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Analysis of Potential for Linear Erosion in the *Cerrado* Biome Using Morphopedology

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ABSTRACT: The *Cerrado* is a vegetation complex with a wide variety of phytophysiognomies, and sustainable management is essential for maintaining biodiversity. Morphopedology is a tool that can assist in developing plans for control of soil and land use, especially in evaluating the potential of soil erosion processes. This technique allows landscape units considered “homogeneous” to be distinguished, as a result of interaction between physiographic conditions. The aim of this study was to evaluate potential for erosion in São Miguel do Araguaia, state of Goiás, Brazil, through definition of morphopedological compartments (MPC), on the assumption that soil use has increased erosion. Landscape units were identified through use of geology overlay, hypsometry, slope, geomorphology, soil, and land use. The map information on a 1:100,000 scale was refined, the base of which was available in the Geographic Information System of Goiás. The morphopedological approach enabled identification of five MPC. Predominant soil classes in São Miguel do Araguaia (with matching categories) are *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids), *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox), *Gleissolos Háplicos Tb Distróficos* (Typic Endoaquents), and *Neossolos Quartzarênicos Órticos* (Typic Quartzipsamments). Generally, every class of soil has some type of limitation that may cause erosion to different degrees. The most dissected areas are associated with lateritic covers, which suggests the importance of these features on topographical formation. The results of analysis of erosion susceptibility and linear erosion potential suggest low risk of erosion, even considering human activities, especially cattle ranching.

Keywords: erosivity, erodibility, pedology, geomorphology, soil science.

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INTRODUCTION

The *Cerrado* (broadly, Brazilian tropical savanna) is Brazil's second largest biome in area, occupying 2,000,000 km^2, or 23 % of the country's territory (Ribeiro and Walter, 2008). This biome has a vegetation complex with a wide diversity of phytophysiognomies, including forests, bushland, and fields, divided into several subtypes (Ribeiro and Walter, 2008). Encompassing the entire state of Goiás, the *Cerrado* has been degradated to various degrees, mainly from agricultural expansion, resulting in the loss of native vegetation.

Goiás is the state with the lowest remaining percentage of its original physiognomy of the *Cerrado* biome (Sano et al., 2008). In the northwest of the state, livestock has gained prominence, and part of the native vegetation has cleared to make way for new pasture. In 2007, the municipality of São Miguel do Araguaia had a deforested area of approximately 924 ha, representing 15 % of its territory (Silva and Ferreira Júnior, 2010).

Erosion tends to accelerate after native vegetation has been removed, especially when favored by soil properties, soil relief, climate, and land use (Dotterweich, 2013; Wang et al., 2013). The erosive processes cause environmental changes that affect food production and the conservation of natural resources (Latrubesse et al., 2009; Coe et al., 2011); the productive potential of some regions may decrease as a result of increased intensity of erosion (Lohmann and Santos, 2005).

Erosion varies depending on time and space; some erosive events leave marks on the landscape, which have also been linked to changes in land use and climate (Dotterweich, 2013). These erosive processes are caused by both natural and anthropogenic factors (Wang et al., 2013; Comino et al., 2016; Mhazo et al., 2016). The former, especially rain, vegetation cover, soil relief, soil types, and the geological substrate, determine the intensity of the process over the long term. The most notable anthropogenic aspects are deforestation, the use of certain soil types, and land occupation (Latrubesse et al., 2009; Coe et al., 2011).

Direct measurement of soil erodibility requires long-term studies of erosion, which are expensive and time-consuming (Bonilla and Johnson, 2012). Morphopedology could enable assessment of the potential for water erosion, especially the potential for and susceptibility to linear erosion, assisting in the development of public policies aimed at agricultural production and natural resource preservation. Morphopedology is a tool that assists in the development of soil use and occupation control plans, particularly related to environmental preservation. The technique enables us to spatialize landscape units considered "homogeneous" by investigating the interaction among geological substrates, soil relief, and soil types (Castro and Salomão, 2000).

Some morphopedological studies on erosion have been based on the relationship between the geological substrate, soil relief, soil type, slope, and land use. Ribeiro and Salomão (2003) described the morphopedological compartments (MPC) of the upper Casca River, in the state of Mato Grosso, to assess the susceptibility of this area to linear erosion caused by the concentration of water flow lines, which may evolve into grooves or gullies. Lohmann and Santos (2005) sought to use morphopedological compartmentalization to assess the genesis and evolution of erosion in the Arroyo Guassupi watershed in the municipality of São Pedro do Sul (RS). Hermuche et al. (2009) used morphopedological compartmentalization to assess susceptibility to linear erosion in the municipality of Jataí (GO) and presented a proposal for land use planning employing this technique.

Based on the assumption that land use and occupation have affected linear erosion in *Cerrado* Biome, this study aims to use morphopedological compartmentalization to assess the erosion potential in the municipality of São Miguel do Araguaia in northwestern Goiás, Brazil.

MATERIAL AND METHODS

Description of the research site

The study was conducted in the municipality of São Miguel do Araguaia, in northwestern Goiás, Brazil, located in the Araguaia river basin (Figure 1). The municipality has an area of 614,7 26 ha and a population of 22,283; 79 % of whom are concentrated in the urban area, and an overall population density of 3.63 inhabitants per km^2 (IBGE, 2016). The regional climate is type Aw, characterized as tropical savanna (Köppen, 1948), with average annual rainfall of 1,640 mm and average annual temperature of 26.8 °C.

The vegetation is predominantly composed of grasslands associated with dense *Cerrado* and *murundus* (termite mounds) in addition to trees, with more than 50 % of coverage exceeding 5 m in height. The region's typical physiognomy is savanna, divided into closed savanna with *murundus*, and open savanna with *murundus* (Ribeiro and Walter, 2008).

Flat terrain represents 81 % of the territory in the municipality, and 19 % is rolling terrain; the municipality also encompasses the Araguaia Depression, a slightly rolling area typical of the Araguaia River plain. Altitude in the region ranges from 180 to 480 m, with the highest elevations located in the center of the research site.

