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Papers

Natural Determinants of Murundus Fields Distribution in the Southwest of the State of Goiás

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Abstract

Murundus fields, also known as *covoais*, are frequent microreliefs in the Cerrado. These are sets of semicircular elevations that protrude from the surface of the land, rounded or oval, with average dimensions of 70 cm in height and 6 m in diameter. The determinants of its regional spatial distribution are still poorly known. This study aimed to identify the natural determinants of its spatial distribution in the Southwest of Goiás, in the Sedimentary Basin of Paraná. All occurrences of *murundus* fields identified by the project Mapping of Remnant *Murundus* Fields in the state of Goiás (SEMAD-GO/LAPIG-UFG) were compared with information referring to lithology, geomorphology, NDWI (Normalized Difference Water Index), and SMI (Soil Moisture Index). The indices were obtained from SENTINEL 2-A (MSI) and Landsat 8 (OLI and TIRS) orbital images. It was found that *murundus* fields preferentially occur in the Alluvial Deposits, Cachoeirinha, Detritic-lateritic Covers, and Serra Geral geological units. *Murundus* fields predominate under slopes of 0 to 8% (flat to gently undulating relief), and in areas with lower drainage density. The NDWI and the SMI indicated that *murundus* fields are concentrated on wet surfaces, occurring less frequently in saturated/very wet areas and in moderate humidity, dry, and very dry surfaces.

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INTRODUCTION

Murundus (earth-mound) fields, also known as *covoais*, are peculiar microreliefs (sets of metric-scale earth mounds), commonly located in areas of flattened surfaces in the *Cerrado*. They are sets of semicircular elevations that protrude from the surface of the land, rounded or oval, with average dimensions of 70 cm in height and 6 m in diameter (Sales *et al.*, 2019). *Murundus* fields have woody vegetation (herbaceous, shrubby, and arboreal), while the space between the *murundus* fields commonly has hygrophilous field vegetation (Darlington, 1985; Araújo Neto *et al.*, 1986). Most occurrences are associated with wetlands situated on alluvial deposits, in amphitheater-shaped headwaters and in top depressions.

Earth-mound fields occur in natural landscapes in several locations worldwide. In Brazil, this type of microrelief is quite common in areas with a predominance of hydromorphic soils and has been studied in several regions, such as in the *Pantanal* of Mato Grosso (Oliveira Filho, 1992), in the Southwest of the Amazon (Silva *et al.*, 2017), in the Semi-arid Northeast (Oliveira *et al.*, 2014) and, above all, in the *Cerrado* (Araújo Neto *et al.*, 1986; Furley *et al.*, 1986; Schneider; Silva, 1991). At the local scale, *Cerrado murundus* fields appear at the edges of isolated wetlands or along hydromorphic valleys, forming a separation strip between well-drained soils (Oxisols, Argisols, Cambisols), located upslope, and hydromorphic soils (Gleisols, Organosols), located downslope (Schneider; Silva, 1991).

As part of the wetlands of the *Cerrado*, *murundus* fields have important environmental roles: they make up the system of recharge and discharge of aquifers, maintaining river flows during the dry season; they retain sediments; they constitute special ecosystems, with unique fauna and flora; they are a source of water for wildlife; they function as organic carbon stock zones (Zedler; Kercher, 2005; Rosolen *et al.*, 2015).

Because they are in the vicinity of wetlands, located along the limits of agricultural soils, *murundus* fields of the *Cerrado* are currently strongly threatened by the expansion of agriculture (Rosolen *et al.*, 2015). Two common practices that allow the incorporation of *murundus* fields into agricultural areas are the artificial lowering of the water table, by draining the soil, and the leveling of its surface (Gomes Filho *et al.*, 2011; Paulino *et al.*, 2015), eliminating the microrelief and its original vegetation.

In the state of Goiás, there has recently been an important discussion about the environmental legislation regarding *murundus* fields. A significant change occurred as a result of the repeal of Law No. 18,104, of July 18, 2013 by Law No. 20,694, of December 26, 2019, through which *murundus* fields are no longer explicitly considered PPAs (Permanent Preservation Areas). However, this exclusion was temporary, since, in 2020, *murundus* fields were clearly reintroduced as PPAs by Law No. 20,773, of May 8.

Murundus fields configure a spatial unit and have an individuality that differentiates them from the landscape of their surroundings. These environments have been studied by researchers from different areas, especially geomorphologists and biologists. Their investigation is almost always carried out on a detailed scale, focusing on one or more mounds of earth within the same *murundus* field, or focusing on the totality of a single or a few occurrences of these fields. Works on a regional scale, which investigate a large number of occurrences of *murundus* fields, are rare. In addition, studies usually focus on a specific aspect of *murundus* fields, such as their phytosociology (Oliveira Filho, 1992; Resende *et al.*, 2004), the morphometry of their relief (Silva *et al.*, 2020; Sales *et al.*, 2021), their soils (Schneider; Silva, 1991; Martins; Rosolen, 2014).

The occurrence of *murundus* fields results from specific interactions of the variables of the natural environment (geological substrate, relief, soils, vegetation, hydrology). Although these interactions are already well known on a local scale, especially concerning the relationship of these features with the presence of hydromorphic soils and seasonal regimes of water table fluctuation (Furley, 1986; Schneider; Silva, 1991; Ponce; Cunha, 1993; Rosolen *et al.*, 2019), studies on a wider scale that integrate many natural variables, such as the research by Lima and Corrêa (2021) for the Federal District, are still uncommon.

In recent years, the need to develop research and computational tools for environmental control and planning, capable of meeting different criteria simultaneously, experienced a rapid growth, with advances in database analytical techniques, software, and hardware. The Geographic Information System (GIS), geoprocessing, and Remote Sensing products stand out, allowing one to integrate techniques with mathematical concepts and postulates, constituting important mechanisms for analysis, studies, and planning (Mantovani; Lelis, 2023).

Spectral indices are results of mathematical operations between numerical values of pixels of the bands of a satellite image. By using satellite orbital images, one can obtain indices that allow for an analysis of the structure and dynamics of the landscape at different spatial and temporal scales, varying according to the configuration of the sensor (De Albuquerque *et al.*, 2014). They are an important resource with applications in different fields, such as agricultural productivity, identification of natural processes, wildfires, changes in vegetation cover and land use, and changes in water bodies, among others. Research (Borges; Baptista, 2019; Sales *et al.*, 2023) using spectral indices to investigate the natural conditions of the occurrence of *murundus* fields is still scarce and recent.

