Periódico Eletrônico "Fórum Ambiental da Alta Paulista"
Electronic Journal "Environmental Forum of Alta Paulista"

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

Influence of the physical, chemical, and hydric attributes of soils and leaf area on degradation levels of cultivated pastures

César de Oliveira Ferreira Silva
PhD student in Agricultural Engineering, UNICAMP, Brazil
cesar.silva@feagri.unicamp.br

Cristina Aparecida Gonçalves Rodrigues
PhD in Plant Biology, UNICAMP, Brazil, and researcher at Embrapa Territorial
cristina.rodrigues@embrapa.br

Célia Regina Grego
PhD in Agronomy, UNESP, Brazil, and researcher at Embrapa Digital Agriculture
celia.grego@embrapa.br

Carlos Fernando Quartaroli
MSc in Agronomy, USP, Brazil, and researcher at Embrapa Territorial
carlos.quartaroli@embrapa.br

Periódico Eletrônico **"Fórum Ambiental da Alta Paulista"**
Electronic Journal **"Environmental Forum of Alta Paulista"**

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

ABSTRACT
Understanding the predominant factors that explain pasture degradation is crucial for developing reliable and feasible restoration plans. This article describes a multivariate analysis used for detecting correlation patterns between soil physicochemical attributes and leaf area in four different levels of degradation of cultivated pastures (without degradation, with low, medium, and high degradation) in the northwestern region of the state of São Paulo. Principal component analysis, exploratory statistics, and hierarchical cluster analysis dendrograms were produced for soil physicochemical attributes in the 0-0.10 m and 0.10-0.20 m depth layers. Water infiltration rate, phytomass, and leaf area were higher in the non-degraded pasture. The top layer showed more recognizable clusters between eigenvectors and degradation levels than the deeper layer. Chemical attributes (P, K, Ca, Mg, organic matter, sum of bases, and base saturation) were more explicative of the variability of degradation, while physical attributes such as granulometry and soil water parameters were less explicative. More effective actions to restore these pastures may prioritize the most explanatory parameters in the 0 to 0.10 m layer. This approach may be replicated for pasture restoration studies and monitoring plans, to indicate parameter prioritization and cost optimization.

KEYWORDS: Compaction. Permeability. Phytomass. Multivariate analysis.

1 INTRODUCTION

Globally, pastures are the main type of land use, and occupy two-thirds of all arable land (FAO, 2022). In Brazil, in 2021, cultivated pastures occupied 164 million hectares (MAPBIOMAS, 2022) and natural pastures, 155.8 million hectares (UNIVERSIDADE FEDERAL DE GOIÁS, 2022), which account for 19.7% and 18.9% of the national territory, respectively. These pastures maintain the largest commercial cattle herd in the world, of 218 million animals (IBGE, 2017), making Brazil the second-largest meat producer and a leader in world exports (ABIEC, 2019).

Within this large expanse of land, there are underutilized areas featuring degraded pastures (MAPBIOMAS, 2022), whose low zootechnical indices are reflected in the productivity of beef cattle (MACEDO; ARAÚJO, 2019). Agricultural activities carried out without conservation practices are reasonably involved in soil degradation and have consequent effects on water resources and declining crop productivity, including pastures (EMBRAPA, 2011a). Also contribute to the degradation of pastures their poor implementation, using forage species or cultivars that are often unsuitable for the edaphoclimatic characteristics of the region, as well as the lack of replenishment of organic and mineral matter in the soil and stocking rates which are unsuitable for the grazing capacity (EMBRAPA, 2011a). Consequently, 70% to 80% of Brazil's cultivated pastures (between 120.6 and 137.8 million ha), mostly occupied by forage plants of the *Urochloa* genus (syn. *Brachiaria*) followed by the *Panicum genus*, are estimated to be in some stage of degradation (IBGE, 2017).

Given the seriousness of this environmental and socio-economic problem, agricultural and livestock policies exist to support projects aimed at recovering degraded pastures and at implementing and expanding Crop, Livestock, and Forest Integration (CLFI) systems, such as the Low Carbon Agriculture Program (ABC, acronym in Portuguese), which encourage the sustainable development of agriculture (GIANETTI; FERREIRA FILHO, 2020).

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

Soil degradation reduces its production capacity, which may be assessed through its chemical and physical attributes. Anthropogenic interference, such as some types of management, may modify soil properties (TORRES; RICHTER; VOHLAND, 2019). When assessing the production capacity of a soil, the physical part is as important as the chemical part or fertility (FELTRAN-BARBIERI; FÉRES, 2021).

2 OBJECTIVES

This study aimed to evaluate the chemical and physical attributes and physical-hydric properties of the soil, as well as attributes of the aerial part of the forage (phytomass and leaf area index, or LAI) of pastures showing different levels of degradation, to recognize patterns of degradation levels by using multivariate analysis.

3 METHODOLOGY

The study area comprising pastures formed basically by *Urochloa brizantha* (A. Rich.) R. D. Webster (syn. *Brachiaria brizantha*) is located in the municipality of Guararapes on the Brazilian Western Plateau, in the northwestern region of the state of São Paulo, between parallels 21°15' and 21°28' S (latitude) and meridians 50°35' and 50°45' W (longitude), at an average elevation of 398 m. Guararapes' climate is Aw (hot, humid summers and mild, dry winters) according to the Köppen climate classification. It's average annual rainfall rate is 1,480 mm, rains are concentrated from September to March, and average annual temperatures are of 27 °C. The municipality's main economic activity is farming and cattle rearing (IBGE, 2022)

We selected four areas of *Brachiaria* pastures for the study, and classified them according to their level of degradation as: non-degraded pasture (Figure 1a), low degradation pasture (Figure 1b), medium degradation pasture (Figure 1c) and high degradation pasture (Figure 1d), represented respectively by the acronyms ND1, ND2, ND3 and ND4. This classification was previously defined in field observations (by estimating soil cover and the frequency of invasive plants) and by collecting aerial parts of the forage plants to estimate phytomass, according to the method adapted from Nascimento Júnior et al. (1994) and described by Rodrigues et al. (2022). The ND2 area was treated with nitrogen fertilization using Ajifer, a liquid organomineral fertilizer which is a byproduct in the manufacturing of the lysine essential amino acid (present in monosodium glutamate) and produced by Ajinomoto (SCHULTZ; REIS; URQUIAGA, 2015).

