SOUZA, F. G.; SILVA, J. V.; SAMPAIO, T. I.; MORAIS, J. T.; MOURA, V.; LIMA, A. F. L.; BRITO, W. B. M.; PINHEIRO, E. N.; SANTOS, R. V.; CAMPOS, M. C. C. Soil erodibility in areas under citrus (*Citrus sinensis* L. Osbeck) and forest in Rondônia, Brazil. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 10, n. 4, e7683, Oct./Dec, 2023. ISSN 2358-6303. DOI: https://doi.org/10.32404/rean.v10i4.7683.

Soil erodibility in areas under citrus (*Citrus sinensis* L. Osbeck) and forest in Rondônia, Brazil

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Received: 26/06/2023; Accepted: 10/11/2023.

ABSTRACT

Few studies have studied soil erodibility in areas that have undergone conversion processes from native forests to agricultural areas, especially in agricultural frontier regions. The present study aimed to evaluate soil erodibility in areas with citrus (*Citrus sinensis* L. Osbeck) and forest under different uses in Southern Rondônia, Brazil, using multivariate statistics and geostatistics. A 42 × 30 m grid with regular spacing between sample points of 6 × 6 m was established for the studied native forest and citrus areas at depths of 0.00-0.20 m. At each sampling point, samples with preserved structures in the studied layer were collected to quantify organic carbon and soil texture, totaling 288 samples in the two studied areas. It was observed that the area cultivated with citrus showed a greater predisposition of the soil to suffer interrill erosion (Ki_{wepp}). The citrus area also presented a greater susceptibility of the soil to suffer rill erosion (Kr_{wepp}); however, this area showed high values of critical shear stress, which signals the soil's resistance to the beginning of the erosive process. On the other hand, the forest area showed a greater predisposition to suffer erosion (K-factor), possibly linked to the high values of silt and sand, favoring the present erodibility conditions.

Keywords: Conversion, Soil management, Erosive process.

Erodibilidade do solo em áreas cultivadas com citrus (*Citrus Sinensis* L. Osbeck) e floresta em Rondônia, Brasil

RESUMO

Poucos estudos avaliaram a erodibilidade do solo em áreas que passaram por processos de conversão de mata nativa para áreas agrícolas, principalmente em regiões de fronteira agrícola. Deste modo, objetivou-se avaliar a erodibilidade do solo em áreas de cultivo de citros (*Citrus sinensis* L. Osbeck) e floresta, utilizando estatística multivariada e geoestatística em áreas sob diferentes usos no sul de Rondônia, Brasil. Uma malha de 42 × 30 m com espaçamento regular entre pontos amostrais de 6 × 6 m foi estabelecida para as áreas de mata nativa e citros estudadas em profundidades de 0,00-0,20 m. Em cada ponto de amostragem foram coletadas amostras com estrutura preservada nas camadas estudadas, para quantificação do carbono orgânico e textura do solo, totalizando 288 amostras nas duas áreas estudadas. Observou-se que a área cultivada com citros apresentou maior predisposição do solo a sofrer erosão entre sulcos (Ki_{wepp}), a área cítrica também apresentou maior susceptibilidade do solo a sofrer erosão em sulcos (Kr_{wepp}), por outro lado, esta área apresentou altos valores de tensão crítica de cisalhamento, fato que sinaliza a resistência do solo ao início do processo erosivo. Por outro lado, a área florestal apresentou maior predisposição a sofrer erosão (fator K), fato possivelmente ligado aos altos valores de silte e areia, que favoreceram as atuais condições de erodibilidade.

Palavras-chave: Conversão, Manejo do solo, Processo erosivo.

1. Introduction

Soil erosion is considered the most damaging form of degradation and the main cause of unsustainability in agricultural production systems on a global scale (Bertol et al., 2004; Wang et al., 2016). Some practices have contributed to the breakdown of the balance of natural ecosystems; one of these practices is the substitution of forested areas for cultivated areas without adopting technical criteria; this situation has been one of the main problems caused by anthropic action in the Amazon region.

Studies have shown the magnitude of forest degradation in the Brazilian Amazon after the conversion process (Aragão and Shimabukuro, 2010; Souza-Junior et al., 2013; Freitas et al., 2015), as well as the impacts and changes on biodiversity and ecological or ecosystem services (Moura et al., 2013; Berenguer et al., 2014), besides bringing changes in chemical, physical, and biological attributes, entailing effects on the environmental quality of the area (Souza et al., 2020; Frozzi et al., 2020).

Erodibility (K-factor) is one of the Universal Soil Loss Equation (USLE) variables that quantitatively expresses soil susceptibility to water erosion. It represents an important factor in estimating soil loss by erosion, characterized by the combination of soil properties, enabling its estimation using equations (Sá et al., 2004). Erodibility is a very variable parameter, especially due to the great diversity of soils and, consequently, the variation of soil attributes, thus making it difficult to estimate based solely on soil classification (Martins et al., 2011; Schick et al., 2014).

Among the methods for analyzing erodibility attributes, we can highlight the techniques of multivariate analysis and geostatistics, in which the multivariate aims to reduce the dimensional number of variables, such as the principal components analysis; these are tools that allow condensing all information contained in a certain number of original variables in smaller sets, called factors, whose linear combinations explain the maximum variance contained in the original variables (Hair et al., 2007), while in geostatistics it is allowed to create spatial distribution mappings through the use of kriging, providing data that allows different soil attributes to be interrelated and the creation of distribution maps (Lourenço et al., 2020).

Thus, this study is justified under the hypothesis that because soils present characteristics with dynamic properties, which in turn can be changed at all times and under different land uses and surface soil management, the same can end up altering, consequently, its erodibility over time, besides leading to the degradation of large areas, causing a decline in their quality. The present study aimed to evaluate soil erodibility in areas with citrus (*Citrus sinensis* L. Osbeck) and forest under different uses in Southern Rondônia, Brazil, using multivariate statistics and geostatistics.

