainfall simulator, for three sizes of rice straw mulch (10 mm, 30 mm and 200 mm). The experimental results showed that for the same mulch application rate (by weight), the smaller mulch sizes (i.e. high surface coverage percentage) presented less soil loss. However, for the tested rice straw application rates, runoff volume decreased with increasing mulch size mainly because of differences for water absorbed by mulch of different sizes.

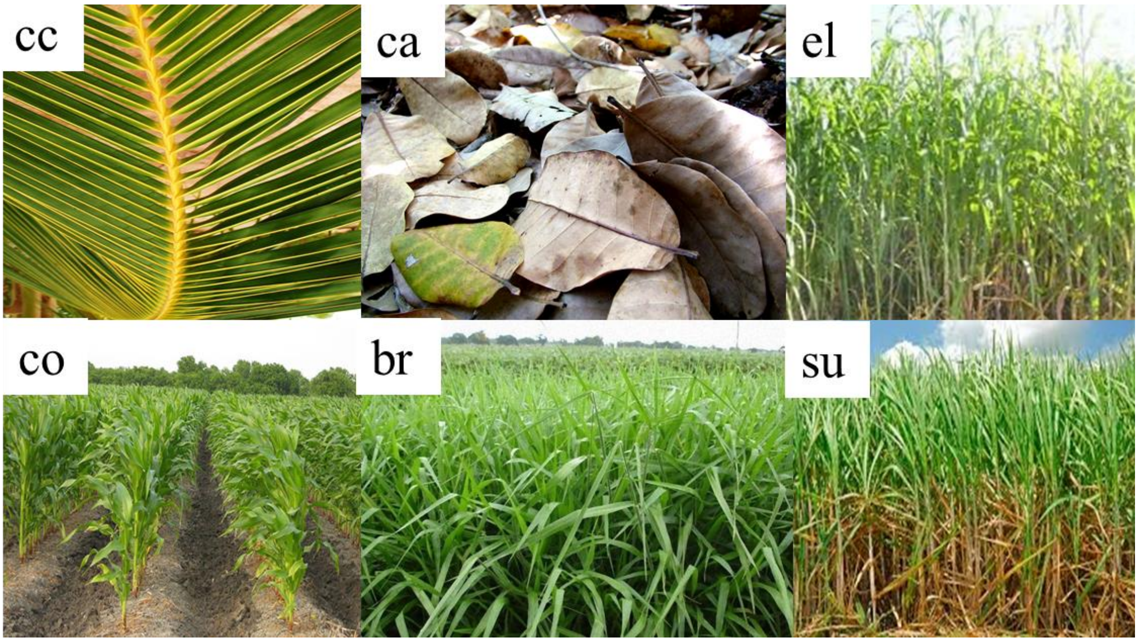
In spite of the previous mentioned works regarding mulching impacts on hydrological processes, studies looking at rainfall interception for different organic mulching densities, cutting sizes, and types are still lacking.

Thus, the aim of this study was to investigate the process of rainwater interception (i.e., retention and absorption) by different types, sizes and densities of some organic coverings that are commonly found in the Brazilian semiarid region. These results are important for the management of soil and water conservation practices in semi-arid environments.

3. MATERIAL AND METHODS

The organic coverings used (Fig. 1) in this study came from tropical crops and have large availability in the Brazilian semiarid region. Six organic coverings were used, being coconut leaf and (cc), cashew leaf (ca), elephant grass (el), corn leaf (co), brachiaria grass (br) and sugar cane leaf (su). Other mulch covers could be studied but these six apparently had more potential, particularly presenting high carbon versus nitrogen ratio, which reduces mulch degradation (OLIVEIRA el al., 2008).

Fig. 1. Photographs of: coconut leaf and (cc), cashew leaf (ca), elephant grass (el), corn leaf (co), brachiaria grass (br) and sugar cane leaf (su).



Thus, the choice of plant materials was based on a higher C / N ratio, which contributes to less degradation, helping to maintain cover for longer time at the soil surface. Corn has a ratio of 35.3 (TORRES et al., 2005), brachiaria grass 32.5 (SOUZA et al., 1999), Sugar cane 122.5 and coconut leaf 63.7 (SILVA et al., 2013), Elephant grass 41.7 (FLOWERS et al., 2013) and cashew leaf 38 (DOMÊNICO et al., 2018).

The use of corn, brachiaria grass and sugar cane straw as soil cover is already widespread, while, with local field experience, elephant grass, cashew leaves and coconut leaves stand out. All the coverages adopted have advantages such as high availability, with no associated costs and presenting a high carbon / nitrogen ratio, thus facilitating use by all farmers.

After their harvest, the vegetable materials were dried and cut to form a homogeneous vegetable mass, adopting the 50, 100 and 200 mm sizes. Subsequently, they were weighed in quantities corresponding to the densities of 1, 2, 4 and 8 t ha^{-1} and distributed uniformly over the test area.