The soil types *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox) represent 60 % of the area and are associated with the surface of the Lower Araguaia Group. *Plintossolos Pétricos Concrecionátios* (Petronodic Haplargids), followed by *Plintossolos Háplicos Alumínicos* (Plinthic Haplaquox), cover 38.6 % of the area and are associated with the Araguaia Formation. *Gleissolos Háplicos Distróficos* (Typic Endoaquents) are

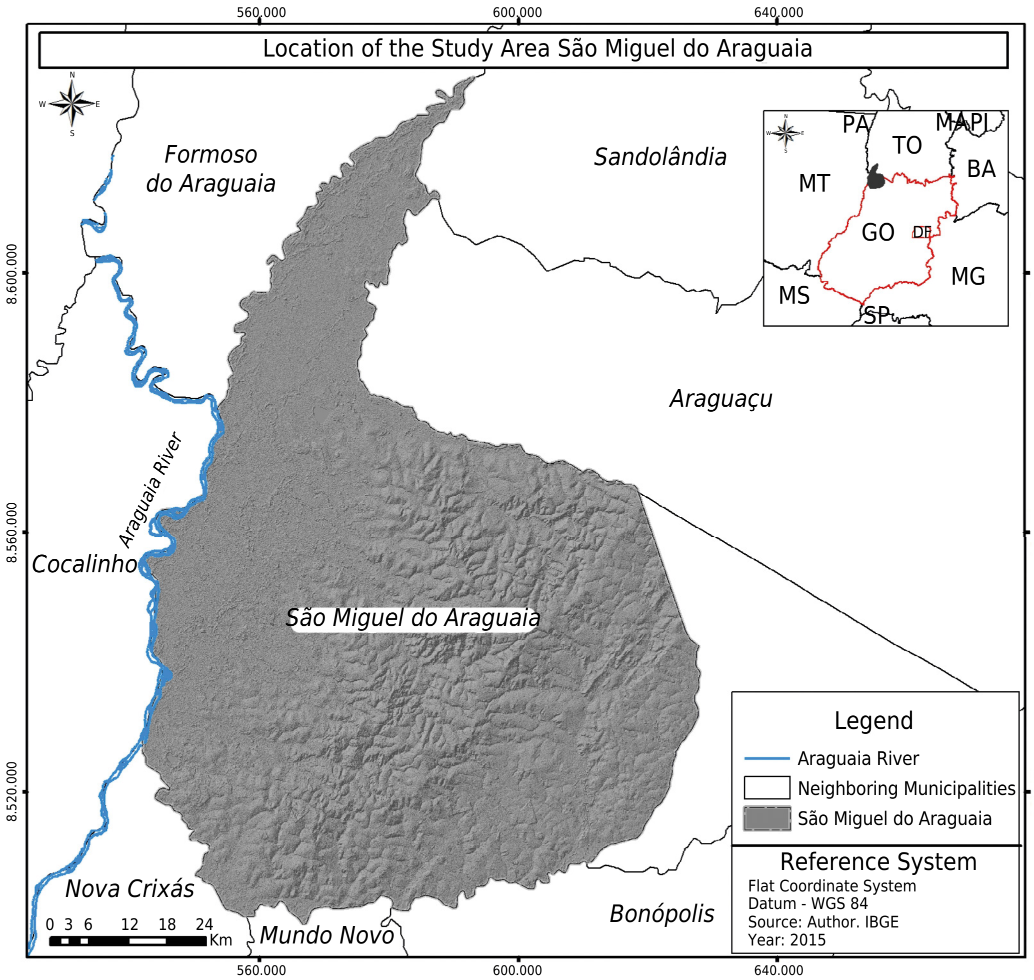

Figure 1. Location of the municipality of São Miguel do Araguaia, state of Goiás, Brazil.

associated with alluvial deposits and account for 0.9 % of the area, followed by *Neossolos Quartzarênicos Órticos* (Typic Quartzipsamments), which are located in the southeastern area of the municipality and make up 0.3 % of the total area (Table 1).

Geomorphological features are divided into three categories (Table 1). Areas associated with surface planing, with dissections ranging from very weak to average (Figure 2) and from 200 to 400 m altitude, occupy approximately 481,117 ha. The areas where sediments have been deposited (aggradation), associated with lower surfaces, were characterized by fluvial tracks, sediment banks, and meandering patterns and cover 123,600 ha. Finally, areas marked by the presence of folded structures forming hogbacks cover 830 ha.

The most common geological units are the Lower Araguaia Group (NPx), predominantly consisting of schist (57 %); the Araguaia - Facies fluvial deposits (Qag2), formed from clay, silt, and sand (28 %); alluvial deposits (Q2a) associated with areas of lower elevation, formed from deposits of sand and gravel (8 %); the plutonic complex of the Goiás volcanic arc - orthogneiss unit of the west of Goiás (NP1), which contains gneiss, tonalite, and granite (3 %); ferruginous lateritic detritus (N1d1), formed from agglomerations, laterites, clay, and sand (3 %); and the Agua Bonita formation (Sdab), formed from sandstone, conglomerate, and siltstone (1 %) (Brasil, 1981).

Methodological criteria of mapping

The mapping procedures were divided into two stages: the first consisted of describing the physiographic units of the municipality in order to determine the morphopedological

Table 1. Soil classes in the municipality of São Miguel do Araguaia, state of Goiás, Brazil

Unit	Order	Soil class		Area	
		Brazilian system of soil classification[(1)]	Soil taxonomy[(2)]		
				ha	%
FFc1	*Plintossolo*	*Plintossolos Pétricos Concrecionários*	Petronodic Haplargids	73,280	12.0
FFc2		*Plintossolos Pétricos Concrecionários*	Petronodic Haplargids	18,606	3.1
FXa1		*Plintossolos Háplicos Alumínicos*	Plinthic Haplaquox	33,148	5.4
FXa2		*Plintossolos Háplicos Alumínicos*	Plinthic Haplaquox	82,630	13.5
FXd		*Plintossolos Háplicos Alumínicos*	Plinthic Haplaquox	28,359	4.6
GXbd1	*Gleissolo*	*Gleissolos Háplicos Distróficos*	Typic Endoquents	1,787	0.3
GXbd2		*Gleissolos Háplicos Distróficos*	Typic Endoquents	3,939	0.6
LVAd1	*Latossolo*	*Latossolos Vermelho-Amarelos Distróficos*	Xanthic Hapludox	98,697	16.2
LVAd2		*Latossolos Vermelho-Amarelos Distróficos*	Xanthic Hapludox	267,407	43.8
RQo	*Neossolo*	*Neossolos Quartzarênicos Órticos*	Typic Quartzipsamments	2,122	0.3

[(1)] Santos et al. (2013); [(2)] Soil Survey Staff (2014).

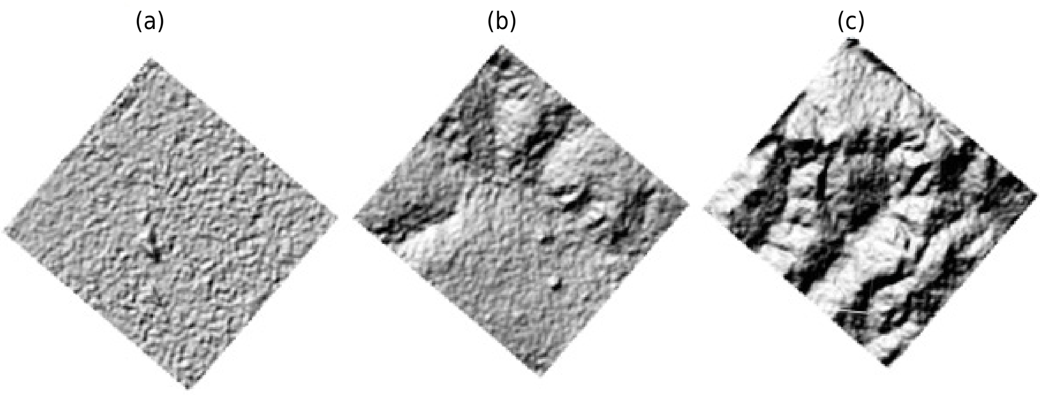

Figure 2. Texture aspects on shaded SRRM images (*shade-relief*), indicating the degree of dissection of the municipality of São Miguel do Araguaia, state of Goiás, Brazil. (a) Very weak dissection (mfr); (b) Weak dissection (fr); and (c) Medium dissection (m).

compartments, while the second assessed the potential for linear erosion based on the compartments established. These procedures are summarized in the flowchart shown in figure 3.