2. Material and Methods

The study was developed in 2018 at the Federal Institute of Rondônia (IFRO), Campus de Colorado do Oeste, at 13º06' S and 60º29' W. For this study, two areas were selected: one cultivated with orange (*Citrus sinensis* L. Osbeck) and another area of forest (Figure 1). The soil of the study area is classified as Argissolo Vermelho-Amarelo followed the criteria established by the Brazilian Soil Classification System (Santos et al. 2018) and Ochric, Hyperdystric, Clayic) Chromic, Abruptic, Acrisol followed the criteria established by the World Reference Base of Soils (IUSS Working Group WRB, 2022).

Originating from autochthonous parent material and metamorphic basic rocks. The region's relief varies from undulating to mountainous, as most of the municipality of Colorado do Oeste is situated on the Southwestern slope of the Chapada dos Parecis at altitudes higher than 400 m above sea level.

Regarding climatic characterization, the region's climate is tropical, hot, and humid, with two well-defined seasons: summer from June to October and winter from November to May. The average rainfall is approximately 1,900 mm annually, with a rainy period between October and June. The average annual temperatures are around 22 ºC, with maximum temperatures of up to 31 ºC and minimum temperatures reaching 10 ºC in the coldest months when there is a cold spell from June to September (Alvares et al., 2013).

The collections were carried out in November 2019, the dry period in the region, establishing meshes according to the dimensions of the crop. In the citrus (*Citrus sinensis* L. Osbeck) and forest areas, 42 × 30 m meshes were established with regular spacing between the sample points of 6 × 6 m. The samples were collected at the mesh intersection points at depths of 0.00-0.20 m, with 48 sampling points in each area. At each sampling point, samples were collected with the structure preserved in clod form at the evaluated depth to determine soil texture and organic carbon, totaling 96 samples in the studied areas. The samples were dried in the shade and slightly crushed by hand, passed through a 4.76 mm mesh sieve, and the material retained on the 2.00 mm sieve was separated for soil texture and organic carbon analysis.

Textural analysis was performed by the pipette method, using 0.1 N NaOH solution as a chemical dispersant and mechanical stirring in a high rotation apparatus for 15 minutes, following the methodology proposed by Teixeira et al. (2017). The clay fraction was separated by sedimentation, the sand by sieving, and the silt calculated by difference (Table 1).

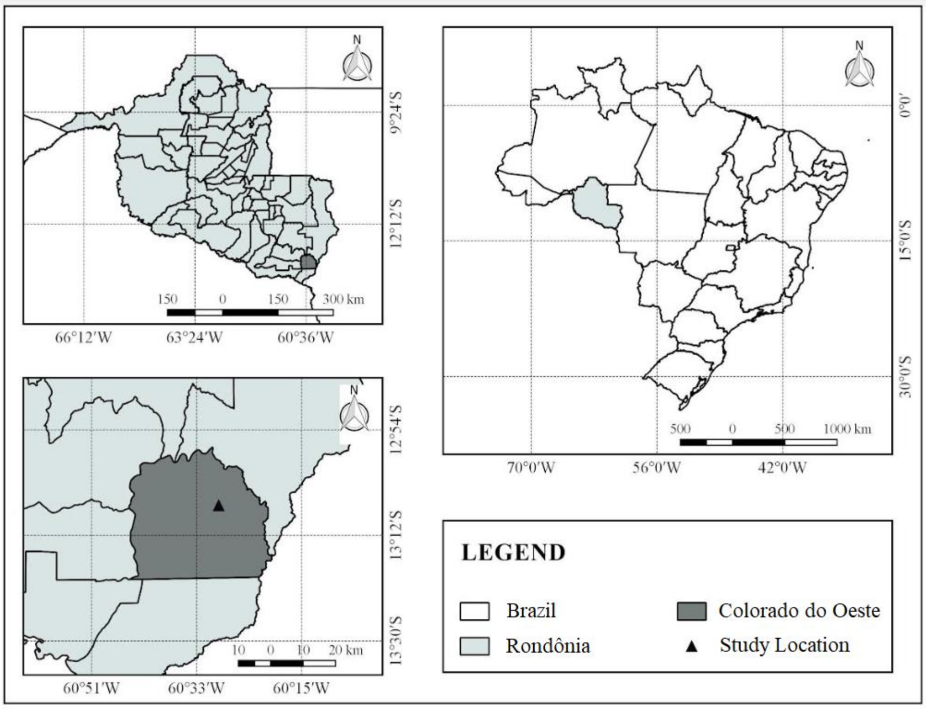

Figure 1. Location of the study area. Map of Brazil, highlighting the state of Rondônia and the study area on the map of the municipality of Colorado do Oeste, RO. Source: Author, 2023.

Table 1. Soil textural and permeability classes

Textural class [1]	Permeability class [2]	Permeability
Clay and Silty clay	6	Very slow
Silt clay loam and Sandy clay	5	Slow
Sandy clay loam e Clay loam	4	Slow and moderate
Loam, Silty loam, and Silty	3	Moderate
Loamy sand and Sandy loam	2	Moderate and fast
Sandy	1	Fast

Source: [1] United States Department of Agriculture (1983); [2] Wischmeier et al. (1971)

Organic carbon (OC) was determined by the Walkley-Black method, modified by Yeomans and Bremner (1988). To determine the estimate of erodibility, the indirect prediction models were used, where they estimate the values of the erodibility factors through equations that involve the values of the soil attributes analyzed in the laboratory. Thus, the present study used the USLE (Universal Soil Loss Equation) and WEPP (Water Erosion Prediction Project) models to determine the factors affecting erosion in the areas under study.

To calculate the total soil erodibility of the USLE (K factor, t ha^{-1} MJ^{-1} mm^{-1} ha h), equation 1 was used.

$$K = 7.48 * 10^{-6} M + 4.48059 * 10^{-3} p - 6.31175 * 10^{-2} X27 + 1.039567 * 10^{-2} X32 \quad \text{(Eq. 1)}$$

Where:

New silt = silt + very fine sand, %; New sand = very coarse sand + coarse sand + medium sand + fine sand, %; M = new silt × (new silt + new sand); p = permeability, according to Wischmeier et al. (1971) (Table 1); X27 = [(0.002 × clay, %) + (0.026 × silt, %) + (0.075 × very fine sand, %) + (0.175 × fine sand, %) + (0.375 × medium sand, %) + (0.75 × coarse sand, %) + (1.5 × very coarse sand, %)] / (clay, % + silt, % + sand, %); X32 = new sand × (organic matter, %/100).