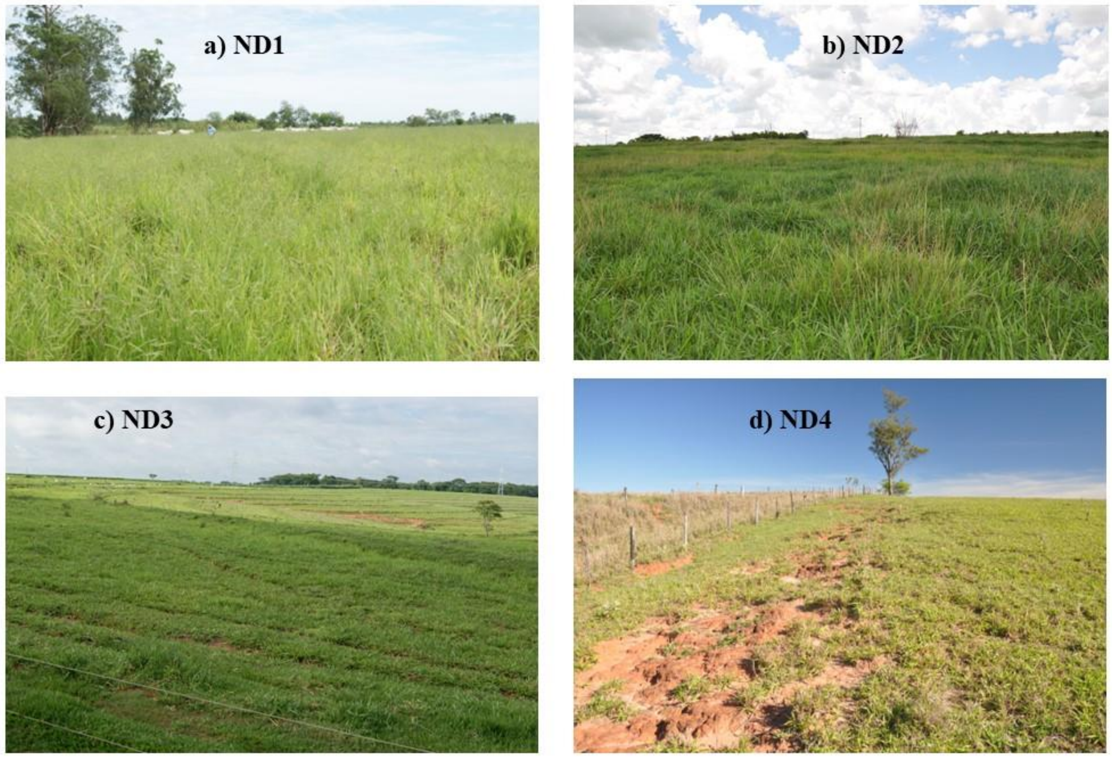
According to Valladares et al. (2012), the soils mapped in the study areas (scale 1:50,000) were[1]: "typical *Latossolo Vermelho Eutrófico* (Ferralsol), with moderate A horizon and medium texture" (LV1); and an association of "typical *Argissolo Vermelho Eutrófico* (Acrisol), moderate A horizon, medium and sandy/medium texture" + "typical *Latossolo Vermelho*

[1] Translator's Note: according to the Brazilian Soil Classification System, SiBCS, with the World Reference Base (WRB) class in parenthesis.

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

Eutrófico (Ferralsol), moderate A horizon, medium texture" (PV1). The ND2, ND3, and ND4 pastures were located in the PV1 mapping unit, and the ND1 pasture, in the LV1 mapping unit. The predominant relief classes in this area are 'gently undulating' and 'undulating' together with the occurrence of 'flat' relief.

Figure 1– Aspect of pastures under different levels of degradation in 2009 in the areas selected for sampling in the municipality of Guararapes, SP (ND1 = no degradation, ND2 = low degradation, ND3 = medium degradation, ND4 = high degradation).



Source: Authors, 2023.

In December 2009, soil samples were collected at two depths, 0 m to 0.10 m and 0.10 m to 0.20 m, to determine the chemical and physical attributes of soils in pastures showing different levels of degradation. The samples were collected at five random points (composite sample) distributed throughout the length of each selected area. The soil samples were subjected to the following chemical analyses: organic matter (OM, g.dm^{-3}), pH obtained using $CaCl_2$, phosphorus (P, mg.dm^{-3}) and potassium (K, mg.dm^{-3}), calcium (Ca, mmolc.dm^{-3}), magnesium (Mg, mmolc.dm^{-3}), potential acidity (H+Al, mmolc.dm^{-3}), sum of exchangeable bases (BS), cation exchange capacity (CEC) and base saturation (V%).

To characterize the granulometry, deformed samples were collected and analyzed to determine their sand, silt, and clay content (g.kg^{-1}) using the pipette method (EMBRAPA, 2011b). A total of 28 soil samples were collected in the 0 m to 0.20 m layer. To determine porosity (PS) in m^3.m^{-3} (macroporosity or MAPS, microporosity or MIPS, and total porosity or PT) and soil density (g.cm^{-3}), undeformed samples were collected using a volumetric ring,

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

according to the method described by Camargo et al. (1986), from two soil layers (0 m to 0.10 m and 0.10 m to 0.20 m).

In December 2010, soil’s physical-hydric characteristics were surveyed in the four areas covered by pastures under different levels of degradation. In each area, the characterization was made using 30 points. At each point, the three-dimensional infiltration rate of water in the saturated soil was determined at a depth of 0.10 m. Three-dimensional infiltration takes into account the directional components of vertical, horizontal and slope flows. To do this, a hole was drilled in the soil using a Dutch auger up to the desired depth and the water infiltration rate was measured at each point using the Guelph permeameter, model IAC (VIEIRA, 1998), thus obtaining the constant infiltration rate in $mm.h^{-1}$.

Soil resistance to penetration (an indicator of soil compaction) was obtained using an impact penetrometer (STOLF, 1991). The resistance (MPa) was calculated for the surface layer up to a depth of 0.20 m. At the time of the penetrometer measurement, the soil was sampled to characterize its water content using the gravimetric method. The field capacities at 6KPa (CAP) and moisture (at saturation point) were then quantified.

The aerial biomass of the pastures under all four levels of degradation was evaluated at two times of the year (January 2010 and August 2010). The material for this assessment was collected at randomly distributed points in each studied area. At each point, the aerial part of the vegetation within a 0.5-m square was cut. The green matter was separated from the dead matter and from invasive species. The IAF was obtained using the LAI-2000 equipment between January 26 and 29, 2010, as described by Andrade et al. (2013).

