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Artigo de Pesquisa

Geomorphologic Map of the Brazilian Cerrado by geomorphometric archetypes

Mapa Geomorfológico do Cerrado por arquétipos geomorfométricos

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Abstract: The Brazilian Cerrado is the second largest biome in Brazil, occupying approximately 25% of the national territory. It is characterized by an expressive biodiversity of fauna and flora, and it is considered the richest savanna in the world. Despite its environmental importance, it is considerably endangered and still undervalued in terms of conservation. Due to its flat lands, agricultural activities are largely developed in the Cerrado. Thus, more detailed studies in this region are necessary to help define mitigation measures against degradation, as well as conservation plans. This paper sets out to represent the geomorphology of the Cerrado based on geomorphometric parameters, using a semi-automatic relief classification method. Four metric parameters were considered for defining and characterizing the relief units: available relief, slope, orientation and shapes of the slopes. Representing geomorphological models with these parameters enables more reliable descriptions of real conditions. The geomorphological mapping of the Cerrado via mathematical modelling allows describing its key geomorphometric archetypes through six metric relief-classes that represent their actual conditions.

Keywords: Cerrado; Geomorphological mapping; Geomorphometry

Resumo: O Cerrado Brasileiro é o segundo maior bioma brasileiro, ocupando cerca de 25% do território nacional. É caracterizado por expressiva biodiversidade de fauna e flora, sendo considerado como a savana mais rica do mundo. Apesar de sua importância ambiental, ele encontra-se bastante ameaçado e pouco valorizado em termos de conservação. Devido aos seus terrenos planos, atividades agropecuárias são largamente desenvolvidas no Cerrado. Assim, estudos mais detalhados nessa região são necessários para a definição de medidas mitigadoras à degradação e de planos de conservação. Este trabalho tem o objetivo de representar a geomorfologia do Cerrado com base em parâmetros geomorfométricos, usando um método

semiautomático de classificação do relevo. Foram considerados quatro parâmetros métricos para a definição e caracterização das unidades de relevo: amplitude, declividade, orientação e formas das vertentes. A representação de modelos geomorfológicos baseados nesses parâmetros possibilita caracterizações mais fidedignas da realidade. O mapa geomorfológico do Cerrado, definido por modelos matemáticos, possibilitou a definição dos arquétipos geomorfométricos e a definição de seis classes métricas do relevo que representam o seu comportamento mais factual.

Palavras-chave: Cerrado; mapeamento geomorfológico; geomorfometria

1. Introduction

Considered a Neotropical savanna, the Brazilian Cerrado is a complex natural system that covers approximately 25% of the national territory. It is the second largest biome in the country (CASTRO *et al*., 2016) and occupies the central portion of Brazil, extending to its Northeast-region and parts of the states of Minas Gerais, São Paulo and Paraná (Figure 1). It is characterized by vegetal formations that include forest, savanna and grassy formations (SANO *et al*., 2010; RIBEIRO & WALTER, 1998).

The Cerrado has a significant biodiversity of fauna and flora marked by endemism (MYERS, 2000; ARRUDA, 2003; STRASSBURG *et al*., 2017). It is recognized as the richest savanna in the world and the habitat of over 12,400 recorded native plant species (FORZZA *et al*., 2012). Climate, soils, the availability of water and nutrients, geology and geomorphology are some of the relevant factors for the formation of this peculiar and unique biome (CASTRO *et al*., 2016; OLIVEIRA *et al*., 2014; FRANCO *et al*., 2014; COE *et al*., 2017; RUGGIERO *et al*., 2006).

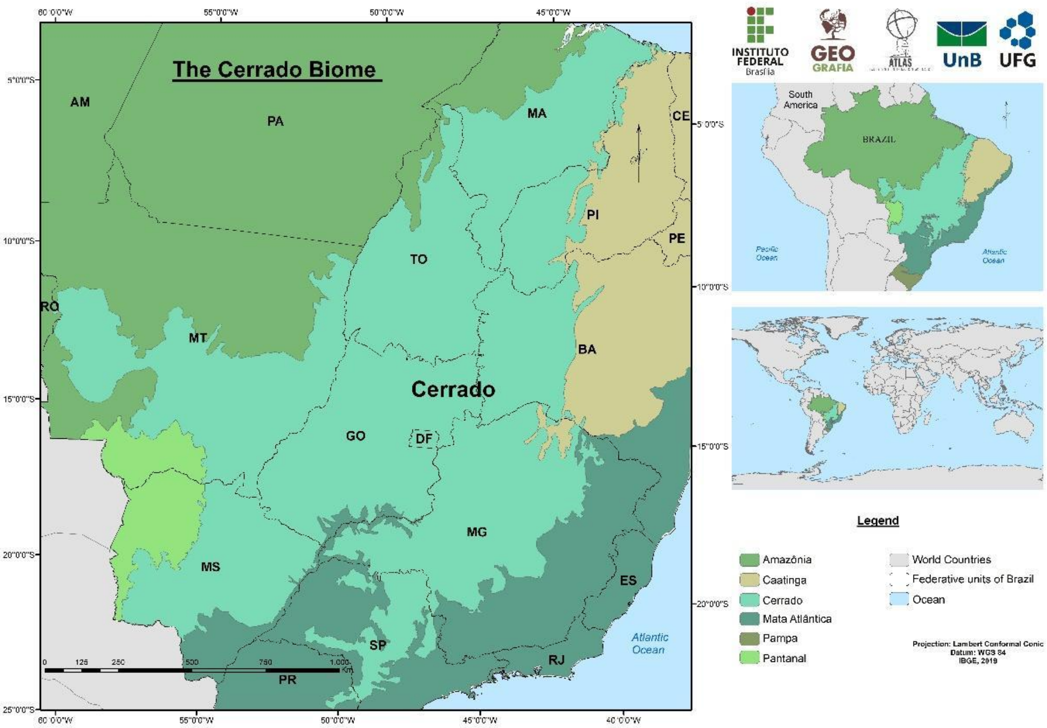

Figure 1. Location map of the Cerrado.