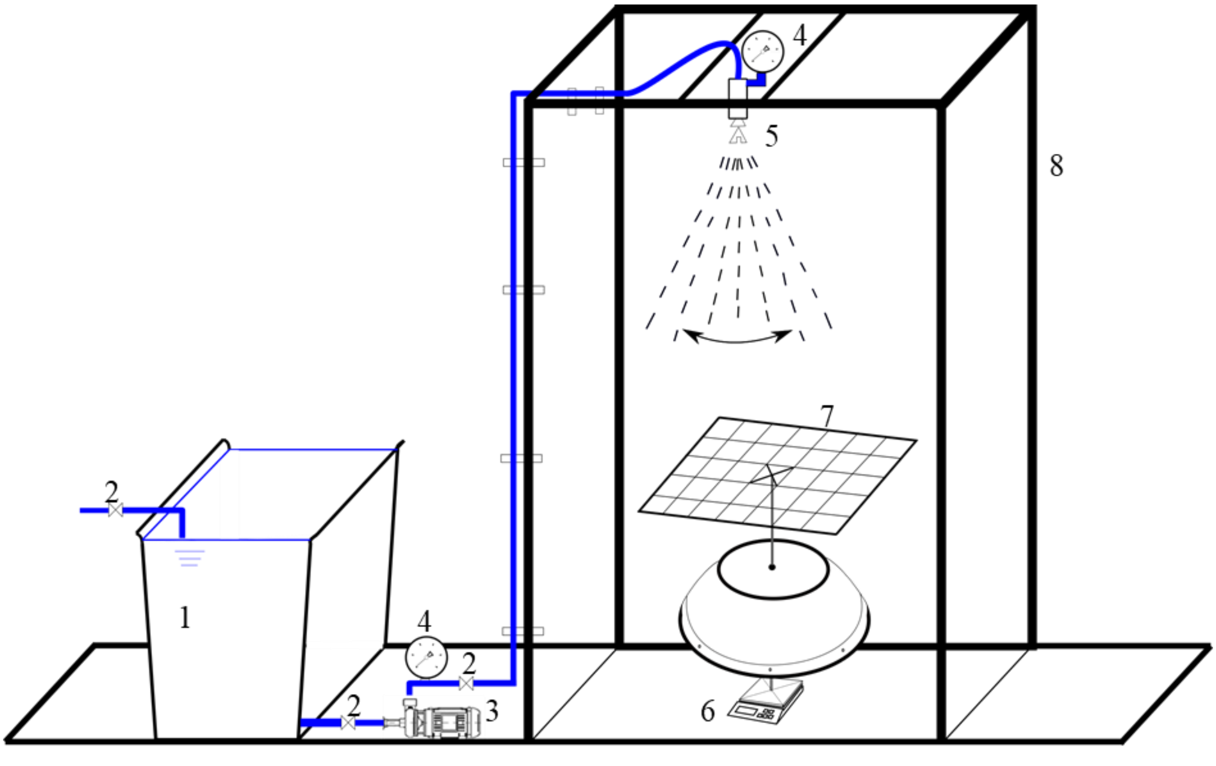
The adopted area was a planar horizontal rectangle with 270 x 420 mm dimensions (the largest size was in the direction of oscillation of the emitting nozzle in the rain simulator, see Fig. 2), and capable of allowing the distribution of all coverings, sizes and densities with adequate uniformity. For each density previously presented, the necessary mass for the adopted area was obtained (Ta*ble 1).

Table 1. Masses used for each density, for the area adopted in the experiment.

Mulch Density (t ha^{-1})	Mass (kg)
1	0.113
2	0.226
4	0.453
8	0.907

The rainfall simulator used consists of a square metallic structure, with a free span of 2 m in length and the emitting nozzle is positioned at a height of 2.5 m (Fig. 2). It has an oscillating nozzle, being adopted the VeeJet 80.100 (Spraying System®) type. The simulator also has a centrifugal pump of 367 W (1/2 CV), working with positive suction head coupled to a 1000 l reservoir. At the outlet of the pump there is a valve and a pressure gauge that allows it to operate at different service pressures, consequently allowing variations in precipitation intensity, uniformity distribution and drop diameter, for each service pressure.

Fig. 2. Sketch of the laboratory setup, being 1 - reservoir, 2 - valves, 3 - pump, 4 - manometer, 5 – oscilating nozzle, 6 – weighing device, 7 – mulch support and 8 – rainfall simulator support.



The simulator was adjusted to operate at a pressure of 80 KPa for all simulations. The simulator was calibrated in a closed environment and without the interference of wind currents or direct solar radiation.

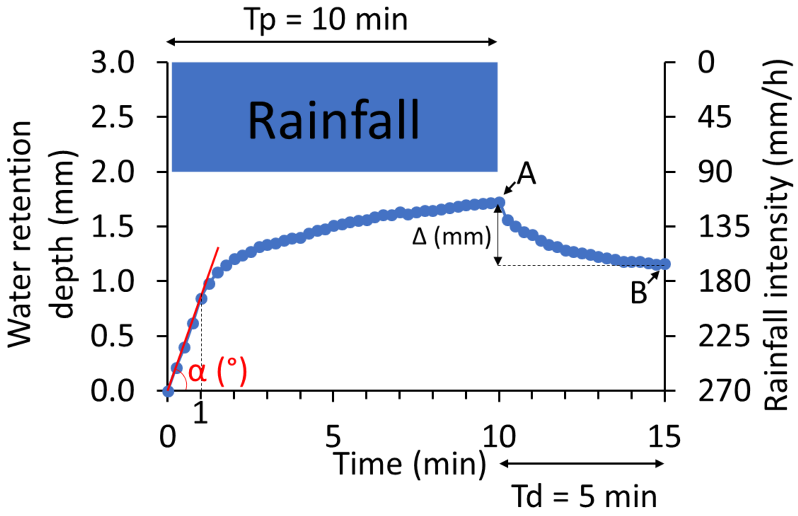
The set of structure together with a high precision digital scale, adapted to support the rectangular structure with the mulch, allowed to monitor every 15 seconds the water retention by the aforementioned organic coverings and in this that allowed the water retention and absorption curve being built for all covers. The readings were performed in a non-automated way and followed an interval time similar to experiments with measurements of flows using vegetation cover.

The time duration of 10 minutes was used for the rainfall simulation adopting a uniform intensity of 90 mm h^{-1}, being observed the interception and water retention processes every 15 seconds through weighing, and an additional 5 minutes period to observe the loss of drainable of the weighing observation. Raindrop sizes were evaluated using the flour pallet methodology, which had a mean diameter of 3.2 mm, with a minimum of 1.9 mm, a maximum of 6.2 mm, and a standard deviation of 0.9.

The time duration choice took into account the studies by Confessor and Rodrigues (2018) that used a period of 30 minutes to verify surface and sub-surface processes. Thus, considering only the coverage assessment carried out in this study, a 10 minute rainfall duration period was adopted. The choice of intensity was based on previous studies that used typical semi-arid rain and therefore 90 mm h^{-1} was used for a recurrence period of ~ 10 years (SANTOS et al., 2008; SILVA et al., 2012), being classified as an extreme rain.

With the registration of the masses displayed on the scale, it was possible to construct the temporal evolution curve of water retained and absorbed, as shown in Fig. 3. The hydrograph is similar to that presented by Niziolomski et al. (2020) which, despite carrying out measurements under natural conditions, successfully built the runoff hydrograph curves since rainfall beginning until the events end, allowing the processes stabilization to be observed.

Fig. 3. Sketch with variables involved water retention and absorption in time for a given organic mulching cover, for a rainfall with 10 minutes duration, being α - angle referring to initial retention speed, and Δ - drained depth.