The Normalized Difference Water Index (NDWI) was developed by McFeeters (1996). It is a graphical indicator that can be used to monitor water content in leaves and vegetation. The Soil Moisture Index (SMI), proposed by Zeng *et al.* (2004), has been used to quantify soil moisture. The SMI is based on the values of two indices, the NDVI and the LST (Land Surface Temperature). The greater the contrast between the two indices, the higher the soil moisture tends to be (Zeng *et al.*, 2004). Based on the premise that *murundus* fields occur associated with wetlands (Furley, 1986; Schneider; Silva, 1991; Ponce; Cunha, 1993; Rosolen *et al.*, 2019), this study proposes to combine the NDWI and the SMI to analyze the relationship between the distribution of areas with *murundus* fields and soil moisture.

The study area for this research was the Southwest of the state of Goiás, comprised by the geological units of the Paraná Sedimentary Basin. The region has significant occurrence of *murundus* fields and is the portion of the state in which these environments have been most affected and erased by economic activities, especially agriculture and livestock.

This study aimed to verify the relationship between the spatial distribution of components of the natural environment (geological units, slope of the relief, drainage density, and soil moisture) and the distribution of *murundus* fields in the southwestern portion of the state of Goiás.

MATERIAL AND METHODS

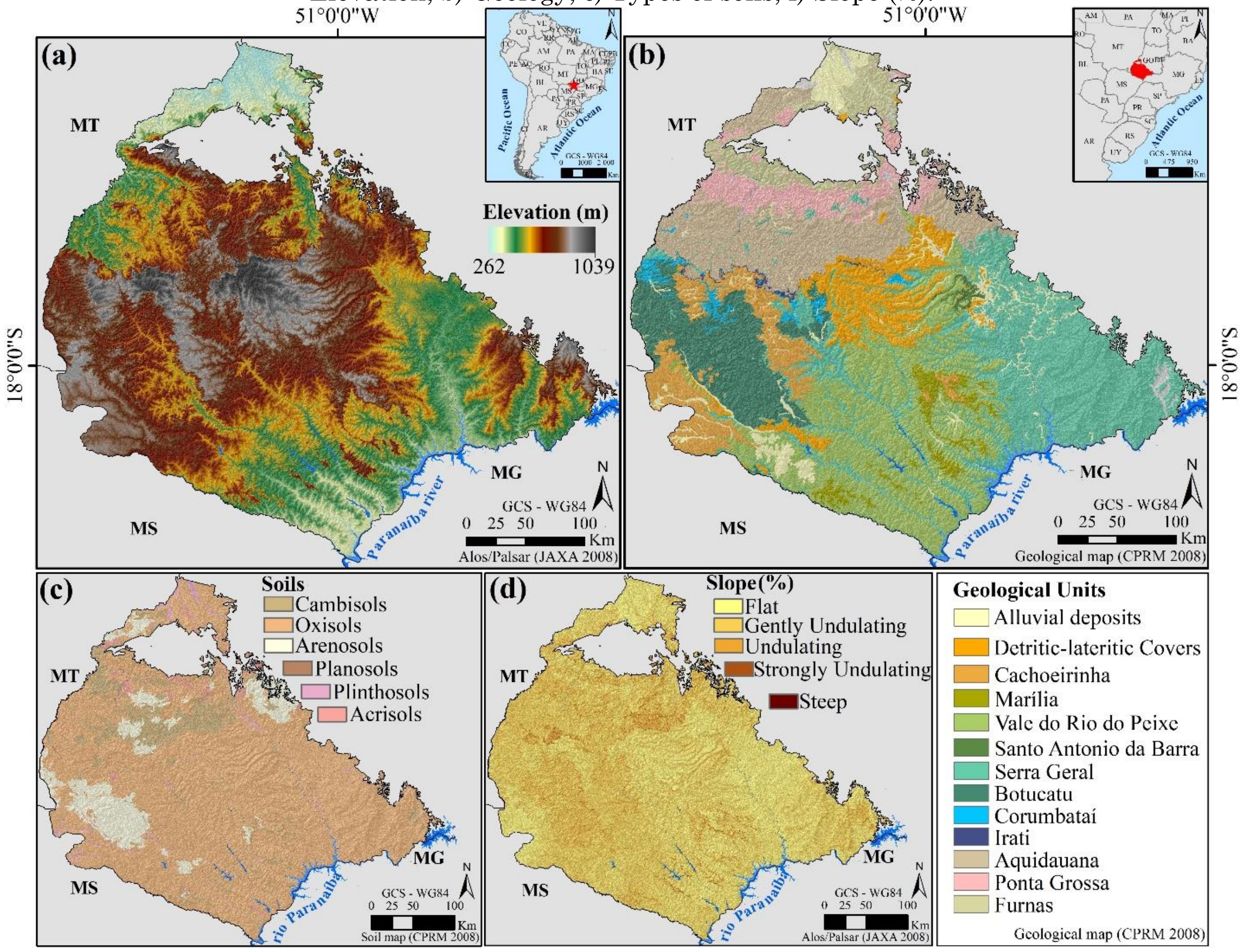
Study area

The study area is located in the Southwestern state of Goiás, with approximately 98,158 km² of surface (Figure 1 [d]). The geological units of the Paraná Sedimentary Basin and its Neogene and Quaternary coverings were chosen as the spacial scope.

The most important geological units of the Paraná Sedimentary Basin in the Southwestern Goiás, including the associated igneous rocks, are, from the oldest to the most recent: Furnas, Ponta Grossa, Aquidauana, Irati, Corumbataí, Botucatu, Serra Geral, Santo Antônio da Barra, Vale do Rio do Peixe, Marília, Cachoeirinha, Detritus-lateritic Covers, and Alluvial Deposits (CPRM, 2008). In the study area, the geological units Serra Geral, Vale do Rio do Peixe, Aquidauana, and Botucatu predominate, occupying, respectively, 24.17%, 20.93%, 13.60%, and 9.36% of the surface (Figure 1 [b]).

Oxisols (Dark-Red and Red-Yellow) are the dominant soils (Nascimento, 1991), occupying 78% of the surface (Figure 1 [e]), followed by Quartzarenic Neosols and Cambisols, each with 9% of the surface. The study area is located in the *Cerrado* phytogeographic domain. According to data produced by PRODES Cerrado (INPE, 2018), remnants of the original vegetation cover (*cerrado stricto sensu*, forest formations, and grassland formations) occupy about 20% of the region; the rest is used by agricultural or livestock activities (76.23%), water bodies, and exposed soil.