Despite its proven socio-environmental importance, the Cerrado continues to be undervalued in terms of conservation, and only 7.5% of its areas are protected (STRASSBURG et al., 2017). According to the Brazilian Ministry of the Environment (MMA), by 2013, approximately 43% of the biome had been converted into different land use and land cover (MMA, 2015) and the current prospect, according to Harfuch *et al*. (2016), points to the legal conversion of 3.1 million hectares of native Cerrado vegetation into agricultural and livestock farming activities by 2030.

Approximately half of the areas destined to agriculture and cattle farming in Brazil are in the Cerrado, which experienced high rates of deforestation in recent years (IBAMA, 2015; SPERA *et al*., 2016). The high levels of vegetation conversion are associated with other threats to the Cerrado's biodiversity, such as soil erosion and compaction, the siltation of rivers and groundwater contamination (Klink & Machado, 2005 and Cunha *et al*., 2008), which may generate serious consequences to the environment.

The emphasis on the development of agricultural and livestock activities in Cerrado areas is associated with its flat lands (demoted tablelands) (SANO *et al*., 2019; OLIVEIRA *et al*., 2019). Consequently, the Cerrado is considered one of the most threatened regions of the planet, due to the destruction and disintegration of its natural habitats (HIDASI-NETO *et al*., 2019; MACEDO *et al*., 2020).

A greater focus on characterization studies of this system is necessary in order to increase the available knowledge and enable the improvement of conservation policies. It is important to count on a consistent database for the construction of models of devastation and susceptibility to degradation, as well as of the respective solutions to these problems. As a fundamental part of this database, more detailed geomorphological studies contribute to the understanding of the Earth's relief, as well as to the enhancement of environmental modeling, which, in turn, facilitates the planning of mitigating measures against environmental degradation.

Within this context, geomorphological maps are essential tools for better physical characterizations of the Cerrado. Geomorphological maps of Brazil are currently available based on parameters such as morphology and altimetry, produced by the RADAM BRASIL Project and IBGE (RADAM, 1982; IBGE, 2009). However, these maps do not yet meet the need for more detailed and specific analyses, due to their small-scale approaches. Regions such as the Brazilian Cerrado require more accurate studies and maps with larger scales that allow a more detailed view. Furthermore, new proposals for geomorphologic mapping are emerging aiming to reduce subjectivity in the map making-process – for instance, semi-automatic methods (JASIEWICZ & STEPINSKI, 2013; TRENTIN *et al*. 2015; SILVEIRA *et al*. 2018).

From the understanding of the relief-dynamics, it is possible to determine areas with higher risk of degradation, their associated vegetation classes, predominant forms of erosion and possible types of agriculture to be developed (MENDES, 2015). With the semi-automatic method, this mapping-effort becomes more impartial and accurate. For Bishop *et al*. (2012), semiautomatic methods refer to the automatic procedures of geographical accident extraction in computational environments. They are of great importance, as they allow more homogeneous and standardized results in geomorphologic cartography (SOARES NETO & MARTINS, 2019).

The classification method of this study is the mapping of Basic Relief Units (BRUs) developed by Soares Neto & Martins (2019). According to the authors, a BRU corresponds to the primordial unit described to begin the classification of geomorphological features, defined by their geomorphometric parameters (available relief and slope). It is based on the combination of the classes of available relief and slope of a digital elevation model.

This paper presents, therefore, the Geomorphologic Map of the Brazilian Cerrado based on geomorphometric parameters, using a semi-automatic method of relief classification. This method enabled the development of a map with a higher level of information and greater scale, when compared to the pre-existing maps (RADAM BRASIL Project).

2. Materials and Methods

The delimitation of Basic Relief Units based on morphometric criteria is weighted following two parameters: the available relief (which denotes the height of the forms) and the slope. The interaction of these variables allows inserting new geomorphometric parameters for an improved definition of their singularities, as well as the characterization of archetypes.

The selection of these two geomorphometric indicators (slope and available relief) is due to the representation of the minimum level of discretization of the common relief at first sight (NAVEH, 1998; BURROUGH, 1998). A digital elevation model (DEM) was developed based on the methodology of Hutchinson (1988), from which it was possible to extract morphometric data to be represented. New ways to obtain DEMs have been developed, such as the interferometric synthetic aperture radar (inSAR), used to obtain the Space Shuttle Radar Topography Mission (SRTM). In this study, SRTM DEMs with 1-arc second global digital elevation models were used, which have a spatial resolution of about 30 meters. Also, it covers most of the world with an absolute vertical height accuracy of less than 16m (USGS, 2021).

The available relief was defined by subtracting the lowest DEM-value from all altimetric values, then zeroing the lowest value and having it represent the highest local height. The slope represents a 1st order derivative of altimetry and was obtained by calculating the maximum rate of change for the value of each cell (pixel) compared to its neighbors. Basically, the maximum change in elevation over the distance between the cell and its eight neighbors identifies the steepest slope descent of the cell.

The methodology developed by Soares Neto & Martins (2019) presents the idea of topographic correlation (Tc) as regions with topographic archetypes concentrated in distinct altimetric gradients. Thus, the Tc-definition took into consideration two ratios: (1) the lowest possible range of available relief (h) divided by the available relief in the analyzed basin (H), represented by the abscissa in the graph; and (2) the area of each available relief's range (a) divided by the total area of the analyzed basin (A), represented by ordinate values.

Thus, the determination of available relief-ranges is defined by the hypsometric inflection (Hif), which, in turn, is defined by the inflection points of the polynomial regression line[1] of the curve resulting from the topographic correlation, and by the hypsometric maximum (Hmax), elucidated by the local maximum points of the curve resulting from the topographic correlation. The points on the graph-curve that either coincide or are closest to Hif and Hmax values represent the limits of the available relief's range (SOARES NETO & MARTINS, 2019).