Absorption capacity was determined based on de Lima et al. (2019) throughout the experiment. For time “t”:

$$Absorption\ capacity\ (\%) = \frac{W_t - W_{dry}}{W_{dry}} \times 100$$

where:

w_t is weight of wet mulch at time t;

w_{dry} is weight of mulch before start of rainfall event.

Additionally, in order to investigate both the interception process, during the rainfall event, and the water drainage from mulch after rainfall stop, for different mulch densities and sizes, a lumped analysis was carried out considering the mean experimental results for all mulch types together. Then, numerical analysis was performed in order to identify possibly typical patterns for the for the hydrographs.

Instead of adopting a power function (like chosen by Samba et al., 2001), exponential functions with asymptotic behaviour were tested, such as:

$$w(\varphi) = c_1(1 - e^{-\left(\frac{\varphi}{a}\right)^{\alpha}})$$

were “φ” is the gross rainfall, for analysing interception during the rainfall period, while “φ” is the time, for the drainage period, after rainfall stop.

Parameter “c_1” is called the sill, “a” is the range of the function, and α is a form factor. Journel and Huijbregths (1978) called such function as exponential (for $\alpha=1$) or as gaussian (for $\alpha=2$). The parameter α is related to the angle in Figure 3.

The reason for selecting such functional is due to the nature of both the interception process and the water drainage from canopy, which usually presents an asymptotic behaviour as φ increases. Hence,

$$lim_{\varphi \to \infty} w(\varphi) = c_1$$

Then, “c_1” will be related either to canopy saturation or the cessation of drainage from the mulch surface, disregarding evaporation from canopy.

The experimental scheme was factorial of 6 types of coverings, as seen above, with 3 much sizes (50, 100 and 200 mm) and 4 densities (1, 2, 4 and 8 t ha^{-1}), totalling 72 experimental treatments, in which repetitions were performed in triplicate. Analysis of variance was performed. Significant means test (Tukey) was applied to significant treatments, at levels of 1 and 5% probability.

The adjustments were evaluated based on the Coefficient of Determination (R^2), as well as the Willmott Agreement Index (d)

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}[|P_i - \bar{O}| + |O_i - \bar{O}|]^2}$$

Willmott's (1981) agreement index (d) is a measure of the degree to which forecasts are error-free, which is to say, reflects the degree to which the observed variation is accurately estimated by the simulated variation. It varies between 0.0 and 1.0, where the value of 1.0 indicates perfect agreement. In addition, the performance index (c) (CAMARGO and SENTELHAS, 1997; CUNHA et al., 2013) was calculated, as the product between the correlation coefficient (r) and Willmott index (d), and classified according to Table 3.

Table 1. Criteria for interpreting the performance index "c"

Index “c”	Classification
> 0.85	Great
0.76 – 0.85	Very good
0.66 – 0.75	Good
0.61 – 0. 65	Median
0.51 – 0.60	Sufferable
0.41 – 0.50	Poor
≤ 0.40	Very poor

Source: CAMARGO and SENTELHAS (1997).

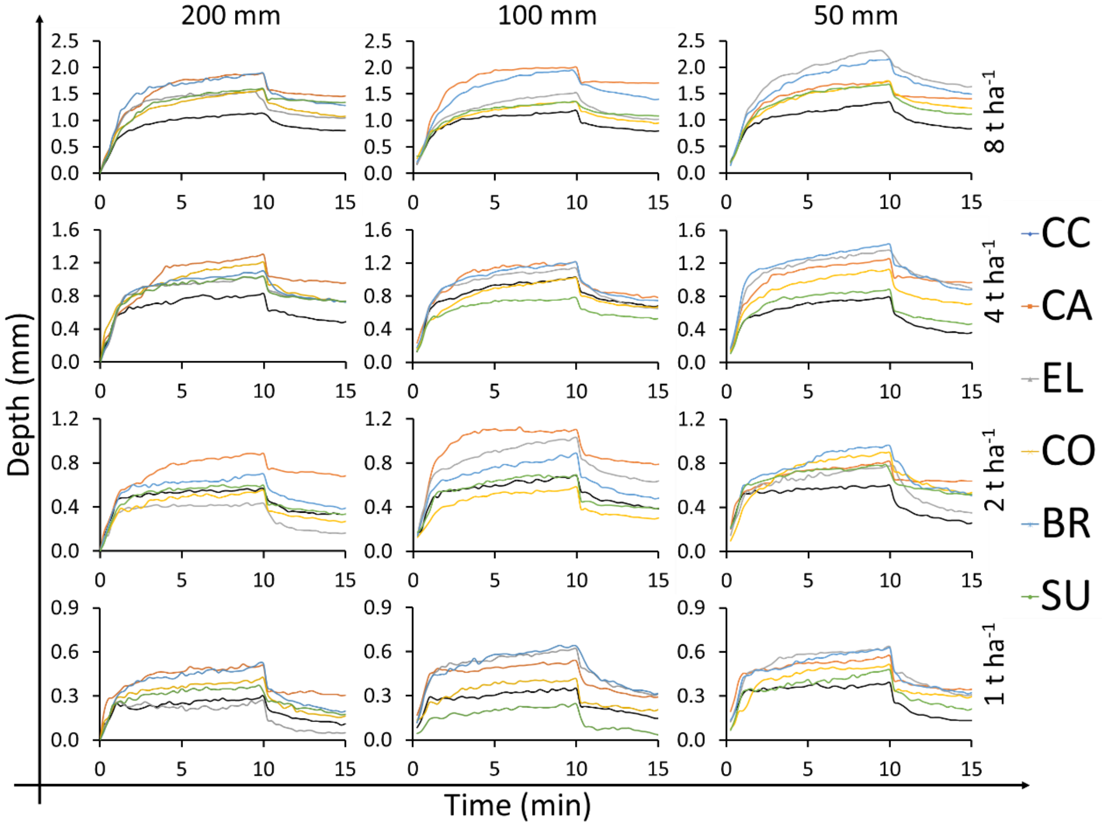
4. RESULTS AND DISCUSSION

4.11 General behavior of retained and absorbed depths

The temporal behavior of the retained and absorbed depths for 15 minutes can be seen in Fig. 4. The behavior presents a standard pattern (see Fig. 3), with retention at a higher rate for the first seconds and later a trend to stabilize when approaching 10 min. When the rainfall event stops (at 10 min), there is a water depth available to drain, presenting a trend to stabilize in 5 minutes time.