Morphopedological compartmentalization

Landscape units were identified through the overlaying of geology, hypsometry, slope, geomorphology, soils, and land use. The cartographic information was shown on a scale of 1:100,000, based on data from the Geographic Information System of Goiás (SIEG, 2015). Images from Landsat 8 OLI with orbit 223 and point 69 of 2015, available in the United States Geological Survey (USGS), were used. After images calibration and the reflectance values processing, the land use map was developed with segmentation, and classification was generated using the ENVI® 5 software.

The hypsometry and slope maps were drawn in ArcGIS® 10.1 software based on data from the Digital Ground Model (DGM) generated by the Shuttle Radar Relief Mission (SRRM), with resolution of 30 m, and made available by INPE (2015). The levels of dissection were determined by identifying other important features of soil relief, according to the IBGE (2009), with a few adaptations. The mapping units contained in each compartment were delineated with soil maps used as a database, and were developed and refined based on 13 control points (soil profiles), in addition to field observations and assessment of physiographic data.

The maps used as a database for compartmentalization, as well as the boundaries of each morphopedological compartment, are in figure 4. The map combination function of the Modelbuilder tool was used to superpose cartographic information and delineate each morphopedological compartment. Additionally, topographical profiles were plotted for each MPC to highlight the altimetry in greater scale, together with aspects related to soils and features of soil relief.

Assessment of susceptibility to linear erosion

The assessment of susceptibility to linear erosion was based on the method proposed by Salomão (1999), in which the degree of erodibility is generated according to each pedological unit, as described below: II - Weak: *Plintossolos Háplicos* (FXa1, FXa2, FXd) and *Gleissolos Háplicos* (GXbd1, GXbd2), corresponding to an area of 141,840 ha (24.4 % of the municipality); III - Moderate: *Plintossolos Pétricos* (FFc1) and *Latossolos Vermelho-Amarelos* (LVAd1, LVAd2), corresponding to an area of 418,612 ha (72.2 % of the municipality); IV - Strong: *Plintossolos Pétricos* (FFc2), corresponding to an area of

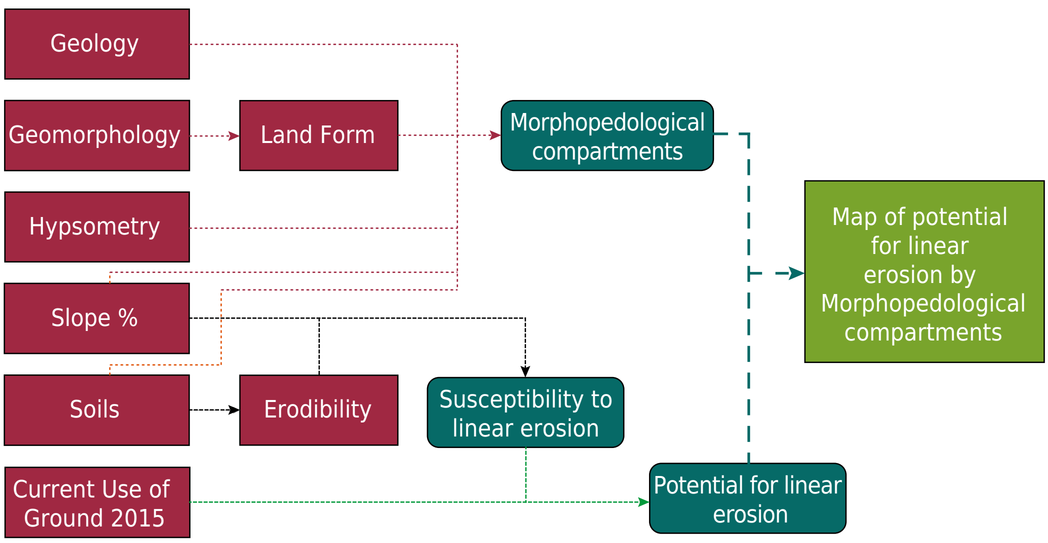

Figure 3. Flowchart of the cartographic procedures adopted to generate the map of linear erosion potential of the municipality of São Miguel do Araguaia, state of Goiás, Brazil.

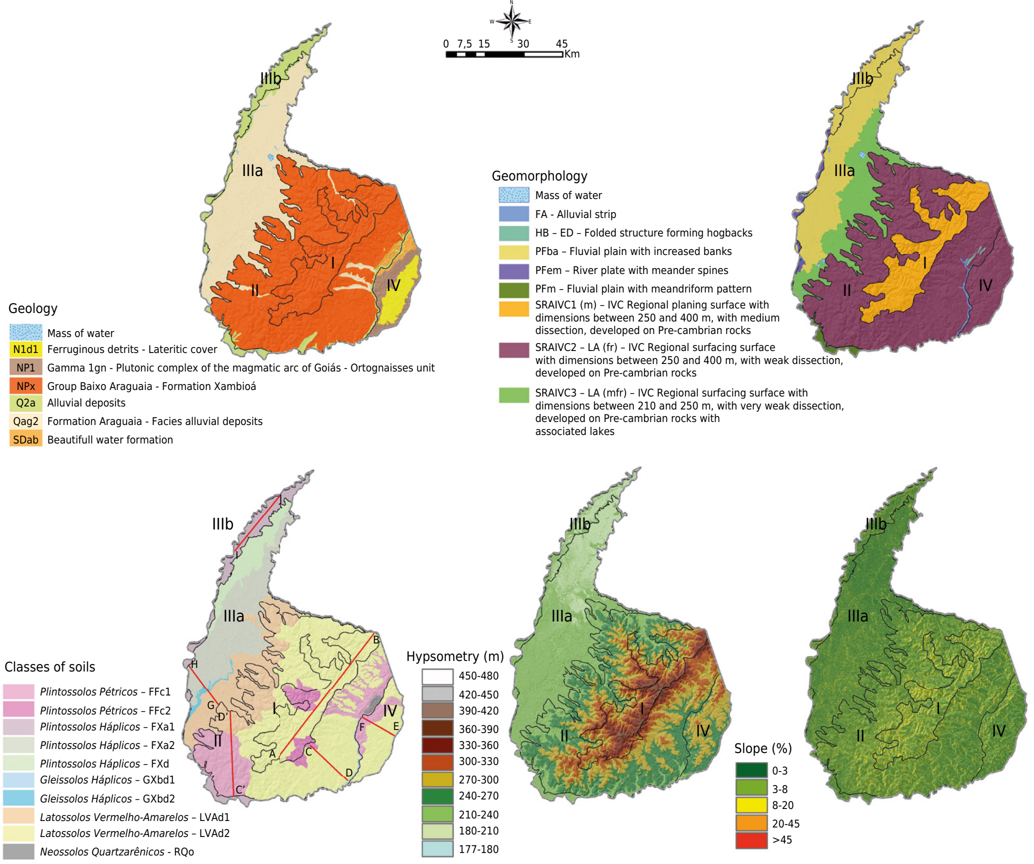

Figure 4. Physiographic maps (geology, geomorphology, soils, hypsometry, and slope) of the municipality of São Miguel do Araguaia, Goiás, Brazil.