Figure 1 - Location of the study area and regional characteristics of the natural environment: a) Elevation; b) Geology; c) Types of soils; f) Slope (%).



Source: The authors (2023).

The geological units were obtained from the Geology Map, also the soil types, of the Geodiversity Map Collection for the state of Goiás by Companhia de Pesquisa de Recursos Minerais (CPRM, 2008), with a scale of 1:800,000 (Figure 1 [b; c]). Data are from the occurrences of *murundus* fields produced by Laboratório de Processamento de Imagens e Geoprocessamento (LAPIG/UFG), which is the Goias Federal University federal responsible for data collection from the Cerrado biome and Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável (SEMAD-GO), which is the state body responsible for implementing the management of Brazilian natural resources of Goiás), were also used, within the scope of the project Mapping of Remnant *Murundus* Fields in the state of Goiás (Silva *et al.*, 2023), with a total of 2,297 occurrences. The map is available at the website of the Sistema de Informações Geográficas Ambientais do Estado de Goiás (SIGA).

The iconographic materials consisted of images of the digital elevation model (DEM) of the SRTM (Shuttle Radar Topography Mission) sensor, available on the ASF (Alaska Satellite Facility) website, resampled from 30 m to 12.5 m pixel dimension, with orthometric altitude (EGM96 geoid model) converted to geometric and altitude (ellipsoidal). Notably, the DEM from resampling operates in the L band (λ ~ 22 cm), unlike other sensors that operate in the C band (λ ~ 7 cm), being less sensitive to interference from tree canopy, improving the visualization of terrain characteristics (Ponzoni, *et al.*, 2012). As a complementary analysis, the geomorphometric variable slope (%) of the selected DEM was extracted. As the number of scenes used to fill the study area was high (approximately 220 scenes), they were not presented here.

Orbital images of the sensors Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) were used, on board of the Landsat-8 Level 2 satellite, dated May 2020, with a resolution of 30 m and a total of 11 scenes. Level 2 data were atmospherically corrected and generated from the LASRC (Landsat-8 Surface Reflectance Code), which produces surface reflectance at a spatial resolution of 30 m, suitable for the proposed study (Zanter, 2019). Scenes from the MSI (Multispectral Imager) sensor were also used, on board of the SENTINEL 2-A satellite, dated May 2020, with a spatial resolution of 10 m, totaling 15 scenes. The images were acquired from the USGS (United States Geological Survey). In addition to the iconographic materials, secondary data from cartographic databases, in shapefile format, were used, regarding the drainage network and other cartographic elements. The drainage network was used to estimate the drainage density (Dd).

The set of information and data used was organized in a geographic database for treatment, conversion, processing, and analysis of the results and implemented in a geographic information system (GIS). The publication scale of the maps is 1:100,000.

Normalized Difference Water Index (NDWI)

To obtain the NDWI, the proposal of Gaos (1996) was used, from the reflectance of Band 8, near-infrared (NIR), and Band 12, middle infrared (MIR), of the MSI sensor. The NDWI index was calculated specifically for May 2020. The index works with (dimensionless) values on a scale from −1 to 1, in which values closer to 1 indicate a higher content of surface water present in leaves and vegetation, and values closer to −1 indicate a lower presence of water (Shimakuburo *et al.*, 1999; Mantovani *et al.*, 2019). The index was calculated according to Equation 1:

NDWI = (NIR−MIR)/(NIR+MIR) (1)

Where: NIR = Band 8 and MIR = Band 12.

After obtaining the index, a reclassification was carried out using the tool "*reclassify*," in ArcGIS (ESRI, 2019) software. A total of 11 NDWI classes were obtained, namely: −1, −0.8, −0.6, −0.4, −0.2, 0, 0.2, 0.4, 0.6, 0.8, 1.

Soil Moisture Index (SMI)

The Soil Moisture Index (Lambin; Ehrlich, 1996; Zhan *et al.*, 2004) was used over the selected area to reconstruct soil moisture for the same period of the NDWI index, May 2020. According to Lambin and Ehrlich (1996), the scatter plot of LST vs NDVI results in a trapezoidal shape, and all types of land cover fall within the trapezoid of LST-NDVI space. The upper envelope of the trapezoid (upper limit of the surface temperature for a given vegetation cover) represents the dry condition (warm edge), while the lower limit represents the wet condition (cold edge) (Parida *et al.*, 2008).

To obtain the SMI index, the methodological procedures described by Hassan *et al.* (2019) were used, with images from the Landsat-8 satellite. Bands 4 (red) and 5 (near infrared) of the OLI (Operational Land Image) sensor were used to calculate the Normalized Difference Vegetation Index (NDVI). Band 10 (thermal infrared) of the TIRS (Thermal Infrared Sensor) was used to calculate Land Surface Temperature (LST). The SMI is based on NDVI and LST values from 0 (drier soil) to 1 (wet soil), and is calculated according to Zhan *et al.* (2004):

$$SMI = \frac{(LST_{max} - LST)}{(LST_{max} - LST_{min})} \quad (2)$$

Where: LSTmax and LSTmin are, respectively, the maximum and minimum LST values within the image for a given NDVI. It is expressed as:

$$LST_{max} = a_1 \times NDVI + b_1 \quad (3)$$

$$LST_{min} = a_2 \times NDVI + b_2 \quad (4)$$

Where: a and b are empirical parameters defining the dry and wet edges, modeled as a linear fit to the data (Zhan *et al.*, 2004; Parida *et al.*, 2008; Potić *et al.*, 2017).

The index was reclassified using the tool "*reclassify*," in ArcGIS software (ESRI, 2019). The following classes were obtained for the SMI map: 0, 0.2, 0.4, 0.6, 0.8, 1. Subsequently, a stratification was made for five classes: very wet, wet, moderate moisture, dry, and very dry.

Drainage Density (Dd)

The spatial distribution of drainage density values in the study area was obtained from the measurement of channel lengths in quadratic cells that covered the entire study area. For the calculation of Dd, following the methodology of Horton (1945), the following equation was used:

$$D_d = \frac{L_b}{A} \quad (5)$$

where: D_d is the drainage density; L_b is the total length of the rivers or canals in the basin; and A is the area of the basin, here corresponding to the study area.

Thus, it was sought to quantitatively correlate density D_d with the areas covered by *murundus* fields per geological unit, from the comparison of thematic maps with isovalue maps of D_d.