The equations proposed by Flanagan and Livingston (1995) (Equations 2 and 3) were used to calculate the interrill erodibility of the WEPP model (Ki, kg s m^{-4}):

$$\text{Kiwepp} = 272{,}8000 + 192{,}100\, VFS, \quad sand \geq 30\% \quad \text{(Eq. 2)}$$

$$Kiwepp = 605{,}4000 - 55{,}130\, CLA, \quad sand < 30\% \quad \text{(Eq. 3)}$$

where:

VFS - percentage of very fine sand, %; CLA - percentage of clay, %. To calculate the rill erodibility (Kr, s m^{-1}) and shear stress (Ss, N m^{-2}) of the WEPP model, the equations proposed by Flanagan and Livingston (1995) were used (Equation 4 to 7):

$$Krwepp = 0.00197 + 0.00030\,VFS + 0.03863\,e^{(-1.84*OM)},\quad sand \geq 30\% \quad \text{(Eq. 4)}$$

$$Sswepp = 2.67 + 0.065\,CLA - 0.058\,VFS,\quad sand \geq 30\% \quad \text{(Eq. 5)}$$

$$Krwepp = 0.0069 + 0.134\,e^{(-0{,}20*CLA)},\quad sand < 30\% \quad \text{(Eq. 6)}$$

$$Sswepp = 3.5 \qquad sand < 30\% \quad \text{(Eq. 7)}$$

where:

VFS - percentage of very fine sand, %; e - Napierian logarithm base; OM - percentage of soil organic matter, %; CLA - percentage of clay, %.

After determining the attributes of erodibility, texture, and soil organic matter, descriptive statistics and univariate and multivariate statistical analysis were performed. The descriptive statistics calculated the mean, median, standard deviation, variance, coefficient of variation, coefficient of asymmetry, kurtosis, and minimum and maximum values of the variables. The normality of the data was assessed using the Kolmogorov-Smirnov test with the Statistica 7.0 software (Statsoft, 2004).

Univariate analysis of variance (ANOVA) was used to compare the means of the attributes individually by Tukey test ($p < 0.05$), using SPSS 21 software (Spss Inc., 2001). Then, the multivariate analysis of variance (MANOVA) was used, through factor analysis, to find the statistical significance of the sets of evaluated attributes that most discriminate the environments, with the area under forest as a reference, aiming to have as a response the attributes that suffer greater influence in the respective areas studied.

The adequacy of the factor analysis was done by the Kaiser-Meyer-Olkin (KMO) measure, which evaluates the simple and partial correlations of the variables, and by the Barlett test of sphericity, which aims to reject the equality between the correlation matrix and the identity. The factors were extracted by principal components (PC), incorporating the variables that present communalities equal to or greater than five (5.0). The number of factors to be used was chosen by the Kaiser criteria (factors that present eigenvalues greater than 1). To simplify the factor analysis, the factors were rotated orthogonal (Varimax) and represented in a factor plan of the two components.

Geostatistics was used to evaluate the spatial variability of the variables in the studied areas and to evaluate the factors (F1 and F2) obtained by factor analysis. The geostatistical analysis was performed based on the experimental semivariogram, estimated by Equation 8:

$$\hat{y}(h) = \frac{1}{2\eta(h)} \sum_{i=1}^{\eta(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad \text{(Eq. 8)}$$

where:

$\hat{y}(h)$ - value of semivariance for a distance; h; $n(h)$ - number of pairs involved in the semivariance calculation; $Z(xi)$ - value of attribute Z at position xi; $Z(xi + h)$ - value of attribute Z separated by a distance h from position xi.

To analyze the degree of spatial dependence (DSD) of the attributes under study, the classification of Cambardella et al. (1994) was used, in which soil properties are considered to have strong spatial dependence if the ratio of the nugget effect (C_0) to the plateau ($C_0 + C_1$) is less than 25%. If the ratio is between 26% and 75%, the spatial dependence is considered moderate, while if the soil property is greater than 75% up to 95%, it is classified as weak spatial dependence.

The semivariogram models for the attributes studied were estimated by the GS+ 7.0 Software (Robertson, 2016). The fit of the semivariograms was done based on the best coefficient of determination (R^2) and maximum correlation coefficient (r) from the cross-validation. The Surfer 13 software program was used to prepare the maps of the spatial distribution of the variables.

3. Results and Discussion

The descriptive statistics and analysis of variance for the erodibility attributes in the 0.00-0.20 m soil layer evaluated in the area cultivated with citrus compared to the forest area are presented in Table 2. The attributes had very close mean and median values, demonstrating little variation among the sampling points. Besides, such results also indicate symmetrical distributions, which is confirmed by the asymmetry value close to zero.

In the face of such fact, most erodibility attributes presented positive asymmetry, except for the attributes OM and Ss_{wepp} for the forest area and OM in the area cultivated with citrus. In the analysis of the results of the kurtosis coefficient, it was verified that a good part of the attributes presented positive values, a situation that evidences a leptokurtic distribution; that is, the distribution presents a frequency curve that is more closed than the normal distribution.

In the analysis of the coefficients of variation, adopting the limits proposed by Warrick and Nilsen (1980), it can be inferred that the attributes studied exhibited low to medium variability for the two areas of the study, indicating results with a certain homogeneity. The results of the Kolmogorov-Smirnov test show normality for all erodibility attributes in the 0.00-0.20 m soil layer.

Table 2. Mean test and descriptive statistics of soil erodibility attributes in areas under citrus and forest in the Southern of Rondônia, Brazil.