Exploratory principal component analysis (PCA) was applied to understand the contribution of each soil’s chemical and physical-hydric attribute to the observed variability. Before performing PCA, the relevance of the samples for PCA was assessed using the Kaiser-Meyer-Olkin (KMO) test, or sample adequacy index (KAISER, 1974). This test analyzes the redundancy of the attributes by means of a partial correlation analysis and returns values between 0 and 1. Values greater than 0.6 indicate that the attributes and samples are relevant for factor analysis (MAO; MO; GUO, 2013; GUMBO; DZAGA; NETHENGWE, 2016; GHOLIZADEH; MELESSE; REDDI, 2016). Before performing PCA, the data, due to their dimensional differences, were standardized using the z-score standardization function (LIU; LIN; KUO, 2003).

The PCA of the soil's chemical and physical attributes was calculated using the ‘princomp’ function, native to the R program (R CORE TEAM, 2023). The ‘multcompView’ package was used for the Tukey test, to evaluate the means of data showing normal distribution (GRAVES, 2015), and the ‘Pgirmess’ package, for the Kruskall-Wallis test, to compare the means of the attributes with data that did not show normal distribution and were not eligible for transformation (GIRAUDOUX; GIRAUDOUX, 2018). The dendrograms were obtained by constructing the standardized data matrix. The coefficients of variation (CV) were classified according to the criteria of Warrick and Nielsen (1980) as low (< 12%), medium (from 12% to 60%), and high (> 60%).

Periódico Eletrônico "Fórum Ambiental da Alta Paulista"
Electronic Journal "Environmental Forum of Alta Paulista"

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

4 RESULTS AND DISCUSSION

4.1 Descriptive statistics and correlation analysis of soil chemical, physical, and hydric attributes

Tables 1 and 2 show the average values of the chemical and physical attributes of the soils at the depths of 0 m to 0.10 m and 0.10 m to 0.20 m for the ND1, ND2, ND3, and ND4 pasture degradation levels, accompanied by the results of the Tukey test. The CVs varied from low to medium at both soil depths.

Table 1 – Analysis of the chemical and physical attributes of the pastures at the soil layer between 0 and 0.10 m (ND1 = no degradation, ND2 = low degradation, ND3 = medium degradation, ND4 = high degradation) by Tukey's test ($p < 0.05$).

	pH	Mg ($mmol_c.dm^{-3}$)	H+Al ($mmol_c.dm^{-3}$)	V%	PS ($m^3.m^{-3}$)	MIPS	Density ($g.cm^{-3}$)	OM ($g.dm^{-3}$)	P ($mg.dm^{-3}$)	K ($mmol_c.dm^{-3}$)	Silt ($g.kg^{-1}$)
ND1	5.1 a	8.6 a	17.6 b	59.0 a	0.484 a	0.330 ab	1.54 b	20.20b	3.8 b	2.5 b	52.8 c
ND2	4.8 b	7.0 ab	27.4 a	54.0 ab	0.484 a	0.358 a	1.54 b	27.4 a	7.0 a	5.4 a	99.8 a
ND3	4.8 b	4.6 b	20.0 b	47.6 b	0.416 b	0.314 ab	1.66 a	14.4 c	1.6 c	3.1 b	71.0 b
ND4	4.7 b	5.6 b	20.6 b	47.4 b	0.456 ab	0.286 b	1.55 ab	15.2 c	1.4 c	1.7 b	68.0 bc
CV%	2.4	21.8	9.9	10.9	7.5	8.3	4.3	4.2	19.8	26.4	13.3

Source: Authors, 2023.

Table 2 – Analysis of the chemical and physical attributes of the pastures at the soil layer between 0.10 and 0.20 m (ND1 = no degradation, ND2 = low degradation, ND3 = medium degradation, ND4 = high degradation) by Tukey's test ($p < 0.05$).

	pH	Mg ($mmol_c.dm^{-3}$)	H+Al ($mmol_c.dm^{-3}$)	V%	PS ($m^3.m^{-3}$)	MIPS	Density ($g.cm^{-3}$)	MAPS
ND1	5.0 a	7.6 a	18.4 b	57.4 a	0.484 a	0.332 a	1.53 a	0.154 a
ND2	4.9 a	7.0 a	25.0 a	56.2 a	0.462 a	0.332 a	1.59 a	0.134 a
ND3	4.8 a	4.6 a	20.4 ab	47.2 a	0.442 a	0.318 ab	1.61 a	0.124 a
ND4	4.8 a	5.4 a	19.8 b	46.6 a	0.454 a	0.276 b	1.59 a	0.176 a
CV%	3.7	26.0	12.6	16.2	7.2	7.6	4.5	25.5

Source: Authors, 2023.

Base saturation (V%), considered an indication of the general fertility conditions of the soil, showed significantly higher average value ($p < 0.05$) in the non-degraded pasture (ND1) at the 0 m to 0.10 m soil depth, and did not differ from the low-degradation pasture (ND2). Mg content showed similar results to V%. Organic matter content and P content in the soil showed significantly higher average values ($p < 0.05$) in the ND2 pasture, followed by the other pastures (ND1, ND3, and ND4) at the 0 m to 0.10 m soil depth. At the same soil depth, K content was significantly higher ($p < 0.05$) only in the ND2 pasture. A possible explanation is

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

the recent application, according to the farmer, of a fertilizer (Ajifer) rich in OM and K, which may have contributed to increasing soil fertility.

At the 0.10 m to 0.20 m soil depth, V%, Mg, and pH did not differ significantly ($p < 0.05$) in any of the pastures. All the soils in the pastures studied were agronomically acidic and featured low pH (< 5.5), which means lower availability of Ca, Mg, and P for plants.

There was no significant difference in MAPS values (pore volume responsible for root aeration) among the soils of the pastures studied, but the most degraded pasture (ND4) showed the highest average value (0.176 $m^3.m^{-3}$). According to Lima et al. (2007), this MAPS value is within the ideal range for this type of soil, which is between 0.170 and 0.250 $m^3.m^{-3}$. This was probably a result of undergrazing and lack of pressure of animal trampling on the ND4 pasture, after it had been previously subjected to an excessive number of animals.

Tables 3 and 4 show the Kruskal-Wallis test ($p < 0.05$) for the means of the chemical and physical attributes of the soils that did not show normal distribution, at both 0 m to 0.10 m and 0.10 m to 0.20 m soil depths.

Table 3 – Analysis of the chemical and physical attributes of the pastures at the soil layer between 0 and 0.10 m (ND1 = no degradation, ND2 = low degradation, ND3 = medium degradation, ND4 = high degradation) by Tukey's test ($p < 0.05$). F indicates no difference and V indicates a difference.