Data analysis

For the analysis of the results, graphs were prepared by cross-tabulation, seeking the relationships between the distribution of *murundus* fields and the distribution of the components of the natural environment: Geological units, Slope, Drainage Density, Normalized Difference Water Index (NDWI), and Soil Moisture Index (SMI).

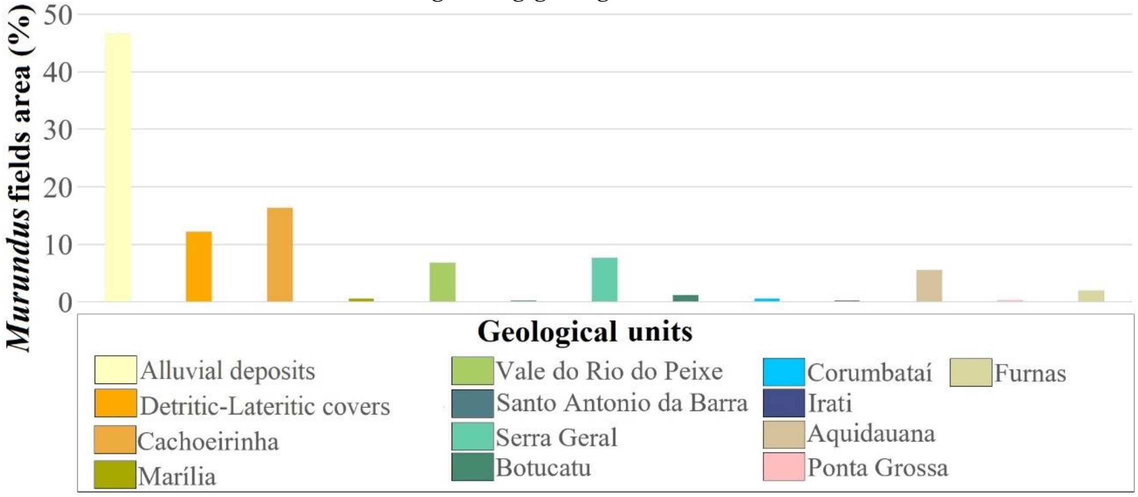
The first step consisted of overlapping occurrences of *murundus* fields with the geological units map (Figure 1 [b]). Subsequently, the occurrences of *murundus* fields were overlapped with the slope map (Figure 1 [f]). The classification proposed by EMBRAPA (1999) was used, with five classes: Flat (0 to 3%), Gently Undulating (3 to 8%), Undulating (8 to 20%), Strongly Undulating (20-45%), Steep (45 to 75%). Very steep terrain (>75%) was not present in the study area.

A correlation was also made between the percentage of Flat to Gently Undulating Relief (slope from 0 to 8%) for each geological unit and the percentage of its surface covered by *murundus* fields, added to the relationship between the density of the surface drainage network and the percentage of the area of each geological unit occupied by *murundus* fields, except for the Alluvial Deposits unit. Finally, the intersection between the occurrences of *murundus* fields and the NDWI and SMI indices was performed.

RESULTS AND INTERPRETATIONS

Figure 2 shows that almost half of the area covered by *murundus* fields on the geological units of the Paraná Sedimentary Basin in the Southwest of Goiás is located in the Alluvial Deposits unit (46.60%), representing 26,000 ha. The Cachoeirinha Formation, which appears in second place, concentrates 16.31% (9,378 ha) of the total surface occupied by *murundus* fields in the studied area; for the Detritic-lateritic Covers and for the Serra Geral Formation the values are, respectively, 12.17% (6,998 ha) and 7.65% (4,398 ha). However, *murundus* fields are found in all geological units, only less representative.

Figure 2 - Percentage of the total area covered by *murundus* fields in the Southwest of Goiás regarding geological units.



Source: The authors (2023).

Figure 3 shows that the *murundus* fields are predominant in the slope classes from 0 to 3% and from 3 to 8%. Flat Relief (0–3%) class comprises 48.46% of the area of occurrence of *murundus* fields (27,658 ha), followed by the Gently Undulating Relief (3 - 8%) class, which represents 43.81% of the area (25,100.6 ha). The Undulating Relief (8–20%) class appears in third place, with 7.59% (4,351.3 ha) of the total area of *murundus* fields in the studied region.

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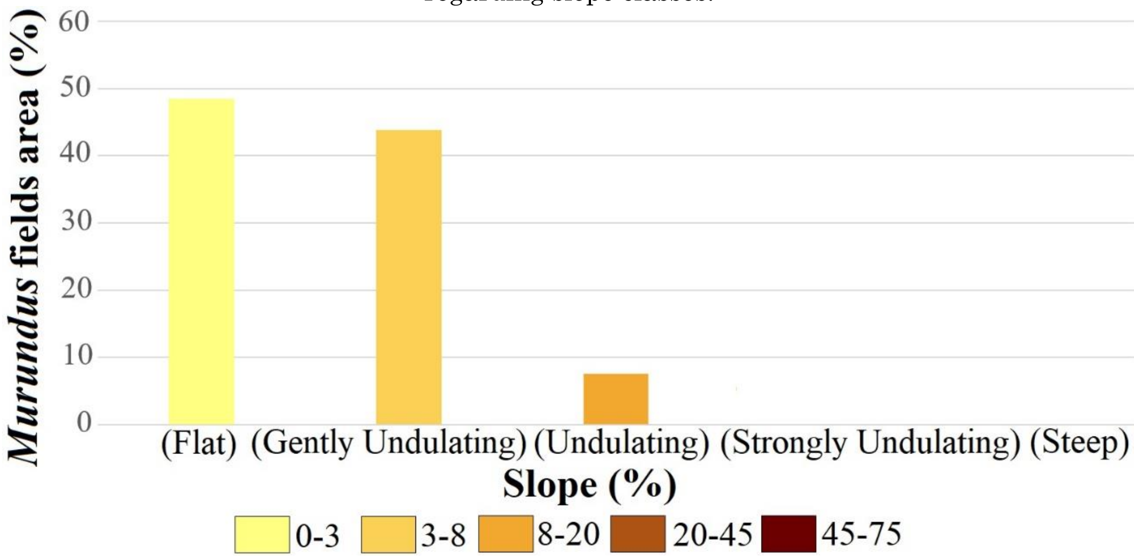
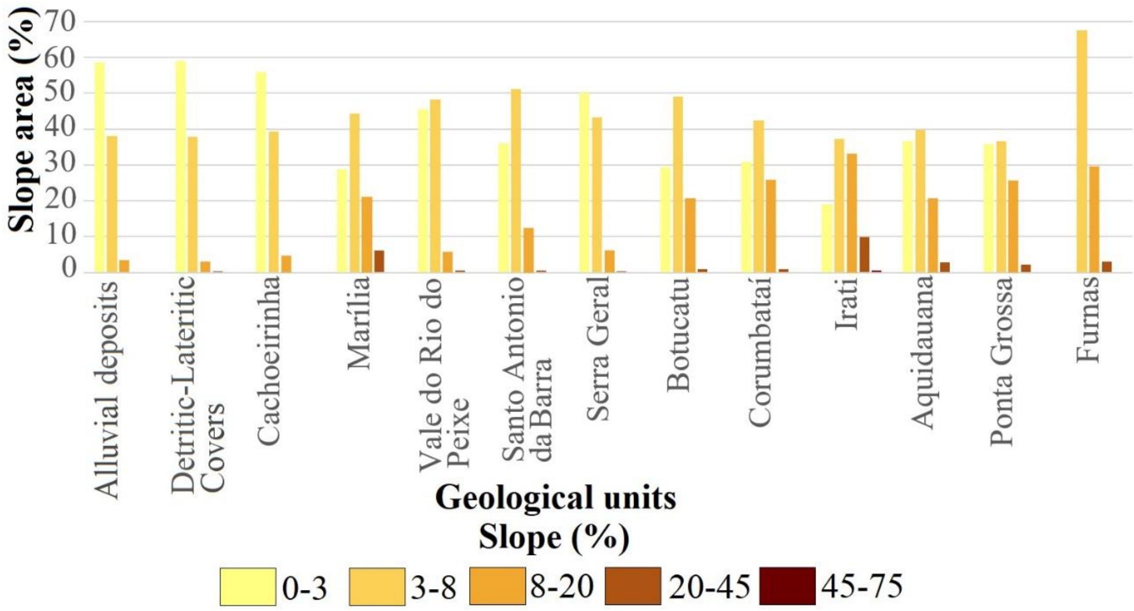
Figure 3 - Percentage of the total area covered by *murundus* fields in the Southwest of Goiás regarding slope classes.