Descriptive Statistics	OM	Sand	Silt	Clay	K-factor	Ki_{wepp}	Kr_{wepp}	Ss_{wepp}
	(g kg^{-1})				t ha^{-1} MJ^{-1} mm^{-1} ha h	kg s m^{-4}	s m^{-1}	N m^{-2}
Forest								
Maximum	50.72	765.00	292.60	112.00	6.40×10^{-2}	9.36×10^{6}	1.33×10^{-2}	3.10
Minimum	19.02	617.00	153.70	44.00	2.35×10^{-2}	5.29×10^{6}	6.01×10^{-3}	0.39
Mean	34.33 a	718.49 a	211.55 a	67.30 b	4.19×10^{-2} a	6.90×10^{6} a	8.70×10^{-3} b	1.84 b
Median	31.98	722.85	208.17	67.00	4.10×10^{-2}	6.82×10^{6}	8.59×10^{-3}	1.89
SD	8.83	28.11	26.55	15.90	9.86×10^{-3}	7.82×10^{5}	1.33×10^{-3}	0.46
CV (%)	25.73	3.91	12.55	23.62	23.52	11.34	15.28	24.90
Asymmetry	0.51	-1.02	0.56	0.62	0.30	1.03	1.26	-0.80
Kurtosis	-0.80	2.18	1.07	0.24	-0.23	1.59	2.72	2.89
K-S	0.07	0.06	0.09	0.07	0.09	0.07	0.05	0.08
Citrus								
Maximum	23.46	778.20	316.80	276.00	5.22×10^{-2}	7.87×10^{6}	1.38×10^{-2}	3.36
Minimum	3.36	533.20	76.20	120.00	2.73×10^{-2}	6.07×10^{6}	9.77×10^{-3}	2.04
Mean	15.10 b	629.23 a	171.97 b	198.80 a	3.53×10^{-2} b	6.94×10^{6} a	1.12×10^{-2} a	2.69 a
Median	15.18	624.35	162.70	190.33	3.31×10^{-2}	6.92×10^{6}	1.12×10^{-2}	2.69
SD	3.14	44.84	48.40	45.96	5.97×10^{-3}	4.33×10^{5}	1.01×10^{-3}	0.33
CV (%)	20.81	7.13	28.14	23.12	16.90	6.24	9.06	12.11
Asymmetry	-0.63	0.60	0.71	0.24	1.05	0.33	0.64	0.07
Kurtosis	3.84	1.73	0.58	-0.98	0.72	-0.32	-0.19	-0.80
K-S	0.07	0.06	0.09	0.07	0.09	0.07	0.05	0.08

SD - Standard deviation; CV - Coefficient of variation (%); K-S - Kolmogorov-Smirnov normality test. * Significant at 5% probability; OM - Organic matter; K-factor - Overall erodibility; Ki_{wepp} - Erodibility in interril; Kr_{wepp} - Erodibility in rills; Ss_{wepp} - Shear stress. Means followed by the same lowercase letter in the column do not differ by Student test ($p < 0.05$). Source: Author, 2023.

These results only justify the mean and median values found previously, which already indicated the possible normal distribution of the data due to the proximity of the central values found. When the results of the variance analysis were analyzed (Table 2) using the Student test ($p < 0.05$), it was possible to observe that the highest OM values followed the sequence forest > citrus, showing that the respective areas presented significant differences. The respective value may be associated with the greater plant litter accumulation derived from the high density of trees in the area. The present results corroborate those found by Hassane et al. (2023) that after the removal of the forest and continuous cultivation, the levels of organic matter decrease in the superficial layers of the soil due to the increase in temperature, the losses by erosion, the greater biological activity, and mainly with the reduction of the supply source of organic residues.

The granulometric fraction of the two areas evaluated presented characteristics between sandy loam in the forest area and sandy clay loam in the area under citrus cultivation, differing statistically only for the silt and clay contents for the studied areas.

The results of the global erodibility presented statistically different values, and it is possible to infer, based on the results, that the area under forest is characterized as more susceptible to erosion when compared to the area cultivated with citrus. The high sand and silt content in the forest areas probably made them more susceptible to erosion (Table 2). The results can be proven by other studies, which also observed higher erodibility rates in soils with high silt and sand contents (Oliveira et al., 2009; Souza et al., 2023). According to Huang and Lo (2015), sand and silt lack adhesion properties, and if hydrated, they become easily broken down and transported, having a greater impact on soil erodibility.

It was possible to observe that both the citrus area and the forest area showed high soil erodibility, according to the classification proposed by Castro et al. (2011), which classifies soil erodibility into classes according to its potential, adopting the following classifications: $K < 9.00 \times 10^{-3}$ (very low); $9.00 \times 10^{-3} < K \leq 1.50 \times 10^{-2}$ (low); $1.50 \times 10^{-2} < K \leq 3.00 \times 10^{-2}$ (medium); $3.00 \times 10^{-2} < K \leq 4.50 \times 10^{-2}$ (high); $4.50 \times 10^{-2} < K \leq 6.00 \times 10^{-2}$ (very high); and, $K > 6.00 \times 10^{-2}$ (extremely high).

The interrill erodibility values (Ki_{wepp}) of the two areas studied presented very similar values, a result similar to that found by Albuquerque et al. (2000), who described that soils with different mineralogy presented different susceptibility to interrill erosion. The erodibility values in rills (Kr_{wepp}) presented a higher average for the citrus area concerning the forest area. Hence, the respective result demonstrates that the area cultivated with citrus presented a greater predisposition to suffer rill erosion (Kr_{wepp}). The mean values of the soil erodibility factors in interrill (Ki_{wepp}) were higher than those obtained by Franco et al. (2012), who studied interrill soil erodibility in an 'Argissolo Vermelho' obtaining a mean value of 1.82 × 106 kg s m^{-4}.

The values found for critical shear stress were similar to the values for rill erosion (Kr_{wepp}), in which it was observed that the citrus area presented a significant difference concerning the forest area, indicating that the area under citrus cultivation presents greater resistance to the onset of the erosive process compared to the forest area, that is, it has greater support power without the removal of its particles. Studies also highlight that the determination of critical shear stress and erodibility parameters makes it possible to evaluate the resistance of soils and are viable alternatives to be adopted in the planning of water erosion control (Oliveira et al., 2009; Dechen et al., 2015; Souza et al., 2023).

The adequacy of the factor analysis proved significant (KMO = 0.72 and $p < 0.05$ for Bartlett test of sphericity) for the attributes evaluated. The two factors formed were responsible for explaining 85.51% of the variance of the variables with eigenvalues greater than 1. PC1 explains 63.06%, composed of sand, clay, Ss, and organic matter; PC2 explains 22.45% of the variance and is composed only of Ki. In PC1, sand and OM presented positive values, while clay and Ss presented negative values; this indicates that attributes that presented the same signs have a direct correlation, while those with opposite signs have an inverse correlation (Figure 2).