17,647 ha (3.0 % of the municipality); and V - Very Strong: *Neossolos Litólicos* (RQo), corresponding to an area of 2,040 ha (0.4 % of the municipality).

The susceptibility map was generated using data on land slope, in which the susceptibility of land with 0 to 3 % slope was defined as I - Very Weak, representing 42.8 % of the municipality (263,310 ha); the susceptibility of land with 3 to 8 % slope was considered II - Weak, corresponding to 49.4 % of the municipality (303,853 ha); the susceptibility of land with 8 to 20 % slope was classified as III - Moderate, corresponding to 7.6 % of the municipality (46,884 ha); the susceptibility of land with 20 to 45 % slope was considered IV - Strong, corresponding to 0.1 % of the municipality (646 ha); and the susceptibility of land with >45 % slope was considered V - Very Strong, corresponding to 1 ha.

The classes of susceptibility to linear erosion were generated from the overlap of the erodibility and slope maps (Table 2). Class I indicates areas extremely susceptible to erosion; Class II corresponds to very susceptible areas; Class III corresponds to moderately susceptible areas; Class IV corresponds to slightly susceptible areas; and Class V corresponds to those areas with little or no susceptibility to erosion.

Current land use was divided into four categories based on potential for causing erosion (Salomão, 1999): I - High potential, II - Moderate potential, III - Low potential, and IV - No potential (Table 2). The potential for linear erosion was determined from the matrix of intersection between the classes of susceptibility and the categories of current land use.

RESULTS AND DISCUSSION

After identifying and delineating the landscape units from an integrated analysis of data collected from charts, satellite imagery, and field observations, five morphopedological compartments were established (Figure 5), as described below:

Table 2. Description of the geomorphologic units of the municipality of São Miguel do Araguaia, state of Goiás, Brazil

Unit	Category	Classification	Area	
			ha	%
HB-ED	Structural	HB-ED - Folded structure forming bulges	830	0.1
m_agua	Water mass	Water mass	2,808	0.5
FA	Aggregate	FA - Alluvial strip	2,399	0.4
PFba	Aggradation	PFba - Fluvial plain with raised banks	110,497	18.2
PFem	Aggregate	PFem - Fluvial plain with meander spirals	3,869	0.6
PFm	Aggregate	PFm - Fluvial plain with meander pattern	6,838	1.1
SRAIVC1 (m)	SRAIV	SRAIVC1 (m) - Surface planing IVC with elevation between 300 and 400 m, with moderate dissection, developed on pre-Cambrian rocks	80,960	13.3
SRAIVC2 (fr)	SRAIV	SRAIVC1 (m) - Surface planing IVC with elevation between 250 and 350 m, with weak dissection, developed on pre-Cambrian rocks	325,555	53.5
SRAIVC3-LA (mfr)	SRAIV	SRAIVC3-LA (mfr) - Regional surface planing IVC with elevation between 200 and 250 m, with very weak dissection, developed on pre-Cambrian rocks with associated lake systems	74,602	12.3

Source: Modified from Goiás (2005).

MPC-I: top of plateau, with a moderately dissected surface associated with lateritic cover and the presence of *Latossolos Vermelhos Distróficos* (Rhodic Haplustox) and *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids). This MPC has an area of 80,960 ha, representing 13.3 % of the territory of the municipality;

MPC-II: A slightly to very slightly dissected surface, associated with unconsolidated ferruginous features with the presence of *Latossolos Vermelhos Distróficos* (Rhodic Haplustox) and *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox). This MPC has an area of 287,481 ha, corresponding to 47.2 % of the territory of the municipality;

MPC-IIIa: Area of flat surface, part of the Araguaia River plain, associated with alluvial deposits, in which abandoned meanders are common, with the presence of *Neossolos Quartzarênicos Órticos* (Typic Quartzipsamments) and *Plintossolos Háplicos Alumínicos* (Plinthic Haplaquox). This MPC has an area of 173,481 ha, corresponding to 28.5 % of the territory of the municipality;

MPC-IIIb: Area of flat surface, associated with Holocene sediments, with the presence of *Plintossolos Háplicos Alumínicos* (Plinthic Haplaquox), *Gleissolos Háplicos Tb Distróficos* (Typic Endoquents), *Argissolos Vermelho-Amarelos Distróficos* (Xanthic Kandiudox), and *Latossolos Vermelhos Distróficos* (Rhodic Haplustox). This MPC has an area of 25,036 ha, corresponding to 4.1 % of the territory of the municipality; and

MPC-IV: Area of slightly dissected surface, associated with lateritic cover, with the presence of *Latossolo Vermelho Distrófico plintossólico* (Plinthic Hapludox), *Plintossolo Pétrico Concrecionário* (Petronodic Haplargids), and *Gleissolo Háplico Tb Distrófico* (Typic Endoquents). This MPC has an area of 41,794 ha, corresponding to 6.9 % of the territory of the municipality.

MPC-II, an area with slight dissection, represents the largest portion of the research site, followed by MPC-IIIa, which has a flat surface, in an area where the water table level oscillates due to its proximity to the Araguaia River. The degree of dissection of soil relief is associated with the development of thalwegs, which can be linked to environmental changes such as Pleistocene glacio-eustatic oscillations and tectonic effects (Casseti, 2005).