Source: The authors (2023).

Figure 4 shows that the flatter reliefs (Flat and Gently Undulating) are dominant in the geological units of Alluvial Deposits (92.98% of its area), Cachoeirinha (92.23%), Detritus-lateritic Cover (92.19%), Vale do Rio do Peixe (85.42%), and Serra Geral (85.32%). On the other hand, in the geological units Corumbataí, Marília, Irati, and Furnas, the most sloping in the region, these slope classes represent 55.23%, 54.39%, and 38.66%, respectively.

Figure 4 - Graph in percentage of slope classes (see caption of Figure 4) per area for each geological unit.



Source: The authors (2023).

When relating the slope to the occurrence of *murundus* fields per geological unit, there is a tendency to increase the representativeness of the *murundus* field areas as a function of the increase in the flat and gently undulating areas (slope from 0 to 8%) in the geological units (Figure 5). Nevertheless, one can also observe, by the distribution of the points, that the slope is not the only factor that explaining the occurrence of *murundus* fields per geological unit.

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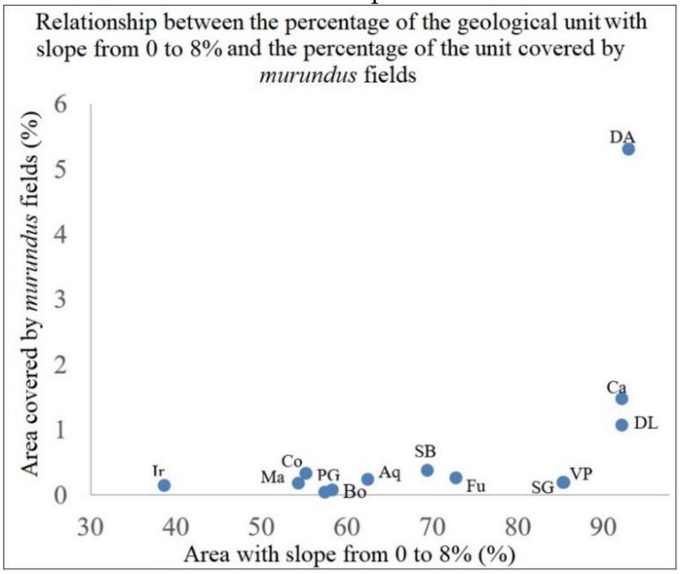
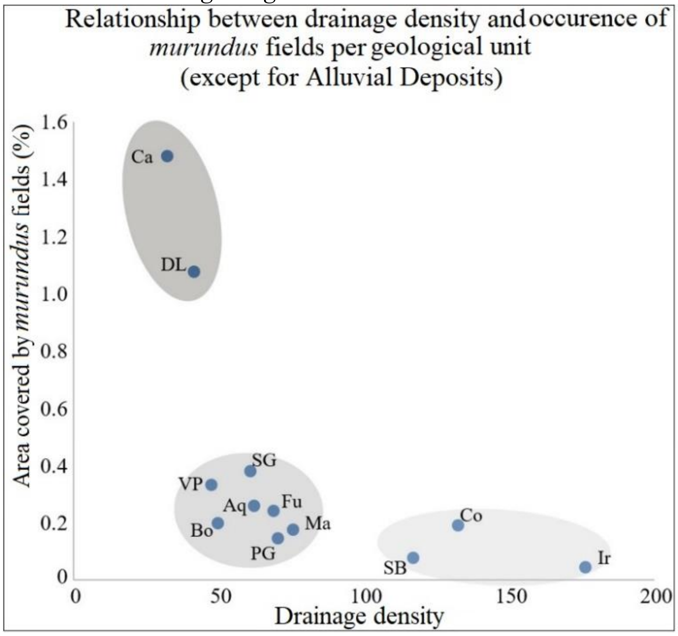
Figure 5 - Relationship between the percentage of flat and gently undulating relief (slope from 0 to 8%) of each geological unit and the percentage of its surface covered by *murundus* fields. Ir: Irati; Ma: Marília; Co: Corumbataí; PG: Ponta Grossa; Bo: Botucatu; Aq: Aquidauana; SB: Santo Antônio da Barra; Fu: Furnas; SG: Serra Geral; VP: Vale do Rio do Peixe; DL: Detritus-lateritic Covers; AD: Alluvial Deposits.



Source: The authors (2023).