	Ca ($mmol_c.dm^{-3}$)	BS ($mmol_c.dm^{-3}$)	CEC ($mmol_c.dm^{-3}$)	Sand ($g.kg^{-1}$)	Clay ($g.kg^{-1}$)	MAPS
ND1–ND2	5.0 F	4.8 F	6.4 F	2.8 F	10.10V	1.9 F
ND1–ND3	6.2 F	6.6 F	5.6 F	9.8 F	9.1 F	6.3 F
ND1–ND4	3.2 F	5.0 F	4.4 F	8.2 F	8.4 F	3.4 F
ND2–ND3	11.2 V	11.4 V	12.0 V	7.0 F	1.0 F	4.4 F
ND2–ND4	8.2 F	9.8 F	10.8 V	5.4 F	1.7 F	5.3 F
ND3–ND4	3.0 F	1.6 F	1.2 F	1.6 F	0.7 F	9.7 F

Source: Authors, 2023.

Table 4 – Analysis of the chemical and physical attributes of the pastures at the soil layer between 0.10 and 0.20 m (ND1 = no degradation, ND2 = low degradation, ND3 = medium degradation, ND4 = high degradation) by Tukey's test ($p < 0.05$). F indicates no difference and V indicates a difference.

	Ca ($mmol_c.dm^{-3}$)	BS ($mmol_c.dm^{-3}$)	CEC ($mmol_c.dm^{-3}$)	OM ($g.dm^{-3}$)	P ($mg.dm^{-3}$)	K ($mmol_c.dm^{-3}$)
ND1–ND2	4.2 F	4.4 F	5.6 F	4.8 F	1.0 F	11.9 V
ND1–ND3	6.2 F	5.2 F	4.2 F	4.3 F	9.7 F	6.3 F
ND1–ND4	3.2 F	3.6 F	2.6 F	6.9 F	9.7 F	0.6 F
ND2–ND3	10.4 V	9.6 F	9.8 F	9.1 F	8.7 F	5.6 F
ND2–ND4	7.4 F	8.0 F	8.2 F	11.7 V	8.7 F	11.3 V
ND3–ND4	3.0 F	1.6 F	1.6 F	2.6 F	0.0 F	5.7 F

Source: Authors, 2023.

According to Tables 3 and 4, there were significant differences ($p < 0.05$) for some of the chemical and granulometric attributes of the soils between the ND1 and ND2 pastures, between the ND2 and ND3 pastures, and between the ND2 and ND4 pastures, both in the 0 m to 0.10 m and 0.10 m to 0.20 m soil depths. At the 0 m to 0.10 m soil depth, the clay content differed ($p < 0.05$) between ND1 and ND2 because, according to the analysis in Tables 1 and 2, these two pastures had similar sand contents, while ND2 had the highest silt content (almost double that of ND1). For these same pastures, the K content was also different ($p < 0.05$) at the

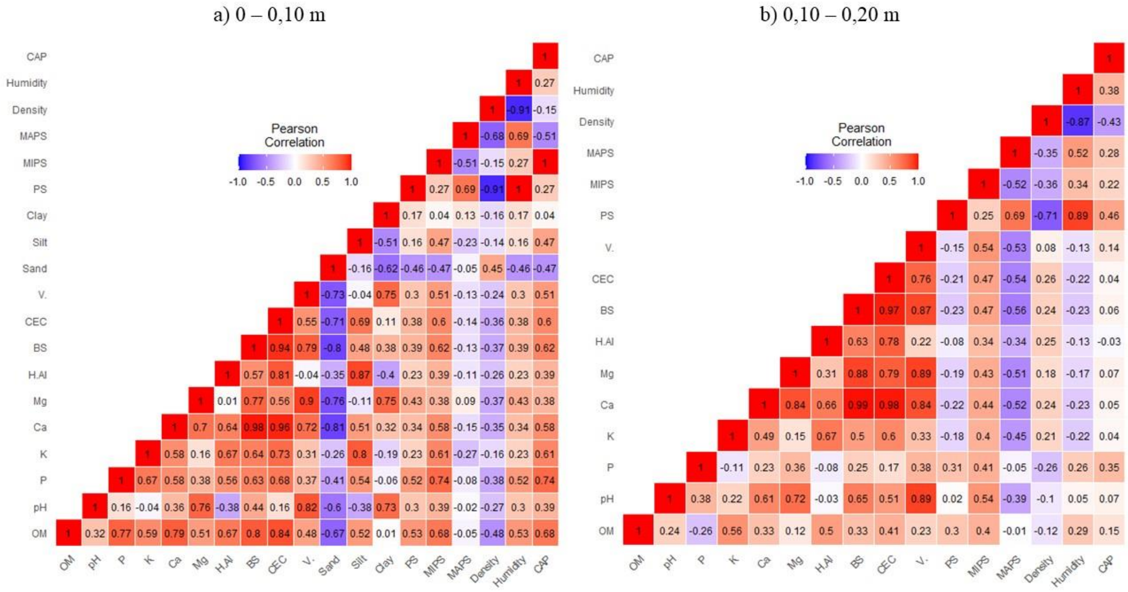
ISSN 1980-0827 – Volume 20, Number 2, Year 2024

0.10 m to 0.20 m layer.

ND2 and ND3 pastures differed significantly in terms of Ca, BS, and CEC content, and Ca content also differed at the 0.10 m to 0.20 m soil depth. CEC differed between pastures ND2 and ND4 in the 0 m to 0.10 m soil depth, and in OM content and K content in the 0.10 m to 0.20 m depth.

Figure 2 shows the positive (shades of red) and negative (shades of blue) correlations between the physical and chemical attributes in both soil layers. In the top layer (0 to 0.10 m), the sand content was negatively correlated with the attributes V% (-0.73), CEC (-0.71), BS (-0.8), and OM (-0.67), which are indicators of soil fertility (CENTERI, 2022). These same fertility indicators showed high positive correlation (greater than 0.75) with some chemical attributes (Ca, Mg, K, and P) in both layers, as expected (ADAMS et al., 2022), and MIPS showed a medium positive correlation (between 0.40 and 0.75) with these same attributes. In the deeper layer (0.10 to 0.20 m), MAPS showed greater negative correlation with chemical and physical attributes than in the shallower layer.

Figure 2 – Multivariate Pearson correlation matrix of the chemical and physical attributes in both soil layers: a) 0 m to 0.10 m and b) 0.10 m to 0.20 m.



Source: Authors, 2023.

The Pearson correlation coefficient between density and PS was -0.91 ($p < 0.05$) in the topsoil layer. Soil density is closely related to soil compaction, as its increase leads to a decrease in PS and MAPS, as well as an increase in MIPS and mechanical resistance to penetration (LIMA et al., 2007). The ND3 pasture showed significant highest density value and lowest PS value (highest compaction) in the 0 m to 0.10 m soil layer (Table 1), but occupied the second place among the pastures in terms of penetration resistance (Table 5), surpassed only by the ND2 pasture, which has hardened materials in its soil, of a lithic nature.

