Universidade Federal Rural do Semi-Árido
Pró-Reitoria de Pesquisa e Pós-Graduação
https://periodicos.ufersa.edu.br/index.php/caatinga

ISSN 0100-316X (impresso)
ISSN 1983-2125 (online)
http://dx.doi.org/10.1590/1983-21252023v36n410rc

Alterations of physical-chemical attributes of a vertisol in a melon production area

Alterações de atributos químicos e físicos de vertissolo em área de produção de meloeiro

Flávio de O. Basílio[1]*, Marcelo T. Gurgel[2], Kaline D. Travassos[3], Neyton de O. Miranda[2], Lucas R. da Costa[4], Peter J. Dumas[5]

[1]Ecosafety, Mossoró, RN, Brazil. [2]Department of Agronomic and Forest Sciences, Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil. [3]Instituto Nacional do Semiárido, Campina Grande, PB, Brazil. [4]Department of Agronomy, Faculdade de Enfermagem Nova Esperança de Mossoró, Mossoró, RN, Brazil. [5]Universidade Federal Rural do Semi-Árido, Mossoró, RN, Brazil.

ABSTRACT - Water quality and soil quality are of great importance for crop yield in the context of small-scale irrigated agriculture in the Northeast region of Brazil. In this respect, this study aimed to determine changes in soil fertility and resistance to root penetration caused by fertigated cropping, as compared to soil under native forest. In each area, a non-regular sampling grid was established, which consisted of 87 georeferenced points in the melon cultivated area and 8 points in the native forest area. At these points, samples were obtained at depths of 0-10, 10-20, 20-30 and 30-40 cm. The determinations performed included soil physical, chemical and mechanical attributes. Multivariate analysis techniques and geostatistical procedures were used to analyze and interpret the data. The cultivation of the Vertisol altered all the variables studied, compared to the area under native forest. Soil decompaction and increase in phosphorus content were positive effects, while organic matter decomposition and reductions in potassium, calcium, magnesium and cation exchange capacity were negative effects. Sodium content and porosity parameters were prominent factors in soil alterations.

Keywords: *Cucumis melo* L. Soil management. Soil attributes. Semi -arid region.

RESUMO - A qualidade da água e do solo têm grande importância para a produtividade das culturas no contexto da pequena agricultura irrigada na região Nordeste do Brasil. Neste sentido, este estudo visou determinar as alterações na fertilidade e na resistência do solo causadas pelo cultivo fertirrigado, em relação ao solo sob mata nativa. Em cada área foi estabelecida uma grade de amostragem não regular, as quais constaram de 87 pontos georreferenciados, na área cultivada com melão, e 8 pontos na área de mata nativa. Nestes pontos foram obtidas amostras nas profundidades de 0-10, 10-20, 20-30 e 30-40 cm. As determinações realizadas incluíram atributos físicos, químicos e mecânicos do solo. Técnicas de análise multivariada e procedimentos de geoestatística foram empregadas para analisar e interpretar os dados. O cultivo do Vertissolo alterou todas as variáveis estudadas, em relação à área sob mata nativa. As alterações positivas foram a descompactação do solo e o aumento no teor de fósforo e as negativas foram a decomposição da matéria orgânica e a redução nos teores de potássio, cálcio, magnésio e na capacidade de troca de cátions. O teor de sódio e os parâmetros de porosidade foram fatores de destaque nas alterações do solo.

Palavras-chave: *Cucumis melo* L. Manejo do solo. Atributos do solo. Região Semiárida.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

Received for publication in: March 7, 2022.
Accepted in: August 16, 2023.

***Corresponding author:**
<fbasilio780@gmail.com>

INTRODUCTION

The Northeast region is important in the Brazilian production of several crops, but stands out as an exporter of fruits, such as melon. Family farming predominates in this region, where more than 80% of the properties are small and socially and economically vulnerable due to rainfall variability, irrigation difficulties, soil degradation, and rural poverty. Although the region produces high-value fruits and uses advanced irrigation technologies, small farmers face great difficulty in implementing, operating and maintaining these technologies and lack information on proper soil and water management to avoid degradation by salinization, erosion and compaction (MARENGO et al., 2022).

Melon (*Cucumis melo* L.) is cultivated in several countries and is highly appreciated by consumers, having high commercial value and excellent acceptance in the international market. In Brazil, 95% of the production of around 600 thousand tons and the largest export of this fruit come from the Northeast region, mainly in the states of Ceará and Rio Grande do Norte, where it is important in generating employment and income. The region has favorable soil conditions, semi-arid characteristics that favor production, and the production sector uses advanced technology, but water scarcity is critical for the sustainability of production, which increasingly depends on the efficient management of soil and water (ARAGÃO et al., 2023; NASCIMENTO et al., 2023; PAIVA et al., 2020).

In this context, Vertisols are widely used for melon production due to their chemical fertility, but they are susceptible to degradation and have management limitations due to their clay content greater than 30%, so depending on their moisture they are sticky or very hard and require great power from the machines in their tillage. Their physical-hydraulic behavior is challenging, as they are structurally unstable in response to changes in moisture and are easily compacted. The wetting and drying cycles cause contraction and expansion, due to the action of expansive clays, such as smectite and montmorillonite. This influences their density and porosity, generating water infiltration and drainage problems that affect gas diffusion and root growth (YANEZ DIAZ; CANTU SILVA; GONZALEZ RODRIGUEZ, 2018; SILVA et al., 2021; RIVERA-HERNÁNDEZ et al., 2022).