According to Figure 6, there is a negative correlation between drainage density and occurrence of *murundus* fields. It is also verified that the geological units (except the Alluvial Deposits unit) are distributed into three groups: Group 1 (dark gray), comprising Cachoeirinha Formation and Detritus-lateritic Covers, which have low drainage density and the highest percentage of the area covered by *murundus* fields; Group 2 (medium gray), comprising the Serra Geral, Vale do Rio do Peixe, Aquidauana, Furnas, Botucatu, Marília, and Ponta Grossa units, with low to intermediate drainage density and low percentages of its surface covered by *murundus* fields; Group 3 (light gray), comprising the Corumbataí, Santo Antônio da Barra, and Irati units, with higher drainage density and lower representativeness of *murundus* fields on their surfaces (Figure 6).

Figure 6 - Correlation between drainage density and the area covered by *murundus* field per geological unit.



Source: The authors (2023).

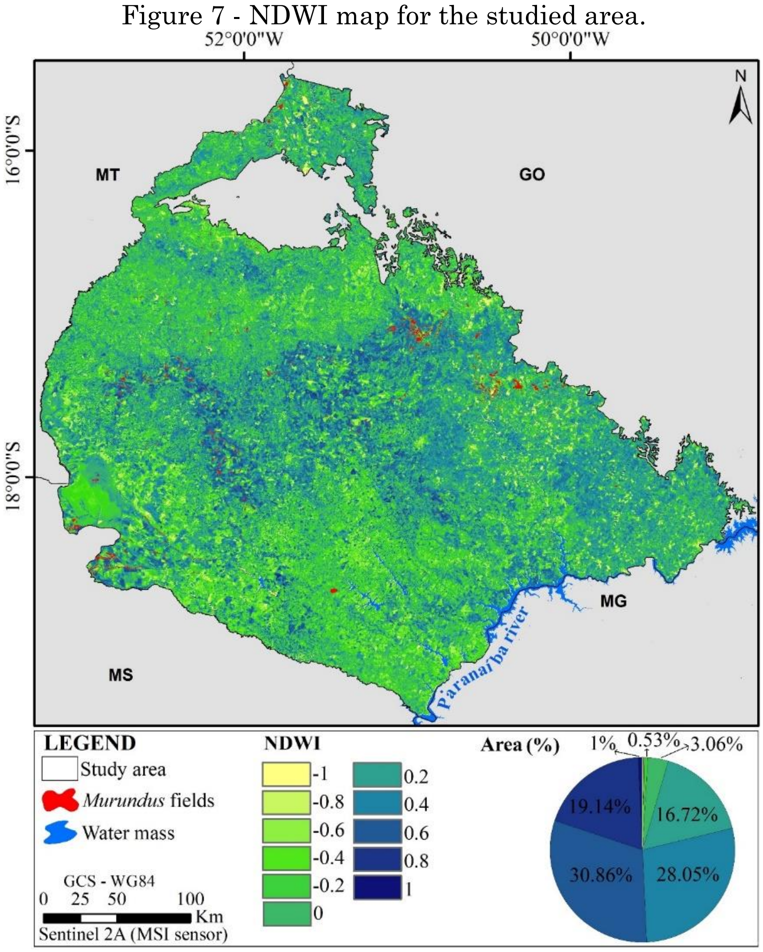
Several factors influence the drainage density in a region (Gao *et al.*, 2022). Drainage is directly related to the infiltration capacity of precipitated waters, which is, in turn, influenced by the relief, the properties of the rock, and the characteristics of its surface formations: more permeable materials favor groundwater flows, while less permeable materials favor surface runoff and its organization in denser drainage networks (Christofoletti, 1981).

Considering the configuration of the graph in Figure 6 and the lithology of the geological units of the studied area, it is verified that, except for the most recent geological units, associated with the flatter reliefs of the region (Alluvial Deposits, Cachoeirinha Formation, and Detritus-lateritic Covers), drainage density is related to the dominant lithology: in Group 2 (Vale do Rio do Peixe, Aquidauana, Furnas, Botucatu, Marília, and Ponta Grossa), sandstones predominate; while in Group 3, pelites predominate in Corumbataí, Santo Antônio da Barra, and Irati and igneous rocks in Santo Antônio da Barra. Serra Geral Formation is the only exception, which belongs to Group 2 and is also igneous in nature, but has a low drainage density and the third highest percentage of coverage by *murundus* fields (except for Alluvial Deposits).

A possible explanation for the low drainage density in the Serra Geral Formation domains is its significant infiltration capacity, which is guaranteed by the dense network of fractures and faults that cross the basalts, by the presence of sandy intertraps (Reis *et al.*, 2014), and by the porosity and thickness of its dominant surface formations (Oxisols with microaggregated structure and high contents of hematite and gibbsite) (Ker, 1997).

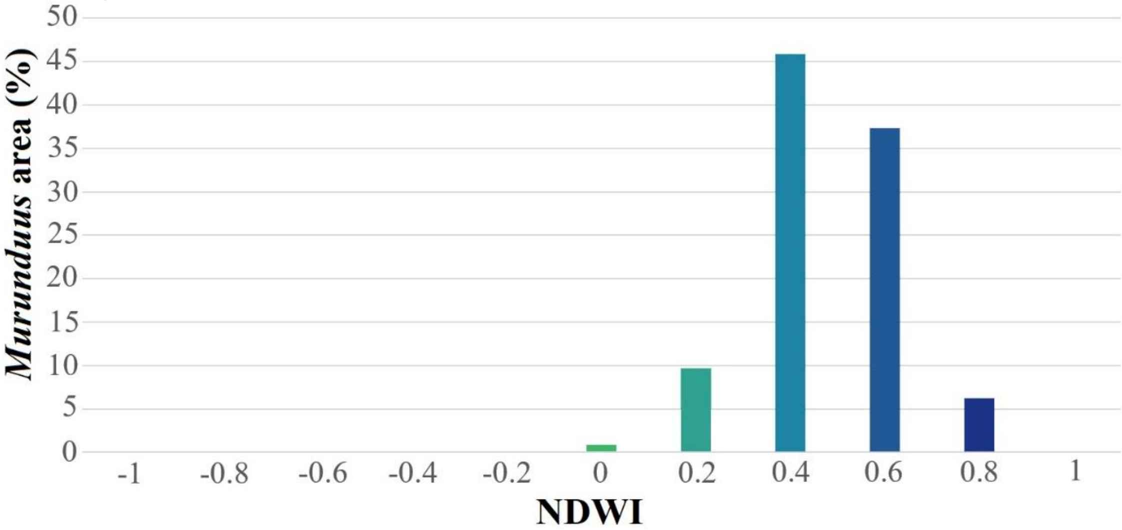
Figures 7 and 8 show that, although soils with NDWI below zero predominate in the Southwest of Goiás (well-drained soils), the occurrences of *murundus* fields are mostly associated with high-moisture soils, that is, with positive values. Figure 8 also shows that *murundus* fields are more common in areas with indices 0.4 and 0.6, indicating that these are areas of imperfectly drained soils, subject to temporary outcropping of the water table, but not to flooding for extended periods or permanently (indices 0.8 and 1.0).