This list of soil chemical and physical attributes is a common standard among soil

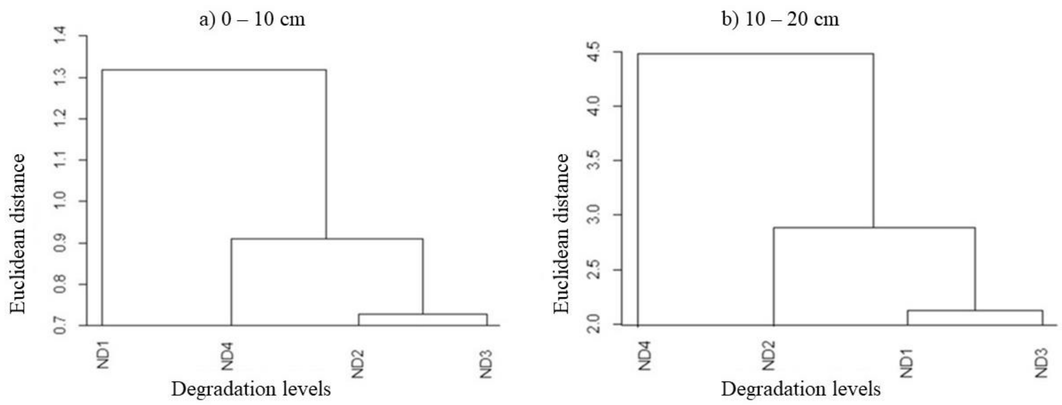
Periódico Eletrônico "Fórum Ambiental da Alta Paulista"
Electronic Journal "Environmental Forum of Alta Paulista"

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

chemistry laboratories. However, it is not possible to generalize these high correlations as redundancy (HAIR et al., 2017), since the number of points is relatively low (less than 50 sampling points) (SILVA; GOVEIA, 2019), therefore it is advisable to have a greater number of attributes to support decision making.

After standardizing the data, dendrograms were generated for an exploratory analysis of the pasture soils under all degradation levels and both soil depths (Figure 3). Euclidean distance values varied between the degradation levels, thus making division into groups possible. The dendrograms resulting from the cluster analysis to assess the similarity of the study areas show the formation of three groups at each of the soil depths (Figure 3a and 3b). The dendrograms show that less distant levels of degradation are more similar than widely distant ones, i.e. groupings based on similarity are more relevant at those levels of degradation showing smaller Euclidean distance between them.

Figure 3 – Dendrograms of hierarchical cluster analysis of pasture soils at four levels of degradation (ND1, ND2, ND3, and ND4) at two depths: a) 0 m to 0.10 m and b) 0.10 m to 0.20 m.



Source: Authors, 2023.

At the 0 m to 0.10 m depth (Figure 3a), the ND2 and ND3 pastures are the most similar (smallest Euclidean distance). On its turn, the group formed by the ND3 and ND2 pastures showed greater similarity with the ND4 pasture than with the ND1 pasture. At the 0.10 m to 0.20 m depth (Figure 3b), the greatest similarity was found between pastures ND1 and ND3. The group formed by these two pastures shows greater similarity with pasture ND2 than with pasture ND4.

One would expect to find better chemical and physical soil indices in a non-degraded environment (SILVA; GOVEIA, 2019), but that was not observed in the data obtained. Consequently, the statistical cluster analysis for the soils' physical and chemical attributes indicates greater similarity between the ND1 area and the ND3 area, while the visual assessment of degradation, obtained from the percentage of bare soil and botanical composition, indicated greater similarity between the ND1 and ND2 areas.

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

4.2 Descriptive statistics for soil water infiltration, soil resistance to penetration, leaf area index, and phytomass

Soil water infiltration rates (INF), soil resistance to penetration (RP) at the 0 m to 0.10 m and 0.10 m to 0.20 m depths, leaf area index (IAF), and phytomass (FIT) were analyzed using descriptive statistics (Table 5), calculating the mean, variance, standard deviation, minimum value, maximum value, skewness, kurtosis, and CV for all four different pasture degradation levels. The CVs of the analyzed dataset are considered average, except IAF in pasture ND4. The average soil water infiltration rate was higher in pasture ND1 and similar in all degraded pastures (ND2, ND3, and ND4). This result may also be associated with animal stocking, since in degraded cultivated or natural pastures the continuous presence of animals with the same stocking density throughout the year generates soil compaction, increase in unvegetated area, reduction in water infiltration, and increase in surface water runoff, with consequent soil loss by erosion (SONE et al., 2020; CENTERI, 2022).

Table 5 – Descriptive statistics for soil infiltration rates (INF) and penetration resistance (RP) at the soil depths of 0 m to 0.10 m and 0.10 m to 0.20 m, leaf area index (LAI), and phytomass in kg DM/ha (FIT) at pasture degradation levels ND1 (no degradation), ND2 (low degradation), ND3 (medium degradation) and ND4 (high degradation).

Attribute	Mean	Variance	Standard deviation	CV*	Minimum	Maximum	Skewness	Kurtosis
INF ND1	14.50	80.62	8.98	61.92	2.21	44.27	1.32	2.99
INF ND2	8.42	18.45	4.30	51.04	2.21	19.92	0.59	0.23
INF ND3	6.81	10.62	3.26	47.89	2.21	14.39	0.93	0.15
INF ND4	8.42	18.45	4.30	51.04	2.21	19.92	0.59	0.23
RP ND1 0– 0,1 m	1.89	0.21	0.46	24.27	1.10	2.85	0.27	-0.69
RP ND1 0,1–0,2 m	2.53	0.45	0.67	26.54	1.33	3.98	0.18	-0.38
RP ND2 0–0,1 m	2.26	0.27	0.52	23.01	1.35	3.93	0.92	2.63
RP ND2 0,1–0,2 m	3.20	1.20	1.10	34.26	0.33	6.52	0.96	4.19
RP ND3 0–0,1 m	2.17	0.35	0.59	27.12	1.19	3.82	0.71	0.68
RP ND3 0,1–0,2 m	2.59	1.74	1.32	50.98	1.49	7.87	2.84	9.28
RP ND4 0–0,1 m	1.55	0.06	0.25	16.41	1.06	2.07	0.21	-0.55
RP ND4 0,1–0,2 m	2.34	0.23	0.48	20.48	1.40	3.61	0.95	1.31
IAF ND1	3.10	1.77	1.33	42.91	1.06	5.20	0.15	-1.50
IAF ND2	2.43	0.35	0.59	24.43	1.19	3.59	0.03	-0.57
IAF ND3	2.20	1.64	1.28	58.38	0.48	4.47	0.39	-1.18
IAF ND4	0.65	0.17	0.41	62.83	0.19	2.29	2.06	5.71
FIT ND1	5442.00	5587000.00	2364.00	43.43	1192.00	10680.00	0.18	-0.37
FIT ND2	3609.00	2681000.00	1637.00	45.37	1245.00	6528.00	0.54	-0.90
FIT ND3	1776.00	1011000.00	1005.00	56.61	247.10	3909.00	0.76	0.00
FIT ND4	536.70	103900.00	322.30	60.06	151.90	1277.00	0.80	-0.30