Farmers in the northeastern semi-arid region irrigate their crops with water from shallow and deep wells, and from intermittent rivers. Climatic conditions favor the accumulation of salts in these waters, which interfere with the flocculation and dispersion of the soil structure. The dispersing action of sodium enhances these processes, harming the soil physically and chemically and impacting crop yields. These types of damage are worse in alluvial soils, rich in expansive clays, which facilitate the retention of water and salts. The presence of dispersant salts in irrigation water causes particles to occupy pores in irrigated soils, while wetting and subsequent machine traffic accelerate destructuring, to the detriment of density and macroporosity, resulting in soil densification and compaction (ASSIS JÚNIOR; SILVA, 2012). Thus, the need for studying the mechanical behavior of soils cultivated with melon is due to the intense traffic of machines for soil tillage, application of fertilizers and pesticides, and harvesting (EMBRAPA, 2017).

Given the above, this work aimed to determine changes in soil fertility and resistance to root penetration caused by fertigated melon cultivation, as compared to soil under native forest.

MATERIAL AND METHODS

Characterization of the study area

The experiment was carried out at Fazenda Lagoa, in the rural area of the municipality of Upanema, RN, Brazil (5° 35'18.40"S; 37°17'24.29"W), belonging to the Association of the Project of Settlement and Agrarian Reform Geraldo Messias, a non-profit organization founded in 2006 by 35 family farmers. According to Köppen's classification, the region's climate is BSw'h', semi-arid, hot, with average monthly temperatures above 18 °C and the predominant rainy season from February to May. The natural vegetation is characterized as Hyperxerophilic Caatinga (ALVAREZ et al., 2013).

The soil of the site was classified as *VERTISSOLO HÁPLICO órtico típico* (Vertisol) from the hyperxerophilic Caatinga phase, consisting of mineral material, with very clayey texture, moderate A horizon, flat relief, according to the Brazilian Soil Classification System (SANTOS et al., 2018). The soil particle-size fractions, at different depths, are presented in Table 1, while the chemical characteristics are presented in Table 3 in Results and Discussion.

Table 1. Particle-size fractions (%) of the soil studied at Fazenda Lagoa, Upanema, RN, Brazil.

	Layer (cm)			
	0 – 10	10 – 20	20 – 30	30 – 40
Clay	48.3	47.6	48.8	48.9
Silt	42.2	42.0	40.7	39.7
Sand	9.5	10.4	10.5	11.4

Two areas with a territorial extension of 1.0 ha were chosen to conduct the experiment, based on the description of the activities carried out by the local families. One area is cultivated and the other is under native forest (Table 2).

Table 2. Environments, history of use and geographic coordinates referring to the areas studied at Fazenda Lagoa, Upanema, RN, Brazil.

Areas	History of use	Geographic coordinates
Cultivated	Melon cropping in the dry period and maize and sorghum cropping in the rainy season, when soil management is difficult. The melon is sold in capitals of the Northeast region, for the Government Purchase Program, and at local markets.	5° 35' 18.31"S 37°17' 23.98"W
Native forest	It is the Association's greatest asset, consisting of a permanent preservation area with well-protected native vegetation and the Umari River, source of water for irrigation.	5° 35'19.95"S 37°17'27.50"W

Cantaloupe type melon (Rangers hybrid, from Takii Seed) was cultivated. Soil tillage consisted of plowing, harrowing, and subsoiling. During the years of cultivation, basal and fertigation fertilizations were carried out, using urea, monoammonium phosphate, potassium chloride, magnesium, zinc and boron. The installation of the localized drip irrigation system and the placement of plastic mulching were carried out before transplanting. Irrigation water was obtained from the Umari River.

Collection and preparation of soil samples

Soil sampling was carried out after the beginning of the rainy season in 2018, when samples with disturbed and undisturbed structure were collected in 25 plots (20 x 20 m) of the cultivated area and 8 locations in the native forest, in the 0 -10, 10-20, 20-30 and 30-40 cm layers. The undisturbed samples were collected in the four layers with three repetitions, using volumetric cylinders (5.0 cm in height and 5.0 cm in diameter), totaling 300 samples (4 layers x 25 plots x 3 repetitions), for the determination of density and porosity parameters, while disturbed samples were used to determine the other variables. The disturbed-structure samples were air-dried, crumbled and passed through 2-mm sieves to obtain air-dried fine earth (ADFE).

Soil analysis

All soil analyses were performed according to methodologies presented by Teixeira et al. (2017). The chemical determinations were: total nitrogen, determined by the Kjeldahl method; pH, potentiometrically determined by a combined electrode in soil-water suspension at a ratio of 1:2.5; electrical conductivity (ECsp), determined in the soil saturation paste extract; soil organic matter (SOM), determined from soil organic carbon by wet oxidation reaction with potassium dichromate in sulfuric medium and titration with ammonium ferrous sulfate; Ca^{2+} and Mg^{2+} contents, extracted with 1 mol L^{-1} KCl solution and quantified by atomic absorption spectrophotometry; K^+, Na^+, and P contents, extracted with the Mehlich-1 solution, with K^+ and Na^+ quantified by flame spectrophotometry and P by colorimetry; potential acidity (H+Al), extracted with buffered calcium acetate solution and quantified by titration with NaOH. From these determinations, the sum of bases (SB), the cation exchange capacity (CEC) and the exchangeable sodium percentage (ESP) were calculated.

The physical determinations carried out were: clay content, by the pipette method after soil dispersion by mechanical shaking and chemical dispersion with NaOH; sand content, by sieving; silt content, as the difference between sand and clay; particle density, by the volumetric flask method; bulk density, by the volumetric cylinder method; total porosity, as the ratio of bulk density to particle density; microporosity, which considered the water retained in the soil at a tension of 6 kPa; and macroporosity, as the difference between total porosity and microporosity.

The levels of the determined chemical parameters were interpreted according to the recommendations for the use of correctives and fertilizers in Minas Gerais (RIBEIRO; GUIMARÃES; ALVAREZ, 1999).