Topographical profiles were plotted in the most representative areas of each compartment in order to demonstrate the occurrence of pedological units along a transect. Thus, MPC-I (A-B) corresponds to the top area (Figure 6), with the highest elevation in the municipality and predominance of *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), followed by *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids) alternating through the landscape, and includes other types associated with the mapping units. In general, this

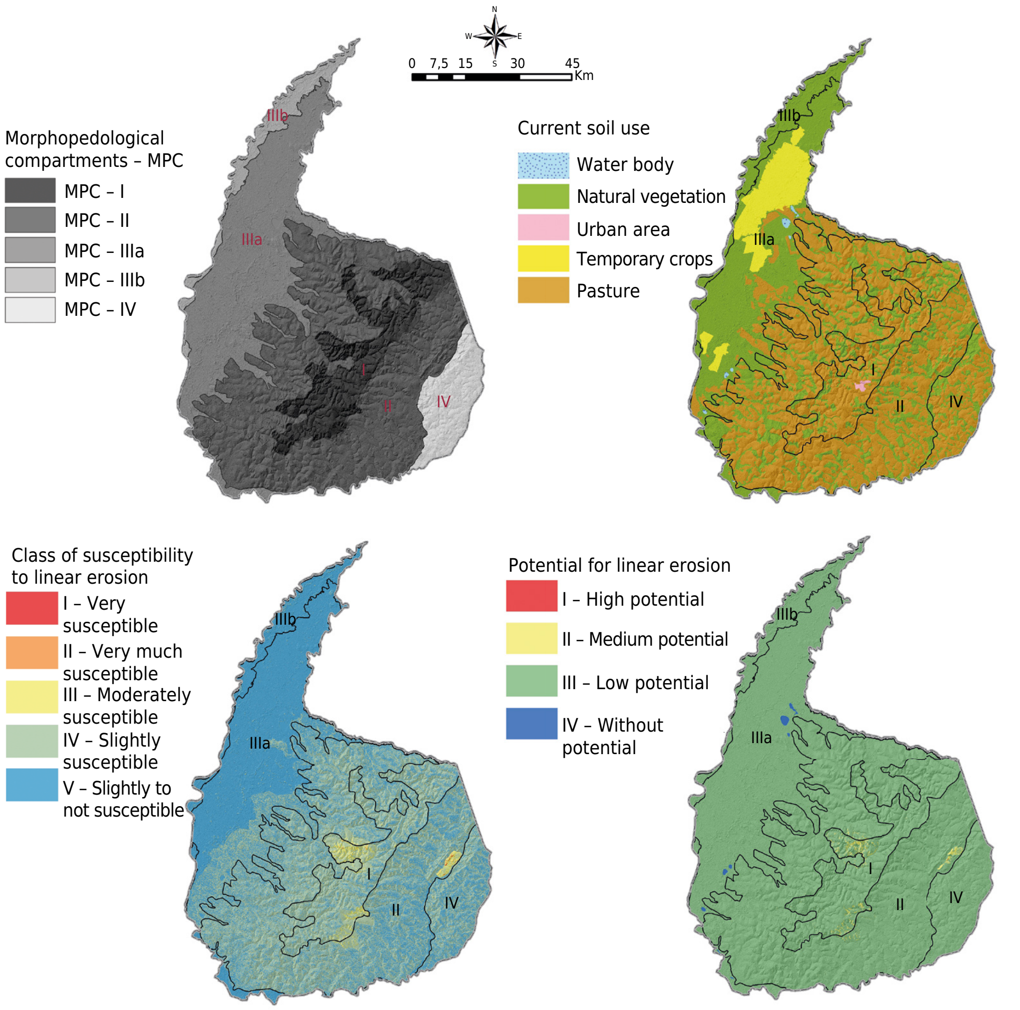

Figure 5. Morphopedological compartment maps, current use, susceptibility to erosion, and erosion potential in the municipality of São Miguel do Araguaia, state of Goiás, Brazil.

region has average dissection, possibly at the expense of the structural control provided by the laterite cover that influences the morphogenesis of the landscape (Bigarella et al., 1996). The dissection of soil relief is shaped by tectonic effects, possibly by positive epeirogeny, creating a steeper slope and increasing the intensity of erosion (Casseti, 2005). The tectonic effect can be confirmed by marks found on exposed rocks in the most dissected areas of the municipality, and especially by the presence of metamorphosed rocks (Brasil, 1981).

The degree of slope observed in the most dissected areas is a factor considered in predictive mathematical modeling of soil erosion, such as the Universal Soil Loss Equation (USLE), which justifies of use od degree of slope as evidence of erosion (Wischmeier and Smith, 1978; Moreti et al., 2003).

Although *Latossolos* (Oxisols) are predominant in MPC-I (A-B), they have hardened ferruginous concretions (petroplinthite), characteristics associated with a highly porous matrix with a granular structure, resulting in greater infiltration of water. However, the vertical flow is stopped when contact with the laterite layer or lithoplinthic horizon; thus, more pronounced slopes can result in runoff, causing particle drag (erosive processes). This occurs is also observed in *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids), although they provide a greater volume of petroplinthite, associated with other types of coarse fractions greater than 2 mm (fragments of quartz, associated with other minerals). The restriction of water infiltration occurs especially in the presence of the F horizon (Santos et al., 2013) at various positions in the soil profile, and this horizon controls the water flow, depending on the depth at which it occurs.