The intervals between inflection and local maximum points of the curve represent distribution-patterns of the topographic behavior in a given area. Thus, the inflection and maximum point of the regression line, of n-th degree polynomial (with R-square ≥ 0.9), of the topographic correlation determine the range of the available relief, which is represented by the following Eq. (1):

$$p(x) = a_n x^n + a_{n-1}x^{n-1}a_{n-2}x^{n-2} + \cdots . + a_0 = \sum_{k=0}^{n} \quad a_k x^k, x = \frac{h}{H}\ \boldsymbol{e}\, R^2 \geq 0{,}9\ \textbf{\textit{local maximum point is such a}}\ \underline{x}\boldsymbol{:} \frac{dp}{dx}(\underline{x}) = 0 \leftrightarrow n a_n \underline{x}^{n-1} + (n-1)a_{n-1}\underline{x}^{n-2} + \cdots + 1a_1 = 0 \leftrightarrow \sum_{k=1}^{n} \quad (k)a_k \underline{x}^{k-1} = 0\ \boldsymbol{\&}\ \textbf{\textit{inflection point is such a}}\ \underline{x}\boldsymbol{:} \frac{d^2p}{dx^2}(\underline{x}) = 0 \leftrightarrow n(n-1)a_n\underline{x}^{n-2} + (n-1)(n-2)a_{n-1}\underline{x}^{n-3} + \cdots + 2.1a_2 = 0 \leftrightarrow \sum_{k=2}^{n} \quad (k)(k-1)a_k\underline{x}^{k-2} = 0 \qquad (1)$$

The delimitation of slope ranges is possible due to the clinographic inflection (Cif) and clinographic maximum (Cmax) values, defined by the inflection points and the local maximum point of the polynomial regression line[2] of the curve resulting from the frequency graph (SOARES NETO & MARTINS, 2019).

The intervals obtained by the inflection and local maximum points denote slope distribution patterns in a given area. These clinographic archetypes show roughness levels on the ground, delimiting flatter and steeper surfaces. Therefore, the rule for delimiting slope ranges can be understood as the local inflection and maximum points of the regression line, of n-th degree polynomial (with R-square ≥ 0.9), of the frequency curve of declivity, represented by the following Eq. (2):

[1] The polynomial order to be set will depend on the best fit of the regression line. Polynomials of lower orders determine smaller numbers of intervals and adjust better when converted into computational algorithms. Thus, it was determined that when the regression line yields an R-square ≥ 0.9, it will represent the best fit to represent the Tc-regression.

[2] The polynomial order to be set will depend on the best fit of the regression line. Polynomials of lower orders determine smaller numbers of intervals and adjust better when converted into computational algorithms. Thus, it was determined that when the regression line yields an R-square ≥ 0.9, it will represent the best fit to represent the regression of the frequency curve.

$$p(x) = a_n x^n + a_{n-1}x^{n-1}a_{n-2}x^{n-2} + \cdots . + a_0 = \sum_{k=0}^{n} \quad a_k x^k, x = \frac{h}{H} \, \boldsymbol{e} \, R^2 \geq 0{,}9 \textbf{ \textit{local maximum point is such a} } \underline{x}\textbf{:} \frac{dp}{dx}(\underline{x}) = 0 \leftrightarrow n a_n \underline{x}^{n-1} + (n-1)a_{n-1}\underline{x}^{n-2} + \cdots + 1a_1 = 0 \leftrightarrow \sum_{k=1}^{n} \quad (k)a_k \underline{x}^{k-1} = 0 \textbf{ \& \textit{inflection point is such a} } \underline{x}\textbf{:} \frac{d^2p}{dx^2}(\underline{x}) = 0 \leftrightarrow n(n-1)a_n\underline{x}^{n-2} + (n-1)(n-2)a_{n-1}\underline{x}^{n-3} + \cdots + 2.1a_2 = 0 \leftrightarrow \sum_{k=2}^{n} \quad (k)(k-1)a_k\underline{x}^{k-2} = 0 \qquad (2)$$

Two other geomorphometric parameters were considered for characterizing Basic Relief Units: the orientation and the shape of slopes. The slope-orientation – a 1st order derivative of altimetry – was calculated from a raster by the direction of the downward curve of the maximum rate of change of the value of each neighboring cell. The shapes of slopes, on their turn, are defined by combining the horizontal (convergent, plane and divergent) and vertical (concave, straight and convex) curvatures of the terrain. They represent 2nd order derivatives of altimetry and were calculated by the altimetric comparison of each cell, in the case of vertical curvature, and by comparing the orientation of slopes via comparison of neighboring cells to a reference cell, in the case of the horizontal curvature.

Thus, to delimit the basic units of relief, an algebra of maps between the intervals is taken into consideration, according to the method of Soares Neto & Martins (2019).

In order to represent the landforms of the Cerrado, five steps were followed in a methodological flow (Figure 2). The methodology starts with the selection of the database and involves delimiting the available relief's range and slope, and cross-linking these data that determine the BRUs. Finally, it involves inserting other geomorphometric parameters (orientation of slopes, and relief shapes) to obtain the final representation of the geomorphological map. The processing of the final product was performed using the MATLAB (2010) and ArcGIS 10.6 (2016) softwares.