Figure 7 - NDWI map for the studied area.



Source: The authors (2023).

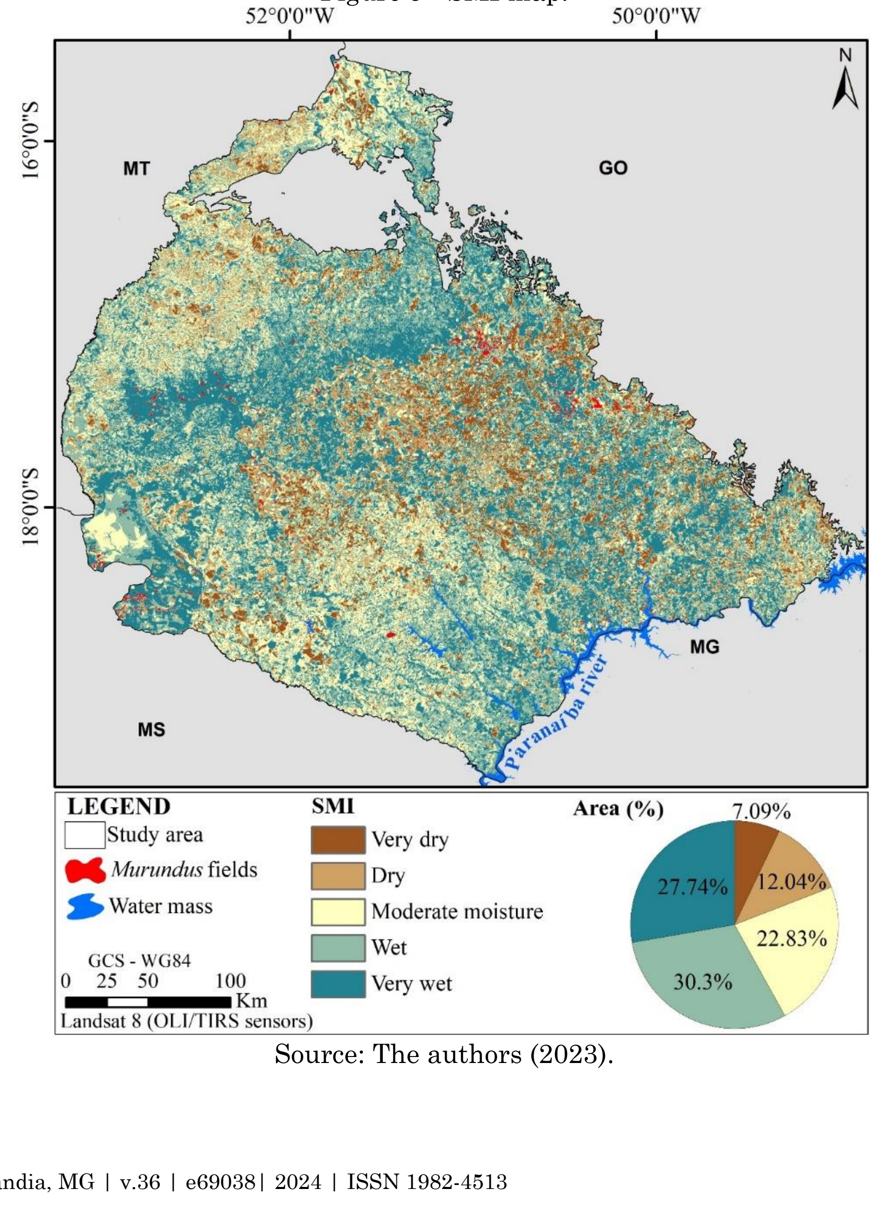
Figure 8 - Relationship between NDWI and the occurrence of *murundus* fields.



Source: The authors (2023).

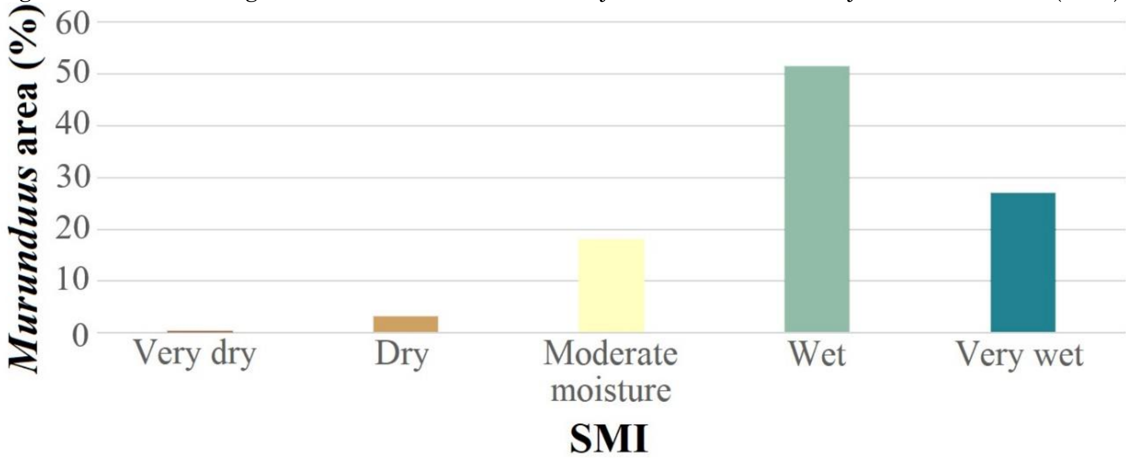
Figures 9 (SMI map) and 10 (graph of the percentage of the total area of *murundus* fields by SMI classes) reinforce the indications of Figures 10 and 11, that is, *murundus* fields predominate on wet soils, decreasing in frequency towards drier environments or very wet environments.

Figure 9 - SMI map.



Source: The authors (2023).

Figure 10 - Percentage of the total area covered by *murundus* fields by moisture class (SMI).