The highest densities showed the largest depths being retained and absorbed. It is observed that CC, CA and El treatments the largest depths.

Fig. 4. Water retention and absorption by the different mulch covers for different mulch sizes and densities, being cc - coconut leaves, ca - cashew leaves, el - elephant grass, co – corn plant, br - brachiaria grass, su - sugar cane plant (see Fig. 1).



4.2 Initial absorption by different covers

Significant differences in the beginning of retention process can be observed among treatments, in which the initial absorption angles of each treatment were evaluated, as can be observed in Fig. 4. Statistical result of analysis of variance for the different organic coverings used can be observed in Table 4. They presented statistical differences when observing the factors type, size, density and the interaction between type and size.

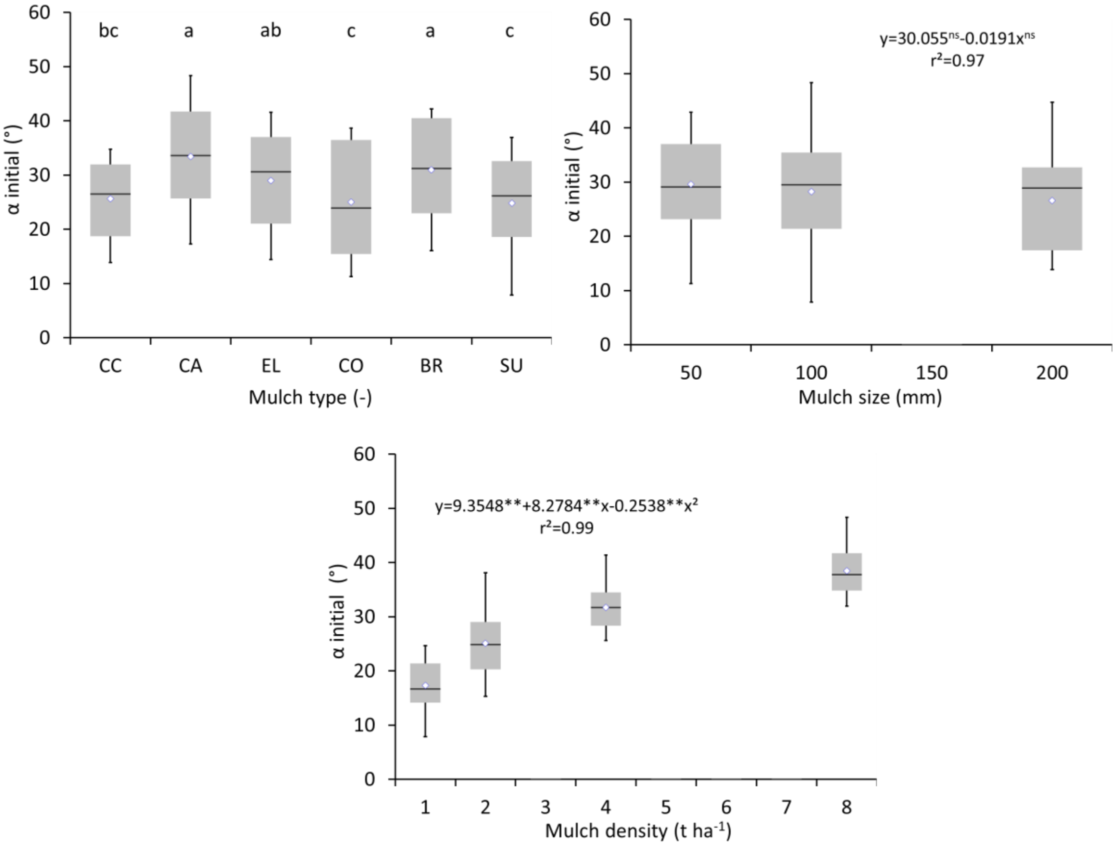
Table 4. Analysis of variance for type, size and density for initial depth retention angle (°).

FV	GL	SQ	QM	Fc	Pr>Fc
TYPE	5	1258.255	251.651	14.541	0.000
SIZE	2	314.958	157.479	9.100	0.000
DENSITY	3	11286.685	3762.228	217.396	0.000
TYPE*SIZE	10	526.004	52.600	3.039	0.002
TYPE*DENSITY	15	428.575	28.572	1.638	0.071
SIZE*DENSITY	6	83.814	13.969	0.801	0.571
TYPE*SIZE*DENSITY	30	648.443	21.615	1.239	0.203
error	150	2595.887	17.306		
Total corrected	215	17058.807			

The results obtained for the initial angle of water absorption by the coverings quantify the observations of several studies that report that the varied densities have an immediate effect on the of soil erosion control, reducing soil erodibility. In this study, with the use of intense rainfall, the importance of using vegetation cover and higher densities is highlighted by the greater initial retention, that is, there is a reduction in the kinetic energy on the soil as observed by Dunkerley (2000) and Montenegro et al. (2013), and for the first minute after the event beginning, low rainwater depth is transmitted to the soil surface.

These initial rain interception speed measurements are rarely performed when evaluating mulch performance. Significant differences were observed for type (Tukey) and density (polynomial regression) of coverage (Fig. 5A and 5C). Thus, it is highlighted that there will be differences among mulch treatments for the time for runoff initiation.

Fig. 5. Initial water retention depths for 10 min after rainfall start, and 5 min after rainfall stop as a function of mulch type (A), size (B) and density (C).



It is also observed that the flow delay contributes to the water infiltration rate in the soil. Yang et al. (2020) observed that the coverage by corn straw, in a no-tillage system, allowed greater grain yield and higher water use efficiency, due to the lower runoff, and also the soil moisture conservation effect.

The results for greater initial retention associated to higher densities can be explained by the greater amounts of surface materials available for adhesion and cohesion processes, in addition to the water storage in the roofs micro relief. Niziolomski et al. (2020) also associates the greater retention capacity with the increase of the surface roughness, enhancing friction to the flow, and increased storage associated to micro-obstacles in the vegetation cover.