Soil penetration resistance (SPR)

SPR was determined using the Solotrack electronic cone penetrometer (Falker, Porto Alegre, RS, Brazil), with an automatic measurement system and a 12.83 mm diameter tip rod that supports a force of up to 90 kgf. These characteristics comply with the ASAE S313.3 FEB04 standard (ASABE, 2006). The collected data were stored centimeter by centimeter until reaching a depth of 40 cm. The average soil resistance to penetration in the 0 to 40 cm layer was expressed as the cone index (Icone) in the comparison between areas under melon cultivation and native forest area.

The classification used to characterize the SPR was proposed by Arshad, Lowery and Grossman (1996), in which the classes are defined according to the soil resistance values: extremely low – values lower than 10 kPa; very low – from 10 to 100 kPa; low – from 100 to 1000 kPa; moderate – from 1000 to 2000 kPa; high – from 2000 to 4000 kPa; very high – from 4000 to 8000 kPa, and extremely high – values greater than 8000 KPa.

Statistical analysis

The soil data of the two areas were statistically analyzed using multivariate data analysis techniques (HAIR Jr. et al., 2009), after determining the Pearson correlations ($p \leq 0.05$) for the variables, with the aim of ensuring that these attributes had minimal correlations that could justify their use in the data matrix. The correlation matrix allowed the application of multivariate techniques such as Cluster Analysis (CA), Factor Analysis (FA) and Principal Component Analysis (PCA). In the factor analysis, the principal components that had eigenvalues greater than 1 were extracted, and the factor axes were rotated using the Varimax method. To consider significant factor loadings, a value of 0.70 was established.

The SPR data were subjected to descriptive analysis to analyze the behavior of the variable in the different areas and depths. Next, geostatistical techniques were employed, in which the SPR values and the geographic coordinates of each reading were used to obtain the experimental semivariogram models. The chosen model was the one that, in addition to spatial dependence, showed the highest coefficient of determination. Based on the models, interpolation was performed using the Ordinary Kriging method, which generated values with a spatial resolution of 1 m. These values were exported to Quantum Gis 2.18, which generated thematic maps.

RESULTS AND DISCUSSION

Soil chemical attributes

All soil chemical attributes of the cultivated area underwent alterations, compared to the soil under native forest (Table 3). The magnitude of these changes depended on the attribute and the analyzed layer. Soil pH suffered a small reduction (3.7%), only in the 0-10 cm layer; the Na^+ content decreased 40% in the 0-10 cm layer, and 5% in the 10-20 and 20-30 cm layers; the reductions in the K^+ content were 22, 33 and 37%, in the layers of 10-20, 20-30 and 30-40 cm, respectively. In turn, ECsp decreased by 18% in the 0-10 cm layer, but increased by an average of 46% in the other layers. A similar behavior was observed for ESP, which decreased 29% in the 0-10 cm layer, but increased 9%, on average, in the other layers. In contrast, SOM increased by 14.8% in the 0-10 cm layer and decreased by 51 and 62% in the 20-30 and 30-40 cm layers. In turn, there was an increase in the P content in all layers, by percentages of 27, 176, 68, and 110%, in the descending sequence of the layers, and a reduction, in the same sequence, in the N contents (16, 21, 12, and 8%), Ca^{2+} (21, 14, 15, and 13%), Mg^{2+} (10, 1, 3, and 7%) and CEC (18, 8, 9, and 9%).

Table 3. Soil chemical attributes in the two areas studied at the Fazenda Lagoa, Upanema, RN, Brazil.

Layer (cm)	Areas	N g kg^{-3}	pH*	ECsp dS m^{-1}	SOM g kg^{-3}	P	K^+	Na^+	Ca^{2+}	Mg^{2+}	CEC	ESP %
						------------mg dm^{-3}-------------			---------cmol dm^{-3}---------			
0-10	Native	1.24	6.26	0.44	13.21	14.84	329.25	637.88	17.43	11.48	32.53	8.54
	Cultivated	1.04	6.49	0.36	15.17	18.84	332.83	384.33	13.73	10.28	26.65	6.09
	Variation (%)	-16.1	3.7	-18.2	14.8	26.9	1.1	-39.7	-21.2	-10.4	-18.1	-28.7
10-20	Native	1.21	6.50	0.27	12.11	6.13	320.30	487.54	16.36	10.82	30.12	6.65
	Cultivated	0.96	6.44	0.40	12.47	16.93	248.09	464.49	14.10	10.68	27.55	7.15
	Variation (%)	-20.7	-0.9	48.1	3.0	176.2	-22.5	-4.7	-13.8	-1.3	-8.5	7.5
20-30	Native	1.03	6.48	0.32	22.11	9.63	281.54	714.44	18.09	11.22	33.14	9.37
	Cultivated	0.91	6.48	0.47	10.88	16.20	187.88	678.18	15.34	10.86	30.11	10.26
	Variation (%)	-11.6	0.0	46.9	-50.8	68.2	-33.3	-5.1	-15.2	-3.2	-9.1	9.5
30-40	Native	0.86	6.62	0.41	28.95	7.31	212.92	952.34	18.59	11.65	34.93	11.77
	Cultivated	0.79	6.64	0.59	10.89	15.93	133.29	960.98	16.20	10.88	31.78	12.94
	Variation (%)	-8.1	0.3	43.9	-62.4	117.9	-37.4	0.9	-12.9	-6.6	-9.0	9.9
CV_{mean}	Native	14.06	1.41	31.85	42.68	46.54	35.12	25.92	9.86	14.98	12.11	18.91
	Cultivated	41.26	2.92	29.17	35.85	40.54	27.37	47.17	17.70	21.74	14.89	41.46
	Difference	27.20	1.51	-2.68	-6.83	-6.01	-7.75	21.25	7.84	6.76	2.77	22.54

Note: *pH in water; SOM is soil organic matter; ECsp is electrical conductivity of the soil saturation paste; CEC is cation exchange capacity; ESP is exchangeable sodium percentage. CV_{mean} is the mean coefficient of variation of the four layers.