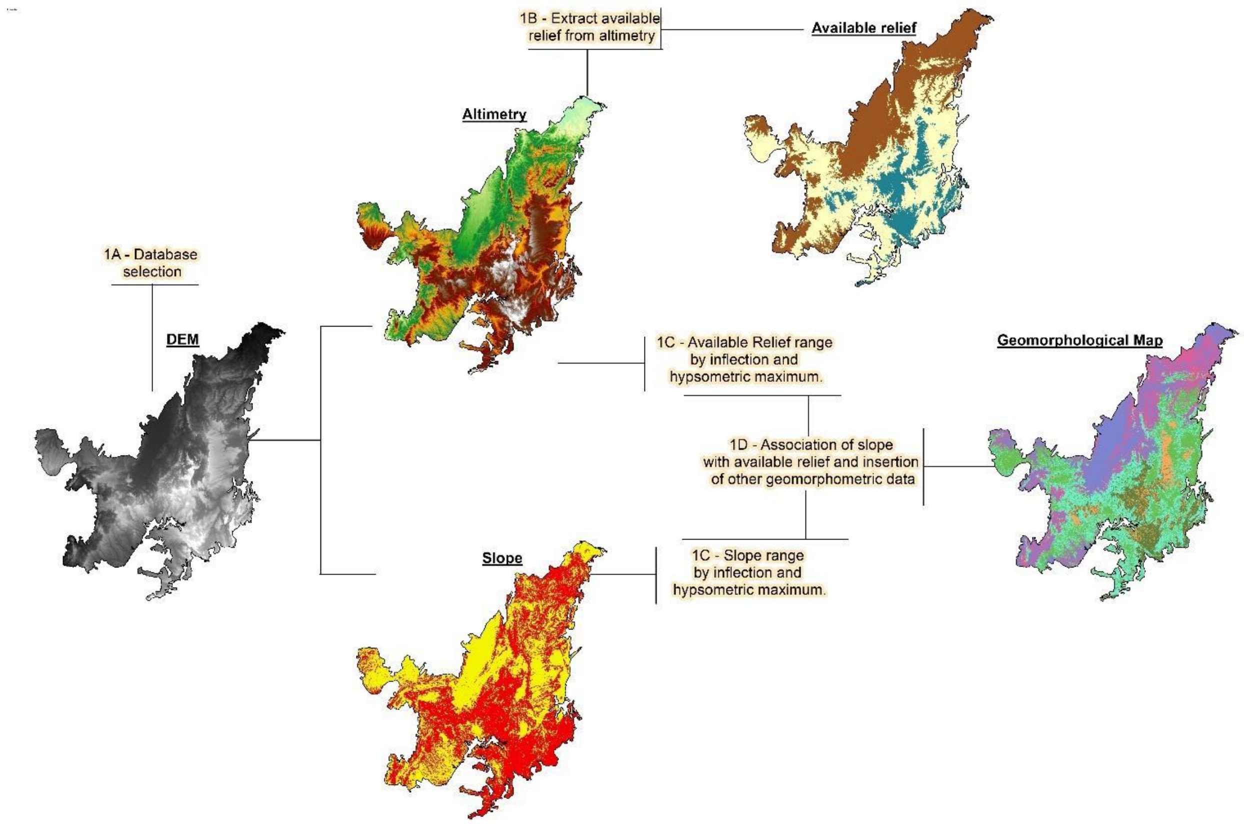

Figure 2. Steps of the methodological procedure. Step 2A: database selection. Step 2B: representation of the available relief from the DEM. Step 2C: delimitation of available relief and slope ranges. Step 2D: algebra of available relief ranges and slope to determine the BRUs, and insertion of other geomorphometric data, to define the geomorphological map.

3. Results and Discussion

With the definition of BRU-limits and other geomorphometric parameters (shape and orientation) (Figure 3), it was possible to determine the singularities of distinct BRUs. The frequency of relief forms and topographic orientations were defined by histogram analysis on a class-by-class basis (Figure 4).

Six Basic Relief Units were obtained from the combination of data on available relief and slope of the relief features of the area under study (Figure 5).

The map presents greater scale (1:100.000), when compared to previous maps (RADAM BRASIL – 1:250.000) and brings a higher level of geomorphometric information, which enables the representation of the landforms that is associated to the 5th taxon in Ross (1992) classification. Information such as slope orientation, form and curvature may be useful to support environmental studies, for instance erosion susceptibility, land use and land cover, wildfires, mineral exploration, groundwater management, flood protection programming and recovery of degraded areas (Rao, 1972; Benavente et al., 2002; Remondo et al., 2008; Ferreira et al., 2016; Schneider et al., 2020; Carabella et al., 2019; Keller et al., 2020; Feoli et al., 2002).