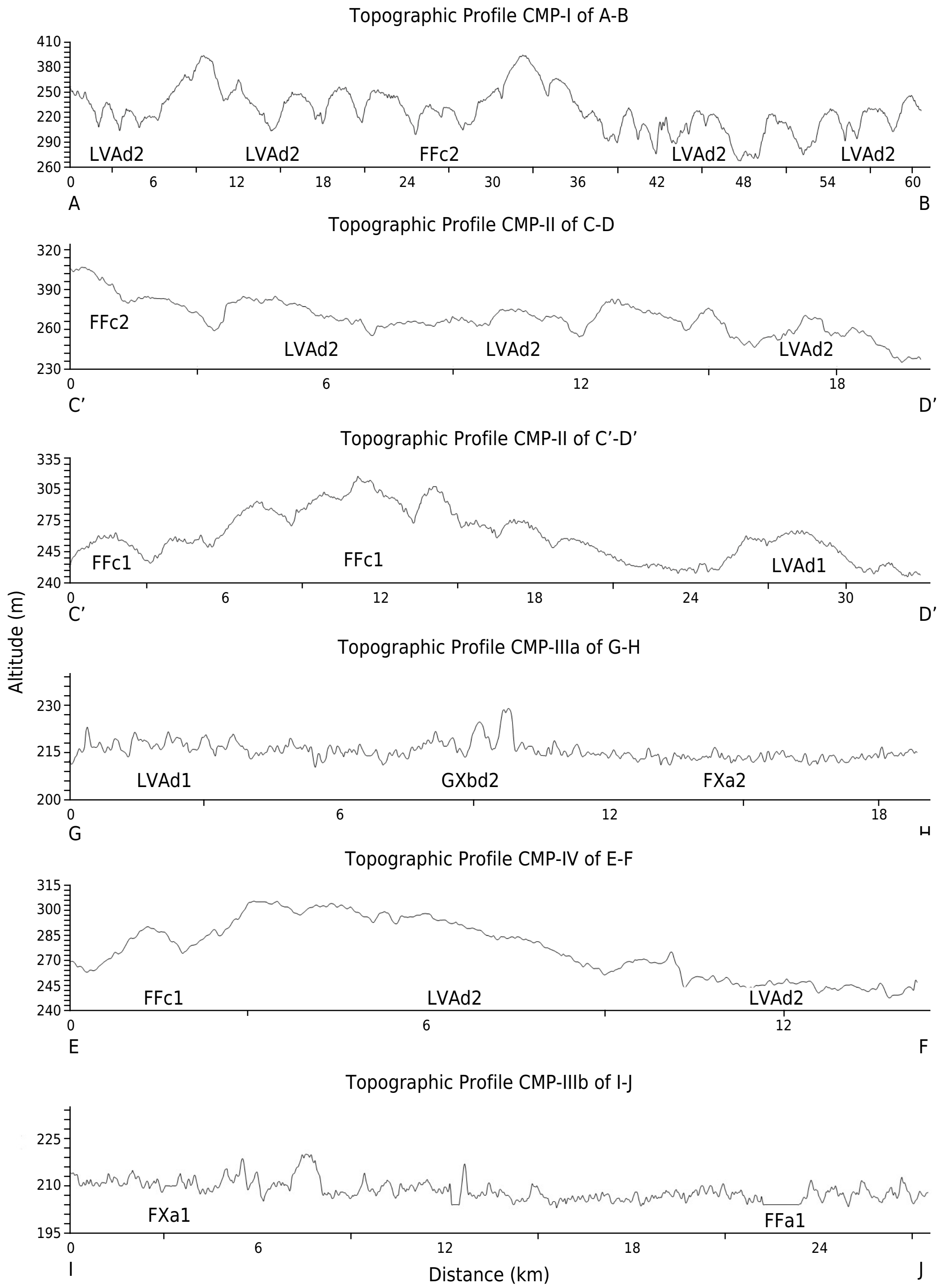

Figure 6. Representative topographic profiles with soil sequences from the municipality of São Miguel do Araguaia, state of Goiás, Brazil.

In MPC-II (C-D; C’-D’), the most common soils types are *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids), followed by *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), associated with laterite cover and a moderate process of landscape dissection (Figure 6). The physio-hydric pattern of this compartment is analogous to that of MPC-I; however, the slope becomes the main aggravating factor in the erosive process, which corroborates the greater degree of dissection observed in this compartment. This shows that the erosive process is more pronounced here than in MPC-I, despite the presence of a more stable cover.

MPC-IIIa (G-H) is predominantly characterized by *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox), and these areas have the lowest elevation in the municipality (Figure 6).

Despite being located at the same elevation, MPC-IIIb (I-J) may be more influenced by the water flow and sediment from the Araguaia River. These areas of lower elevation have low hydraulic conductivity; in the case of *Plintossolos Háplicos* (Plinthic Haplaquox), the soil texture with predominance of silt and clay fractions leads to this result, although the slope of the terrain reduces the surface runoff, reducing particle drag.

In MPC-IIIb (I-J), the most common soil types are *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox), associated with dystrophic *Gleissolos Háplicos Tb Distróficos plintossólicos* (Plinthic Haplaquox) (Figure 6). Both include marked ferruginous and manganous features from oscillation of the water table, along with a source of Fe and Mn in the soil solution. These features result from the segregation, mobilization, transport, and concentration of Fe and Mn ions and compounds (Coelho et al., 2001). The class of *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox) has characteristics that resemble those in MPC-IIIa, but they differ due to the juvenility of the source material. The meander features are clearly visible on the satellite image, in contrast to MPC-IIIa.

The *Gleissolos* (Entisols) class located in MPC-IIIb was subjected to hydromorphism and has a variable texture, primarily formed in this case by alluvial sediments, due to the proximity of the Araguaia River. These soils vary from poorly to very poorly drained, and may have plinthic features within a 1.00 m depth, or a plinthic horizon under the control section (Santos et al., 2013).

MPC-IV contains *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), followed by *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids) in the most dissected areas (Figure 6). This compartment has characteristics similar to MPC-II, especially with regards to its physical properties, which shaped the hydraulic dynamic. Additionally, the *Plintossolos* (Oxisols) with these characteristics have severe limitations in use, with low water storage capacity (Coelho et al., 2012). In their assessment of the erosivity and erodibility of soils in the region of Lavras (MG), Silva et al. (2009) reported that although the *Latossolos Vermelhos* (Rhodic Haplustox) have greater permeability, there is little cohesion among the aggregates, resulting in high erosivity.

MPC-I consists mainly of mapping unit LVAd2, which contains *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox) with clayey texture, located in soil relief areas that range from flat to slightly rolling, along with *Argissolos Vermelho-Amarelo Distróficos* (Xanthis Kandiudox) with low-activity clay located in soil relief areas that range from flat to slightly rolling, and *Latossolos Vermelho Distróficos* (Rhodic Haplustox) with clayey texture located in soil relief areas ranging from flat to slightly rolling. Next in order of importance is unit FFc2, which contains *Plintossolos Pétrico Concrecionário* (Petronodic Haplargids) of a dystrophic nature, with low activity clay and medium texture, located in relief areas from slightly rolling to rolling, and *Latossolo Vermelho-Amarelo Distrófico petroplíntico* (Petronodic Haplargids) of medium texture in a slightly rolling relief, with inclusions in *Latossolos Vermelho-Amarelo Distrófico petroplíntico* (Petronodic Haplargids) with a clayey texture. In part of unit FFc1, *Plintossolo Pétrico Concrecionário típico* (Petronodic Haplargids) was observed with low-activity clay of medium texture. In addition, *Latossolo Vermelho-Amarelo Distrófico petroplíntico* (Petronodic Haplargids) of medium texture and *Neossolos Litólico Distróficos* (Typic Udorthents) with medium texture were found in a soil relief ranging from slightly rolling to rolling, along with *Cambissolo Háplico Tb Distrófico petroplíntico* (Petronodic Haplargids), with medium-texture, low-activity clay.

MPC-II is composed primarily of mapping units LVAd2 and FFc1, both described previously, plus unit LVAd1, characterized by *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), with medium texture, and *Neossolos Litólicos Distróficos* (Typic Udorthents) in slightly rolling soil relief. To a lesser extent, it includes units FFc2, RQo, and GXbd1, predominantly consisting of *Plintossolo Pétrico Concrecionário típico* (Petronodic Haplargids), *Neossolo Quartzarênico Órtico* (Typic Quartzipsamments), and *Gleissolo Háplico Tb Distrófico plintossólico* (Plinthic Haplaquox).

MPC-IIIa consists primarily of the mapping unit FXa2, characterized by *Plintossolos Háplicos Alumínico* (Plinthic Haplaquox), with low activity clay and clayey texture, followed by *Plintossolo Argilúvico Alumínico abrúptico* (Kandic Plinthaquults), with low activity clay and medium/clayey texture, and *Planossolo Háplico Alumínico plintossólico* (Plinthaquic Kandiustox), with low activity clay and medium/clayey texture. This unit is associated with flat soil relief, including *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox), with low activity clay, medium/clayey texture, and *Latossolo Amarelo Distrófico plintossólico* (Plinthic Acraquox), with clayey texture. Additionally, unit LVAd1 makes up a large portion of MPC-IIIa, composed of *Latossolos Vermelho-Amarelo Distróficos* (Xanthis Hapludox), followed by unit FXd, characterized by *Plintossolos Háplico Distróficos* (Plinthic Haplaquox), with low activity clay, medium/clayey texture. This unit is associated with *Latossolo Vermelho-Amarelo Distrófico plintossólico* (Plinthic Acraquox), with clayey texture and Gleissolos Háplicos Tb Distróficos (Typic Endoquents), with low activity clay and clayey texture, on flat soil relief. To a lesser extent, there is unit GXbd1, composed of *Gleissolo Háplico Tb Distrófico plintossólico* (Plinthic Haplaquox) and *Plintossolo Háplico Distrófico típico* (Plinthic Haplaquox).