The soil nitrogen content decreased with depth in both areas and was lower in the cultivated area, compared to the area under native forest. This can be justified by the fact that cultivation accelerated the mineralization of SOM, the main source of nitrogen in preserved areas, which is distributed on the surface and in the underlying layers, due to the deposition of plant residues, litter from the vegetation itself and roots (BARRETO; GAMA-RODRIGUES; GAMA-RODRIGUES, 2014). As for the N added via fertigation using soluble nitrogen fertilizers, it was consumed to meet the crop's demand and, as it is one of the macronutrients most susceptible to environmental losses, it must have been lost by several processes, among which the main ones are ammonia volatilization, nitrous oxide emissions, and nitrate leaching (MAHMUD et al., 2021).

Soil pH only changed in the 0-10 cm layer, with a slight increase in the cultivated area. This can be attributed to soil management, especially the chlorides and carbonates present in irrigation water. However, all layers showed values close to neutrality, corroborating the statement by Moustakas (2012) according to which Vertisols have a generally neutral to alkaline pH, due to the calcareous nature of the parent material, or the high proportion of basic cations. According to Malavolta (2006), the pH values observed are within the range of greater availability of most nutrients. On the other hand, compared to soil under natural vegetation, Corrêa et al. (2009) observed that different forms of cultivation increased pH, ECsp, SB and base saturation in soils of an irrigated project in the semi-arid region of the state of Pernambuco.

The decrease in ECsp in the 0-10 cm layer of the cultivated area, compared to the native forest area, accompanied by a progressive increase between the depths of 10 and 40 cm, indicates salt leaching. According to Ayers and Westcot (1999), over the irrigation time, salinity increases with the depth of the root zone if low leaching fractions are used. Despite increasing with depth, the observed ECsp values are considered low compared to the indicative values of saline soil because they are between 4 and 7 dS m^{-1} at some time of the year (SANTOS et al., 2018). Therefore, the EC values of the studied soil do not raise concerns about salinity problems.

The increase in SOM observed in the 0-10 cm layer of the cultivated area, compared to the native forest, can be explained by the residues of annual crops deposited in the soil and accumulated over the cultivation period, as well as by the roots, which are more abundant near the surface (CORAZZA et al., 1999). According to the same authors, the progressive reduction of SOM along the profile, starting from the surface layer, is due to the edaphoclimatic conditions of the semi-arid region, which are unfavorable to the accumulation and maintenance of SOM, to the replacement of native vegetation by annual crops, and to soil mobilization by tillage implements.

With regard to phosphorus, it was found that its content was much higher in the cultivated area than in the native area, in all layers, and was distributed relatively uniformly with depth. P contents in all layers are classified as high, according to Ribeiro, Guimarães and Alvarez (1999). According to Leite et al. (2016), an increase in soil P content, as observed in the cultivated area, can be obtained by inorganic and organic sources, which vary in importance depending on factors such as the form of fertilization, which in the present study was a soluble source of P; the soil preparation system; the amount of P exported at harvest, and the replacement rate of exported P. The same authors clarify that the decomposition of crop residues and the decomposition of SOM from native vegetation, as observed in this study, contributed to the increase of more labile forms of P, because the organic acids from SOM block adsorption sites. It was also evident that the reason for P, which is an element of low mobility in the soil, to have increased with depth, is the decomposition of SOM from the roots of native vegetation. Due to the fact that P in plant tissues is found in organic compounds, their decomposition process is essential for the mineralization and availability of P. The release of organic acids and the complexation of aluminum also contribute to the redistribution of P in the profile.

As for the K^+ content, it was classified as very high in all layers of the two areas (RIBEIRO; GUIMARÃES; ALVAREZ, 1999). Compared to the native forest, the K^+ content was higher only in the 0-10 cm layer of the cultivated area and progressively decreased at the other depths. In a study by Paiva et al. (2020), the highest K^+ contents in the 0-20 cm layer of a Vertisol were attributed to fertilization, which occurred in this layer, but also due to the high CEC of the soil and its mineralogy, which decrease the susceptibility to leaching of this soil.

However, there was a progressive decrease in the K^+ content with increasing depth in both areas. In fact, K^+ can be lost in the soil in several ways. Most losses (up to 150 kg ha^{-1} per harvest) occur through extraction and export by crops such as melon, for which K^+ is the most extracted nutrient. It is even possible that, under conditions of high K^+ availability, plants absorb the element in quantities greater than necessary. In second place, there are losses by leaching, because due to its high mobility, K^+ percolates and reaches the deeper layers. The leaching of K^+ is greater in moist soils, as is the case of the soil in this study at certain times of the year, because this element is present in greater concentration in the soil solution (GOULDING et al., 2021).

With regard to Ca^{2+} and Mg^{2+}, their contents were lower in all layers of the cultivated area, compared to the native forest. This may be related to the removal by plants and the intensity of irrigation, which influences the leaching of these nutrients. An increase in the Ca^{2+} content and a uniform Mg^{2+} content with depth were also observed in the cultivated area. In a study by Leite et al. (2012), conducted in an irrigation project in the Sertão region of the state of Paraíba, an increase in the contents of both Ca^{2+} and Mg^{2+} was observed with increasing depth.

The Ca^{2+} and Mg^{2+} values observed in the study area were classified as very high (RIBEIRO; GUIMARÃES; ALVAREZ, 1999). Excess of these two nutrients can inhibit the absorption of other nutrients, including K^+. This happens because K^+, Ca^{2+}, and Mg^{2+} compete for the same absorption sites in the root, so the cation in the highest concentration in the soil solution has preferential absorption over the others (MIRANDA; MEDEIROS; LEVIEN, 2008).