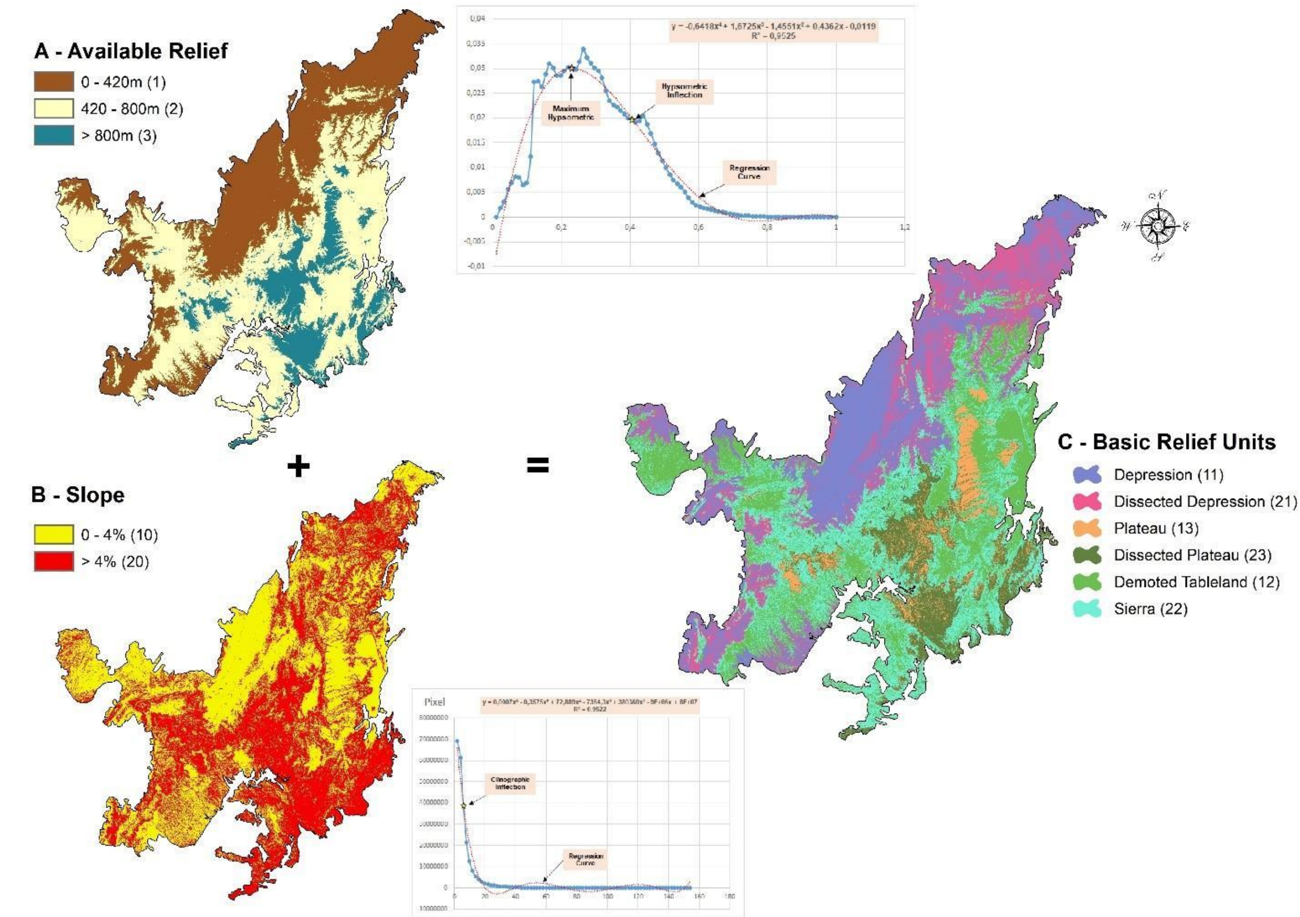

Figure 3. Correlations between available relief (A) and slope (B) determining the classes of Basic Relief Units (C) and graphs used to obtain the available relief's and slope's intervals. R-values higher than 0.9.

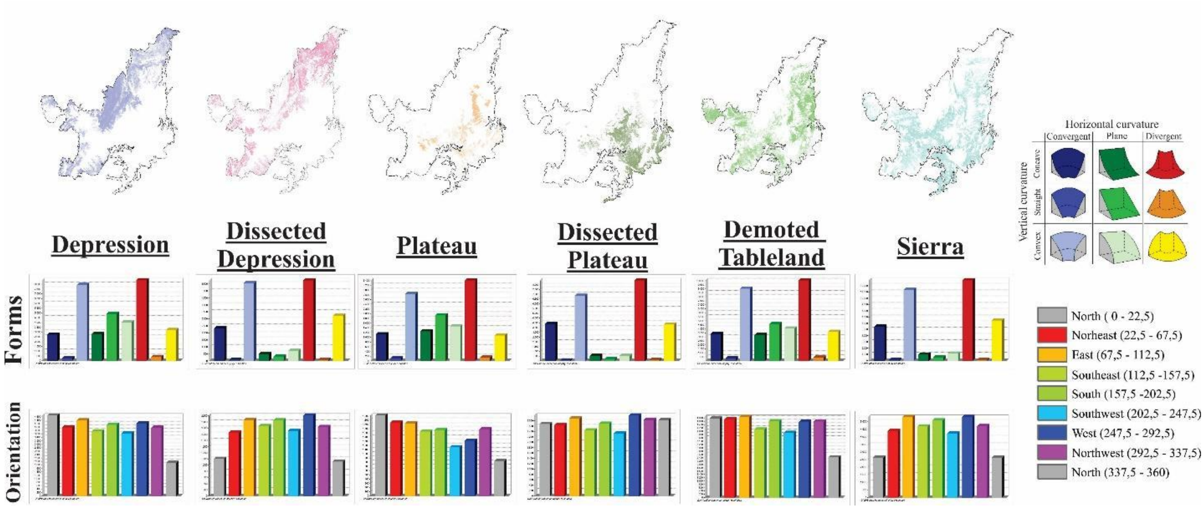

Figure 4. Histograms of orientation and slope forms determining the frequency of each BRU-class.