Source: Authors, 2023

RP increased significantly with depth in all pastures, which is common in sandy soils (with sand contents greater than 75%). The ND2 pasture's soil showed the highest resistance to penetration, due to the natural stoniness in its surface profile. The ND3 pasture's soil showed the lowest water infiltration and the second highest soil resistance to penetration, which may be explained by the high stocking rate (the highest among the pastures studied) and, consequently, greater soil compaction due to overgrazing. Soil resistance to penetration

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

creates a barrier for root growth of up to 2.6 times the force exerted by the root, and also reduces water infiltration, which intensifies the process of pasture degradation (ADAMS et al., 2022). In sandy soils, there is an even greater risk of erosion due to soil disintegration. The ND4 pasture (most degraded) comes from a continuous history of undergrazing, after a period of overgrazing for a few years, followed by a lack of soil nutrient replenishment and pasture renovation.

The classification of degraded pastures is usually based on a drop in their vigor and productivity, low forage populations, and the presence of termite mounds and invasives, i.e. based on elements of the landscape and epigean vegetation, as found in the literature (SONE et al., 2020). However, the classification of pastures in terms of their degree of degradation must also take into account many soil parameters, and not just the evaluation of the aerial part (phytomass, soil cover, botanical composition, IAF, and others). In this case, according to Dias-Filho (2014), the visual characteristics directly observed in the pasture area, such as percentage of weeds (or biomass) and bare soil, would be secondary indicators of pasture degradation.

4.3 Principal component analysis (PCA)

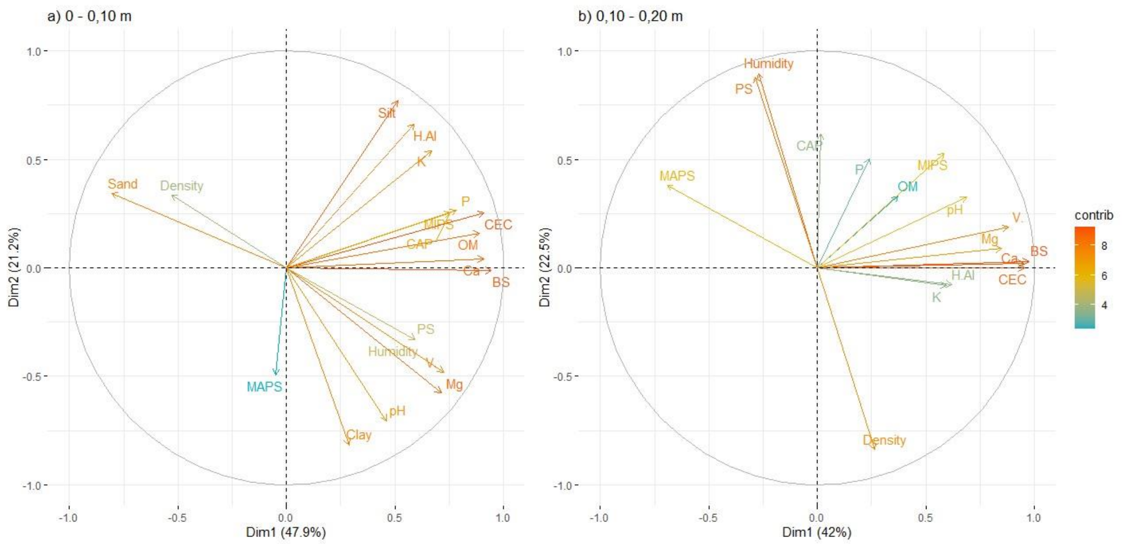
The KMO test resulted in a coefficient of 0.79, indicating that data sampled from pastures may be studied using factor analysis, provided there are no redundancies (MAO; MO; GUO, 2013; GUMBO; DZAGA; NETHENGWE, 2016; MEDEIROS et al., 2017).

Applying PCA to the soil's physicochemical parameters generated four principal components (PCs) with eigenvalues greater than 1 in both layers. There is more than one criterion for choosing the PCs to be considered. Kaiser (1974) suggests using factors with an eigenvalue above 1, while Hair et al. (2017) suggest that the number of components be represented by 60% of the accumulated variance. In this case, both criteria are met.

Figure 4 shows the two-dimensional representation of the first two PCs in each soil layer. In the 0 m to 0.10 m soil layer, the variance explained by the first two PCs amounts to 69.2% (Figure 4a) of the total variability of the pastures' soil attributes, while in the 0.10 m to 0.20 m soil layer, the first two PCs show accumulated variance of 64.6%. The four PCs in each layer explain 85% and 83% of the total variation in the first and second layers, respectively.

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

Figure 4 – Two-dimensional representation of the principal components (PCA): a) soil from 0 m to 0.10 m, and b) soil from 0.10 m to 0.20 m.



Source: Authors, 2023.

Table 6 shows the loadings of the attributes studied in each PC in each layer. The first PC, in the 0 to 0.10 m layer, is explained by various chemical attributes (P, K, Ca, Mg, BS, CEC, and V) and physical attributes (OM, MIPS, field capacity, and sand content). The second PC is explained by the chemical attributes pH, H+Al, and by the silt and clay contents. The physical attributes of PS, MAPS, and density only explain the third PC.

In the 0.10–0.20 m layer, the same attributes also predominate in explaining the first PC (except for OM, P, and field capacity), while MIPS explains PC1 in this layer. The second PC is explained by P, PS, density, saturation moisture content, and CAP.

Table 6 – Principal components (PCs) and loadings of each attribute (chemical and physical) of the analyzed pastures.