When we evaluate the score clouds of the factorial plan, we see that the environments are distinguished, forming two distinct groups. The first group is formed by citrus cultivation, characterized by higher clay content and Ss. The second group is formed by the forest, which is discriminated by higher sand and organic matter contents. These results corroborate Lima et al. (2020), who studied soil erodibility in forest areas and different crops in Southern Amazonas and observed higher sand contents in secondary forest areas, in addition to observing a greater predisposition of the forest area to undergo erosion.

The spatial dependence analysis is shown in Table 3. It was observed that the attributes studied presented spatial dependence, fitting predominantly the exponential and spherical models, with R^2 and C-V values above 0.77 and 0.70, respectively. Silva et al. (2021), studying soil erodibility in pasture and forest areas, observed the predominance of the spherical and exponential models.

The attributes were within the limits of the degree of spatial dependence (DSD), expressed by the ratio between the nugget effect and the plateau, ranging from moderate to strong dependence, according to Souza et al. (2023) classification. These results corroborate those found by Miqueloni and Bueno (2011), who performed multivariate analysis and spatial variability in the estimation of the erodibility of an “Argissolo Vermelho-Amarelo".

The results show that the highest DSD occurred for sand, silt, OM, K-factor, and Kiwepp in the secondary forest area and OM and Kiwepp in the citrus area, both showing a value between 26 and 45%, considered a moderate DSD. The lowest DSD values occurred for the attributes clay, Krwepp, and Sswepp in the forest area and sand, silt, clay, K-factor, Krwepp, and Sswepp in the citrus area, both presenting values lower than 25%, showing a strong DSD (Table 3). The area with the highest concentration of attributes with strong spatial dependence was cultivated with citrus, indicating that these variables are more influenced by intrinsic soil properties linked to formation factors (Silva et al., 2021).

The ranges (a) for the attributes studied in the respective areas exhibited values of different intervals. In the secondary forest area, the lowest value was observed for the attributes clay and Kr_{wepp}, while in the citrus area, the lowest value was observed for the attribute Ki_{wepp}. Considering all the areas studied, the range values for the other attributes were around 9.52 to 46.00 m; this means that all the neighbors within this radius can be used to estimate values at closer spacings.

These results further demonstrated that the sampling grid could capture the spatial variability of the attributes and that the value estimates performed by kriging generated reliable values. According to Dalchiavon et al. (2012), the range (a) is a geostatistic parameter that indicates the boundary distance between correlated points. Nowadays, it has been used as a subsidy in sample planning since the range values imply, in general, a higher or lower sample density.

The variables presented in each area studied, as shown in Figures 3 and 4, allow the data obtained to be visualized, with the darker shade of the maps indicating a higher concentration of the respective variable in that particular location, and the lighter the shade, the lower the concentration, the value of the variable. According to some authors, kriging maps allow the establishment of land use and management criteria in isolation for each variable evaluated, making it possible to improve the use of the area, reducing production costs and making quick and accurate decisions, enabling greater yield and also environmental conservation **(**Alencar et al., 2016**;** Santos et al., 2017**).**

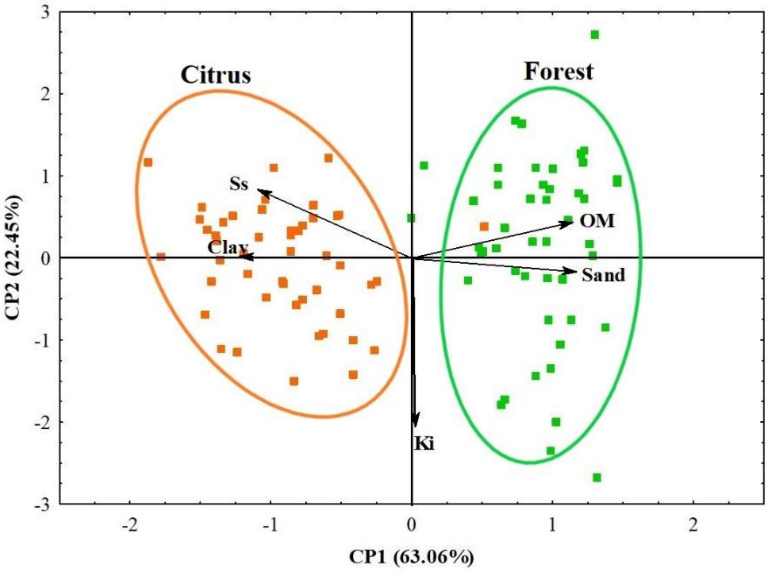

Figure 2. Factorial plot of soil erodibility, texture, and soil organic matter in forest and citrus areas, Colorado do Oeste, RO, Brazil. Source: Author, 2023.

Table 3. Geostatistical parameters of soil erodibility attributes in areas under citrus and forest in the Southern of Rondônia, Brazil.

Geostatistics	OM	Sand	Silt	Clay	K-factor	Ki_{wepp}	Kr_{wepp}	Ss_{wepp}
				Native forest				
Model	Sph.	Sph.	Gauss.	Sph.	Sph.	Sph.	Exp.	Sph.
C_0	20.50	248.00	195.00	4.20	3.00e^{-5}	1.81e^{11}	3.40e^{-7}	0.04
$C_0 + C_1$	67.30	560.60	433.50	194.20	1.07e^{-4}	7.18e^{11}	1.84e^{-6}	0.21
a (m)	30.5	33.23	40.00	9.52	37.00	25.00	14.20	25.00
R^2	0.86	0.91	0.92	0.84	0.86	0.79	0.91	0.77
C-V	1.00	0.77	0.75	0.99	0.95	0.99	0.99	1.00
DSD (%)	30.46	44.24	44.98	2.16	28.03	25.18	18.48	20.19
				Citrus				
Model	Sph.	Sph.	Exp.	Sph.	Sph.	Sph.	Exp.	Sph.
C_0	1.14	500.00	1.00	493.00	4.90e^{-6}	4.80e^{10}	2.30e^{-7}	4.00e^{-3}
$C_0 + C_1$	4.18	2,310.00	1,908.00	2,794.00	3.90e^{-5}	1.62e^{11}	1.05e^{-6}	0.13
a (m)	41.00	25.00	30.00	46.00	34.50	18.50	25.00	42.20
R^2	0.90	0.82	0.98	0.93	0.85	0.82	0.81	0.88
C-V	0.75	0.81	0.95	0.85	0.70	0.86	0.80	0.75
DSD (%)	27,27	21,64	0,05	17,64	12,56	29,70	21,90	2,96