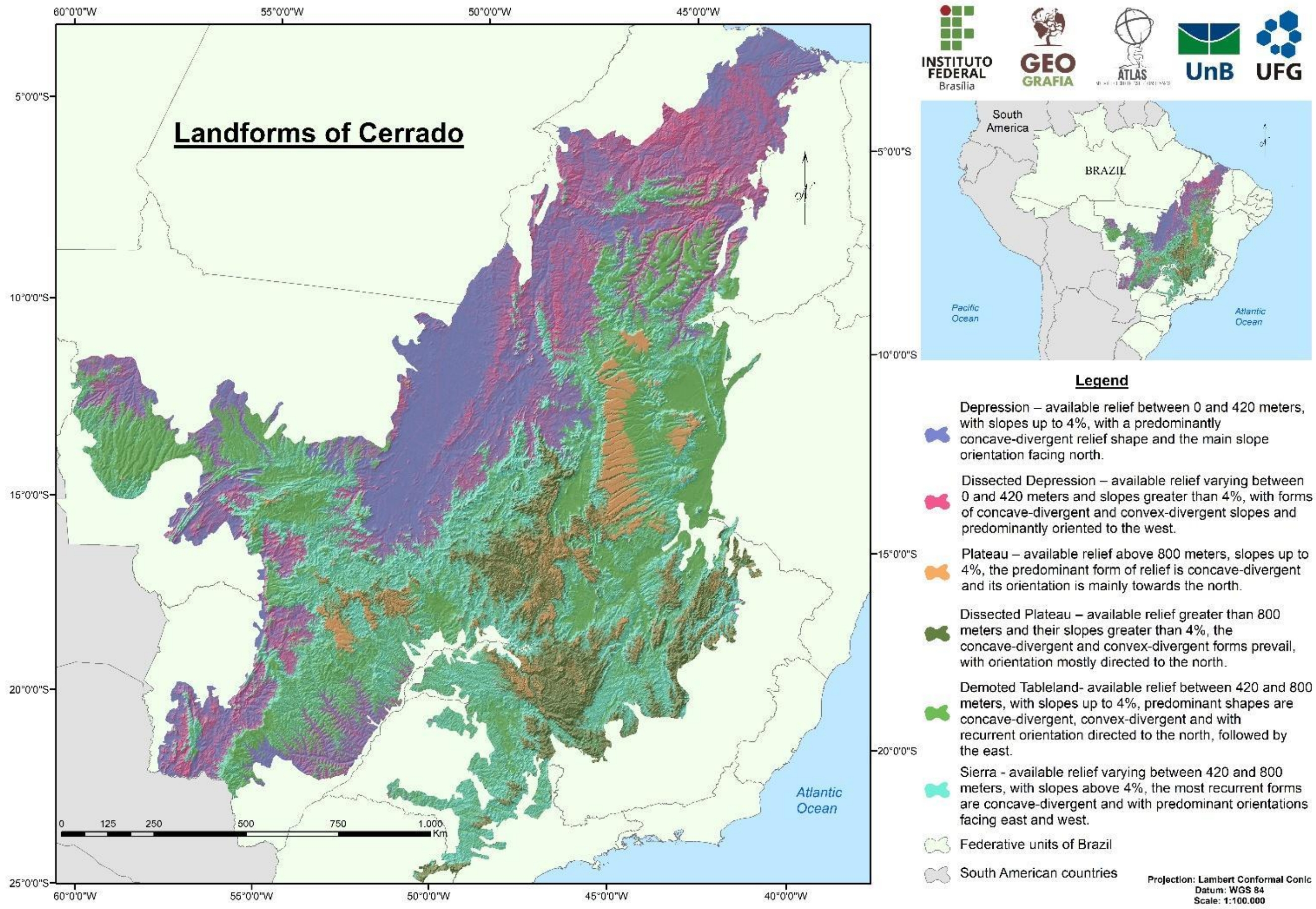

Figure 5. Geomorphological map of the Cerrado.

Depression

This BRU extends from north to south of the study area. It is more expressive in the central portion of Brazil, mainly in the states of Tocantins (TO) and Mato Grosso (MT), representing approximately 24.5% of the Cerrado-area. The available relief of this BRU ranges from 0 to 420 meters, with slopes of up to 4%. Its predominant relief shape is concave-divergent, followed by convex-divergent, with main slopes directed to the north.

Dissected Depression

Dissected depression areas are located predominantly in the northern portion, in the states of Maranhão (MA) and Piauí (PI) and correspond to 13.22% of the Cerrado-area. The available relief in these areas ranges from 0 to 420 meters with slopes greater than 4%. It includes recurrent concave-divergent and convex-divergent slopes, predominantly facing the west.

Plateau

Plateau areas are concentrated in isolated regions in the states of Bahia (BA), Goiás (GO), Distrito Federal (DF), Minas Gerais (MG) and Mato Grosso do Sul (MS), accounting for approximately 5% of the Cerrado-area. This BRU is characterized by an available relief above 800 meters with flattened top areas and slopes of up to 4%. Its predominant relief shape is concave-divergent, mainly oriented towards the north.

Dissected Plateau

This BRU represents 9.14% of the study region and is located mainly in the states of Goiás (GO) and Minas Gerais (MG). Its available relief is greater than 800 meters and its slopes are greater than 4%. Its prevailing forms are concave-divergent and convex-divergent, mostly facing the north.

Demoted Tableland

The demoted tablelands are distributed in the eastern and southwestern portions of the study area. These formations represent the greatest part of the Cerrado with 25% of its overall area. Their available relief ranges between 420 and 800 meters, with slopes of up to 4%. Predominant forms are concave-divergent and convex-divergent, recurrently facing the north, followed by the east.

Sierra

This BRU is dispersed throughout the study area and corresponds to 23.13% of the Cerrado's overall area, but it is concentrated in its center-south portion. Its available relief ranges between 420 and 800 meters, with slopes above 4%. Its most recurrent forms are concave-divergent and convex-convergent, predominantly directed to the east and west.

4. Concluding Remarks

The representation of geomorphological models based on geomorphometric parameters enables more reliable characterizations of reality. The Brazilian Cerrado's geomorphological map, defined by mathematical models, made it possible to define its key geomorphometric archetypes and to define the relief metric classes that represent its actual conditions.

Producing a specific geomorphological map for the Cerrado can significantly contribute to its physical characterization and, consequently, help meeting the needs of environmental analyses. Maps with larger scales through the method described above allow for greater detail and improved visualization of geomorphological features, thereby enabling more accurate analyses.

Each represented class defines distinct levels of dissection. Plateaus are currently the best preserved class, and Dissected Depressions are the most dissected class. Defining classes that represent metric patterns of relief enables cartographic representations that can be more easily interpreted.

A region at once affluent and threatened such as the Brazilian Cerrado needs more attention and carefulness. A geomorphological map of the Cerrado provides an improved basis for further studies, such as environmental analyses and studies on land use and land occupation, as well as for setting limits to agricultural expansion and promoting deforestation control, among other uses. Such analyses are crucial for the definition and execution of preventive and mitigating actions against environmental damage.

Authors' Contributions: Study conception and design: Gervásio Barbosa Soares Neto and Karla Maria Silva Faria; acquisition of data: Gervásio Barbosa Soares Neto andVitória Rodrigues Ferreira Barbosa; data processing: Gervásio Barbosa Soares Neto; Ana Beatriz de Alcantara Rocha and Vitória Rodrigues Ferreira Barbosa; analysis and interpretation of data: Gervásio Barbosa Soares Neto; Ana Beatriz de Alcantara Rocha and Vitória Rodrigues Ferreira Barbosa; text contributions: Gervásio Barbosa Soares Neto, Ana Beatriz de Alcantara Rocha and Vitória Rodrigues Ferreira Barbosa; drafting of article: Gervásio Barbosa

Soares Neto, Ana Beatriz de Alcantara Rocha and Vitória Rodrigues Ferreira Barbosa; critical revision for important intellectual content: Eder de Souza Martins; revision: Gervásio Barbosa Soares Neto, Ana Beatriz de Alcantara Rocha; Karla Maria Silva Faria and Vitória Rodrigues Ferreira Barbosa. All authors read and agreed with the published publication of the manuscript