MPC-IIIb is composed of unit FXa1, characterized by *Plintossolo Háplico Alumínico típico* (Plinthic Haplaquox) with low activity clay, clayey texture, *Plintossolo Argilúvico Alumínico abrúptico* (Kandic Plinthaquults), with low activity clay, medium/clayey texture, and *Planossolo Háplico Alumínico* with plinthic features (Plinthaquic Kandiustox), low activity clay, medium/clayey texture, on flat soil relief, where occur inclusions of *Plintossolos Argilúvico Distróficos* (Kandic Plinthaquults), with low activity clay, medium/clayey texture, and *Latossolo Amarelo Distrófico plintossólico* (Plinthic Acraquox) with clayey texture. The other mapping units that make up this compartment are FXd, GXbd2, FXa2 and LVAd1, all already described.

MPC-IV is composed of the mapping units LVAd2, with predominance of *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), followed by the units FFc1 and GXbd1, predominantly consisting of *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids) and *Gleissolos Háplicos Tb Distróficos* (Typic Endoquents).

With regards to susceptibility to erosion, the areas of the municipality of São Miguel do Araguaia do not have aggravating factors, and are mostly classified as low to moderately susceptible (Figure 5). It should be noted that the scale of this study may not include important data when creating the model, considering that the greater the scale used in data input (physiographic constraints), the greater the level of detail, especially with regards to the accuracy of assessment. These limitations are offset here by field observations and prior knowledge of the research site.

An area corresponding to approximately 0.3 % of the northeastern territory of the municipality was classified as extremely susceptible to erosion, coinciding with the soil type *Neossolos Quartzarênicos* (Typic Quartzipsamments). These soils are mainly composed of the sand fraction (Santos et al., 2013), which confers greater drag potential due to low cohesion among the particles. High risk of degradation can be inferred in this soil type due to its fragility, which may be accelerated by the removal of natural vegetation, especially arising from irregular agricultural practices or excessive trampling by cattle (Silva et al., 2014). In general, soil texture is an essential element in predicting its erosive potential (Bonilla and Johnson, 2012).

The yellow-shaded areas on the susceptibility map represent moderate susceptibility to linear erosion, almost always associated with the presence of petroplinthic soils and laterite cover. Some *Plintossolos* (Oxisols) have a subsurface horizon of type B texture (Bt), mostly due to the pedogenetic processes of clay eluviation and illuviation (Nascimento et al., 2013; 2015). This reduces the subsurface hydraulic conductivity and increases surface runoff, depending on the slope of the terrain and the rainfall. Both aspects are considered in the Universal Soil Loss Equation (Wischmeier and Smith, 1978), a mathematical model which combines factors affecting soil erosion to predict soil loss, expressed in tons per hectare per year.

With regards to soil use (Figure 5), most of the municipality is occupied by planted pastures, particularly *Urochloa brizantha* (Table 3), with different levels of pasture degradation due to the high intensity of grazing. The areas covered by native species are grassland, almost always associated with *murundus* (termite mounds); they have been widely used for animal husbandry. Deforestation can change the hydrological cycle, geomorphological features, and biochemical flows, reducing evapotranspiration on the land surface and increasing surface runoff, soil erosion, and sediment flows (Coe et al., 2011).

A portion of the municipality has low potential for linear erosion (Figure 5). However, 50 % of the municipality is occupied by extensive ranching, which may contribute to the processes that trigger linear erosion. It is possible to establish appropriate soil use and management through awareness of the potential for and susceptibility to linear erosion, especially through use of conservation practices that mitigate water erosion (Moreti et al., 2003). Given the predominant activity in the research site, the possibility of using integrated production systems to maintain soil quality, reduce soil loss, and minimize human impact on this portion of the Araguaia River basin should be considered.

The physiographic data and results of this analysis of erosive potential in the *Cerrado* biome are summarized and presented in table 4.

Table 3. Degree of erodibility by pedological units of the municipality of São Miguel do Araguaia, Goiás, Brazil

Degree of erodibility	Pedological units	Area	
		ha	%
II - Weak	*Plintossolos Háplicos* (FXa1, FXa2, FXd) *Gleissolos Háplicos* (GXbd1, GXbd2)	141,840	24.4
III - Moderate	*Plintossolos Pétricos* (FFc1) *Latossolos Vermelho-Amarelos* (LVAd1, LVAd2)	418,612	72.2
IV - Strong	*Plintossolos Pétricos* (FFc2)	17,647	3.0
V - Very strong	*Neossolos Litólicos* (RQo)	2,040	0.4

Source: Adapted from Salomão (1999).

Table 4. Degree of susceptibility according to classes of slope in the municipality of São Miguel do Araguaia, state of Goiás, Brazil

Slope	Degree of susceptibility	Area	
		ha	%
0-3	I - Very weak	263,310	42.8
3-8	II - Weak	303,853	49.4
8-20	III - Moderate	46,884	7.6
20-45	IV - Strong	646	0.1
>45	V - Very strong	1	0.0

Source: Adapted from Salomão (1999).

Table 5. Classes of susceptibility to linear erosion in the municipality of São Miguel do Araguaia, state of Goiás, Brazil

Class	Slope				
	0-3	3-8	8-20	20-45	>45
			%		
I	n/a	n/a	n/a	n/a	n/a
II	V	V	IV	IV	III
III	V	IV	IV	III	n/a
IV	IV	IV	III	II	n/a
V	IV	III	II	I	n/a

Source: Adapted from Salomão (1999).

Table 6. Classes of potential for linear erosion in the municipality of São Miguel do Araguaia, state of Goiás, Brazil

Susceptibility	Temporary cultivation	Pasture	Area of natural vegetation	Water
	Class I	Class II	Class III	Class IV
I	n/a	I	II	n/a
II	n/a	II	II	n/a
III	II	II	III	IV
IV	III	III	III	IV
V	III	III	III	IV

Source: Adapted from Salomão (1999).