Depth	0 – 0.10 m				0.10 – 0.20 m			
Attribute	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**
OM	**0.890**	0.159	0.102	0.038	0.371	0.33	**0.706**	0.107
pH	0.463	**-0.705**	-0.362	0.256	**0.688**	0.326	-0.399	0.216
P	**0.782**	0.264	0.134	0.321	0.241	**0.505**	-0.541	-0.131
K	**0.669**	0.54	-0.008	0.027	**0.595**	-0.083	0.591	0.181
Ca	**0.909**	0.041	-0.154	-0.348	**0.953**	0.021	0.017	-0.231
Mg	**0.713**	-0.577	-0.228	-0.126	**0.85**	0.09	-0.368	-0.172
H+Al	0.588	**0.662**	0.259	-0.325	0.621	-0.077	**0.642**	-0.201
BS	**0.943**	-0.013	-0.166	-0.259	**0.975**	0.03	-0.023	-0.186
CEC	**0.911**	0.255	-0.018	-0.316	**0.953**	0	0.167	-0.203
V	**0.724**	-0.481	-0.423	-0.031	**0.881**	0.186	-0.335	0.01
Sand	**-0.804**	0.342	0.109	0.248	–	–	–	–
Silt	0.514	**0.771**	0.181	-0.132	–	–	–	–
Clay	0.288	**-0.816**	-0.346	-0.18	–	–	–	–
PS	0.593	-0.330	**0.692**	0.215	-0.287	**0.879**	0.186	-0.152
MIPS	**0.755**	0.255	-0.298	0.496	**0.585**	0.528	0.052	0.498
MAPS	-0.051	-0.493	**0.840**	-0.157	**-0.692**	0.381	0.137	-0.504
Density	-0.529	0.334	**-0.706**	-0.072	0.263	**-0.837**	0.01	-0.236
Moisture	0.593	-0.330	**0.692**	0.215	-0.272	**0.896**	0.14	0.088
CAP	**0.755**	0.255	-0.298	0.496	0.017	**0.617**	0.007	-0.371

Source: Authors, 2023.

Based on the PCA, one may identify (Table 6, in bold) the chemical attributes that are most relevant to explain the variability in levels of pasture degradation. Usually, most companies quantify these attributes in soil samples sent to the laboratory (P, K, Ca, Mg, OM, BS, CEC, and V). Physical attributes such as granulometry and soil water parameters are less explanatory.

4.4 Possible implications for agri-environmental management

Once the attributes most relevant for explaining pasture degradation have been identified, guidelines may be created for the interventions needed to restore the environmental quality of these pastures. Notably, PCA, dendrograms, and correlation analysis grouped the attributes and related them to the levels of degradation. We suggest prioritizing the monitoring of the most explanatory attributes, namely the chemical attributes (P, K, Ca, Mg, OM, BS, CEC, and V). This strategy could be useful to economically optimize the assessment of degraded pasture levels.

4 CONCLUSIONS

1. The topsoil layer showed more clearly recognizable clusters between eigenvectors and degradation levels, as well as in dendrograms, when compared to the deeper layer. Between 0 m and 0.10 m, pH and clay content predominate to explain non-degradation, while H+Al, silt content, organic matter, microporosity, and

compaction explain low degradation.

2. In the deeper layer, the distinction between the parameters is smaller and the correlation between them and the level of degradation is lower.
3. This approach may be replicated in preliminary studies for pasture restoration and monitoring plans, to indicate parameter prioritization and cost optimization.

REFERENCES

ABIEC – Associação Brasileira das Indústrias Exportadoras de Carnes. **Perfil da Pecuária no Brasil.** São Paulo: ABIEC, 2019. Available in: http://abiec.com.br/publicacoes/beef-report-2019/. Accessed on: Aug. 1, 2023.

ADAMS, T. C.; ASHWORTH, A. J.; OWENS, P. R.; POPP, M.; MOORE, P. A., PENNINGTON, J. Pasture conservation management effects on soil surface infiltration in hay and grazed systems. **Journal of Soil and Water Conservation**, Ankeny, v. 77, n. 1, p. 59-66, 2022.

ANDRADE, R. G.; RODRIGUES, C. A. G.; SANCHES, I. D.; TORRESAN, F. E.; QUARTAROLI, C. F. Uso de Técnicas de Sensoriamento Remoto na Detecção de Processos de Degradação de Pastagens. **Engenharia na Agricultura**, Botucatu, v. 21, p. 234-243, 2013.

CAMARGO, O. A.; MONIZ, A. C.; JORGE, L. A.; VALADARES, J. M. A. S. **Métodos de análise química, mineralógica e física de solos do Instituto Agronômico de Campinas**. Campinas: Instituto Agronômico de Campinas, 93 p., 1986.

CENTERI, C. Effects of grazing on water erosion, compaction and infiltration on Grasslands. **Hydrology**, Basel, v. 9, n. 2, p. 34, 2022.

DIAS FILHO, M. B. **Diagnóstico das pastagens no Brasi**l. Belém: Embrapa Amazônia Oriental, 36 p., 2014.

EMBRAPA. **Boas práticas agropecuárias: bovinos de corte: manual de orientações**. Campo Grande: Embrapa Gado de Corte, 69 p., 2011a.

EMBRAPA. Centro Nacional de Pesquisa de Solos. **Manual de métodos de análises de solos**. Rio de Janeiro: Embrapa, 230 p., 2011b.

FAO. **FAOSTAT – Food and agriculture data. Crop Statistics.** Roma: FAO, 2022. Available in: http://www.fao. org/faostat/. Accessed on: Aug. 1, 2023.

FELTRAN-BARBIERI, R.; FÉRES, J. G. Degraded pastures in Brazil: improving livestock production and forest restoration. **Royal Society Open Science**, London, v. 8, n. 7, p. 201854, 2021.

GHOLIZADEH, M. H.; MELESSE, A. M.; REDDI, L. Water quality assessment and apportionment of pollution sources using APCS-MLR and PMF receptor modeling techniques in three major rivers of South Florida. **Science of the Total Environment**, New Jersey, v. 566, p. 1552-67, June 2016.

GIANETTI, G. W.; FERREIRA FILHO; J. B. D. S. O Plano e Programa ABC: uma análise da alocação dos recursos. **Revista de economia e sociologia rural**, Piracicaba, v. 59, 2020.

GIRAUDOUX, P.; GIRAUDOUX, M. P. **Package 'pgirmess'**. Wien: R Core Team, 2023. Available in: https://CRAN.R-project.org/package=pgirmess/. Accessed on: Aug. 1, 2023.

GRAVES, S. **Package 'multcompView'.** Wien: R Core Team, 2023. Available in: https://CRAN.R-project.org/package= multcompView/. Accessed on: Aug. 1, 2023.