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References

1. ARRUDA, M. B. Representatividade ecológica com base na biogeografia de biomas e ecorregiões continentais do Brasil o caso do bioma Cerrado. (Unpublished doctoral thesis). Universidade de Brasília, Brasília. 2003.
2. BENAVENTE, J.; DEL RÍO, L.; ANFUSO, G.; GRACIA, F.J.; REYES, J.L. Utility of Morphodynamic Characterisation in the Prediction of Beach Damage by Storms. **Journal of Coastal Research**, v. 36, p. 56-64, 2002.. https://doi.org/10.2112/1551-5036-36.sp1.56
3. BISHOP, M.P.; JAMES, L.A.; SHRODER Jr, J.F.; WALSH, S.J. Geospatial technologies and digital geomorphological mapping: Concepts, issues and research. **Geomorphology**, v.137, p. 5-26, 2012. https://doi.org/10.1016/j.geomorph.2011.06.027
4. BURROUGH, P.A., MCDONELL, R.A. **Principles of Geographical Information Systems**. New York: Oxford University Press, 1998. 190p.
5. CARABELLA, C.; MICCADEI, E.; PAGLIA, G.; SCIARRA, N. Post-Wildfire Landslide Hazard Assessment: The Case of The 2017 Montagna Del Morrone Fire (Central Apennines, Italy). Geosciences 2019, 9, 175. https://doi.org/10.3390/geosciences9040175
6. CASTRO, A.P.; SILVA, M.R.S.S.; QUIRINO, B.F.; BUSTAMANTE, M.M.C.; KRÜGER, R.H. Microbial Diversity in Cerrado Biome (Neotropical Savanna) Soils. **PLoS ONE,** v. 11, p. 1-16, 2016. https://doi.org/10.1371/journal.pone.0148785
7. COE, M.T.; BRANDO, P.M.; DEEGAN, L.A.; MACEDO, M.N.; NEILL, C.; SILVÉRIO, D.V. The Forests of the Amazon and Cerrado Moderate Regional Climate and Are the Key to the Future. **Tropical Conservation Science**, v. 10, p. 1-6, 2017. https://doi.org/10.1177/1940082917720671
8. CUNHA, N.R.S.; LIMA, J.E.; MACIEL, M.F.; BRAGA, M.J. A intensidade da exploração agropecuária como indicador de degradação ambiental na região dos Cerrados. **Economia e Sociologia Rural**, v. 46, n. 2, p. 291-323, 2008. https://doi.org/10.1590/S0103-20032008000200002
9. FEOLI, E., VUERICH, L.G. & WOLDU, Z. Processes of environmental degradation and opportunities for rehabilitation in Adwa, Northern Ethiopia. Landscape Ecology 17, 315–325 (2002). https://doi.org/10.1023/A:1020566801067
10. FERREIRA, M.E.; FERREIRA, L.G.; LATRUBESSE, E.M.; MIZIARA, F. Considerations about the land use and conversion trends in the savanna environments of Central Brazil under a geomorphological perspective. **Journal of Land Use Science**, v. 11, p. 33-47, 2016. https://doi.org/10.1177/1940082917720671
11. FORZZA, R.C.; BAUMGRATZ, J.F.A.; BICUDO, C.; CANHOS, D. New Brazilian Floristic List Highlights Conservation Challenges. **BioScience**, v. 62, n.1, p. 39-35, 2012. https://doi.org/10.1525/bio.2012.62.1.8
12. FRANCO, A.C.; ROSSATO, D.V.; SILVA, L.C.R.; FERREIRA, C.S. Cerrado vegetation and global change: the role of functional types, resource availability and disturbance in regulating plant community responses to rising CO_2 levels and climate warming. **Theoretical and Experimental Plant Physiology**, v. 26, p. 19-38, 2014. https://doi.org/10.1007/s40626-014-0002-6
13. HARFUCH, L.; NASSAR, A. M.; ZAMBIANCO, W. M.; GURGEL, A. C. Modelling beef and dairy sectors' productivities and their effects on land use change in Brazil**. Revista de Economia e Sociologia Rural**, v. 54, n. 2, p. 281-304, 2016. https://doi.org/10.1590/1234.56781806-947900540205
14. HIDASI-NETO, J.; JONER, D.C.; RESENDE, F.; MONTEIRO, L.M.; FALEIRO, F.V.; LOYOLA, R.D.; CIANCIARUSO, M.V. Climate change will drive mammal species loss and biotic homogenization in the Cerrado Biodiversity Hotspot**. Perspectives in Ecology and Conservation**, v. 17, p. 57-63, 2019. https://doi.org/10.1016/j.pecon.2019.02.001
15. HUTCHINSON, M.F. Calculation of hydrologically sound digital elevation models. Proceedings: Third International Symposium on Spatial Data Handling at Sydney, Australia, 1988.
16. IBAMA. Monitoramento do desmatamento dos biomas brasileiros por satélite: Cerrado 2010-2011. Brasília: IBAMA, 2015.
17. IBGE. **Manual Técnico de Geomorfologia**. Coordenação de Recursos Naturais e Estudos Ambientais. 2ª ed. Rio de Janeiro:IBGE, 2009. 182p.
18. JASIEWICZ, J.; STEPINSKI, T. Geomorphons – a pattern recognition approach to classification and mapping of landforms. **Geomorphology**, vol. 182, 147-156. 2013. https://doi.org/10.1016/j.geomorph.2012.11.005