The CEC values observed in both areas fit the range of 20 to 45 cmol kg^{-1}, generally observed for CEC in Vertisols, according to Coulombe, Dixon and Wilding (1996). These values are lower in the cultivated area than in the native forest area and tend to consistently increase with depth in both areas. However, when looking at Table 2, the lowest CEC values at the different depths of the cultivated area cannot be explained by the soil pH, nor by the SOM content. The possible effect of soil mineralogy on the CEC of the Vertisol of this study can be inferred from the discussion by Coulombe, Dixon and Wilding (1996).

Only in the 0-10 cm layer were the ESP values lower in the cultivated area than in the area under native forest. In the layers of 10-20 and 20-30 cm, the values were slightly higher in the cultivated area and the superiority was more evident between 30 and 40 cm. With the exception of the surface layer of the area under native forest, the ESP tended to increase with depth. In general, the values observed in the two areas and different layers allow classifying the soil as solodic, whose ESP varies between 6 and 14%. In Table 2, it can be seen that the behavior of ESP is similar to the behavior of Na^+ levels. In this context, the increase in Na^+ can occur naturally, due to the area's propensity for salinization, and also due to the inadequate use of irrigation and fertilizers, as stated by Coulombe, Dixon and Wilding (1996). As for the higher ESP observed in the 30 to 40 cm layer, Dias and Blanco (2010) state that it may increase the tendency for clay dispersion and the formation of impermeable layers that hinder the movement of water in the soil.

Correlations between variables

When analyzing the correlation matrix between the soil chemical and physical variables of the cultivated area (Table 4), some relationships are more evident. Phosphorus showed negative correlations with N, Ca^{2+} and CEC, evidencing what has already been discussed about the increase in P content being due to SOM mineralization, which influences N and Ca^{2+} contents and is determinant for the soil CEC. On the other hand, effects of excessive levels of some elements are inferred when examining the positive correlations obtained from EC with Na^+ and CEC, and negative correlation with K^+, indicating the effects of the predominance of Na^+ over K^+ and its great influence on the ESP, in addition to the great influence of the Ca^{2+} content on soil CEC. This can lead to an imbalance between exchangeable cations in the soil, as discussed by Miranda, Medeiros and Levien (2008).

Table 4. Correlation matrix between physical and chemical variables of soil layers at Fazenda Lagoa, Upanema, RN, Brazil.

	N	pH	ECsp	SOM	P	K	Na	Ca	Mg	CEC	ESP	PT (%)	Micro (%)	Macro (%)	PA (%)	Clay (%)	Silt (%)	FS (%)
N	1.00																	
pH	0.01	1.00																
ECsp	-0.13	0.13	1.00															
SOM	-0.06	-0.06	-0.20	1.00														
P	-0.37	0.00	0.27	-0.28	1.00													
K	0.28	-0.16	-0.42	0.07	-0.11	1.00												
Na	-0.14	0.42	0.47	0.02	-0.14	-0.25	1.00											
Ca	-0.12	-0.02	-0.12	0.30	-0.42	0.02	0.21	1.00										
Mg	0.02	0.07	0.15	0.09	-0.19	-0.14	0.12	0.33	1.00									
CEC	-0.09	0.16	0.13	0.23	-0.40	-0.08	0.51	0.83	0.70	1.00								
ESP	-0.10	0.40	0.47	-0.05	-0.03	-0.27	0.95	-0.01	-0.08	0.27	1.00							
PT (%)	-0.16	0.27	0.37	-0.03	-0.10	-0.40	0.43	0.22	0.07	0.29	0.38	1.00						
Micro (%)	0.04	0.10	0.00	-0.12	-0.04	0.14	0.07	0.05	-0.03	0.05	0.04	0.55	1.00					
Macro (%)	-0.01	-0.14	-0.03	0.23	-0.13	-0.14	-0.02	0.11	0.05	0.08	-0.03	-0.18	-0.65	1.00				
PA (%)	0.09	0.10	-0.03	-0.10	-0.07	0.17	0.03	0.04	-0.07	0.01	0.01	0.49	0.90	-0.53	1.00			
clay (%)	-0.19	0.20	0.09	0.03	-0.01	-0.26	0.12	-0.06	0.00	-0.01	0.13	-0.24	-0.46	0.04	-0.43	1.00		
silt (%)	0.23	-0.28	-0.29	-0.14	0.11	0.47	-0.41	-0.23	-0.16	-0.33	-0.36	-0.23	0.35	-0.20	0.38	-0.61	1.00	
FS (%)	0.04	-0.01	0.14	-0.01	-0.05	-0.05	0.18	0.22	0.12	0.25	0.13	0.51	0.37	-0.07	0.26	-0.70	-0.05	1.00
CS (%)	-0.01	0.07	0.10	0.29	-0.12	-0.17	0.22	0.29	0.14	0.30	0.15	0.19	-0.19	0.47	-0.14	-0.17	-0.46	0.30

ECsp: electrical conductivity of the soil saturation paste; SOM: soil organic matter; CEC: cation exchange capacity; ESP: exchangeable sodium percentage; PT: total porosity; Micro: microporosity; Macro: macroporosity; PA: porosity of aeration; FS: fine sand, and CS: coarse sand.

Factor Analysis

The three factors determined by the factor analysis of the physical and chemical variables of the soil profile explain 52.06% of the total data variance (Table 5). These factors were determined by principal components, and it should be noted that the soil chemical and physical variables showed loadings greater than 0.70 (modulus) at the four depths of the cultivated area.