4.3 Absorption and retention by different covers

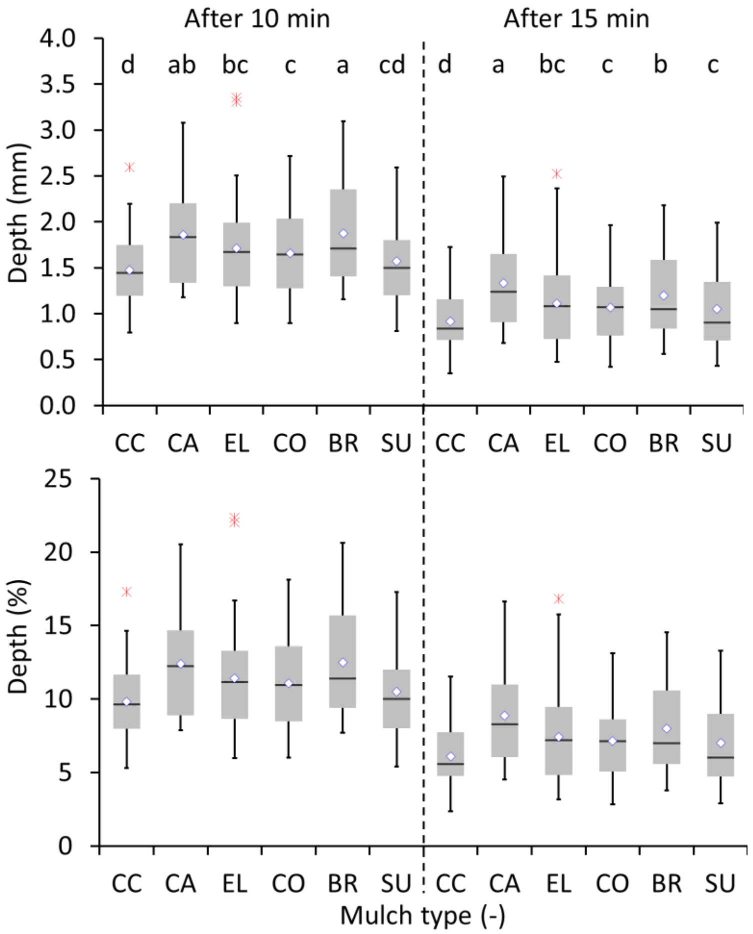
Table 5 shows the analysis of variance, which shows the significance of the isolated factors, as well as their interactions.

Table 5. Analysis of variance for type, size and density.

FV	GL	SQ	QM	Fc	Pr>Fc
TYPE	5	4.438	0.888	23.258	0.000
SIZE	2	0.921	0.460	12.061	0.000
DENSITY	3	40.970	13.657	357.861	0.000
TYPE*SIZE	10	1.835	0.183	4.808	0.000
TYPE*DENSITY	15	1.078	0.072	1.884	0.029
SIZE*DENSITY	6	0.451	0.075	1.968	0.074
TYPE*SIZE*DENSITY	30	1.005	0.033	0.878	0.652
Error	144	5.495	0.038		
Total corrected	215	56.192			

When looking at the coverings types, brachiaria grass and cashew leaf were the most efficient to retain the largest depths, while for the absorption depths, cashew was superior to brachiaria grass, differing significantly (Fig. 6). Values of the retained and absorbed depths by the coconut leaf were low, being the smallest ones statistically.

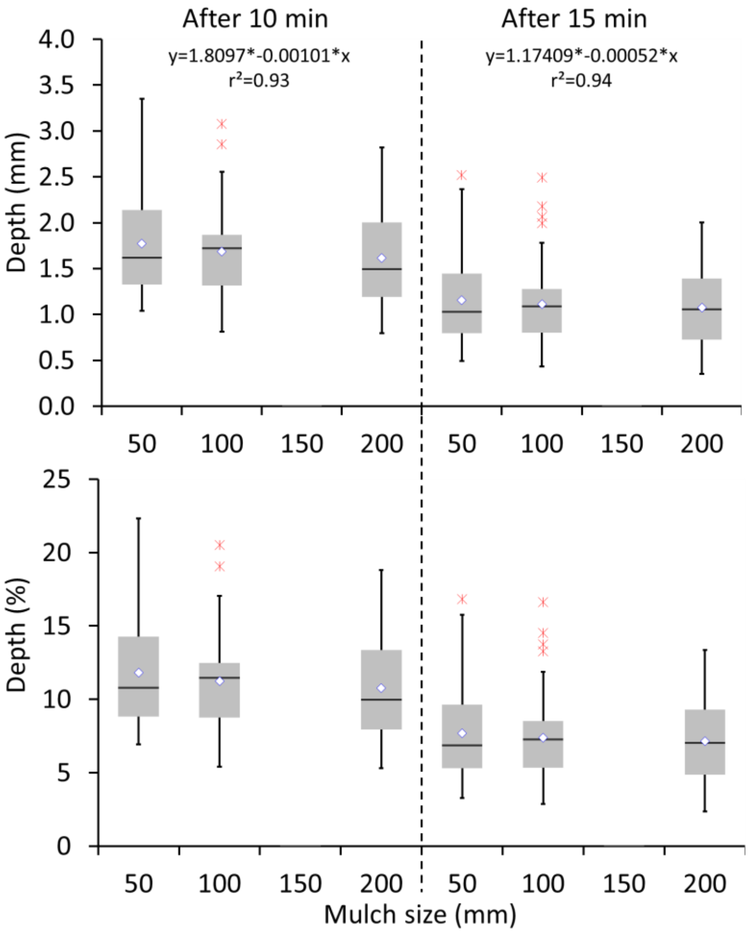
Fig. 6. Water retention (after 10 min) and absorption (after 15 min), in mm (on top) and a percentage of rainfall (on bottom) for all mulch types (all mulch sizes and all densities).



Dosages greater than 8 t ha^{-1} of elephant grass have already been used for the purpose of controlling agricultural and hydrological pathogens, showing similar results due to the amount of soil covered area. Yagi et al. (2020) observed positive results for the use of chopped elephant grass, at a dose of 60 t ha^{-1} (84.8% humidity), which corresponds to approximately 9 t ha-1 in dry mass, which was applied over an area cultivated with potato.