19. KELLER, K.; ADAMAITIS, C.; ALESSIO, P.; ANDERSON, S.; GOTO, E.; GRAY, S.; GURROLA, L.; MORELL, K;. Applications in geomorphology, **Geomorphology,** Volume 366, 2020,106729, ISSN 0169-555X, https://doi.org/10.1016/j.geomorph.2019.04.001.
20. KLINK, C.A.; MACHADO, R.B. Conservation of the Brazilian Cerrado. **Conservation Biology**, v. 19, p. 707-713, 2005. https://doi.org/10.1111/j.1523-1739.2005.00702.x
21. MACEDO, R.; AUDINO, L.D.; KORASAKI, V.; LOUZADA, J. Conversion of Cerrado savanas into exotic pastures: The relative importance of vegetation and food resources for dung beetle assemblages. **Agriculture, Ecosystems and Environment**, v. 288, p. 1-9, 2020. https://doi.org/10.1016/j.agee.2019.106709
22. MENDES, B.C. Mapeamento Geomorfológico aplicado ao estudo do uso e cobertura da terra no Planalto Central. (Unpublished master's thesis). Universidade de Brasília, Brasília, 2015.
23. MMA. Mapeamento do uso e cobertura do Cerrado: Projeto TerraClass Cerrado. Brasília: MMA, 2015. 67p.
24. MYERS, N.; MITTERMEIER, R. A.; FONSECA, G.A.B.; KENT, J. Biodiversity hotspots for conservation priorities. **Nature,** v. 403, p. 853-858, 2000. https://doi.org/10.1038/35002501
25. NAVEH, Z. Culture and Landscape Conservation: a landscape-ecological perspective. In: GOPAL B.P., PATHAK P., SAYENA K.G. (Ed.) **Ecology today: an anthology of contemporary ecological research international scientific publications**, New Delhi, 1998, p. 19–48. https://doi.org/10.1007/1-4020-4422-4_10
26. OLIVEIRA, P.T.S.; NEARING, M.A.; MORAN, M.S.; GOODRICH, D.C.; WENDLAND, E.; GUPTA, H.V. Trends in water balance components across the Brazilian Cerrado. **Water Resources Research**, v. 50, p. 7110-7114, 2014. https://doi.org/10.1002/2013WR015202
27. OLIVEIRA, H.F.M.; CAMARGO, N.F.; GAGER, Y.; MUYLAERT, R.L.; RAMON, E.; MARTINS, R.C.C. Protecting the Cerrado: where should we direct efforts for the conservation of bat-plant interactions? **Biodiversity and Conservation,** v. 28, p. 2765-2779, 2019. https://doi.org/10.1007/s10531-019-01793-w
28. RADAM. Projeto RADAM Brasil. Folha SD-23 Brasília: geologia, geomorfologia, pedologia, vegetação, uso potencial da terra. Rio de Janeiro: MMA, 1982. 655p.
29. RAO, D.P. Utility of landsat coverage in small scale geomorphological mapping-some examples from India. **Journal of the Indian Society of Remote Sensing,** v. 6, p. 49-56, 1978. DOI: 10.1016/j.geomorph.2006.10.041
30. RIBEIRO, J.F.; WALTER, B.M.T. **Fitofisionomias do bioma cerrado**. Planaltina: EMBRAPA-CPAC, 1998.
31. REMONDO, J.; BONACHEA, J.; CENDRERO, A. Quantitative landslide risk assessment and mapping on the basis of recent occurrences. **Geomorphology**, v. 94, p. 496-507, 2008. https://doi.org/10.1016/j.geomorph.2006.10.041v
32. ROSS, J.L.S, O Registro Cartográfico Dos Fatos Geomórficos e a Questão da Taxonomia do Relevo. Revista do Depto. de Geografia – FFLCH-USP, v. 6: 17-29, 1992.
33. RUGGIERO, P.G.C.; PIVELLO, V.R.; SPAROVEK, G.; TERAMOTO, E.; PIRES NETO, A.G. Relação entre solo, vegetação e topografia em área de cerrado (Parque Estadual de Vassununga, SP): como se expressa em mapeamentos? **Acta Botanica Brasilica**, v. 20, n. 2, p. 383-394, 2006. https://doi.org/10.1590/S0102-33062006000200013
34. SANO, E.E.; BRITO, J.L.S.; FERREIRA, L.G. Land cover mapping of the tropical savanna region in Brazil. **Environmental Monitoring and Assessment,** v. 166, p. 113-124, 2010. https://doi.org/10.1007/s10661-009-0988-4
35. SANO, E.E.; RODRIGUES, A.A.; MARTINS, E.S.; BETTIOL, G.M.; BUSTAMANTE, M.M.C.; BEZERRA, A.S.; COUTO JR, A.F.; VASCONCELOS, V.; SCHÜLER, J.; BOLFE, E.L. Cerrado ecoregions: A spatial framework to assess and prioritize Brazilian savanna environmental diversity for conservation. **Journal of Environmental Management,** v. 232, p. 818-828, 2019. doi: 10.1016/j.jenvman.2018.11.108.
36. SCHNEIDER, A.; BONHAGE, A.; RAAB, A.; HIRSCH, F.; RAAB, T. Large-scale mapping of anthropogenic relief features—legacies of past forest use in two historical charcoal production areas in Germany. **Geoarchaeology**, v. 35, p. 545-561, 2020. https://doi.org/10.1002/gea.21782
37. SILVEIRA, C. T.; SILVEIRA, R. M. P.; TRENTIN, R.; ROBAINA, L. E. S. Classificação Automatizada de Elementos de Relevo no Estado do Paraná (Brasil) por Meio da Aplicação da proposta dos Geomorphons. **Revista Brasileira de Geomorfologia**, v. 19, n. 1, p. 33-57, 2018. http://dx.doi.org/10.20502/rbg.v19i1.1263
38. SOARES NETO, G.B.; MARTINS, E.D.S. Semi-automatic method delimitation of basic relief units. **Revista Brasileira de Geomorfologia**, v. 20, n. 2, 2019. http://dx.doi.org/10.20502/rbg.v20i2.1403
39. SPERA, S.A.; GALFORD, G.L.; COE, M.T.; MACEDO, M.N.; MUSTARD, J.F. Land-use change affects water recycling in Brazil's last agricultural frontier. **Global Change Biology,** v. 22, p. 3405-3413, 2016. doi: 10.1111/gcb.13298
40. STRASSBURG, B.B.N.; BROOKS, T.; FELTRAN-BARBIERI, R.; IRIBARREM, A.; CROUZEILLES, R.; LOYOLA, R.; LATAWIEC, A.E.; FILHO, F.B.O.; SCARAMUZZA, C.A.M.; SCARANO, F.R.; SOARES-FILHO, B.; BALMFORD, A. Moment of truth for the Cerrado hotspot. **Nature Ecology and Evolution**, v. 1, p. 99, 2017. https://doi.org/10.1038/s41559-017-0099
41. TRENTIN, R.; ROBAINA, L.; SILVEIRA, C.T.D. Geomorphometric compartmentation of River Basin Itu/RS. **Revista Brasileira de Geomorfologia**, v.16, p. 219-237, 2015. http://dx.doi.org/10.20502/rbg.v16i2.460