Factor 1 explained 21.06% of the total variation and is related to Na^+ availability and ESP, which vary together and contributed to the highest vector loadings, that is, they had the greatest influence on the distinction of soil fertility. Thus, the indication that high levels of Na^+ are a factor of nutritional imbalance in the soil is reinforced, leading to the negative consequences for plants and the soil, as discussed by Ferreira et al. (2005) and by Cunha (2018). Factor 2, which explains 17.61% of the total data variance, highlights soil physical variables, such as macro and microporosity and aeration porosity, related to structure, which is very characteristic of Vertisols. This is evidence that the water regime of the studied soil had a great influence on its chemical characteristics, as commented by Moustakas (2012). In these soils, the most serious limitations are related to physical aspects. Due to its low permeability, drainage is slow, causing waterlogging during rainy periods.

Factor 3 explains 13.39% of the total variation and is related to the Ca^{2+} content, whose importance in the composition of the CEC is evident. A point to be considered is the fact that, as it is a soil with little weathering, its CEC is high, as evidenced by the high factor loading found in this study. So, the high concentrations of exchangeable bases may have contributed to its high fertility. Such results are corroborated by a study by Lima, Silva and Silva (2013).

Table 5. Matrix of factor loadings after orthogonal rotation by the Varimax Method for the physical and chemical variables of the soil profile at Fazenda Lagoa, Upanema, RN, Brazil.

Soil attributes	Factor Loadings		
	Factor 1	Factor 2	Factor 3
N	-0.35	0.14	0.08
pH	0.52	0.09	0.00
EC	0.67	-0.01	-0.06
SOM	-0.11	-0.13	0.41
P	0.16	-0.03	-0.59
K	-0.62	0.25	-0.03
Na	0.76	0.06	0.31
Ca	0.01	0.06	0.78
Mg	0.08	-0.03	0.53
CEC	0.27	0.05	0.83
ESP	0.76	0.03	0.11
BD	0.22	-0.53	0.29
PD	0.68	0.27	-0.12
PT (%)	0.59	0.49	0.31
Micro (%)	0.08	0.94	-0.01
Macro (%)	-0.16	-0.70	0.38
PA (%)	0.02	0.90	-0.02
Clay (%)	0.38	-0.59	-0.28
Silt (%)	-0.64	0.45	-0.27
FS (%)	0.09	0.46	0.47
CS (%)	0.16	-0.21	0.57
Eigenvalues	4.42	3.70	2.81
Total variance (%)	21.06	17.61	13.39
Accumulated variance (%)	21.06	38.67	52.06

Soil penetration resistance

Soil penetration resistance (SPR) increases with depth in the native forest area and also in the cultivated area, which showed clearly lower values at all depths. Reductions in SPR varied between 25 and 47%, depending on the layer considered (Table 6). Results similar to those found in the present study were obtained by Gondim et al. (2015), who observed significant differences between the four depths due to the decrease in soil water content, resulting in lower soil resistance as soil moisture increased.

Table 6. Soil penetration resistance in cultivated soil and under native forest, Fazenda Lagoa, Upanema, RN, Brazil.

	Soil penetration resistance (kPa)				
	PR_{0-10}	PR_{10-20}	PR_{20-30}	PR_{30-40}	Icone
Native forest	210.59	969.79	1472.34	1722.33	1072.21
Cultivated area	129.27	513.38	926.23	1292.01	706.07
Difference (%)	-38.61	-47.06	-37.09	-24.98	-34.15
	Coefficient of variation (%)				
Native forest	38.42	25.24	20.74	30.11	17.08
Cultivated area	32.44	39.13	34.45	32.43	29.92
Difference (%)	-5.98	13.89	13.71	2.32	12.83

PR – Penetration resistance. Icone – cone index.

The SPR values in the cultivated area, as well as in the native forest, do not represent a limitation for root development, considering that they do not exceed the critical value of 2000 kPa (2.0 MPa), considered in the literature as an impediment to development of the roots of most crops (TORMENA; SILVA; LIBARDI, 1999). In fact, the critical value varies according to the plant species considered, and a value lower than 1,000 kPa was considered the most suitable for the development of roots of *Panicum maximum*, according to Costa et al. (2012).

The reduction in SPR, observed in the cultivated area, is a beneficial consequence of the tillage operations, which promoted a decompaction, considering the original conditions of the studied soil. According to Vezzani and Mielniczuk (2011), conventional tillage reduces soil bulk density and SPR in the short term, in addition to increasing aeration porosity.

Figure 1 presents the spatial distribution of the SPR in the different soil layers of the cultivated area. In Figure 1A, it is observed that the SPR of the 0-10 cm layer has values of up to 200 kPa throughout the area, hence the uniformity of the color. This is the result of the intense mobilization of this layer by tillage implements. However, the greater color variation in the 10-20 cm layer (Figure 1B) is due to the existence in this layer of regions in the field with different SPR, which increases from 300 to 900 kPa, from the lower region of the map toward the center and top right. This distribution of the SPR along the field can be caused by preferential directions for the traffic of machines and animals, in addition to differences in relief that may influence the dynamics of soil moisture (NASCIMENTO et al., 2020). These variations in SPR are much more evident in the maps of the lower soil layers (Figures 1C and 1D), in which a progressive increase in SPR can be observed from the lower region to the upper region of the two maps.