OM - Organic matter; K-factor - Overall erodibility; Ki_{wepp} – Interrill erodibility; Kr_{wepp} – Rill erodibility; Ss_{wepp} - Shear stress. Sph. - Spherical; Exp. - Exponential; Gauss. - Gaussian; C_0 - Nugget effect; $C_0 + C_1$ - plateau; a - range (m); R^2 - Coefficient of determination; C-V - cross-validation; DSD - degree of spatial dependence (%). Source: Author, 2023.

The semivariograms for adjusting the scoring factors obtained from the principal component analysis. The F1 semivariograms of the forest and citrus areas are related to sand, clay, OM, and Ss, while the F2 semivariograms are related only to Ki. These results observed for the F1 semivariograms highlight the correlated attributes and are more sensitive for defining management zones. Lima et al. (2022) observed that environments that are more influenced by high sand and clay contents interfere with soil aggregation, compaction, porosity, and organic carbon accumulation. It is necessary to generate specific management zones that affect these soil properties. (Figure 5). The semivariograms fitted the spherical model and showed R^2 and cross-validation ranging from 0.75 to 0.93 and 0.75 to 1.00, respectively. Spatially analyzing F1 and F2, the range varied from 15.90 to 46.00 m. Concerning the DSD, we observed that the forest area showed moderate spatial dependence for F1 and F2; however, in the citrus environment, strong spatial dependence was observed for F1 and F2. The DSD classification corroborates with Brito et al. (2020), who studied soil erodibility in different areas in the Southern Amazonas and observed strong and moderate spatial dependence for F1 and F2.

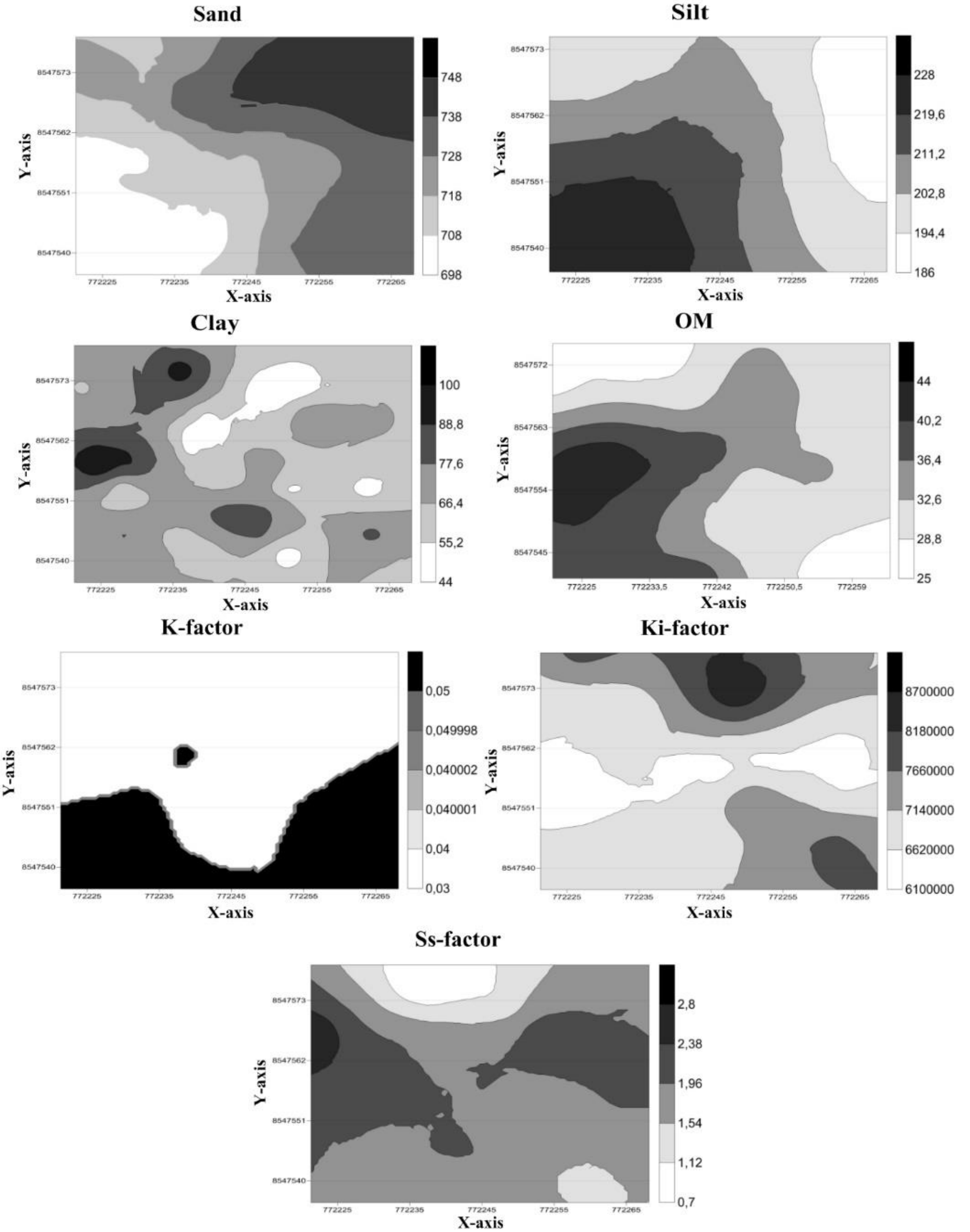

Figure 3. Kriging maps interpolated from geostatistical parameters obtained from soil erodibility variables in a Native Forest area, Colorado do Oeste, RO, Brazil. Source: Author 2023.