GUMBO, J. R.; DZAGA, R. A.; NETHENGWE, N. S. Impact on water quality of Nandoni water reservoir downstream of municipal sewage plants in Vhembe District, South Africa. **Sustainability**, Basel, v. 8, n. 7, p. 597, June 2016.

HAIR, J. F.; ANDERSON, R. E.; TATHAN, R. L.; BLACK, W. C. **Multivariate data analysis.** New Jersey: Prentice Hall, 2017.

IBGE. **Censo Agropecuário**. Rio de Janeiro: IBGE, 2017. Available in: https://censos.ibge.gov.br/agro/2017/. Accessed on: Aug. 1, 2023.

IBGE. **PAM - Produção Agrícola Municipal**. Rio de Janeiro: IBGE, 2022. Available in: http://seriesestatisticas.ibge.gov.br/. Accessed on: Aug. 1, 2023.

KAISER, H. F. An index of factorial simplicity. **Psychometrika**, Berlin, v. 69, n. 1, p 31-6, Mar. 1974.

LIMA, C. G. da R.; CARVALHO, M. de P.; MELLO, L. M. M. de; LIMA, R. C. Correlação linear e espacial entre a produtividade de forragem, a porosidade total e a densidade do solo de Pereira Barreto (SP). **Revista Brasileira de Ciência do Solo**, Viçosa, v. 31, n.6, Nov./Dec. 2007.

LIU, C. W.; LIN, K. H.; KUO, Y. M. Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. **Science of the Total Environment**, New Jersey, v. 313, n. 1-3, p. 77-89, Sep. 2003.

MACEDO, M. C. M.; ARAUJO, A. R. de. Sistemas de produção em integração: alternativa para recuperação de pastagens degradadas. In: BUNGENSTAB, D. J.; ALMEIDA, R. G. de; LAURA, V. A.; BALBINO, L. C.; FERREIRA, A. D. (ed.). **ILPF**: inovação com integração de lavoura, pecuária e floresta. Brasília: Embrapa, 2019. p. 295-317.

MAO, L.; MO, D.; GUO, Y. Multivariate analysis of heavy metals in surface sediments from lower reaches of the Xiangjiang River, southern China. **Environmental Earth Sciences**, Berlin, v. 69, n. 3, p. 765-71, June 2013.

MAPBIOMAS. **Coleção 7 (1985 – 2021) da série anual de mapas de cobertura e uso de solo do Brasil.** Brasília: Mapbiomas, 2022. Available in: https://mapbiomas.org/. Accessed on: Aug. 1, 2023.

MEDEIROS, G. A.; TRESMONDI, A. C. C. L.; QUEIROZ, B. P. V.; FENGLER, F. H.; ROSA, A. H.; FIALHO, J. M.; LOPES, R. S.; NEGRO, C. V.; SANTOS, L. F.; RIBEIRO, A. I. Water quality, pollutant loads, and multivariate analysis of the effects of sewage discharges into urban streams of Southeast Brazil. **Energy, Ecology and Environment**, Berlin, v. 2, n. 4, p. 259-76, 2017.

NASCIMENTO JR., D.; QUEIROZ, D. S.; SANTOS, M. V. F. **Degradação das pastagens e critérios para avaliação.** In: SIMPÓSIO SOBRE MANEJO DAS PASTAGENS, 11, 1994 Anais. Piracicaba: Fundação de Estudos Agrários Luiz de Queiroz, p. 107-151, 1994.

R CORE TEAM. **R: a language and environment for statistical computing.** Wien: R Core Team, 2023. Available in: https://cran.r-project.org/. Accessed on: Aug. 1, 2023.

RODRIGUES, C. A. G.; DE QUEIROZ, H. P.; QUARTAROLI, C. F. **Avaliação em campo de pastagens de *Urochloa* spp. (syn. *Brachiaria* spp.) no bioma Cerrado para estimar níveis de degradação: parâmetros qualitativos**. Campinas: Embrapa Territorial, 34 p., 2022.

SILVA, C. O. F.; GOVEIA, D. Avaliação da qualidade ambiental de corpos hídricos urbanos utilizando análise multivariada. **Interações**, Campo Grande, v. 20, p. 947-958, 2019.

ISSN 1980-0827 – Volume 20, Number 2, Year 2024

SONE, J. S.; OLIVEIRA, P. T. S.; EUCLIDES, V. P. B.; MONTAGNER, D. B.; de ARAUJO, A. R.; ZAMBONI, P. A. P.; SOBRINHO, T. A. Effects of nitrogen fertilisation and stocking rates on soil erosion and water infiltration in a Brazilian Cerrado farm. **Agriculture, Ecosystems & Environment**, Berlin, v. 304, p. 107159, 2020.

STOLF, R. Teoria e teste experimental de fórmulas de transformação dos dados de penetrômetro de impacto em resistência do solo. **Revista Brasileira de Ciência do Solo**, Lavras, v.15, p.229-235, 1991.

SCHULTZ, N.; REIS, V. M.; URQUIAGA, S. **Resposta da cana-de-açúcar à adubação nitrogenada: fontes nitrogenadas, formas de aplicação, épocas de aplicação e efeito varietal.** Seropédica: Embrapa Agrobiologia, 52 p, 2015.

TORRES, F. N.; RITCHER, R.; VOHLAND, M. A multisensoral approach for high-resolution land cover and pasture degradation mapping in the humid tropics: A case study of the fragmented landscape of Rio de Janeiro. **International Journal of Applied Earth Observation and Geoinformation**, New Jersey, v. 78, p. 189-201, 2019.

UNIVERSIDADE FEDERAL DE GOIÁS. Laboratório de Processamento de Imagens e Geoprocessamento da Universidade Federal de Goiás (LAPIG-UFG). **Atlas digital das pastagens brasileiras**. Área de pastagem Brasil 2021. Available in: https://pastagem.org/atlas/map. Accessed on: Aug. 1, 2023.

VALLADARES, G. S.; GOMES, A. S.; TORRESAN, F. E.; RODRIGUES, C. A. G.; GREGO, C. R. Modelo multicritério aditivo na geração de mapas de suscetibilidade à erosão em área rural. **Pesquisa Agropecuária Brasileira**, Brasília, v. 47, p. 1376-1383, 2012.

VIEIRA, S.R. Permeâmetro: novo aliado na avaliação de manejo do solo. **O Agronômico**, Piracicaba, v.47-50, p.32 - 33, 1998.

WARRICK, A. W.; NIELSEN, D. R. Spatial variability of same physical properties of the soil. In: HILL, D. (ed.). **Applications of Soil Physics.** New York: Academic Press, 13. p.319-344, 1980.