When assessing the size of the mulch covers, it appears that although there is a significant difference (Table 2), the degree 1 polynomial equation does properly represent (at 5%) the variations in the mean retained or absorbed depth as a function of the size values of 50, 100 and 200 mm (Fig. 7). Qu et al. (2019) used different soil coverings, including organic ones which despite having varying sizes, did not provide changes for soil moisture content, and were still superior than the inorganic coverings, successfully decreasing the soil evaporation rate.

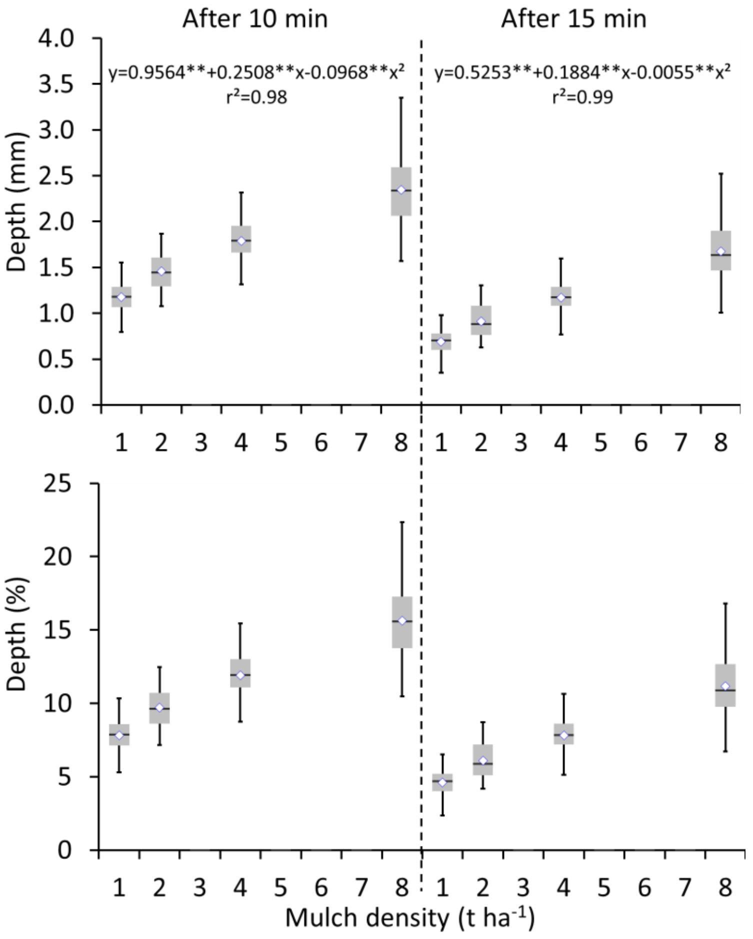
Fig. 7. Depth retained (after 10 min) and absorbed (after 15 min), in mm (top) and as % of rainfall (bottom), for different mulch sizes (all mulch types and all densities)



Retained and absorbed depths as a function of mulch density is presented in Fig. 8. It is possible to observe the proper adjustment to the data by the second order polynomial equation, with significance at 1% probability. It is also observed a 8-fold increment in density induced an increase of approximately 2.5-fold in absorption.

Considering all mulch types and sizes, the highest absorptions and retentions are observed for 8 t ha^{-1} density. Niziolomski et al. (2020) observed that in addition to water retention by the surface of, high-density mulch treatments (already reported above), the time for the beginning of runoff is controlled by to the formation of barriers over the cover / soil interface, particularly when density is high, enhancing water storage that delay runoff generation and promote higher infiltration rates.

Fig. 8. Depth retained (after 10 min) and absorbed (after 15 min), in mm and in%, for mulch densities (all mulch type and all sizes)



4.4 Depth drained by different covers

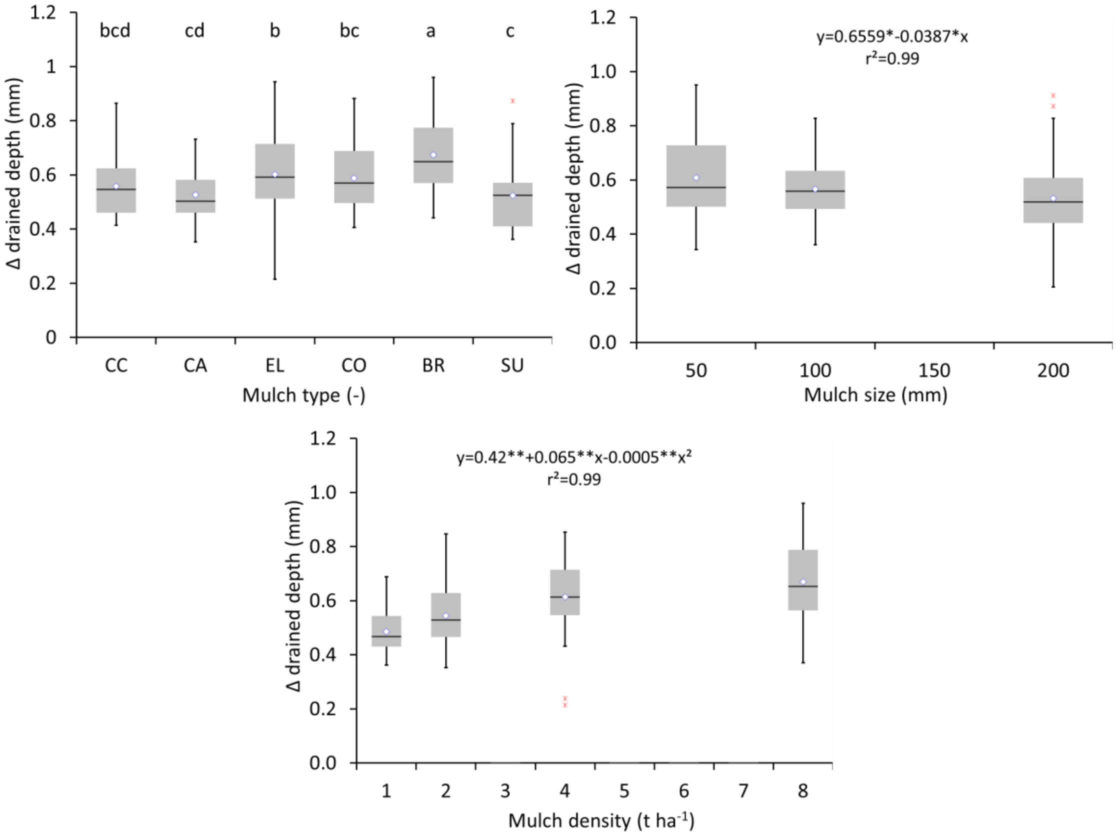
It can be seen in Table 6 that the drained depths (delta value represented in Fig. 3) presented statistical differences when observing the factors type, size, density and the interaction between type and size. The local evaporative capacity was neglected, due to the indoors simulation, and the short exposure time of the experiment.