By evaluating the kriging maps of the scores (Figure 6), we observe the formation of five management zones. For F1 in the forest and citrus area, complex management zones for the attributes related to texture, Ss, and OM were formed. However, for F2 in both environments, management zones were formed only for Ki, agreeing with the statements by Burak et al. (2012).

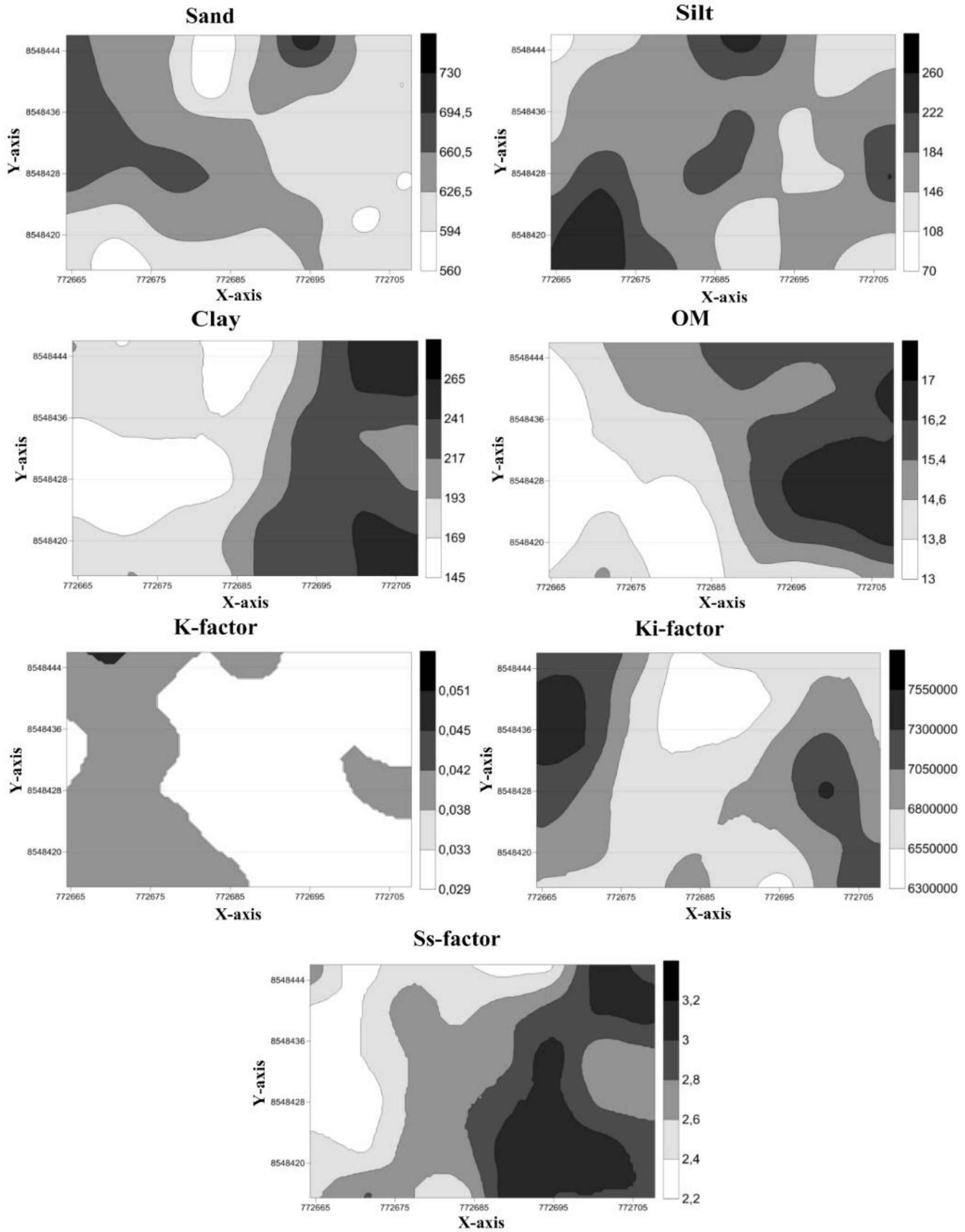

Figure 4. Interpolated kriging maps from geostatistical parameters obtained from soil erodibility variables in citrus area, Colorado do Oeste, RO, Brazil. Source: Author, 2023.

Thus, when we observe the F1 and F2 maps, it is evident that most of the positive scores are present in the forest areas in F1, while the other factors in the two areas presented most of the negative scores. For Santos et al. (2017), each management zone within each environment requires specific management that is more or less intensive, favoring greater efficiency in the use of natural soil resources and thus reducing the impacts caused by agriculture on the variables related to soil erodibility and thus the susceptibility of these soils to erosion. Through the maps, it is possible to observe spatial correlations between attributes and verify which attributes are most influenced by the relief (Silva et al., 2021).