Table 7. Criteria for defining the morphopedological compartments (MPC)

MPC	Criteria for definition	Area	
		ha	%
MPC-1	Top of plateau, moderately dissected surface, associated with lateritic cover and the presence of dystrophic Red Latosols and concretionary Petric Plinthosols.	80,960	13.3
MPC-II	A slightly to very slightly dissected surface, associated with unconsolidated ferruginous features with the presence of dystrophic Red Latosols (Rhodic Haplustox) and dystrophic Haplic Plinthosols (Plinthic Haplaquox).	287,481	47.2
MPC-IIIa	Area of flat surface, part of the Araguaia River plain, associated with alluvial deposits, in which abandoned meanders are common, with the presence of Orthic Quartzarenite Neosols and Aluminium Haplic Plinthosols.	173,481	28.5
MPC-IIIb	Area of flat surface, associated with Holocene sediments, with the presence of Aluminium Haplic Plinthosols, Dystrophic Haplic Tb Gleysols, Dystrophic Red-Yellow Argisols, and Dystrophic Red Latosols.	25,036	4.1
MPC-IV	Surface area of slight dissection associated with lateritic cover with the occurrence of Dystrophic Plinthosolic Red Latosol, concretionary Petric Plinthosol, and Dystrophic Tb Haplic Gleysol.	41,794	6.9

Table 8. Description of the types of soil present in the municipality of São Miguel do Araguaia, state of Goiás, Brazil

Type of use	Description	Area	
		ha	%
Bodies of water	Rivers and canals, naturally closed bodies of water without movement, and artificial reservoirs.	1,203	0.2
Natural vegetation	Physiognomy of the natural vegetation, divided into tree-size (forests), shrubs, and grassland. Areas of closed Cerrado, riparian, and forest vegetation.	272,121	44.3
Urban area	Area of continuous construction and urban infrastructure.	670	0.1
Temporary cultivation	Includes areas of agricultural cultivation.	37,447	6.1
Pasture	Includes areas of planted pastures such as *Brachiaria Brizantha* and *Andropogom.*	303,250	49.3

In short, morphopedology is a technique that can contribute to interpretation of processes involving pedogenesis and morphogenesis when data is scarce, as in Brazil, especially with regards to erosion control and prevention, which could assist in development of public policies that target systems of agricultural production and natural resource preservation. The *Cerrado* biome is a complex system, particularly in the Araguaia River Basin, which has been the site of intense geomorphological changes resulting from anthropogenic action in recent decades. This anthropogenic action has triggered a rapid fluvial response and caused great environmental disruption (Latrubesse et al., 2009).

Table 9. Overview of the physiographic features and summary of the results of analysis of erosive potential in the Cerrado biome

		MPC-1[1]	MPC-II	MPC-IIIa	MPC-IIIb	MPC-IV
Area	ha (%)	80,395 (13.3)	285,351 (47.3)	171,350 (28.4)	24,520 (4.1)	41,544 (6.9)
Soil	Class	*Latossolos* 67,200 ha (84 %), *Plintossolos* 12,634 ha (16 %)	*Latossolos* 215,786 ha (76 %), *Plintossolos* 65,700 ha (23 %), *Neossolos* 2,086 ha (0.7 %)	*Plintossolos* 117,687 ha (69 %), *Latossolos* 49,900 ha (29 %), *Gleissolos* 3,691 ha (2.2 %)	*Plintossolos* 23,800 ha (98 %)	*Latossolos* 30,966 ha (75 %), *Plintossolos* 10,482 ha (25 %)
Geology	Lithology	Ferruginous shale quartzite, graphite schist, marble, meta to conglomerate, meta-arkose 79,815 ha (99 %)	Ferruginous shale quartzite, graphite schist, marble, meta paraconglomerate, meta-arkose 79,815 ha (99 %)	Deposits of clay, silt, and sand 156,413 ha (92 %)	Deposits of sand, gravel, silt, and clay 23,336 ha (98 %)	Gneiss, tonalite, Granite 18,526 ha (45 %), Agglomerate, Laterite, Clay, Sand-deposits of silt, sand, and clay 17,143 ha (41 %)
	Group - formation	Lower Araguaia Group 79,815 ha (99 %)	Lower Araguaia Group 79,815 ha (99 %)	Araguaia Formation 156,413 ha (99 %)	Alluvial Deposits 24,206 ha (98 %)	Detritus cover - Ferruginous Laterite 23,018 ha (55 %); Plutonic complex of the Goías volcanic arc 18,526 ha (44 %)
Relief	Geomorphology	Regional Surface Planing with moderate dissection 80,120 ha (99 %)	Regional Surface Planing with slight dissection 282,071 ha (98 %)	Fluvial plain with raised banks 88,141 ha (51 %), Regional Surface Planing with very weak dissection 73,964 (43 %)	Fluvial plain with raised banks 20,532 ha (84 %)	Regional Surface Planing with weak dissection 41,450 ha (99 %)
	Hypsometry	85 % 390	90 % 330	98 % 240	100 % 240	91 % 300
	Slope less than 8%	54 %	93 %	98 %	95 %	96 %
Current use		Area of pasture 53,130 ha (66 %), and area of natural vegetation 26,601 ha (33 %)	Area of pasture 194,701 ha (68 %), and area of natural vegetation 90,650 ha (32 %)	Area of natural vegetation 107,020 ha (62 %), area of temporary cultivation 36,708 ha (21 %), and area of pasture 26,427 ha (15 %)	Area of natural vegetation 24,519 ha (99.5 %)	Area of pasture 26,944 ha (64 %), and area of natural vegetation 14,600 ha (35 %)
Susceptibility to linear erosion		Top - III	Top and slope - IV	Flat areas - V; Slope - IV	Flat Areas and Water courses - V	Slope - IV
Linear erosion potential		Class III - Low potential 75,500 ha (97 %); Moderate potential 2,050 ha (2 %)	Class III - Low potential 285,925 ha (99 %)	Class III - Low potential 172,152 ha (99 %)	Class III - Low potential 24,570 ha (99 %)	Class III - Low potential 41,755 ha (99 %)

[1] MPC: Morphopedologic compartments.

CONCLUSIONS

The most common soil types in the municipality of São Miguel do Araguaia are *Latossolos Vermelho-Amarelo Distróficos* (Xanthic Hapludox), *Plintossolos Pétricos Concrecionários* (Petronodic Haplargids), *Plintossolos Háplicos Distróficos* (Plinthic Haplaquox), *Gleissolos Háplicos Tb Distróficos* (Typic Endoquents), and *Neossolos Quartzarênicos Órticos* (Typic Quartzipsamments). In general, all soil types have some limitations, which may lead to varying degrees of erosion, depending on physio-hydric aspects and the slope of the land.

The most dissected areas are associated with laterite cover, suggesting the importance of these features in forming soil relief. In these areas, the F horizon or layer occurs at various positions in the soil profile; this variation in depth influences water flow, together with the slope of the terrain and the soil cover. These factors affect erosion and, consequently, the degree of dissection of the soil relief.

The morphopedology technique made it possible to identify and spatialize five morphopedological compartments that resulted from the interaction between physiographic conditions; this aided evaluation of linear erosion of the soil in an area used primarily for cattle ranching.

Results of analyses of susceptibility to and potential for linear erosion show low risk of erosion, even in areas affected by anthropogenic activity, particularly livestock raising, considering aspects related to prior knowledge of the area and the number of field observations.

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