Table 6. Analysis of variance for drained depth.

FV	GL	SQ	QM	Fc	Pr>Fc
TYPE	5	0.570	0.114	14.954	0.000
SIZE	2	0.222	0.111	14.604	0.000
DENSITY	3	1.056	0.352	46.199	0.000
TYPE*SIZE	10	0.374	0.037	4.915	0.000
TYPE*DENSITY	15	0.118	0.008	1.038	0.420
SIZE*DENSITY	6	0.106	0.018	2.334	0.035
TYPE*SIZE*DENSITY	30	0.306	0.010	1.341	0.130
error	144	1.098	0.008		
Total corrected	215	3.855			

The water flow through the voids for each organic cover, which represents the inverse of the delta value, can be crucial for the surface runoff beginning, and have consequences in terms of water and soil losses. In Figure 9A it can be seen that the brachiaria grass had the largest drained depth, with a value of approximately 1.2 higher than cashew cover.

Fig. 9. Difference of water retention between 10 min and 15 min depths (5 min after rainfall ends) as a function of mulch type, size and density.



It is noteworthy the statistical difference provided by the size of the organic coverages adopted, in which the highest retentions are associated with smaller sizes. After rainfall events, the water trapped in the substrates will be partly evaporated and partly transmitted to the soil.

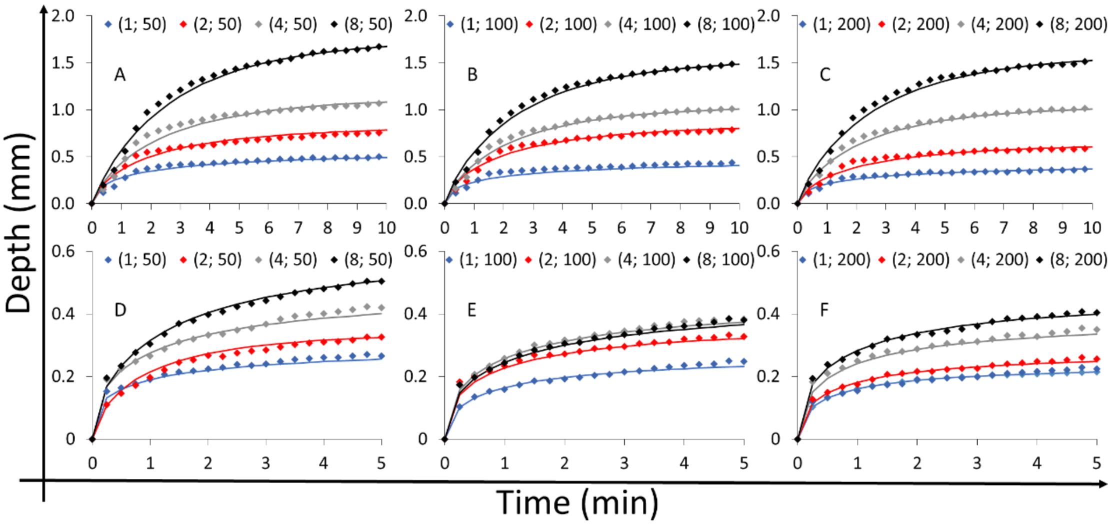
The use of organic cover dosages close to 2 t ha^{-1} already promotes the retention / absorption of a significant amount of rainwater when compared to not using it (Fig. 9C), delaying runoff and consequently water and soil losses. It was also verified by Cerdà et al. (2017), in a study with a 30-year database, observing that the use of soil cover with oat straw at 1.25 t ha^{-1} provided a runoff of 7 to 1.9% of precipitation, with an average value of 4.2%. And for the control (bare soil) the discharge was greater, varying from 12.7 to 3.3% of the rains, with an average of 7.3%.

Storage capacities vary according to the geometric shape of the cover, with the highest storage capacity observed for coverage with brachiaria grass. When this capacity is exceeded, water can be channelled in a flow similar to that of the rainfall and delivered more efficiently to the soil, due to less kinetic energy. Similarly, with the use of natural cover, it allows retention that could be allowing greater runoff if the interception had not occurred, increasing the water use efficiency, especially for light rainfalls (Dunkerley, 2000).

De Lima et al. (2019) used rice straw (Oryza sativa L. ssp. japonica) with three sizes: 10 mm, 30 mm and 200 mm and found that, under rainfall of 84 mm h^{-1} intensity during 15 min, the rice straw capacity to absorb water is greater for the longer stripes (~70% by weight) and lower for the 10 mm and 30 mm sizes (respectively with 25% and 55%). de Lima et al. (2019) estimated the absorption capacity of the rice straw by placing 100 grams of dry mulch on a 20% slope covered with impermeable sheet.

The lumped experimental values based on the mean measurements for all mulch types together is presented in Fig. 10, for the rainfall period and for the drainage period (after rainfall cessation), regardless the mulch type. Exponential fitting is also presented, for each mulch size and mulch density. It can be verified that canopy saturation was achieved during the rainfall period (10 minutes, delivering a gross amount of 15 mm), and that drainage from mulch surface reached an equilibrium. Note that the delta value was inverted, in order to represent drainage (and, then, potential soil moisture increase in field underneath mulching).

Fig. 10 - rainfall interception for 1, 2, 4, 8 t ha^{-1} mulch densities, and 50 ,100, 200 mm mulching sizes (A,B and C, respectively); rainfall drainage for 1, 2, 4, 8 t ha^{-1} mulch densities, and 200, 100, 50 mm mulching sizes (D, E and F, respectively).