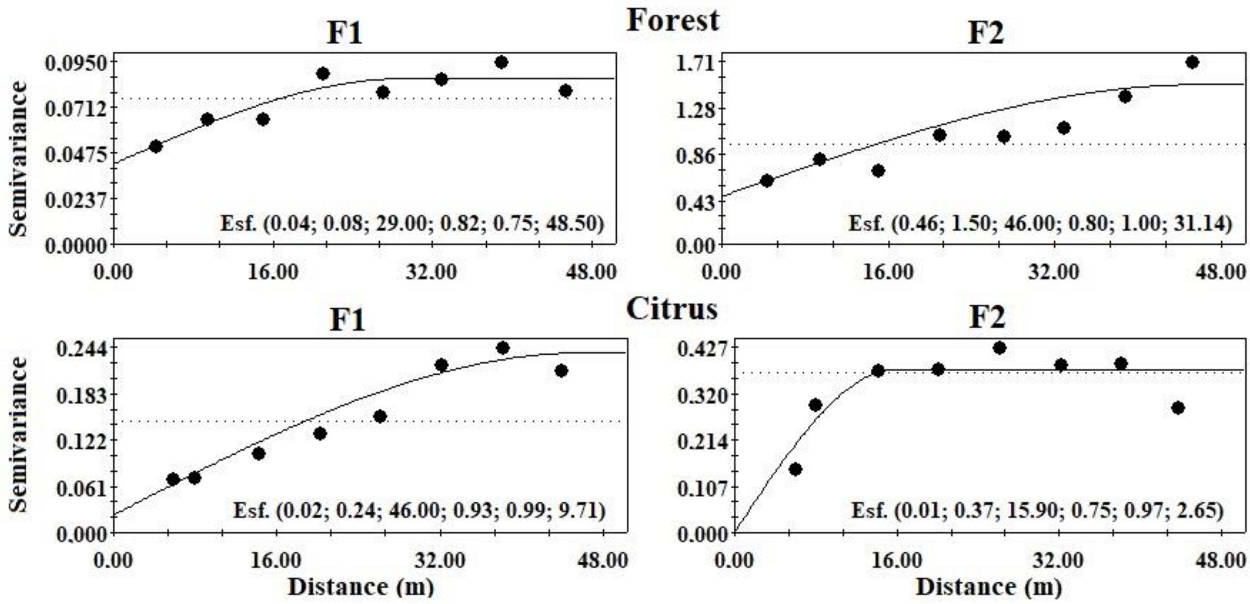

Figure 5. Experimental semivariograms fitted to principal component score values for citrus and forest areas in Southern Rondônia, Brazil. The values in parentheses are, respectively, Sph. = spherical; nugget effect; plateau; reach; R^2; cross-validation; and DSD. Source: Author, 2023.

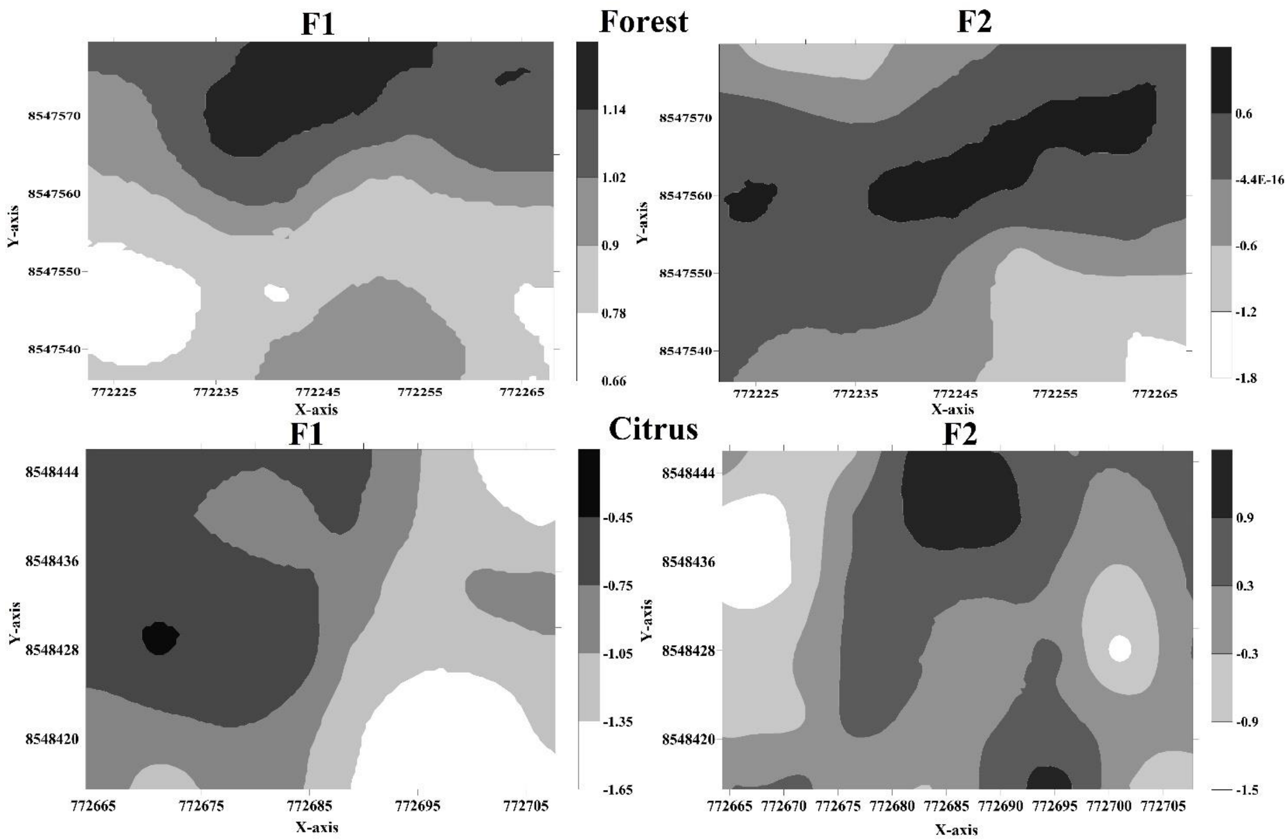

Figure 6. Kriging maps of the principal component score values for citrus and forest areas in Southern Rondônia, Brazil. Source: Author, 2023.

4. Conclusions

The forest and citrus areas showed a greater soil predisposition to suffer interrill erosion, and the area cultivated with citrus showed greater susceptibility of the soil to rill erosion. The area under the forest was more prone to erosion, possibly due to the high levels of silt and sand, favoring the current conditions of erodibility. The Forest and Citrus areas presented high spatial variability, generating specific management zones for texture, shear, interrill erosion, and organic matter. The multivariate analysis allowed the formation of two groups. Group I is formed by the forest, which is discriminated by higher sand and organic matter contents, and Group II by the citrus crop, characterized by higher clay content and Ss.

Authors' Contribution

Fernando Gomes de Souza, José Vagner Silva, Taismara Inglesia Sampaio, Janaina Teixeira de Morais, and Valdir Moura carried out the conception and design of the study; Fernando Gomes de Souza, José Vagner Silva, Taismara Inglesia Sampaio, Janaina Teixeira de Morais, and Valdir Moura carried out the acquisition, analysis, and interpretation of the data.

Alan Ferreira Leite de Lima, Wildson Benedito Mendes Brito, and Elyenayra Nogueira Pinheiro contributed to writing the manuscript; and Robson Vinício dos Santos and Milton César Costa Campos contributed to the critical review of the intellectual content.

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