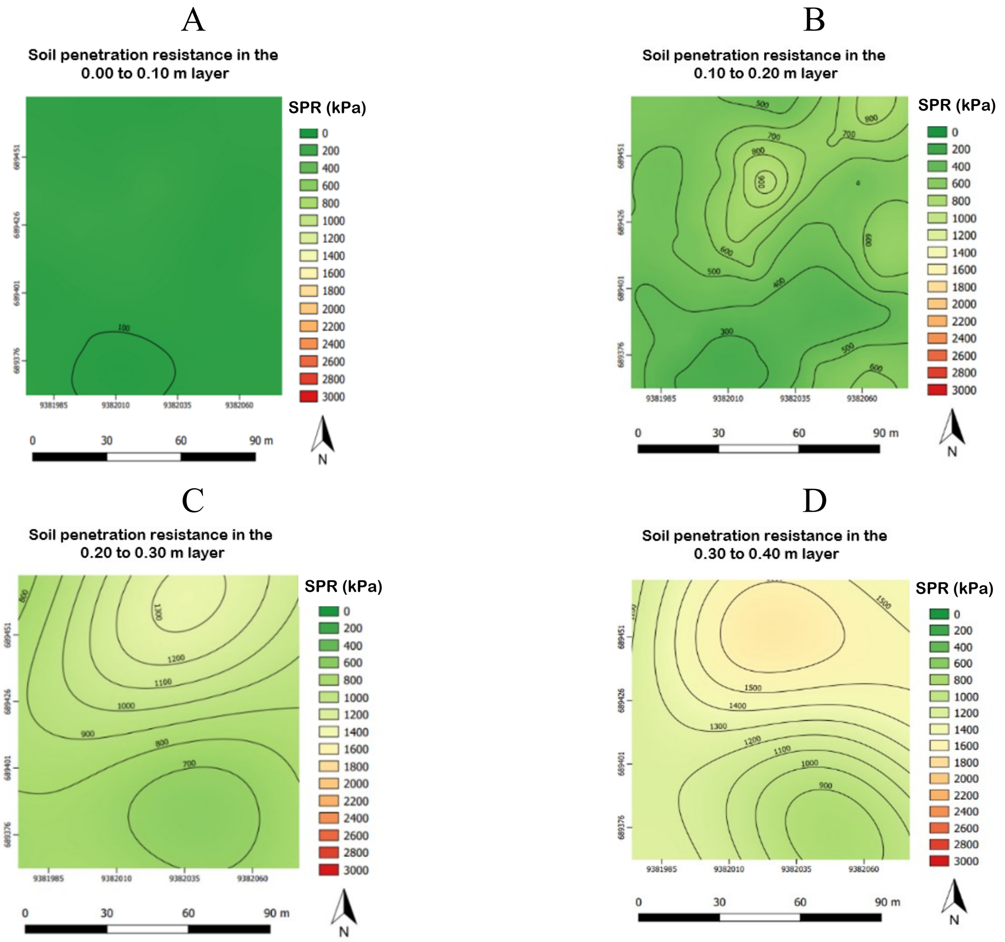

Figure 1. Maps of soil penetration resistance per layer in the cultivated area: A. 0-10 cm, B. 10-20 cm, C. 20-30 cm, and D. 30-40 cm. UTM coordinates; Datum WGS 84; zone 24S and scale of 1:1500, Upanema, RN, Brazil.

The study showed that, currently, according to the classification criteria adopted, there is no limitation to root development in any region of the field. However, the importance of these maps lies in the possibility of comparing them with maps of the same area that represent the yield and quality of the crop, thus identifying regions where soil compaction is harmful and allowing the area to be managed to carry out site-specific decompaction (OLIVEIRA FILHO et al., 2015).

CONCLUSIONS

The fertigated cultivation of the Vertisol caused changes in all variables studied, compared to the area under native forest. Some changes were positive, such as soil decompaction and an increase in phosphorus content, while other changes were negative, such as the decomposition of organic matter and the reduction in contents of potassium, calcium, and magnesium, and in cation exchange capacity. In addition, sodium content and porosity parameters were identified as prominent factors in soil alterations.

REFERENCES

ASABE - American Society of Agricultural and Biological Engineers. **Soil cone penetrometer**. Saint Joseph: ASABE, 2006. p. 902-904. (ASABE standard: ASAE S313.3 FEB04).

ALVAREZ, C. A. et al. Climate classification map for Brazil. **Meteorologische Zeitschrift**, 22: 711-728, 2013.

ARAGÃO, M. et al. Evaluation of crop water status of melon plants in tropical semi-arid climate using thermal imaging. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 27: 447-456, 2023.

ARSHAD, M. A.; LOWERY, B.; GROSSMAN, B. Physical tests for monitoring soil quality. In: DORAN, J. W; JONES, A. J. **Methods for Assessing Soil Quality**. Madison: SSSA Special publication, 1996. v. 49, p. 123-142.

ASSIS JÚNIOR, R. N.; SILVA, E. F. Efeito da qualidade da água de irrigação sobre os atributos físicos de um Neossolo Flúvico do município de Quixeré, CE – Brasil. **Revista Brasileira de Ciência do Solo**, 36: 1778-1786, 2012.

AYERS, R. S.; WESTCOT, D. W. **A qualidade da água na agricultura**. 2 ed. Campina Grande, PB: UFPB, 1999. 153 p. (Estudos FAO Irrigação e Drenagem, 29).

BARRETO, P. A. B; GAMA-RODRIGUES, E. F; GAMA-RODRIGUES, A. C. Carbono das frações da matéria orgânica em solos sob plantações de eucalipto de diferentes idades. **Scientia Forestalis**, 42: 581-590, 2014.

CORAZZA, E. J. et al. Comportamento de diferentes sistemas de manejo como fonte ou depósito de carbono em relação à vegetação de cerrado. **Revista Brasileira de Ciência do Solo**, 23: 425-432, 1999.

CORRÊA, R. M. et al. Atributos químicos de solos sob diferentes usos em perímetro irrigado no semiárido de Pernambuco. **Revista Brasileira de Ciência do Solo**, 33: 305 -314, 2009.

COSTA, M. A. T. et al. Resistência do solo à penetração e produção de raízes e de forragem em diferentes níveis de intensificação do pastejo. **Revista Brasileira de Ciência do Solo**, 36: 993-1004, 2012.

COULOMBE, C. E.; DIXON, J. B.; WILDING, L. P. Mineralogy and chemistry of Vertisols. In: AHMAD, N.; MERMUT, A. (Eds.) **Vertisols and technologies for their management**. Amsterdam: Elsevier, 1996. p. 115-200.