The optimal parameters for the exponential model and the fitting metric values are presented in Table 4. Coefficient of determination, Willmott and performance coefficients were all very high. Hence, the adopted exponential model with three parameters represented well the experimental data.

Table 4- Exponential model parameters and performance, for different mulching sizes and densities, regardless mulching types.

Rainfall interception

	1;200	2;200	4;200	8;200	1;100	2;100	4;100	8;100	1;50	2;50	4;50	8;50
c1	0.41	0.64	1.05	1.60	0.45	0.85	1.05	1.55	0.55	0.83	1.14	1.75
a	1.90	2.20	2.30	2.70	1.90	2.20	2.30	2.60	2.00	2.20	2.50	2.80
alfa	0.50	0.70	0.80	0.86	0.50	0.70	0.80	0.86	0.50	0.70	0.80	0.90
R^2	0.97	0.97	0.99	0.99	0.97	0.98	0.99	0.99	0.97	0.99	0.98	0.99
d	0.99	0.99	1.00	1.00	0.96	0.99	1.00	1.00	0.99	0.99	0.99	1.00
c	0.98	0.98	0.99	0.99	0.95	0.98	0.99	1.00	0.97	0.99	0.98	0.99

Rainfall drainage

	1;200	2;200	4;200	8;200	1;100	2;100	4;100	8;100	1;50	2;50	4;50	8;50
c1	0.23	0.27	0.37	0.45	0.26	0.36	0.43	0.43	0.30	0.34	0.46	0.58
a	0.70	0.80	0.90	1.00	1.00	1.00	1.20	1.40	1.00	1.00	1.20	1.50
alfa	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.40	0.70	0.50	0.60
R^2	0.98	0.99	0.99	0.99	0.99	0.99	1.00	0.99	0.99	0.99	0.99	1.00
d	0.99	0.99	1.00	1.00	0.96	0.99	1.00	1.00	0.99	0.99	0.99	1.00
c	0.98	0.98	0.99	0.99	0.95	0.98	0.99	1.00	0.97	0.99	0.98	0.99

As c1 is associated to a threshold interception depth, either in terms of canopy storage capacity or of drainage from canopy surface, it is worth to analyse c1 as function of mulch size and mulch density.

It has been verified that a linear multiple regression model fits well to experimental data (from Table 4), as following, respectively for the rainfall and no rainfall periods:

$$c_1 = 0.4970 + 0.1588\,MD - 0.0009\,MS \qquad (R^2 = 0.9692)$$

$$c_1 = 0.3257 + 0.0306\,MD - 0.0006\,MS \qquad (R^2 = 0.8524)$$

Where MD is the mulch density and MS is the mulch size, referring to the mean behavior of both interception (storage capacity) and drainage potential of the mulching materials (jointly) adopted in this study.

In this study, a contrasting behaviour has been found for 200 mm, 100 mm and 50 mm sizes. According to Fig. 7, which is consistent to the multiple linear model developed from the lumped analysis, an increase on size produces a decrease in mulch storage, from the mean experimental data for coconut tree, Elephant Grass, Brachiaria, Sugar Cane, Cashew leaves, and corn leaves jointly.

As expected, mulching density increase resulted in an increase in water retention by the mulching surface.

5. CONCLUSIONS

In this paper mulch cover retention and absorption under simulated rainfall of several organic residues with different sizes and densities were evaluated.

It is observed that the increase in application density systematically leads to an increase in water retention and absorption. For 8 t ha^{-1} the values were 11-23% and 7 to 16% of the rainfall depth, respectively, for the studied conditions. When comparing 8 t ha^{-1} with 2 t ha^{-1}, increases higher than 100% in rainfall retention and absorption were obtained.

We obtained higher performance for cashew leaf and brachiaria grass and cashew leaf, whcih promoted better water retention and absorption, respectively. Coconut leaves promoted only 83% retention and 67% water absorption, when compared to the cashew and brachiaria grass, respectively.

The highest retentions are associated with smaller sizes adopted for organic coverings. The depth retained for 50 mm varied from 7 to 23% of the rainfall and, for the 200 mm, it varied from 5 to 18%. For the absorbed depth, the percentages were 4 to 18% and 2 to 14%, respectively.

The adoption of organic cover dosages from 2 t ha^{-1} promotes significant retention/absorption, contributing to a possible delay in the onset of runoff, an increase in water infiltration and a consequent reduction in water and soil losses.

The results obtained in the laboratory should be confirmed in situ in erosion plots under natural rainfall. Further evaluation on slopes, with full and partial coverage, is a suggestion for future research.

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FINAL CONSIDERATIONS

In view of the results obtained, relevant information has been provided from investigations of surface hydrological processes, soil conservation techniques and cultivation conditions in the semi-arid region of Pernambuco State. The emphasis was on the use of mulch and experiments on experimental plots. Final considerations can be summarized as follws:

1. The electromagnetic induction equipment (EM38®) used was efficient to verify the presence of salts in the alluvial soil of the Brígida River valley, in Parnamirim, Pernambuco State, Brazil.
2. The effect of mulch due to the deciduous characteristics of the Caatinga vegetation is important for soil moisture maintenance, contributing to the development and preservation of the vegetation biomass of the riparian forest.
3. High covariance between soil moisture and apparent electrical conductivity was identified in the fallow area and in cultivation at 0 - 0.3; 0.3 - 0.6 and 0.6 - 0.9 m layers, under conditions of extreme water scarcity. For alluvial areas, a covariance of soil moisture with ECa is detected, as well as the occurrence of strong spatial dependence.
4. An initial detailed sampling in the field for monitoring and precision management purposes allows future sampling to be minimized to sample points, being at distances no greater than the pre-established dependency range lengths.
5. Mulch cover is more efficient as a soil conservation technique than Palma cactus, although Palma has significantly increased soil moisture and reduced water erosion in comparison to bare soil.
6. Natural cover semi-arid scrub forest (Caatinga) produces less runoff and sediment loss when compared to bare soils and soil conservation practices (mulch and palm).
7. The intensity was found to be the rainfall most important factor in generating runoff and soil losses.
8. Increasing mulch density application leads to increased water retention and absorption in the mulch cover.
9. The adoption of organic cover dosages from 2 t ha^{-1} already promotes significant retention/absorption, contributing with possible delay to the start of runoff, increased water infiltration and consequent reduction of water and soil losses.