Source: The authors (2023).

DISCUSSION

Among the geological units of Southwestern Goiás, the areas of Alluvial Deposits (river terraces and floodplains) seem to best combine the main conditions for the occurrence of *murundus* fields: i) low slope (92.98% of flat and gently undulating relief); and ii) imperfectly drained soils (NDWI from 0.4 to 0.6 and Wet class for the SMI). Therefore, the floodplain and terrace areas are the most conducive to the development of these microreliefs in the studied area. In the other geological units, *murundus* fields occur associated with depressions and top ponds, drainage headwaters, and upstream part of hydromorphic channels, especially *veredas* (palm swamps). For their occurrence, in these cases, the presence of areas of flat to gently undulating relief, low density of the surface drainage network, and the possibility of accumulation or exfiltration of water in some parts of the landscape are necessary.

The Cachoeirinha Formation and Detritus-lateritic Covers are recent geological units (Neogene), associated with remnants of still poorly dissected flattening surfaces. For this reason, they have low slope, low drainage density, and generally thick and porous surface formations, thus being conducive to the occurrence of wetlands and *murundus* fields associated with them.

For the oldest geological units (Cretaceous and earlier), the slope of the relief and drainage density seem to have a direct relationship with the dominant lithology: where sandstones predominate, flatter reliefs, lower drainage density, greater infiltration capacity (Christofoletti, 1981) are more common and, thus, greater presence of wetlands and *murundus* fields can be observed. Where finer-grained rocks (pelites) predominate, there is a tendency for less flat reliefs, higher drainage density, greater surface runoff (Christofoletti, 1981) and, thus, fewer wetlands and *murundus* fields.

In the case of basalts, the greater permeability guaranteed by the fracture network, the presence of sandy intertraps (Reis *et al.*, 2014), and the thick and porous surface formations, in association with the predominantly flat relief, may explain the low drainage density and the development of wetlands and *murundus* fields. The presence of permeable strata overlapped with poorly permeable strata within the regolith of sedimentary geological units may also contribute to the appearance of hydromorphic areas (Moreira *et al.*, 2023) and to the development of *murundus* fields.

Lima and Corrêa (2021), in their study in the Federal District, found that *murundus* fields occur more frequently on quartzite-type rocks, on detritus-lateritic covers, and on colluvial-alluvial deposits. Considering that no quartzite rocks are found in the Paraná Sedimentary Basin, these results are in line with ours. Regarding the slope of the relief, Lima and Corrêa (2021) indicated that the 2–10% range is the one with the highest occurrence of *murundus* fields, a result also in line with ours, which pointed out the range of 0 to 8% as the most frequent. These authors also found that the *murundus* fields predominate over soils of the Plinthosol type and indiscriminate hydromorphic soils, and preferentially occupy the Contagem-Rodeador pediplain, located about 1,200 m high, showing their association with wetlands and with the remnants of old planation surfaces, still little addressed.

CONCLUSION

Murundus fields, as special components of the *Cerrado* wetlands, have an important environmental role. Despite this, because they are located on the border between *Cerrado* wetlands and well-drained soils, they have been strongly impacted by the expansion of agriculture. *Murundus* fields should be protected by environmental legislation and the scientific knowledge on them should be deepened, especially in the context of water crisis in the central region of Brazil.

This study allowed us to discuss the relationships between variables of the physical environment and the occurrence of *murundus* fields. Regarding the geological units of the Paraná Sedimentary Basin, in the Southwest of Goiás, there was a greater occurrence of *murundus* fields in Alluvial Deposits, the Cachoeirinha Formation, Detritus-lateritic Covers, the Serra Geral and Vale do Rio do Peixe Formations, and the Aquidauana Group. It was observed that, for the geological units studied, the slope of the relief, the density of the drainage network, and the predominant presence of sandstones or basalts, are determining factors for the presence of wetlands and *murundus* fields.

Concerning the relief aspect, it was possible to identify that *murundus* fields predominate in areas with low slopes, from 0 to 8% (flat to gently undulating), and low drainage density (<62.27 km/km^2). These areas are more conducive to the infiltration of precipitated waters and the supply of aquifers, whose waters can exfiltrate in specific parts of the landscape, creating supersaturated environments with hydromorphic soils. Geological units where rocks of greater granulometry predominate (sandstones, for example) present more favorable conditions for the development of *murundus* fields.

By the NDWI and SMI analysis, it was shown that the *murundus* fields of the studied area occur in wet soils, that is, in a moisture range between moderate moist and very wet environments. This is in accordance with their distribution in the landscape on a local scale, where they preferentially occupy the edge of wetlands, being located in the strip that separates well-drained soils from the saturated soils of the more central zones of these areas.

Murundus fields are greatly complex environments. This study presented correlations between their occurrence and some characteristics of the natural environment, with emphasis on geological and geomorphological aspects. For this, geological databases and information extracted from remote sensing products were used, enabling regional resolution analysis. Studies at a more detailed level or with better resolution products, and including other natural variables, may bring new elements to the understanding of the spatial distribution of *murundus* fields on a regional scale.

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AUTHOR CONTRIBUTION

Amanda Morais Malheiro and Veronica Natalia Boeira participated, as interns, in the mapping of the remaining murundus fields through the cooperation project between SEMAD (Secretaria de Meio Ambiente do Estado de Goiás) and LAPIG (Laboratório de Processamento de Imagens e Geoprocessamento) from UFG. As authors, they helped organize the databases, prepare thematic maps of natural elements, construct indices based on remote sensing products and cross-reference data from the natural environment with the occurrence of murundus fields. They also helped with the interpretation of graphic and cartographic products and with the writing of the article.

The author Guilherme Taitson Bueno was a technical consultant for the specific project of mapping the remnants of murundus fields, developed in partnership between SEMAD-GO and LAPIG-UFG and was the research advisor for the first authors, the starting point for this article. Assisted in the general conception of the article (scientific question, hypotheses), in proposing the methodological path and converted the interpretations of correlations and graphic and cartographic products obtained, based on theoretical knowledge about the relationships between covered areas, soils, relief and lithology. Assisted in the general writing of the article.

The author José Roberto Amaro Mantovani was co-supervisor of the first authors. He was responsible for the methodological and technical conception of the information processing, remote sensing and geoprocessing part. He carried out the qualification and technical training of the first two authors. He assisted in the interpretation of graphic and cartographic products and refined the products according to the general conception of the research. He helped with writing the article, especially in the methodological section.