CUNHA, R. R. **Avaliação das características do solo em cultivo de palma forrageira irrigada com águas salinas**. 2018. 104 f. Dissertação (Mestrado em Manejo de Água e Solo: Área de concentração em Manejo de Solo e Água do Semiárido. Universidade Federal Rural do Semi-Árido, Mossoró, 2018.

DIAS, N. S.; BLANCO, F. F. Efeitos dos sais no solo e na planta. In: GHEYI, H. R.; DIAS, N. S.; LACERDA, C. F. (Eds.) **Manejo da salinidade na agricultura**: Estudos Básicos e Aplicados. Fortaleza, CE: INCTSal, 2010. p. 129-141.

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. **A cultura do melão**. 3. ed. Brasília, DF: Embrapa, 2017. 202 p.

FERREIRA, P. A. et al. Estresse salino em plantas de milho: II - Macronutrientes catiônicos e suas relações com o sódio. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 9: 11-15, 2005.

GONDIM, J. E. F. et al. Resistência mecânica do solo à penetração em diferentes manejos do solo e da caatinga em Governador Dix-Sept Rosado-RN. **Agropecuária Científica no Semiárido**, 11: 72-76, 2015.

GOULDING, K. et al. Outputs: potassium losses from agricultural systems. In: MURREL, S. T. et al. (Eds.) **Improving potassium recommendations for agricultural crops**. Cham: Springer, 2021. p. 75-97.

HAIR Jr., J. F. et al. **Análise multivariada de dados**. 6. ed. Porto Alegre, RS: Bookman, 2009. 688 p.

LEITE, J. N. F. et al. Frações orgânicas e inorgânicas do fósforo no solo influenciadas por plantas de cobertura e adubação nitrogenada. **Pesquisa Agropecuária Brasileira**, 51: 1880-1889, 2016.

LEITE, M. J. H. et al. Avaliação da fertilidade do solo em perímetros irrigados: Engenheiro Arcoverde e São Gonçalo, PB. **Revista Verde**, 7: 214-225, 2012.

LIMA, J. S. S.; SILVA, S. A.; SILVA, J. M. Spatial variability of chemical attributes of a Red-Yellow Latosol under no-tillage cultivation. **Revista Ciência Agronômica**, 44: 16-23, 2013.

MAHMUD, K. et al. Nitrogen losses and potential mitigation strategies for a sustainable agroecosystem. **Sustainability**, 13: 1-23, 2021.

MALAVOLTA, E. **Manual de nutrição mineral de plantas**. 1. ed. São Paulo, SP: Ceres, 2006. 638 p.

MARENGO, J. A. et al. Drought in Northeast Brazil: A review of agricultural and policy adaptation options for food security. **Climate Resilience and Sustainability**, 1: e17, 2022.

MIRANDA, N. O.; MEDEIROS, J. F.; LEVIEN, S. L. A. Relações entre cátions trocáveis do solo e suas correlações com a qualidade de frutos de melão. **Horticultura Brasileira**, 26: 271-275, 2008.

MOUSTAKAS, N. K. A study of Vertisol genesis in north eastern Greece. **Catena**, 92: 208-215, 2012.

NASCIMENTO, L. S. et al. **Resistência do solo à penetração em diferentes sistemas de uso e manejo na região do Cerrado**. Campo Grande, MS: Embrapa Gado de Corte, 2020. 32 p. (Documentos / Embrapa Gado de Corte, 285).

NASCIMENTO, L. et al. Efficiency of phosphorus use by melon genotypes. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 27: 9-17, 2023.

OLIVEIRA FILHO, F. X. et al. Zona de manejo para preparo do solo na cultura da cana-de-açúcar. **Revista Brasileira de Engenharia Agrícola e Ambiental**, 19: 186-193, 2015.

PAIVA, K. F. et al. Potassium availability in Brazilian semiarid soils cultivated with melon. **Pesquisa Agropecuária Tropical**, 50: e63663, 2020.

RIVERA-HERNÁNDEZ, B. et al. Using splines in the application of the instantaneous profile method for the hydrodynamic characterization of a tropical agricultural Vertisol. **Revista Brasileira de Ciência do Solo**, 46: e0210086, 2022.

RIBEIRO, A. C.; GUIMARÃES, P. T. G.; ALVAREZ, V. H. **Recomendações para uso de corretivos e fertilizantes em Minas Gerais**. 5ª Aproximação. Viçosa, MG: Comissão de Fertilidade do Solo do Estado de Minas Gerais, 1999. 359 p.

SANTOS, H. G. et al. **Sistema Brasileiro de Classificação de Solos**. 5. ed. Brasília, DF: Embrapa. 2018. 356 p.

SILVA, P. L. F. et al. Efeito de diferentes sistemas de manejo na qualidade físico-hídrica de um vertissolo (vertisol) no semiárido brasileiro. **Ciencia del Suelo**, 39: 146-156, 2021.

TEIXEIRA, P. C. et al. **Manual de Métodos de Análise de Solo**. 3. ed. Rio de Janeiro, RJ: Embrapa Solos, 2017. 573 p.

TORMENA, C. A.; SILVA, A. P.; LIBARDI, P. L. Soil physical quality of a Brazilian Oxisol under two tillage systems using the least limiting water range approach. **Soil and Tillage Research**, 52: 223-232, 1999.

VEZZANI, F. M.; MIELNICZUK, J. **O solo como sistema**. Curitiba, PR: Ed. dos autores, 2011. 104 p.

YANEZ DIAZ, M. I.; CANTU SILVA, I.; GONZALEZ RODRIGUEZ, H. Efecto del cambio de uso de suelo en las propiedades químicas de un vertisol. **Terra Latinoamericana**, 36: 369-379, 2018.